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Methods for Fabrication of Freestanding Nanocellulose Film as a Sustainable Material for Packaging and Biomedical Applications: A Review

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Abstract: Biopolymers are a sustainable alternative to traditional plastics in the medical and packaging fields. Biopolymers are biodegradable and can be used to reduce plastic pollution. They are derived from renewable resources like cornstarch, sugarcane, or cellulose. Cellulose nanomaterials have the potential to revolutionize various industries. However, the production process of nanocellulose films is time-consuming, and there is a need for quick and adaptable methods to fabricate these films. Techniques such as solvent casting, spin coating, roll-to-roll printing, layer-by-layer assembly, vacuum filtration, and spraying are used to fabricate free-standing nanocellulose films, each with its advantages and limitations. The spraying process shows promise in producing nanocellulose films quickly and efficiently. In addition to that, the need for free-standing nanocellulose films in medical packaging and tissue engineering areas was admirable. However, the rapid process for fabrication of the film should be developed for large-scale production and commercialization of films.

Keywords: Nanocellulose; Casting; Coating; Spraying; Filtration; Medical packaging and tissue engineering

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1. Introduction

Biopolymers are rapidly gaining traction as a sustainable and versatile alternative to traditional plastics in both the medical and packaging fields. Some of the key advantages of using biopolymers include environmental benefits, material performance, and functional applications such as packaging and biomedical fields. Unlike petroleum-based plastics, which can take centuries to decompose and often end up in landfills or polluting the ecosystem, biopolymers are biodegradable. This means they can be broken down by microorganisms into harmless substances like water and carbon dioxide, significantly reducing plastic pollution. Biopolymers are derived from renewable resources like corn starch, sugarcane, or cellulose, reducing dependence on finite fossil fuels for plastic production. This also helps to mitigate the greenhouse gas emissions associated with traditional plastic production.

Biopolymers can be engineered to possess specific properties, such as strength, flexibility, or barrier properties, making them suitable for a wide range of applications. For example, some biopolymers are strong enough for making medical devices, while others are designed for food storage and preservation. Certain biopolymers offer superior barrier properties against moisture, oxygen, and grease compared to traditional plastics. These properties can improve the shelf life of packaged goods and reduce food waste.

Biopolymers are often well-tolerated by the human body, making them ideal for use in medical devices, implants, and drug delivery systems. This can reduce the risk of infections and adverse reactions compared to some traditional materials. Biopolymers can be designed to release drugs or other therapeutic agents at a controlled rate over time, improving the efficacy and reducing the side effects of certain medications.

Some biopolymers are compostable, meaning they can break down completely in a compost bin or industrial composting facility, further reducing waste and promoting a circular economy. Consumers are increasingly seeking sustainable packaging options, and biopolymers can help brands meet these demands and improve their environmental footprint. However, it is important to note that not all biopolymers are created equal. Some have higher production costs or require specific disposal conditions. Additionally, research is still ongoing to optimize the performance and affordability of certain biopolymers. Overall, the advantages of biopolymers make them a promising alternative to traditional plastics in both the medical and packaging fields. As research and development continue, we can expect to see even more innovative and sustainable biopolymer applications emerge in the future.

Cellulose nanomaterials (CNMs) have been rapidly developing with immense potential to revolutionize various industries. They are essentially a class of materials derived from cellulose, the main building block of plant cell walls, but shrunk down to the nanoscale. This gives them unique properties that make them attractive for a wide range of applications. The cellulose nanomaterials are classified into cellulose nanofibrils (CNFs) – thread-like structures with high flexibility and strength, cellulose nanocrystals (CNCs) – rod-shaped particles with exceptional mechanical strength and stiffness, and **bacterial nanocellulose (BNC) –** produced by bacteria and boasts high purity and biocompatibility.

CNMs can be stronger than steel on a per-weight basis, making them ideal for lightweight composites and structural materials. Their light weight makes them suitable for applications where like the aerospace and automotive industries. Derived from plants, CNMs are biodegradable and can be produced from sustainable sources, aligning with environmental goals. Besides, they are generally safe for human contact, making them promising for medical and food packaging applications. The surface of CNMs can be modified to achieve desired properties, like improved adhesion or functionality.

CNMs are being explored for drug delivery, tissue engineering, and biosensing due to their biocompatibility and unique properties. Their lightweight, biodegradable nature makes them ideal for sustainable packaging solutions, reducing plastic waste. CNMs can reinforce various materials, like polymers and concrete, leading to stronger, lighter, and more durable structures. Their potential for electrical conductivity and transparency opens doors for flexible electronics and energy storage applications. CNMs can be used as thickeners, stabilizers, and even active ingredients in cosmetic and personal care products.

However, there are many challenges, and further research on cellulose nanomaterials is required. CNMs can be expensive to produce, hindering their widespread adoption. However, research is ongoing to develop more efficient and cost-effective production methods. Scaling up production to meet the demand for various applications remains a challenge. A lack of standardized production and characterization methods can hinder the development and commercialization of CNMs. Despite these challenges, the future of CNMs is bright. With continuous research and development, they have the potential to revolutionize various industries and contribute to a more sustainable future.

One of the most common challenges is the fabrication of the films from the cellulose nanomaterial. This paper reveals the various methods for the fabrication of freestanding cellulose nanomaterial film and its application in packaging and medical applications.

2. Nanocellulose

Nanocellulose is a class of nanomaterial derived from cellulose fibers, a natural polymer that is the main component of plant cell walls. It is a renewable and biodegradable resource with several unique properties that make it promising for a wide range of applications. Nanocellulose is typically produced by breaking down cellulose fibers into smaller pieces, either chemically or mechanically. The resulting nano-fibers are typically only a few nanometers in diameter, which is about 100,000 times smaller than the width of a human hair. Nanocellulose has several properties that make it attractive for a variety of applications. It is strong, stiff, and lightweight, and it has a high surface area. It is also biocompatible, meaning that it is not harmful to living cells. These properties make nanocellulose a promising material for use in a variety of applications. Firstly, they can be made into reinforcement materials: Nanocellulose can be used to reinforce polymers, composites, and concrete, making them stronger and lighter. Besides, nanocellulose can be combined with other materials to create biocomposites, which are materials that are made from both natural and synthetic materials. Biocomposites are often lighter and stronger than traditional materials, and they can also be biodegradable. Moreover, nanocellulose can be used to improve the strength and stiffness of paper and board. This can make it possible to produce lighter and thinner paper products that are still strong enough for their intended uses. In addition, nanocellulose can be used to make a variety of electronic devices, such as transistors, sensors, and batteries. Lastly, nanocellulose can be used to deliver drugs to specific cells or tissues in the body. This allows the development of new treatments for diseases that are currently difficult to treat. Nanocellulose is still a relatively new material, and its full potential is still being explored. However, it is clear that it has a wide range of promising applications. As research into nanocellulose continues, we can expect to see even more innovative uses for this remarkable material.

3. Production of nanocellulose

There are two main pathways for producing nanocellulose: top-down and bottom-up. In the top-down method, lignocellulosic biomass like wood pulp, agricultural residues, or even textiles can be used as feedstock for the manufacture of nanocellulose. Cellulose fibers can be broken down into nanofibrils Through various approaches such as mechanical, chemical, and biological processes. There are several types of mechanical treatment. (1) Microfluidization: Cellulose suspension is forced through narrow channels under high pressure, splitting fibers into nanofibrils. (2) Cryocrushing: Freeze-dried cellulose is crushed at low temperatures, making it brittle and prone to fragmentation. (3) High-intensity ultrasonication: Cellulose fibers are disintegrated using ultrasound waves. Chemical treatment includes acid hydrolysis and oxidation. (1) Acid hydrolysis utilizes strong acids like sulfuric acid to break down hemicellulose and lignin, resulting in isolated cellulose fibers. On the other hand, oxidation involves the use of oxidizing agents such as sodium hypochlorite to selectively target amorphous regions of cellulose, thereby facilitating subsequent mechanical treatment. In the bottom-up method, fermentation processes are initiated using glucose or other simple sugars, with specific microbes responsible for biosynthesizing the cellulose nanofibrils. Particularly in BNC production, specialized bacteria like *Gluconacetobacter xylinus* are employed to synthesize and secrete cellulose nanofibrils into a culture medium. While this process offers advantages such as high purity, a unique nanofiber structure, and potential customization through bacterial strain modification, it is also associated with disadvantages such as a relatively slow production rate and a complex fermentation process.

Each method comes with its advantages and disadvantages. Top-down methods are generally faster and more scalable, but they require chemical modifications of the cellulose and post-processing to remove impurities. In contrast, bottom-up methods produce highly pure BNC with unique properties but are slower and consume more energy. The choice of method depends on several factors, such as the desired properties of the nanocellulose, cost considerations, and environmental impact. Some additional aspects to consider are sustainability, scalability, and cost-effectiveness. Sustainability involves choosing renewable and environmentally friendly feedstocks and using efficient production processes. Scalability involves ensuring that the method is suitable for large-scale production. Cost-effectiveness involves identifying economically viable routes for nanocellulose production. Researchers are constantly exploring new and innovative methods for producing nanocellulose, aiming to address these challenges and unlock its full potential in various applications.

4. Freestanding nanocellulose films

Freestanding nanocellulose films are a remarkable innovation in the materials science field. They are composed of nanofibrils derived from cellulose, a readily available and renewable resource. These films exhibit a unique combination of properties, making them highly promising for diverse applications across various industries. The k**ey characteristics of freestanding nanocellulose films are described below.**

(1) Lightweight and flexible: Their low density and interconnected cellulose network grant them excellent flexibility and resilience.
(2) High strength and mechanical properties: Despite their lightness, some types can rival the strength of steel, offering remarkable potential for structural applications.
(3) Biodegradable and sustainable: Derived from renewable resources, these films offer a sustainable alternative to synthetic materials and contribute to a circular economy.
(4) Tailorable properties: Their surface chemistry and morphology can be modified through chemical treatments, enabling customization for specific applications.
(5) Functional versatility: They can be incorporated into composites, used as filters, energy storage materials, and even printed electronics substrates.

The common applications of freestanding nanocellulose films were as follows,

(1) Packaging: As sustainable alternatives to plastic films, they offer enhanced barrier properties and improved shelf life for food and other products.
(2) Electronics: Their insulating and flexible nature makes them suitable for printed electronics, sensors, and biocompatible electrodes.
(3) Energy storage: They can be used as separators or electrodes in batteries and supercapacitors due to their high porosity and good ionic conductivity.
(4) Biomedical applications: Their biocompatibility and tailorable properties open doors for wound dressings, drug delivery systems, and tissue engineering scaffolds.
(5) Water purification: Their absorbent and functionalized surfaces make them efficient filters for removing contaminants from water.
(6) Construction: Lightweight and strong nanocellulose composites can be used for building materials, offering thermal insulation and improved structural stability.

While highly promising, some challenges remain before widespread adoption. Scalable production methods, consistent film quality, and cost-effectiveness are key areas for continued research and development. However, the remarkable properties and diverse applications of freestanding nanocellulose films hold immense potential for a more sustainable and efficient future. Their versatility and environmental benefits position them as a game-changer in various industries, and further advancements are expected to unlock even more exciting possibilities.

5. Nanocellulose films

One of the main byproducts of the nanocellulose nanomaterial is freestanding nanocellulose film [1]. This is widely used in a number of different fields. Due to the remarkable mechanical strength, barrier effectiveness, and surface characteristics of the nanocellulose-derived film [2]. The exceptional performance of nanocellulose films has led to their use in a variety of applications, including food packaging materials [3], flexible printed electronics base substrates [4], membranes for water and wastewater treatment [5], filtration media [6] for airborne virus removal, fabrication of nanocomposites [7] for a range of uses, scaffolds for tissue engineering and other biomedical applications [8], etc. Furthermore, the cellulose structure of nanocellulose is similar to the glycosaminoglycans found in the extracellular matrix (ECM), making it biocompatible with tissues. This explains why this material can be used as a basis for applications such as drug delivery vehicles and drug targeting, biomedical nanocomposite with antimicrobial agents for wound dressings [9], and tissue engineering constructs [10,11]. As mentioned in the previous section, nanocellulose is a biodegradable and environmentally benign nanomaterial. In order to improve the paper's barrier performance against oxygen and water vapor, nanocellulose film can be laminated to paper substrates using a variety of techniques [12,13].

The use of nanocellulose films is not restricted to the aforementioned. These days, a lot of research is being done on freestanding nanocellulose films. Because of this, there is an exponential increase in the demand for nanocellulose films, which can serve as a good substitute for synthetic plastics. The high energy consumption of nanocellulose production and the time-consuming nature of film formation and drying are the process constraints in the preparation of freestanding nanocellulose films. A variety of techniques are available for producing freestanding nanocellulose films. Among the noteworthy techniques for creating self-standing nanocellulose films are solvent casting, vacuum filtration, hot pressing, layer-by-layer coating, and spraying [14]. The ensuing headings will cover each process's comprehensive description.

The commercialization of nanocellulose films in the market is delayed because of limitations in the production process. The primary issue with film fabrication is the length of time it takes for the film to form. For this reason, it is necessary to form the film quickly in order to increase the rate at which free-standing nanocellulose films are produced. Furthermore, a technique ought to have the capacity to manage elevated concentrations of nanocellulose fibers in suspension. In order to tailor the nanocellulose film's basis weight and thickness, there are options for process change in spraying such as change in CNF suspension consistency and change in engineering parameters. The film's mechanical strength, barrier effectiveness, and other bulk and surface characteristics also depend on the basis weight and thickness of the films. In summary, a quick and adaptable method is needed to fabricate nanocellulose films and modify the parameters of the film formation processes to customize the film's characteristics [15].

6. Methods for producing nanocellulose films

6.1. Solvent casting

Solvent casting is the method used in laboratories to prepare nanocellulose films. Using this technique, the suspension of nanocellulose was put into a Petri dish and left to dry for several hours. The process of drying took longer than a few hours or days, and after the casting was formed, the dried nanocellulose film was removed from the Petri dish [16]. The uniformity and shrinkage of the casted film negatively impact the different properties of nanocellulose films. Furthermore, the concentration of nanocellulose suspension determines the film's thickness and basis weight, both of which are critical factors in regulating the film's mechanical strength and barrier performance. Furthermore, longer drying times for solvent casting to form the film would result from higher nanocellulose suspension concentrations. The method's drawbacks include its limited application to laboratory-scale film formation, and the development of shrinkage and wrinkles on the nanocellulose film, which lead to low mechanical strength and inadequate barrier performance. It is unable to scale up for pilot scale and large-scale production of the films to meet the enormous demand in the current era due to the slow evaporation of the solvent from the nanocellulose suspension cast on the Petri dish [14].

6.2. Spin coating

One of the methods for creating these films on the surface is called spin coating, and it can be applied to a variety of thin-film research projects. Freestanding nanocellulose films with nanometric thickness are created using this technique. The films made by spin coating can be used to study how different biomolecules behave with the hydroxyl group of the nanocellulose in the film as well as how biological molecules interact with the film. Using high-speed spinning, this technique eliminates extra NC suspension, leaving behind ultra-thin NC films. This is a lab-scale technique that can satisfy the demands of the current lab research on nanocellulose films while still meeting the requirements of nanocellulose film. The method for creating thin films to study the interaction of biomolecules with cellulose fibrils is fully finished [17,18].

6.3. Roll-to-roll printing

A quick and efficient method for producing nanocellulose films in a semi-batch or continuous operation mode is roll-to-roll coating/printing. Furthermore, this technique can be used to coat nanocellulose on cellulose substrates like paper and other paper boards in a continuous board. In order to improve the paper's barrier performance by increasing its mechanical strength, coated nanocellulose on the substrates of the paper formed a barrier film. Nanocellulose coating is applied in a similar way on the plastic substrates, and the nanocellulose film on the plastic peels off. The film can be peeled off of the plastic substrates and utilized as a building block to create a variety of functional materials. This method replicates the 400 nm surface roughness of the nanocellulose film from the plastic substrates. The film's surface roughness can be used to create printed and flexible electronic substrates. The concentration of the nanocellulose suspension, the kind of plastic substrates used, and the web velocity during the coating process can all affect the nanocellulose film's thickness and basis weight [17,18].

6.4. Layer-by-layer assembly

This is the process of using coating to prepare a nanocellulose film with a thickness ranging from nanometers to microns. This technique can be applied to thin functional films as well as coatings on various substrates for particular uses. This technique is typically applied when coating substrates or films to engineer their surfaces. The surface functionalization of the substrates in the nanometer range of the functional material's thickness was also accomplished using this technique [17].

6.5. Vacuum filtration

Vacuum filtration is the standard procedure for producing free-standing nanocellulose films as of now [1]. This process is a lab-based adaptation of the Fourdrinier machine, which is used to produce large quantities of paper and related cellulose fiber materials. The nanocellulose suspension is poured into the column during the vacuum filtration process, and the bottom of the column is covered in a metallic mesh. Upon applying the vacuum at the bottom of the column, the water contained in the nanocellulose suspension is drained through the mesh.

The metallic mesh is then covered in a sheet of nanocellulose fibers, and the wet film can be removed from the mesh by couching it with blotting paper. Next, the wet film is peeled and dried in a drum dryer. The type of mesh and the size of its pores determine how long the nanocellulose fibers stay on the mesh. A smaller mesh will result in a longer drainage time. The drainage time in the filtration process increases exponentially with the suspension of nanocellulose. Consequently, wet film formation on the mesh takes anywhere from 10 minutes to 24 hours. Ball milling, high-pressure homogenization, and acid hydrolysis of cellulose nanofibers can all be used to fibrillate nanocellulose and reduce the amount of time needed for filtration to create the wet film of nanocellulose. This measure reduces the drainage or dewatering period to 10 minutes [1]. In addition to being a time-consuming process, the wet film's thickness and basis weight increase as the filtration time increases. The developed wet film on the mesh functions as a barrier to additional filtration procedures. The main disadvantage of this method is that there will be filter markings on the films produced, which will impact the film's surface roughness and uniformity [17].

6.6. Spraying process

The process of creating mist or atomized particles on the base surface is known as spray coating [19]. Compared to other coating processes like rod coating, bar coating, etc., this coating offers several advantages [20]. Recently, this technique has also been reported for the development of nanocellulose coating on paper substrates and free-standing nanocellulose films [20]. After drying, a film is created using the idea of spraying a suspension of nanocellulose fibers on a solid surface [21]. As a base surface, the solid surface can be used for impermeable substrates like silicon wafers, fabric media, and stainless-steel plates, or permeable substrates like paper and paper boards [15]. Spraying has a number of benefits, including contour coating, contactless coating with the base surface, and the base surface's topography not affecting the coating procedure [15].

A novel method for producing nanocellulose films in a free-standing mode is spraying fibers [20]. **Figure 1** illustrates several spraying process sequences. The steps in the spray coating process are as follows: first, a spray jet of cellulose nanofibers is formed from the nanocellulose suspension; next, the sprayed jet is atomized into the cellulose nanofiber suspension mist. The process of atomization involves the disintegration of liquid lamella and the disintegration of the suspension jet of nanocellulose. A film forms on the base surface as a result of the fine droplets from atomization coalescing on the contact surface. The film-forming properties of the polymers through hydrogen bonding cause sprayed droplets to coalesce when these nanofibers are sprayed onto a solid surface. After drying, the film that forms on the surface can be peeled off the substrates [17].

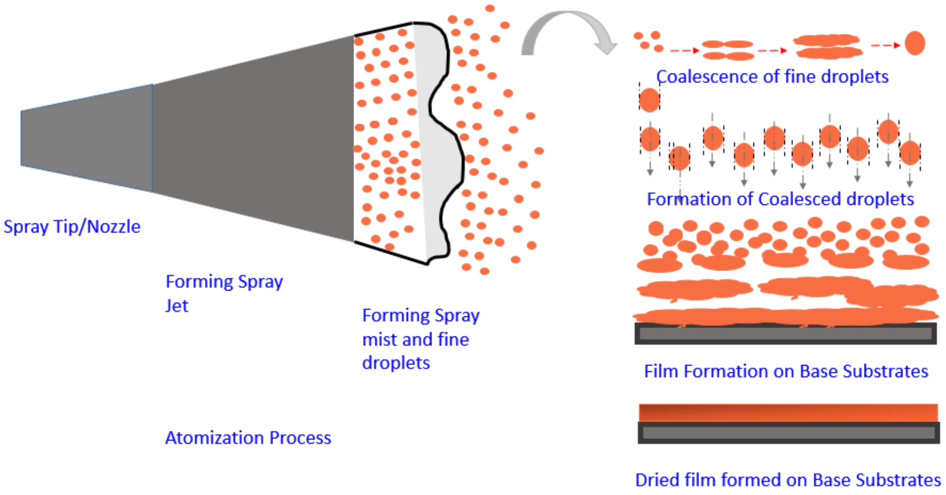

Figure 1. Sequences in the spraying process on the base surface [17]

Table 1. Processing time for nanocellulose films using the conventional method

Processing method	Processing time	Basis weight (g/m^2)
Spray deposition	10–27 min	13.7–124
Vacuum filtration	3 min	56.4
Membrane filtration	55 min	56
Filter paper-based filtration	~48 h	NA
Fabric filtration	1–3 h	55
Current spray coating*	< 1 minute	52.8–193.0

There are two types of nanocellulose fiber spraying: (1) on permeable substrates like paper substrates and paper boards; and (2) on the base surface. Recent experiments with spraying cellulose nanofibers on newsprint, blotting, and packaging papers improved the mechanical strength and barrier performance of the paper substrates. To create free-standing nanocellulose films, cellulose nanofibers are sprayed onto impermeable solid substrates like silicon wafers, super-polished stainless-steel plates, and stainless-steel plates [15].

When it comes to spraying cellulose nanofibers onto permeable substrates, this technique outperforms all others, including vacuum filtration, rod coating, and bar coating, in terms of coat weight on paper substrates. The amount of nanocellulose sprayed on the surface depends on the suspension's viscosity and is not affected by the concentration of the nanocellulose. This technique can be used to create barrier layers of nanocellulose on paper substrates [22]. Spraying a high solid content of nanocellulose suspension on the paper substrates can reduce the water content to accelerate the drying process [23].

To fabricate the freestanding cellulose film, nanocellulose fiber can be deposited on a stainless-steel plate during the process of spraying fibers on impermeable substrates [15]. Stainless steel plates [20], silicon wafers [24], and fabric surfaces [24] are the other impermeable substrates. Furthermore, an attempt has been made to fabricate a three-dimensional free-standing film by spraying microfibrillated cellulose on 3D brass architecture. This method allowed for the observation of the spray-coated film's creases and scratches. Each process for creating free-standing nanocellulose film comes with its advantages and disadvantages [21]. A new spraying method has been developed and its performance in terms of speed and flexibility in comparison to other conventional methods has been discussed [15]. In short, the production of freestanding nanocellulose films using solvent casting is a laborious process. The solvent from the nanocellulose suspension takes a long time to evaporate, and the surface of the films produced is uneven. The solid content in the nanocellulose suspension increases the drainage time in the vacuum filtration process. One of the most important tasks in this method is to peel the wet nanocellulose film from the filter mesh, which will often leave some markings. For this reason, standards have been developed for the preparation of freestanding nanocellulose films and nanocellulose barrier coats on paper substrates [14].

7. Criteria for fabrication of freestanding nanocellulose films

The current methods for preparing freestanding nanocellulose films are slow compared to the extrusion method used to manufacture plastic films or synthetic plastic coating on paper substrates. Besides, they cannot be scaled up for large-scale production. To meet the demand for the films and expand their use in a variety of fields, the production of barrier coatings on paper and nanocellulose films must be quick and flexible.

Therefore, an efficient technique that produces high-quality freestanding nanocellulose should be developed. There are several aspects that should be taken into account in developing this technique.

(1) The method of adjusting the nanocellulose film's basis weight and thickness should be efficient.

(2) The concentration of the nanocellulose suspension should be adjusted to optimize the strength of the films without compromising the operating time.

(3) The film produced should be uniform and on par with traditional techniques like vacuum filtration.

(4) To avoid additional processing steps like dewatering, vacuum drying, and couching of the wet film, nanocellulose films should be produced in a single step.

(5) The nanocellulose films produced should not require any chemical or physical modification to adjust their roughness [14].

8. Medical packaging application of freestanding nanocellulose films

Freestanding nanocellulose films hold immense potential for revolutionizing medical packaging due to their unique combination of properties that cater to the stringent requirements of this field.

(1) Wound dressings

Free-standing nanocellulose films can be used as a base biomaterial for the development of wound dressings due to some of their characteristics.

- (i) Biocompatibility: Freestanding nanocellulose films are non-toxic and non-irritating, ideal for direct contact with skin or wounds.
- (ii) High absorbency: Their porous structure absorbs exudates effectively, promoting healing and reducing the risk of infection.
- (iii) Antibacterial properties: Freestanding nanocellulose films can be functionalized with antimicrobial agents to combat wound infections.
- (iv) Controlled drug delivery: Drugs can be embedded within the nanocellulose network for sustained and targeted release at the wound site.

(2) Surgical instrument packaging

Nanocellulose films can used to develop packaging for surgical instruments due to the following advantages:

- (i) Sterilization: Freestanding nanocellulose films can be sterilized effectively with various methods, making them suitable for sterile packaging of surgical instruments.
- (ii) Barrier properties: Freestanding nanocellulose films can be tailored to provide excellent barrier properties against moisture, oxygen, and microorganisms, maintaining instrument sterility.
- (iii) Transparency: Some freestanding nanocellulose films are transparent, allowing visual inspection of instruments without compromising sterility.

(3) Pharmaceutical packaging

Nanocellulose films can be considered to be a potential alternative for pharmaceutical drugs and intermediates.

- (i) Blister packs and strips: Freestanding nanocellulose films can be sustainable alternatives to plastic blister packs for tablets and capsules.
- (ii) Controlled-release coatings: Freestanding nanocellulose films can be applied as coatings on pills or capsules for controlled drug release within the body.
- (iii) Sensor integration: Freestanding nanocellulose films can be embedded with sensors to monitor

temperature, humidity, or even drug degradation within the packaging, ensuring product quality and patient safety.

(4) Blood and tissue storage

Nanocellulose films can be used for blood and tissue storage due to the following characteristics:

- (i) Biocompatibility: Freestanding nanocellulose films are compatible with blood and tissues, minimizing the risk of contamination or adverse reactions.
- (ii) Oxygen and moisture regulation: Tailored freestanding nanocellulose films can create microenvironments optimized for specific blood or tissue types, prolonging their storage life.
- (iii) Antimicrobial properties: Freestanding nanocellulose films can be functionalized to prevent bacterial growth, further enhancing the safety of stored blood and tissues.

9. Environmental benefits

(1) Sustainability: Freestanding nanocellulose films are derived from renewable resources and are biodegradable, reducing the environmental impact of medical packaging waste.

(2) Lightweight and flexible: Freestanding nanocellulose films are lightweight and flexible, making packaging and transportation easier and more efficient.

(3) Customization: Freestanding nanocellulose films can be tailored to specific requirements in terms of barrier properties, biocompatibility, and functionality, offering versatile solutions for diverse medical packaging needs.

Overall, freestanding nanocellulose films have the potential to significantly improve medical packaging, enhancing patient safety, reducing environmental impact, and offering cost-effective solutions for the healthcare industry. Continued research and development are expected to further refine their properties and unlock even more innovative applications in medical packaging.

10. Tissue engineering applications of freestanding nanocellulose films

Freestanding nanocellulose films are novel materials with promising applications in the field of tissue engineering. Their unique properties offer several advantages for creating scaffolds and other implantable structures to promote tissue regeneration. Here are some potential applications for freestanding nanocellulose films in tissue engineering.

10.1. Scaffold material

(1) Biocompatibility: Nanocellulose is a natural polymer with inherent biocompatibility, meaning it is well-tolerated by the body and does not trigger harmful immune responses. This makes it ideal for scaffolding materials that interface directly with cells and tissues.

(2) High porosity and surface area: Freestanding films can be engineered with controlled porosity and high surface area, mimicking the natural extracellular matrix where cells reside and proliferate. This encourages cell attachment, migration, and differentiation, which is crucial for tissue regeneration.

(3) Mechanical properties: Depending on the processing technique and composition, nanocellulose films can be tailored to exhibit specific mechanical properties similar to various tissues. This includes flexibility for soft tissues like skin and muscles, or rigidity for bone and cartilage repair.

(4) Tailorable functionality: The surface of nanocellulose films can be chemically modified to incorporate specific functional groups or biomolecules. This allows for targeted cell adhesion, controlled drug

delivery, or even incorporation of electrical conductivity for nerve regeneration.

10.2. Applications in tissue engineering

(1) Skin tissue engineering: Nanocellulose films offer a promising alternative for wound dressings and skin grafts. Their biocompatible nature facilitates wound healing, while their porosity promotes proper cellular infiltration and vascularization. They can also be loaded with growth factors or antimicrobial agents to further enhance healing.

(2) Cartilage and bone tissue engineering: The mechanical properties of nanocellulose can be tuned to resemble cartilage and bone. Additionally, their porous structure allows for cell infiltration and matrix deposition, essential for these tissues' regeneration.

(3) Vascular tissue engineering: Nanocellulose films can be engineered into tubular structures for blood vessel replacement. Their flexibility aligns with the natural movement of blood vessels, while their surface can be modified to promote endothelial cell adhesion and blood clotting.

(4) Neural tissue engineering: Due to their high surface area and ability to be patterned, nanocellulose films hold promise for guiding and supporting nerve regeneration. Their electrical conductivity can even be enhanced to promote nerve signal transmission.

11. Challenges and prospects

While freestanding nanocellulose films offer immense potential in tissue engineering, some challenges remain. Controlling these films' mechanical properties and long-term degradation behavior requires further research. Additionally, optimizing cell-material interactions and developing fabrication techniques for complex tissue structures are ongoing areas of exploration. Overall, freestanding nanocellulose films represent a significant advancement in tissue engineering materials. Their versatility, biocompatibility, and tailorable properties offer exciting possibilities for the development of next-generation implantable structures and scaffolds for various tissue regeneration applications.

12. Conclusion

Nanocellulose films demonstrate exceptional mechanical strength, barrier effectiveness, and surface characteristics, making them suitable for various applications such as food packaging, flexible electronics, water treatment, filtration, and biomedical applications. However, the production of nanocellulose films is time-consuming, and there is a need for quick and adaptable methods to fabricate these films. Techniques such as solvent casting, spin coating, roll-to-roll printing, layer-by-layer assembly, vacuum filtration, and spraying are used to create nanocellulose films, each with its advantages and limitations. The spraying process shows promise in producing nanocellulose films quickly and efficiently. In addition to that, the need for freestanding nanocellulose films in medical packaging and tissue engineering area was commendable. However, the rapid process for fabrication of the film should be developed for large-scale production and commercialization of films.

Disclosure statement

The author declares no conflict of interest.

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