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Application of Spray Coating in the Fabrication of Free Standing Nanocellulose Films and Barrier Coating on the Paper Substrates

Kirubanandan Shanmugam*

Independent Research Professional, Chennai, India

***Corresponding author:** Kirubanandan Shanmugam, ksh1005@yahoo.com

Abstract: Spray coating is a novel concept for fabricating free-standing film and producing barrier coating on paper substrates. The spraying gives comparable efficacy with vacuum filtration in terms of operation time, film quality, and process intensification approach. The smooth films created by spraying nanocellulose onto the polished impermeable surface could serve as a platform for a variety of sustainable functional devices. Finally, the application of spray-coating barriers and nanocellulose films on paper substrates is the focus of the spray-coating concept designed to create smooth nanocellulose films. One of the most important factors that affect the performance of different cellulose-based functional materials is the smoothness of nanocellulose film coated with sprays in the production of flexible and printed electronics. The uses of nanocellulose film as a high-performance barrier material and the possible replacement of synthetic plastic packaging are expanded by spray coatings. The process of creating a nanocellulose film using spray coating takes less than a minute. Compared to vacuum filtering, this method offers excellent speed potential for nanocellulose films. The wet layer of spray coating takes more than 24 hours to dry in a controlled laboratory environment, using air drying. Future research projects will improve the drying process of wet films. The film spray process serves as a proof of concept, and the quality of the film produced by this method contrasts with vacuum filtration. Studying spray coating wet film drying outside the scope of this research is not part of the scope of this study, and additional research is needed in this area. The shiny film that is created by spraying nanocellulose on the impermeable polished surface can serve as a platform for various sustainable functional devices.

Keywords: Spray coating; Nanocellulose; Freestanding film; Barrier coating; Biomaterial and tissue engineering

1. Introduction

Synthetic plastics are widely used as packaging materials due to their versatility and durability. They offer excellent protection, are lightweight, and can be molded into various shapes and sizes. However, their non-biodegradable nature poses environmental challenges. Efforts are being made to develop more sustainable alternatives to reduce plastic waste and promote a circular economy. The environmental problem posed by synthetic plastics as packaging materials stems from their non-biodegradable nature. While these plastics offer numerous benefits such as versatility, durability, and lightweight properties, they do not break down naturally and contribute to pollution and waste accumulation. To address this issue, efforts are being made to develop more sustainable alternatives that promote a circular economy and reduce plastic waste.

Biopolymers such as cellulose fibers and nanocellulose are emerging as promising solutions to the environmental problem caused by synthetic plastics used as packaging materials. Unlike traditional plastics, biopolymers are biodegradable and can naturally break down over time, reducing pollution and waste accumulation. Despite their eco-friendly nature, biopolymers still offer the same benefits as synthetic plastics, including versatility, durability, and lightweight properties. Promoting the use of biopolymers in packaging can contribute to a more sustainable future, fostering a circular economy and minimizing plastic waste. Biopolymers are increasingly being explored as barrier materials due to their sustainable and environmentally friendly nature. These materials offer several advantages over traditional petroleum-based polymers, such as being biodegradable, renewable, and often sourced from abundant natural resources like plants or microorganisms. Below are some key points about biopolymers as barrier materials. Renewable sourcing: Biopolymers can be sourced from renewable resources such as starch, cellulose, chitosan, proteins, and lipids. This reduces reliance on finite fossil fuels and helps mitigate environmental impact. Biodegradability: Many biopolymers are inherently biodegradable, meaning they can be broken down by microorganisms into harmless byproducts like water, carbon dioxide, and biomass. This makes them attractive for applications where reducing plastic waste is a priority, such as in single-use packaging. Barrier properties: Biopolymers can be engineered to possess excellent barrier properties against moisture, gases such as oxygen and carbon dioxide, and other substances. This makes them suitable for various packaging applications, including food packaging, where maintaining freshness and extending shelf life are crucial. Functionalization: Biopolymers can be chemically modified or combined with other materials to enhance their barrier properties further. For example, nanocomposites, which incorporate nanoparticles into the biopolymer matrix, have shown promise in improving mechanical strength and barrier performance. Compatibility with existing processes: Biopolymers can often be processed using existing equipment and manufacturing processes, making them easier to integrate into current production systems. Regulatory considerations: Regulatory agencies increasingly favor biopolymers due to their reduced environmental impact. However, ensuring compliance with safety standards and regulations is essential for widespread adoption. Challenges: Despite their promise, biopolymers still face challenges such as cost competitiveness with petroleum-based alternatives, limited mechanical properties in some cases, and the need for further research and development to optimize their performance. Biopolymers offer a promising avenue for the development of sustainable barrier materials, with the potential to significantly reduce environmental pollution and contribute to a more circular economy.

1.1. Nanocellulose

Nanocellulose (NC) is gaining recognition as a potential replacement for synthetic plastics in packaging materials. Obtained from natural sources, nanocellulose presents a promising solution to the environmental issues associated with conventional plastics. Unlike their synthetic counterparts, nanocellulose is biodegradable and can naturally decompose over time, reducing pollution and waste accumulation. Despite its environmentally friendly characteristics, nanocellulose still offers the same benefits as synthetic plastics, such as versatility, durability, and lightweight properties. Advocating for the use of nanocellulose in packaging can contribute to a more sustainable future, promoting a circular economy and minimizing the generation of plastic waste. Nanocellulose, derived from cellulose, the most abundant biopolymer on Earth, has garnered significant interest for various applications due to its unique properties. Below are some of the diverse applications of nanocellulose. Packaging materials: Nanocellulose can be used as a sustainable alternative to conventional petroleum-based packaging materials. It offers excellent barrier properties against gases and moisture, which is crucial for preserving the freshness and shelf life of packaged goods. Biomedical applications: Nanocellulose has shown promise in biomedical applications such as tissue engineering, wound dressings, drug delivery systems, and scaffolds for regenerative medicine. Its biocompatibility, biodegradability, and ability to mimic the extracellular matrix make it an attractive material for these purposes. Films and coatings: Nanocellulose can be used to produce thin films and coatings with enhanced mechanical strength, flexibility, and barrier properties. These films can be applied to various surfaces to protect against moisture, oxygen, and UV radiation, making them suitable for applications in food packaging, electronics, and cosmetics. Composites: Nanocellulose can be incorporated into polymer matrices to produce lightweight and high-strength composites for automotive, aerospace, and construction industries. These composites offer improved mechanical properties, such as stiffness and toughness, while reducing the overall weight of the final product. Paper and textiles: Nanocellulose can enhance the strength, durability, and absorbency of paper products and textiles. It can be used as a coating or additive in papermaking processes to improve printability, smoothness, and water resistance. In textiles, nanocellulose can impart functional properties such as moisture management, flame retardancy, and antibacterial activity. Oil and gas industry: Nanocellulose-based materials have potential applications in the oil and gas industry for drilling fluids, cement additives, and enhanced oil recovery. Their rheological properties, biodegradability, and environmental compatibility make them attractive alternatives to conventional chemicals used in these processes. Electronics: Nanocellulose-based materials have been explored for applications in flexible electronics, energy storage devices, and sensors. Their transparency, flexibility, and electrical conductivity make them suitable for use in displays, touchscreens, batteries, and capacitors. Environmental remediation: Nanocellulose can be functionalized with various chemical groups to adsorb pollutants from water and soil, making it useful for environmental remediation applications such as wastewater treatment and oil spill cleanup. Overall, nanocellulose holds great promise for a wide range of applications across diverse industries, offering sustainable and environmentally friendly solutions to current challenges. Continued research and development efforts are expected to further expand its commercial potential in the coming years [1–4].

1.2. Spray coating

Spray coating is a technique used to prepare free-standing nanocellulose film. This film, derived from natural sources, is a promising alternative to synthetic plastics in packaging materials. Spraying nanocellulose on the polished metal surface is a novel concept for fabricating the free-standing film and producing barrier coating on the paper substrates. Recently, this process was reported to fabricate the free-standing films and barrier coating on the paper substrates. The operation time for forming wet nanocellulose film and barrier coating on the paper was less than 1 minute. The spraying gives comparable efficacy with vacuum filtration in terms of the operation time, film quality, and process intensification approach. Spray coating is indeed a versatile fabrication method for producing free-standing nanocellulose films as well as for applying barrier coatings onto paper substrates. Below is the process works and its application in creating nanocellulose films and barrier coatings. Spray coating process: Preparation of nanocellulose solution: Nanocellulose is typically dispersed in a solvent to form a solution. The solvent choice depends on the type of nanocellulose used and the desired properties of the final film or coating. Spraying: The nanocellulose solution is then sprayed onto a substrate using a spray gun or nozzle. The substrate can be a solid surface, such as a glass slide or silicon wafer, for producing free-standing films, or a flexible substrate like paper for creating coatings. Drying: After spraying, the solvent evaporates, leaving behind a uniform layer of nanocellulose on the substrate. The drying conditions can be adjusted to control the film thickness and properties.

Spray coating is a rapid process for fabricating free-standing nanocellulose films. Spray coating enables the fabrication of thin, uniform nanocellulose films on various substrates. By controlling the spraying parameters such as spray rate, nozzle distance, and solution concentration, the thickness and morphology of the films can be tailored to specific applications. Free-standing nanocellulose films find applications in flexible electronics, biomedical devices, sensors, and barrier materials due to their transparency, mechanical strength, and barrier properties. In addition to that, spraying can be used for nanocellulose barrier coating on papers. Spray coating can also be used to apply nanocellulose-based barrier coatings onto paper substrates to enhance their properties. Nanocellulose coatings can improve the barrier performance of paper against moisture, oxygen, and grease, thereby extending the shelf life of packaged products. These coatings can be applied using industrial spray coating equipment in large-scale manufacturing processes, offering a cost-effective and sustainable solution for paper packaging. The advantages of spray processing of spray coating offers several advantages, including uniform coating deposition, scalability to industrial production, and compatibility with a wide range of substrates. Nanocellulose-based coatings produced by spray coating are environmentally friendly, renewable, and biodegradable, making them attractive for sustainable packaging applications. However, there are some challenges and considerations such as the optimization of spray coating parameters is crucial to achieve desired film thickness, uniformity, and adhesion to the substrate, Selection of appropriate solvent and nanocellulose type is important to ensure compatibility and desired film properties, Adhesion between the nanocellulose coating and the paper substrate needs to be optimized to prevent delamination and ensure mechanical integrity. In summary, spray coating is a versatile fabrication method for producing free-standing nanocellulose films and applying barrier coatings onto paper substrates, offering opportunities for the development of sustainable packaging materials with enhanced barrier properties.

2. Application for spray coating

The idea of spraying nanocellulose on the base surface could be used to coat paper substrates to improve their mechanical strength and barrier qualities [5–6]. The surface of paper can be coated with nanocellulose using a variety of coating techniques such as bar coating, rod coating, solvent casting, vacuum filtration, and spray coating [7]. A barrier layer is created on the paper surface by the nanocellulose coating on the paper substrates [8]. The transfer of gaseous substances such as oxygen, air, and water vapor is resisted by this layer. The coated paper substrates' mechanical strength and barrier effectiveness are increased as a result. However, wide pores in the cellulose fiber structure of the pure paper substrate allow for significant air and water vapor passage [9]. To address this problem, the paper can be waxed, coated with synthetic polymers, or extruded with some of them to improve the mechanical characteristics and barrier effectiveness of the paper substrates [10]. Nevertheless, these surface coatings on paper are not recyclable and may pollute the land, endangering the environment. For this reason, to improve the coating's material compatibility with paper materials, nanocellulose coating of the paper or paper board was necessary. Furthermore, the coating creates a pathway on the paper surface that increases the barrier qualities of the paper substrates. Nanocellulose is also a biodegradable and environmentally friendly nanomaterial [11].

The uncoated paper's SEM micrograph in **Figure 1** demonstrates the pores on its surface, which greatly facilitate the passage of air and water vapor. These pores can be filled by the paper's nanocellulose coating, which also creates a barrier layer on the surface of the paper [12]. The paper's porosity guarantees effective control over the movement of gaseous substances. Additionally, the pores guarantee that water vapor or air diffuses across the paper substrates in a regulated manner. The surface, barrier, and tensile characteristics of the substrates can be tailored by the coating NC on the paper substrate [10, 13].

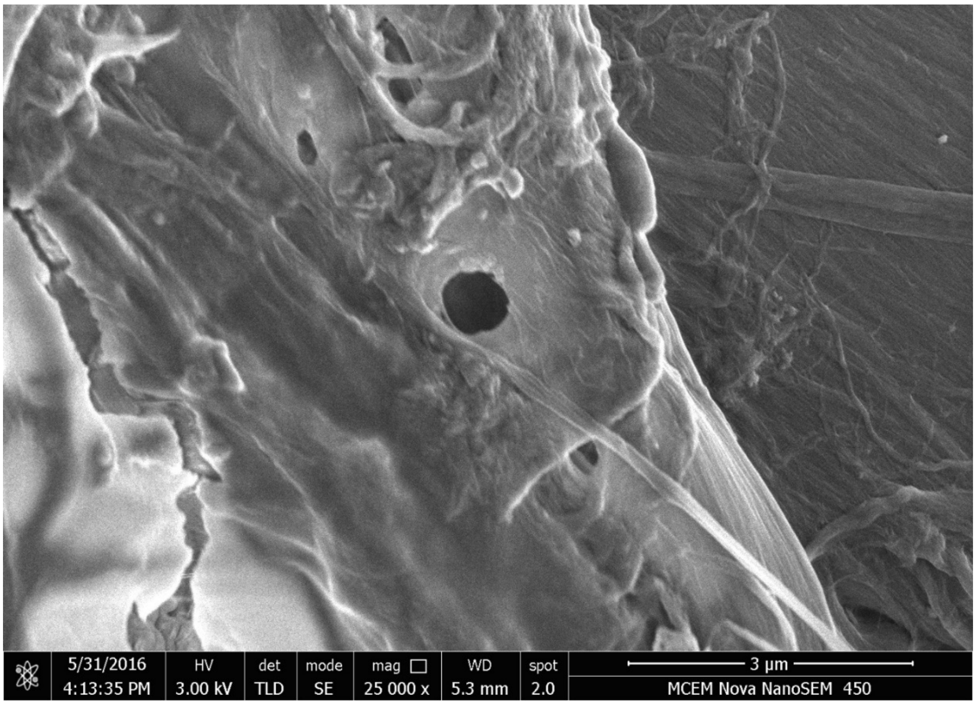


Figure 1. SEM micrograph of plain packaging paper

The SEM micrograph of the paper coated with nanocellulose by spray coating is displayed in **Figure 2**. The spray-coated surface exhibits cellulose nanocrystal and nanocellulose particles, which form a complex pathway for the diffusion of oxygen, air, and water vapor. Within the cellulose nanofibrous matrix, the nanocellulose is composed of both crystalline and amorphous regions [14]. These areas are crucial in the development of the intricate, winding pathways that carry oxygen, air, and water vapor. The coated substrates' barrier performance improved as a result [15].

The barrier properties of nanocellulose-coated paper substrates arise from several mechanisms that contribute to the effective prevention of the permeation of gases, liquids, and other substances. Below are some key mechanisms involved. Tortuosity effect: Nanocellulose coatings create a tortuous path for the diffusion of gases and liquids through the paper substrate. The presence of nanocellulose nanoparticles on the surface and within the pores of the paper increases the path length that molecules must traverse, slowing down their movement and reducing permeation rates. Nanostructure formation: Nanocellulose coatings can form dense and uniform nanostructures on the surface of the paper substrate. These nanostructures create physical barriers that hinder the passage of molecules, effectively blocking the permeation of gases and liquids. Hydrophobicity/hydrophilicity: Depending on the surface properties of the nanocellulose and any additional surface modifications, nanocellulose coatings can exhibit hydrophobic or hydrophilic characteristics. Hydrophobic coatings repel water and other liquids, while hydrophilic coatings enhance moisture absorption and retention. By controlling the surface chemistry of the nanocellulose coating, the barrier properties against specific substances can be tailored accordingly. Intermolecular interactions: Nanocellulose coatings can interact with molecules through hydrogen bonding, electrostatic interactions, and van der Waals forces. These intermolecular interactions can further impede the diffusion of gases and liquids through the paper substrate, enhancing its barrier properties. Film formation and thickness: The formation of a continuous and uniform nanocellulose film on the paper substrate, achieved through techniques such as spray coating or roll-to-roll coating, contributes to effective barrier performance. Thicker nanocellulose coatings typically provide better barrier properties due to the increased path length and density of the barrier material. Mechanical reinforcement: Nanocellulose coatings can reinforce the mechanical strength of the paper substrate, reducing the likelihood of defects and permeation pathways. This mechanical reinforcement helps maintain the integrity of the barrier over time, even under external stresses such as bending or stretching. Chemical resistance: Nanocellulose coatings can be chemically modified to enhance resistance against specific substances, such as oils, greases, or acidic or alkaline solutions. These modifications further improve the barrier properties of the coated paper substrate against targeted contaminants. By leveraging these mechanisms, nanocellulose coatings can effectively enhance the barrier properties of paper substrates, making them suitable for a wide range of packaging applications where protection against moisture, oxygen, and other external factors is essential.

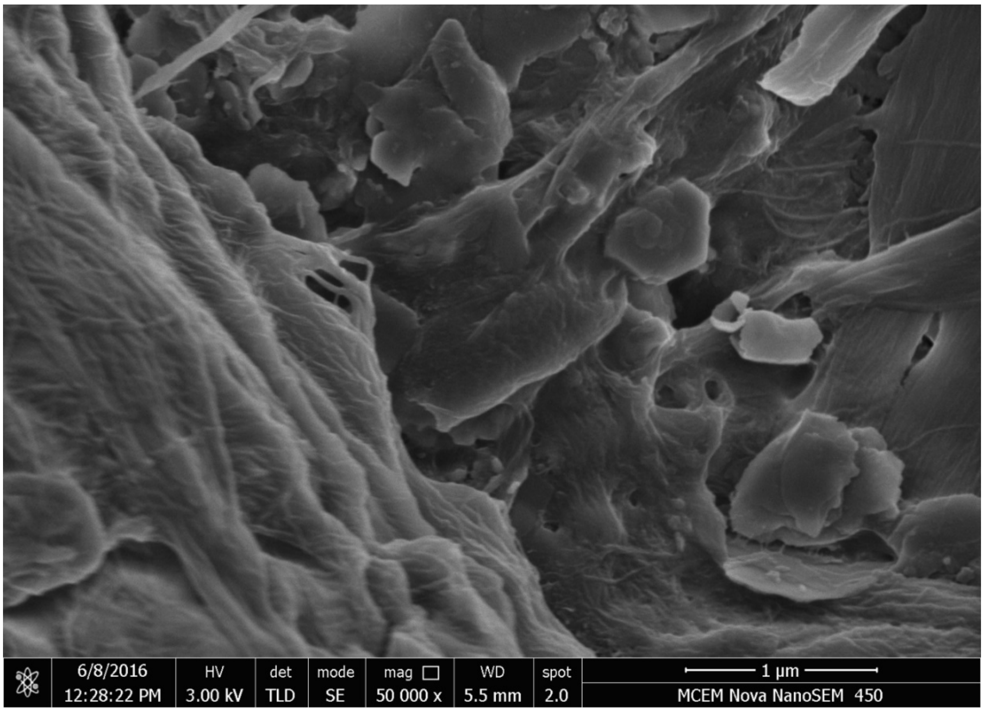


Figure 2. SEM Image of nanocellulose-coated paper via spray coating

The SEM micrograph of the uncoated paper is shown in **Figure 3**, demonstrating how widely open the pores are on the surface. The diameter and length of the fibers in the paper substrates are both good sizes. A good coating or layer is formed on the surface of the paper and its substrates by the spraying of nanocellulose. The uncoated paper substrate's surface pores are widely open, making it easy for oxygen and water vapor to transfer, which reduces the material's barrier potential. The coating of paper substrate with nanocellulose can obstruct the surface pores [10, 16]. Scanning Electron Microscopy (SEM) analysis of paper provides valuable insights into its microstructure, surface morphology, and fiber characteristics. An interpretation of SEM images of paper is as follows. Fiber morphology: Long fibers: SEM images reveal the presence of long cellulose fibers that make up the bulk of the paper structure. These fibers appear as elongated structures with varying thicknesses and surface roughness.

Cross-sectional view: Cross-sectional SEM images show the layered structure of paper, with individual fibers arranged in parallel layers. The arrangement of fibers contributes to the strength and flexibility of the paper. Fiber bonding: Fiber-to-fiber bonds: SEM images can show the points where individual fibers bond together to form a cohesive paper structure. These bonds, facilitated by hydrogen bonding and mechanical interlocking, are crucial for the integrity of the paper. Interfiber spaces: Gaps or pores between adjacent fibers are visible in SEM images. The size and distribution of these spaces affect the permeability of the paper to gases and liquids. Surface morphology: Surface roughness: SEM images reveal the surface roughness of the paper, which influences properties such as printability, ink adhesion, and surface texture. Smooth surfaces are desirable for high-quality printing applications. Coating layers: In coated papers, SEM can identify the presence of additional layers applied to the paper surface, such as clay or polymer coatings. These coatings improve the paper's smoothness, brightness, and print quality. Fiber orientation: Alignment: SEM images provide information about the orientation and alignment of fibers within the paper. Uniform fiber orientation contributes to the paper's mechanical strength and dimensional stability. Distribution: SEM analysis can reveal the distribution of fibers within the paper matrix, including areas of fiber clustering or uneven dispersion. Microscale features: Microfibrils: High-resolution SEM images may show the presence of cellulose microfibrils within individual fibers. These microfibrils contribute to the mechanical strength and stiffness of the paper. Surface treatments: SEM can detect surface treatments or modifications applied to the paper, such as sizing agents or coatings, which alter its surface properties and performance characteristics. SEM analysis of the paper provides detailed information about its microstructure, fiber characteristics, surface morphology, and any defects or contaminants present, enabling a comprehensive understanding of its properties and performance.

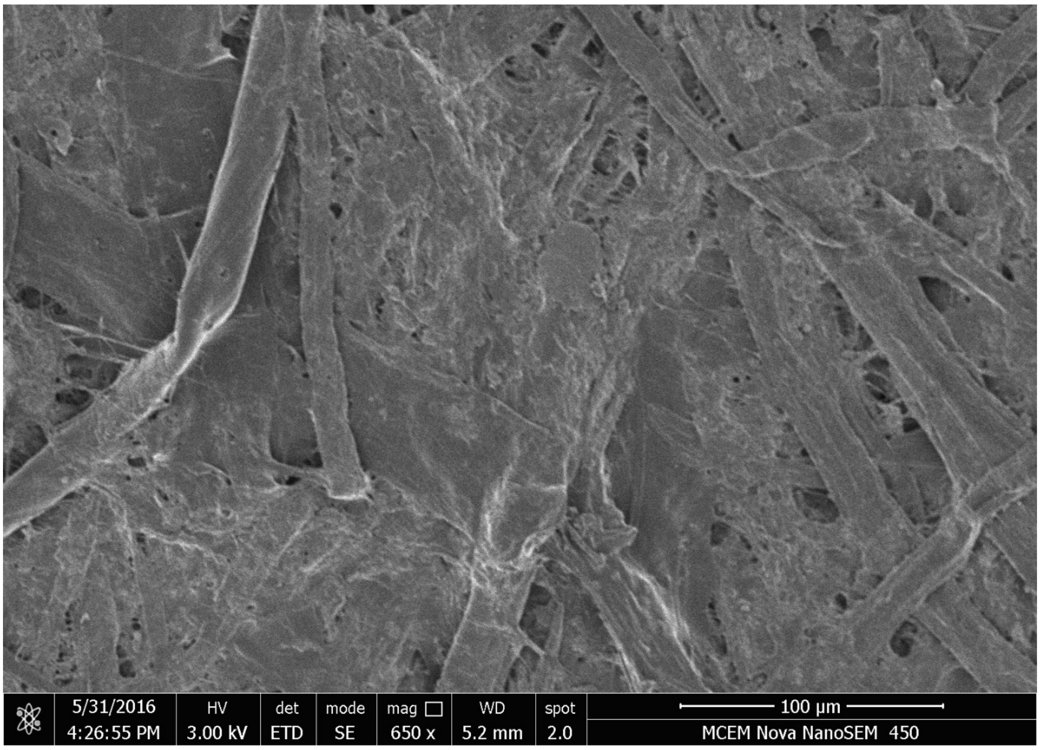


Figure 3. SEM micrograph of uncoated paper

The micrograph of the spray-coated paper with 1.25 weight percent nanocellulose at low magnification is displayed in **Figure 4**. The 100 µm micrograph displays the clumps and fibers of deposited cellulose on the base sheet's surface. Additionally, it verified that the fiber entangled in the clumps of cellulose fibers on the surface was of a different size. Furthermore, the 100 µm micrograph verifies that the base sheet is fully coated in the formulation of the micro-fibrillated cellulose coating. The coated paper demonstrated that the coating formulation filled many surface pores and void spaces between the cellulose fibers when compared to the micrograph (100 µm) of the uncoated paper [12].

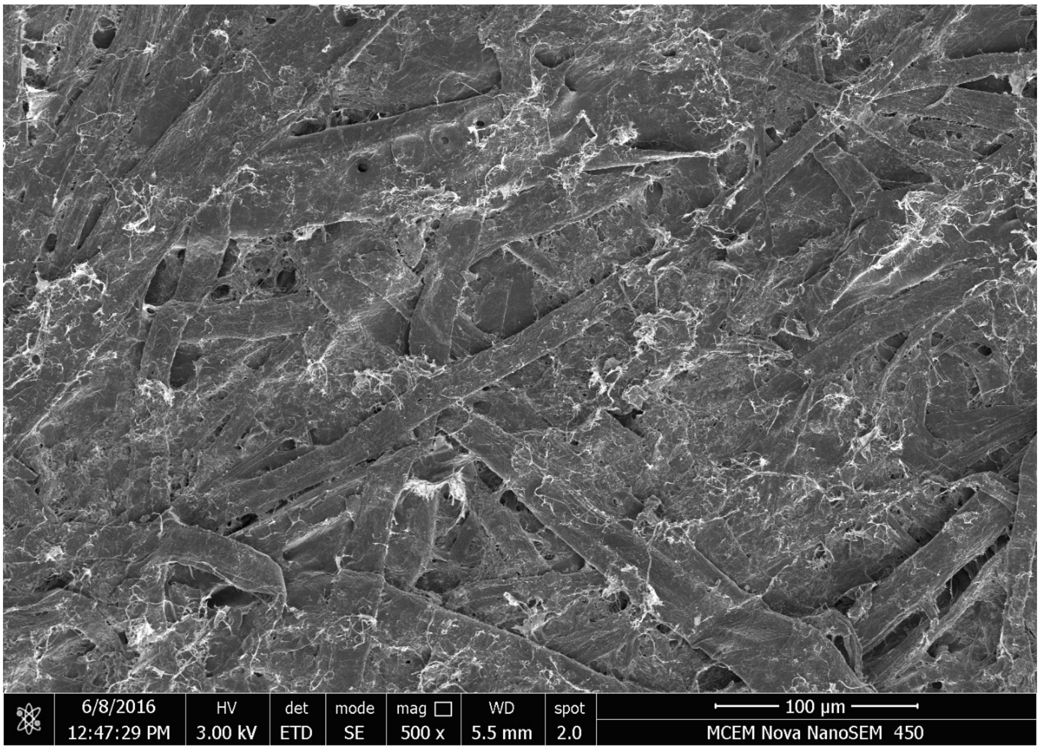


Figure 4. SEM micrograph of coated paper

The SEM micrograph of the coated paper with 0.25 weight percent of nanocellulose sprayed on the surface is displayed in **Figure 5**. Nanocellulose fibers are used to fill the pores in the 0.25-weight percent coating. Owing to the low cellulose nanofiber concentration in the nanocellulose suspension, pores are filled more effectively than layers formed on the paper's surface [12].

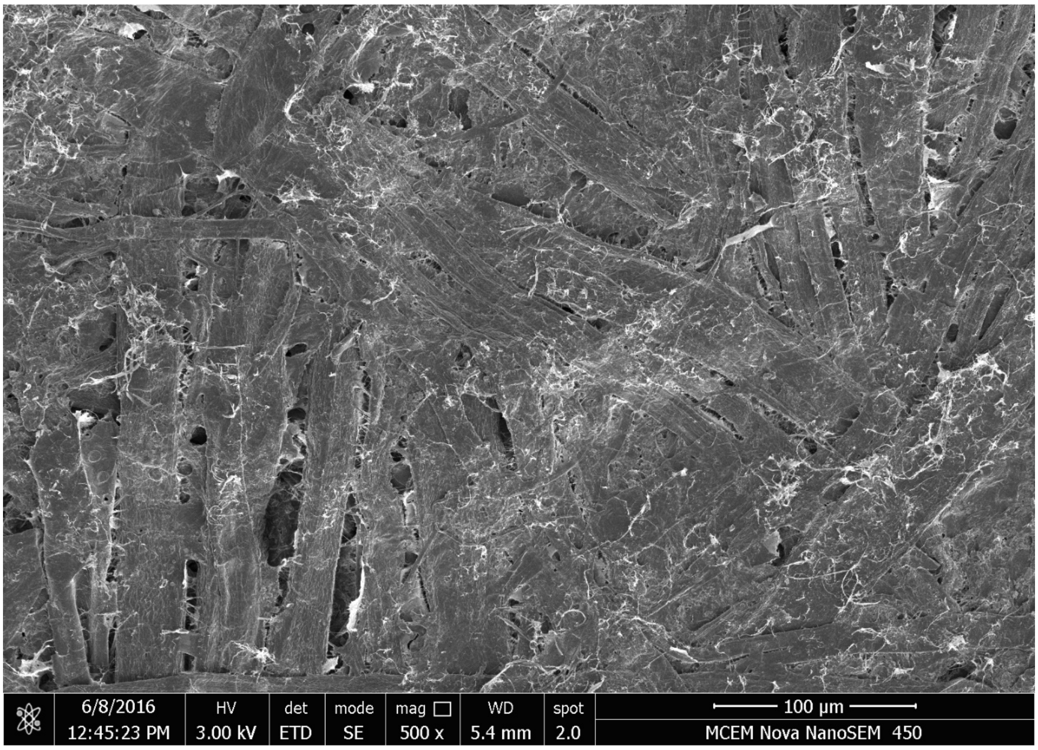


Figure 5. SEM micrograph of coated paper

The SEM micrograph of the uncoated paper in **Figure 6** makes the large pores on the paper surface very evident. This further verified the large diameter and length of the fibers. The uneven size distribution and wide-open formation of the pores lead to subpar mechanical strength and barrier performance [13].

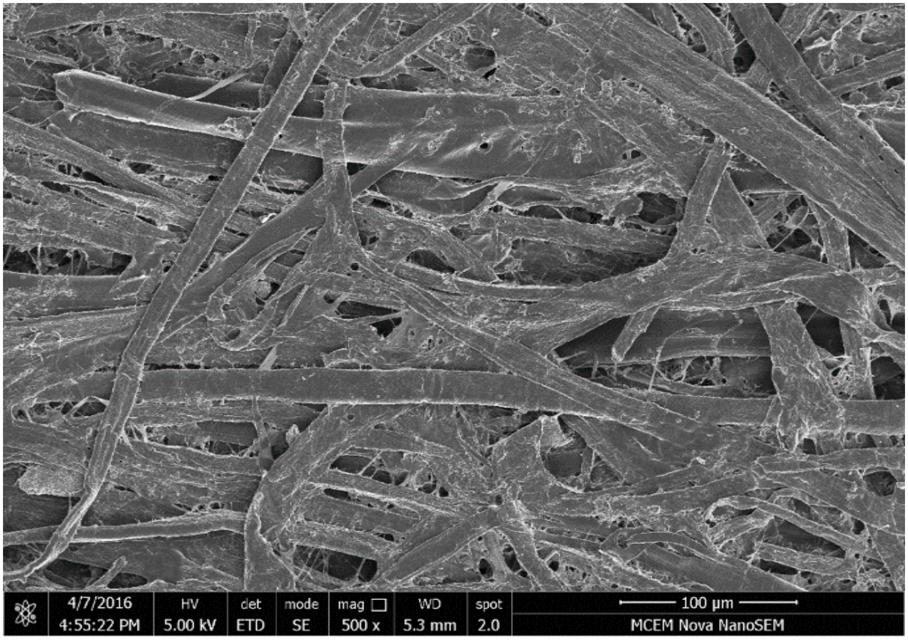


Figure 6. SEM micrograph of uncoated paper

The spray-coated 1.25-weight percent nanocellulose on the paper surface is shown in **Figure 7**. This micrograph shows the entire surface of the paper covered in barrier layers of nanocellulose, which act as a barrier against air and water vapor. The paper's surface is uniformly coated with nanocellulose thanks to the spraying, leaving no holes or fissures. It validates the possibility of scaling up to the industrial level for mass production [13].

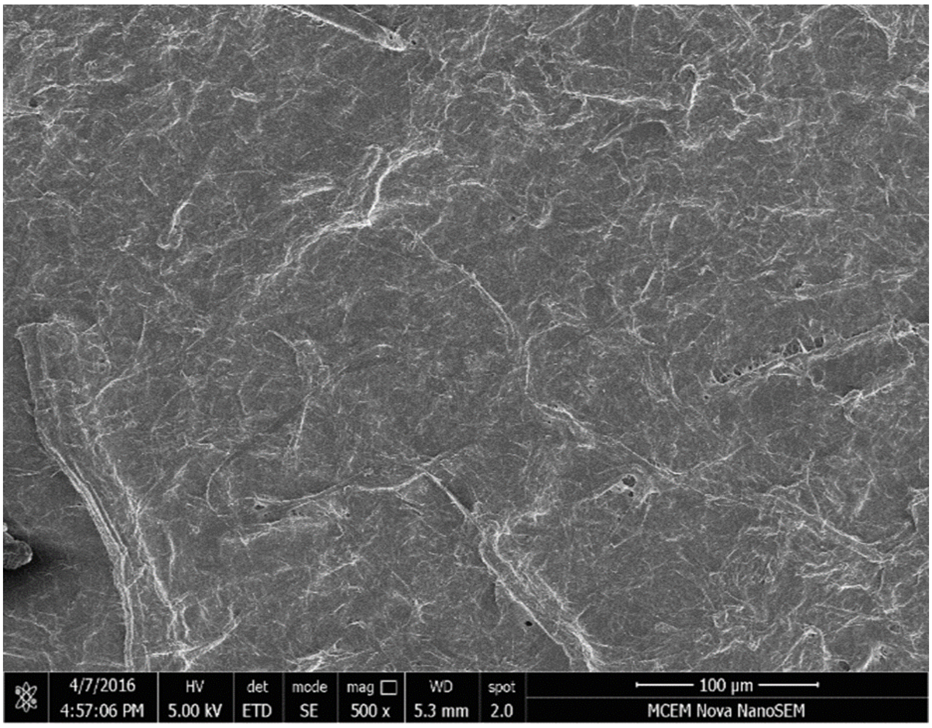


Figure 7. SEM micrograph of spray-coated nanocellulose on the paper surface

3. Air permeance of spray-coated nanocellulose paper

The air permeance of the spray-coated nanocellulose barrier layers on the paper substrates is depicted in **Figure 8**. Plotting shows that when spraying the coating on paper substrates, the concentration of NC significantly decreased the air permeance of the coated sheet. The air permeance of the paper substrates decreased from its initial value of 3.15 µm/Pa*S. At lower percentages of NC, NC filled the surface pores of the substrates. This is the uncoated paper's air permeance value. Higher NC coating percentages cause the spray-coated NC to elevate the barrier properties by forming a barrier layer on the paper surface. The coated sheet turned into a more environmentally friendly packaging material since it was fully impermeable to air. As was previously mentioned, when NC coating was applied to paper substrates, the basis weight of the coat and its thickness were linear [13].

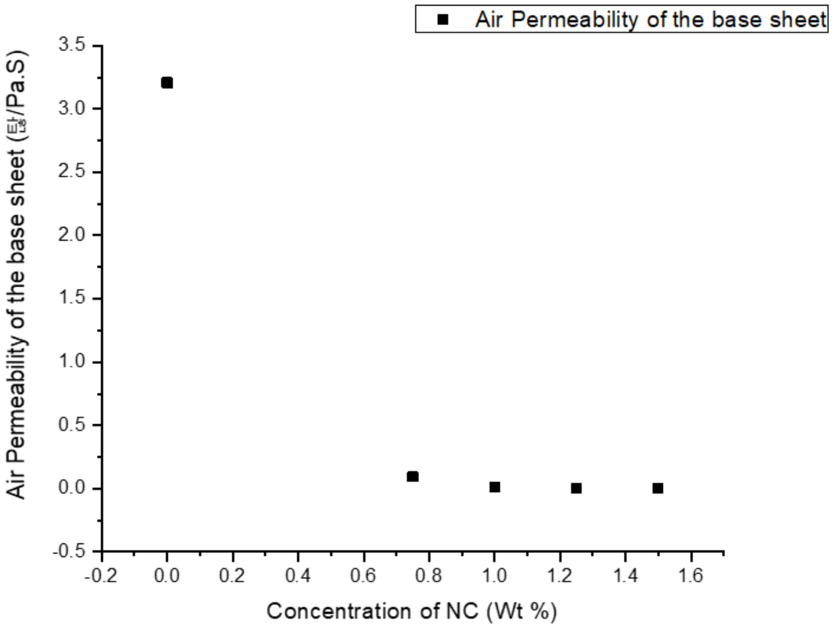
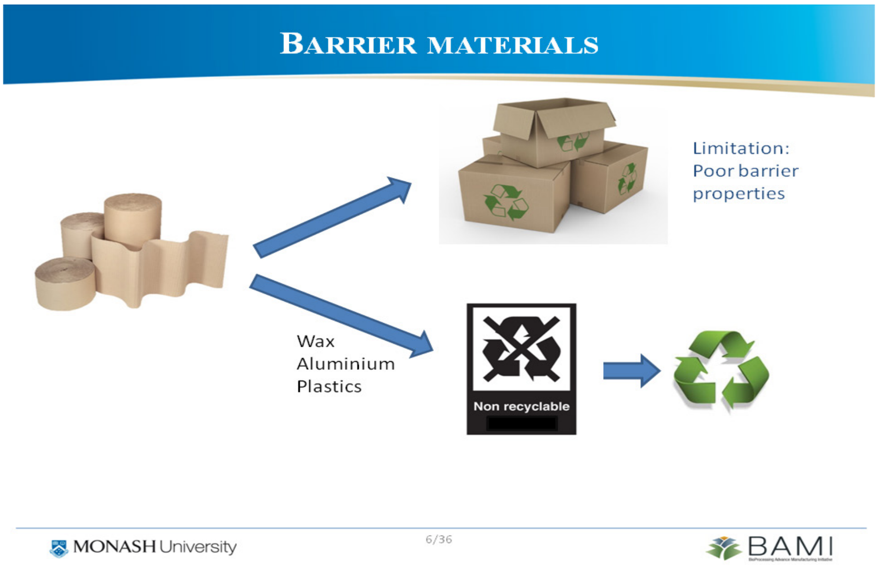


Figure 8. Air permeance of the nanocellulose-coated paper via spray coating

Figure 9 illustrates the need for the biopolymer coating on paper and paper boards. Typically, cellulose macrofibre substrates have a highly porous structure that permits a substantial amount of air, water vapor, and oxygen to pass through, which are used to make paper. Consequently, the mechanical strength and barrier performance of the paper are not up to par. To solve this issue, the paper substrates were extruded with aluminum or synthetic plastics, or coated with wax. These coatings on the paper substrates are not environmentally friendly or recyclable. To increase the paper's mechanical strength and barrier effectiveness, a biopolymer coat must be applied to the substrates. In this attempt, the paper substrates were coated with nanocellulose using spray coating, and the barrier performance was enhanced by applying an NC barrier coat to the paper substrates [10]. Air permeance is a measure of the ease with which air can pass through a material. When it comes to spray-coated nanocellulose paper, the air permeance can be influenced by various factors such as the thickness of the nanocellulose layer, the density of the coating, and the porosity of the paper substrate. Nanocellulose, being a lightweight and porous material, can provide good breathability and air permeance properties to the paper when coated onto it. The spray coating process can help in controlling the thickness and uniformity of the nanocellulose layer, which in turn can affect the air permeance of the final paper product. To measure the air permeance of spray-coated nanocellulose paper, standard testing methods such as the Gurley method or the Bendtsen method can be used. These methods involve measuring the time it takes for a specific volume of air to pass through a defined area of the material under standard pressure conditions. By conducting these tests, researchers and manufacturers can evaluate and optimize the air permeance properties of the nanocellulose paper for specific applications like packaging, filtration, or barrier coatings.

The air permeance of spray-coated nanocellulose paper refers to the rate at which air can pass through the paper substrate that has been coated with nanocellulose using a spray-coating technique. This property is crucial for various applications, including packaging, where controlling the airflow through the material is essential for maintaining product freshness and shelf life. Several factors can influence the air permeance of spray-coated nanocellulose paper as shown below. Nanocellulose concentration: The concentration of nanocellulose in the coating solution affects the density and thickness of the coating layer. Higher concentrations typically result in denser coatings, which may reduce the air permeance. Coating thickness: The thickness of the nanocellulose coating applied to the paper substrate plays a significant role in determining its air permeance. Thicker coatings may provide better barrier properties against air permeation. Coating uniformity: The uniformity of the nanocellulose coating across the paper substrate is important for consistent air permeance properties. Non-uniform coatings may result in variations in permeance across the material. Paper porosity: The porosity of the paper substrate itself affects its inherent air permeance. Papers with higher porosity allow more air to pass through, regardless of the coating. Spray coating parameters: Factors such as spray pressure, nozzle type, spraying distance, and drying conditions during the coating process can influence the final air permeance of the coated paper. Optimal parameters need to be determined to achieve the desired permeance levels. To measure the air permeance of spray-coated nanocellulose paper, standardized testing methods such as the Gurley method or the Bendtsen method can be employed. These methods involve measuring the time it takes for a specific volume of air to pass through a defined area of the material under controlled pressure conditions. By evaluating the air permeance, researchers and manufacturers can assess the effectiveness of the coating process and optimize the paper for specific applications requiring controlled airflow.



BARRIER MATERIALS

Limitation:
Poor barrier
properties

Wax
Aluminium
Plastics

Non recyclable

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BAMI

Figure 9. Coating of biopolymers on the paper and paper board

Figure 10 displays the spray-coated nanocellulose barrier layers on the paper surface, along with nanocellulose layers on the paper substrates visible on the coated surface. The density of the layer on the paper substrates would increase with an increase in the nanocellulose suspension used for spray coating. As was previously mentioned, low NC suspension can fill the paper's surface pores, whereas high NC suspension forms barrier layers on substrates to completely seal the sheet against the passage of air and water vapor [13]. Coating biopolymers onto paper and paperboard substrates offers numerous advantages, including enhancing barrier properties, improving printability, providing moisture resistance, and adding strength and durability. An overview of the process and benefits is as follows. Process of coating biopolymers on paper: Selection of biopolymers: Biopolymers chosen for coating depend on the desired properties of the final product. Common examples include cellulose derivatives such as methyl cellulose and carboxymethyl cellulose, starch-based polymers, chitosan, alginate, and proteins like gelatin or casein. Coating formulation: Biopolymers are typically dissolved or dispersed in water or other suitable solvents to form coating solutions. Additives such as plasticizers, cross-linkers, and fillers may be included to adjust properties like flexibility, adhesion, and barrier performance. Application methods: Coating can be applied using various methods, including roll coating, blade coating, spray coating, or extrusion coating. Each method offers different levels of control over coating thickness, uniformity, and coverage. Drying and curing: After application, the coated substrate is dried or cured to remove solvent and solidify the biopolymer coating. Drying methods include air drying, hot air drying, infrared drying, or UV curing, depending on the biopolymer and substrate properties. The benefits of biopolymer coating on paper and paperboard are as follows. Improved barrier properties: Biopolymer coatings can enhance the barrier against moisture, gases, and grease, extending the shelf life of packaged goods. Enhanced Printability: Coated papers provide smoother surfaces for printing, resulting in sharper graphics and better color reproduction. Moisture resistance: Biopolymer coatings can impart water resistance to paper, protecting it from damage due to humidity or liquid spills. Increased strength and durability: Biopolymer coatings can improve the strength, tear resistance, and folding endurance of paper and paperboard, making them suitable for demanding applications. Biodegradability and sustainability: Biopolymers are often biodegradable and derived from renewable resources, offering environmentally friendly alternatives to petroleum-based coatings. The applications of biopolymer-coated paper and paperboard are listed below. Food packaging: Biopolymer-coated papers are commonly used in food packaging applications, where they provide barrier protection against moisture, oxygen, and grease, ensuring the freshness and safety of packaged food products. Labels and tags: Coated papers are used for printing labels, tags, and stickers due to their smooth surfaces and excellent printability. Disposable tableware: Biopolymer-coated paperboard is used to manufacture disposable cups, plates, and trays, offering a sustainable alternative to single-use plastics. Medical and pharmaceutical packaging: Biopolymer-coated papers are suitable for packaging medical and pharmaceutical products, where barrier properties and sterilizability are critical. Overall, coating biopolymers onto paper and paperboard substrates offers a versatile and sustainable approach to enhancing their properties for various packaging, printing, and specialty applications. Nanocellulose coating on paper and paperboard offers enhanced properties such as improved strength, barrier properties, and printability. Nanocellulose, being a renewable and sustainable material, provides a biodegradable alternative to conventional petroleum-based coatings. The nanoscale dimensions of nanocellulose particles allow for a smooth and uniform coating on the paper surface, resulting in improved surface properties. The high surface area of nanocellulose facilitates better adhesion to the paper substrate, which can enhance the overall performance of the paper product. Additionally, nanocellulose coatings can provide functionalities such as water resistance, grease resistance, and UV protection, depending on the specific formulation used. Furthermore, nanocellulose coatings can contribute to the development of eco-friendly packaging materials by reducing the need for synthetic coatings and improving the recyclability of paper and paperboard products. Overall, the application of nanocellulose coatings in the paper industry represents a promising avenue for achieving more sustainable and high-performance paper products.

Figure 10. Spray-coated nanocellulose barrier layers on the paper substrates

The idea of a continuous spray coating procedure for nanocellulose on paper substrates is depicted in **Figure 11**. The proof of concept for nanocellulose coating in a continuous process can be met by roll-to-roll coating, also known as Dow web coater. Dow web coater can be combined with a spray system to effectively remove water from the spray-coated nanocellulose suspension by spraying nanocellulose onto the paper web and then drying it with an infrared heater. For commercial use, the dried paper substrates can be rolled into a web [10]. The Dow Web Coater is a type of coating machine commonly used in the paper and packaging industry for applying coatings onto paper and paperboard substrates. It is manufactured by Dow Coating Materials, a division of The Dow Chemical Company, which specializes in providing innovative coating solutions for various industries. The Dow Web Coater is designed to apply coatings continuously and efficiently, typically using roll-to-roll or web-based coating techniques. Some key features and capabilities of the Dow Web Coater are as follows. Roll-to-roll coating: The Dow Web Coater is equipped with precision rollers and coating stations that enable the application of coatings onto continuous webs of paper or paperboard. The coating material is typically supplied from a reservoir or coating unit and transferred onto the substrate using applicator rolls or other coating methods. Versatile coating capabilities: The Dow Web Coater is capable of applying a wide range of coatings, including water-based, solvent-based, and UV-curable coatings. These coatings can enhance the surface properties of the substrate, such as barrier properties, printability, gloss, and durability. Precision control: The Dow Web Coater is equipped with advanced control systems that allow for precise adjustment of coating thickness, speed, temperature, and other parameters. This ensures uniform coating coverage and consistency across the entire web. High-speed production: The Dow Web Coater is designed for high-speed production environments, enabling rapid coating application and increased throughput. This makes it suitable for large-scale manufacturing operations in the paper and packaging industry. Customizable configurations: The Dow Web Coater can be customized to meet specific customer requirements and application needs. This includes options for single-sided or double-sided coating, inline drying or curing systems, and additional features for process monitoring and quality control. Integration with other equipment: The Dow Web Coater can be integrated seamlessly with other equipment in the production line, such as printing presses, laminators, and converting machinery. This allows for efficient and streamlined production processes from raw material to finished product. Overall, the Dow Web Coater is a versatile and reliable solution for applying coatings onto paper and paperboard substrates, offering precision control, high-speed production capabilities, and customizable configurations to meet the diverse needs of the paper and packaging industry.

While there may not be a specific product named Dow Web Coater designed explicitly for coating nanocellulose onto paper substrates, Dow Coating Materials could potentially offer customized coating solutions suitable for this application. The Dow Web Coater or similar coating equipment might be used for coating nanocellulose onto paper substrates as follows. Adaptation for nanocellulose coating: The Dow Web Coater or similar coating machinery can be adapted or customized to accommodate the application of nanocellulose coatings onto paper substrates. This adaptation may involve modifying the coating units, applicator rolls, and drying/curing systems to ensure compatibility with the unique properties of nanocellulose dispersions. Precision control: These coating machines typically offer precision control over coating parameters such as coating thickness, speed, temperature, and drying/curing conditions. This level of control is crucial for optimizing the application of nanocellulose coatings to achieve uniform coverage and desired properties on the paper substrate. Roll-to-roll coating: The roll-to-roll coating process employed by the Dow Web Coater is well-suited for applying nanocellulose coatings onto continuous webs of paper substrates. The nanocellulose dispersion can be supplied from a reservoir and transferred onto the paper substrate using applicator rolls or other coating methods. Integration with nanocellulose dispersion systems: The coating equipment can be integrated with nanocellulose dispersion systems to ensure consistent and efficient delivery of the coating material to the coating units. This integration may include pumps, mixers, and filtration systems for preparing and maintaining the nanocellulose dispersion. Process optimization: Dow Coating Materials may provide technical support and expertise to optimize the coating process for nanocellulose applications. This may involve conducting trials, testing different formulations, and fine-tuning process parameters to achieve the desired coating performance and properties on the paper substrates. Overall, while there may not be a specific off-the-shelf product named Dow Web Coater designed explicitly for nanocellulose coating applications, Dow Coating Materials could offer customized coating solutions and technical support to enable the coating of nanocellulose onto paper substrates using roll-to-roll coating equipment.

Figure 11. The concept for a continuous process for spray coating nanocellulose on the paper substrates

4. Application of spray-coated nanocellulose films

For many uses, including barrier materials, antimicrobial materials, substrates for flexible electronics, and so on, spray-coated nanocellulose film is an excellent choice [17–19]. As was previously mentioned, spray-coated nanocellulose films have two distinct surfaces, which are a smooth surface on the metal side and a rough surface on the other. Functional materials can be created by utilizing the film's smoothness [10]. Furthermore, nanocellulose offers a recyclable platform and is an eco-friendly and biodegradable material, serving as a substitute for synthetic plastics.

4.1. Flexible and printed electronics

Nanocellulose, with its unique combination of properties such as high aspect ratio, mechanical strength, biocompatibility, and sustainability, holds significant potential for various applications in printed and flexible electronics. How nanocellulose can be utilized in this field is elaborated as follows. Substrates for printed electronics: Nanocellulose-based substrates can serve as a flexible and lightweight platform for printed electronic devices. These substrates offer excellent mechanical properties, including flexibility, tensile strength, and dimensional stability, making them suitable for flexible and stretchable electronics applications. Ink formulations: Nanocellulose can be incorporated into conductive ink formulations to improve their printability, adhesion, and mechanical properties. By dispersing conductive nanoparticles, such as silver, graphene, or carbon nanotubes, in nanocellulose suspensions, inkjet or screen-printable inks can be developed for printing conductive tracks and electrodes on flexible substrates. Dielectric materials: Nanocellulose-based dielectric materials can be used in printed capacitors, energy storage devices, and flexible displays. Nanocellulose offers low dielectric loss, high dielectric strength, and tunable dielectric properties, making it suitable for insulating layers in electronic devices. Transparent conductive films: Nanocellulose can be functionalized or combined with conductive materials to produce transparent conductive films for touchscreens, flexible displays, and solar cells. By incorporating conductive nanomaterials such as graphene, carbon nanotubes, or silver nanowires into nanocellulose matrices, transparent and flexible conductive films with high transparency and conductivity can be fabricated. Sensors and biosensors: Nanocellulose-based substrates and films can be functionalized with sensing materials such as nanoparticles, polymers, or biomolecules to create sensors and biosensors for various applications, including healthcare monitoring, environmental sensing, and food safety. Energy storage devices: Nanocellulose-based materials can be utilized in energy storage devices such as supercapacitors and batteries. Nanocellulose aerogels or composites can serve as electrode materials or separators in these devices, offering high surface area, porosity, and mechanical strength. 3D printing of electronics: Nanocellulose-based materials can be used as feedstocks for 3D printing of electronic components and devices. By combining nanocellulose with conductive and insulating materials, complex structures with customized functionalities can be fabricated using additive manufacturing techniques. Biodegradable electronics: Nanocellulose-based electronics offer the advantage of being biodegradable and environmentally friendly. This makes them suitable for disposable or transient electronics applications, where sustainability and reduced environmental impact are important considerations. Overall, nanocellulose holds great promise for advancing the field of printed and flexible electronics by providing versatile and sustainable materials for various device components and applications. Continued research and development efforts are expected to further expand the capabilities and commercial viability of nanocellulose-based electronics.

An environmentally friendly nanomaterial used to create a variety of functional materials is cellulose nanofiber (CNF). It serves as a substitute for synthetic plastic and other materials derived from petroleum [20]. Owing to the demand for CNF film, a quick and efficient method of CNF film fabrication is needed. A novel spray-coating technique was created to create smooth cellulose nanofiber films. Using this method, a smooth, polished surface was sprayed with CNF suspension. The wet film was then left to dry in the air under standard laboratory conditions. One of the main benefits of spraying is that it can be used for contactless and contour coating of the base substrate. Through adjustments to the CNF suspension during the spraying process, the basis weight and thickness of the CNF film can be tailored. The unique two-sided surface roughness of CNF film prepared by spray coating is characterized by a much smoother surface on the surface in contact with the material than on the air-contact side. One of the factors influencing the CNF film's barrier performance is its surface roughness, and changes to this parameter change the wettability. The two surfaces studied by optical profilometry had respective RMS roughness values of 2087 nm on the rough side and 389 nm on the spray-coated side. On the side of the CNF film that is exposed to the polished stainless steel surface, it is incredibly smooth thanks to spray coating. The size of the cellulose fibrils and the smoothness of the base surface are two examples of the factors that regulate the film's roughness and were utilized in the creation of flexible electronics. **Figure 12** illustrates the variables governing the surface smoothness specifications needed for substrate applications in flexible and printed electronics.

Paper is typically made of cellulose, which can be recycled and biodegraded. It was originally used as the substrate for printed and flexible electronics (**Figure 13**). Its surface roughness is high and it absorbs a lot of water. The advancement of printed electronics on paper substrates is restricted by these characteristics. Furthermore, the paper substrates' surface roughness, which ranges from 2 to 10 microns, restricts how widely the conductive ink can spread across them. The smoothness and effectiveness of the spray-coated nanocellulose film as a barrier against water vapor and air are good.

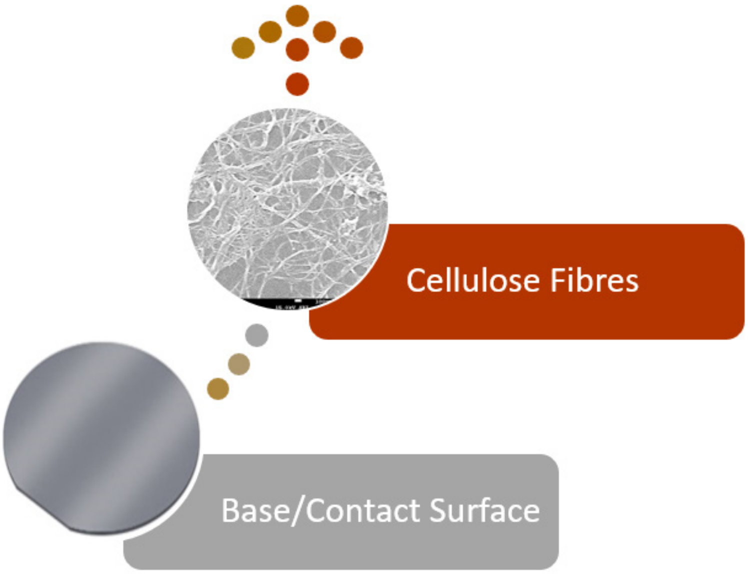

Figure 12. Factors controlling the surface roughness of the nanocellulose films

The surface roughness of nanocellulose films can be influenced by various factors, both during the film formation process and due to the inherent characteristics of the nanocellulose material. Some key factors that control the surface roughness of nanocellulose films are listed below. Nanocellulose source and characteristics: Type of nanocellulose: The source and type of nanocellulose used, such as cellulose nanocrystals and cellulose nanofibrils, can impact the surface roughness of the resulting film. Different types of nanocellulose may have varying dimensions, aspect ratios, and surface properties, which can influence film morphology. Particle size and distribution: The size distribution of nanocellulose particles affects the packing arrangement and surface roughness of the film. Smaller particles may result in smoother films, while larger particles can lead to increased roughness. Processing parameters: Solvent and dispersion method: The choice of solvent and dispersion method used to prepare the nanocellulose suspension can influence film morphology and surface roughness. Proper dispersion and uniform distribution of nanocellulose in the solvent are essential for achieving smooth films. Film formation technique: The methods used for film formation such as casting, spin-coating, and spray-coating affect the drying kinetics and solvent evaporation rate, which in turn influence the final surface roughness of the film. Drying conditions: The temperature, humidity, and drying rate during film formation can impact the organization and packing of nanocellulose particles, thereby affecting surface roughness. Slow and controlled drying conditions may result in smoother films. Additives and processing aids: Surfactants and dispersants: Surface-active agents used to stabilize nanocellulose suspensions can affect film morphology and surface roughness. Proper selection and optimization of surfactants and dispersants can promote uniform dispersion and reduce agglomeration of nanocellulose particles. Plasticizers and cross-linkers: Additives such as plasticizers or cross-linking agents may be incorporated into the nanocellulose matrix to modify film flexibility and mechanical properties, which can indirectly influence surface roughness. Substrate properties: Substrate surface energy: The surface energy and properties of the substrate onto which the nanocellulose film is deposited can affect film adhesion and morphology. Substrates with high surface energy may promote better wetting and adhesion of nanocellulose, potentially leading to smoother films. Substrate roughness: The roughness of the substrate can influence the final surface roughness of the nanocellulose film. Smooth substrates may result in smoother film surfaces, while rough substrates can introduce additional topographical features. By carefully controlling these factors, researchers and engineers can optimize the surface roughness of nanocellulose films for specific applications, such as coatings, membranes, and electronic devices, where surface smoothness is critical.

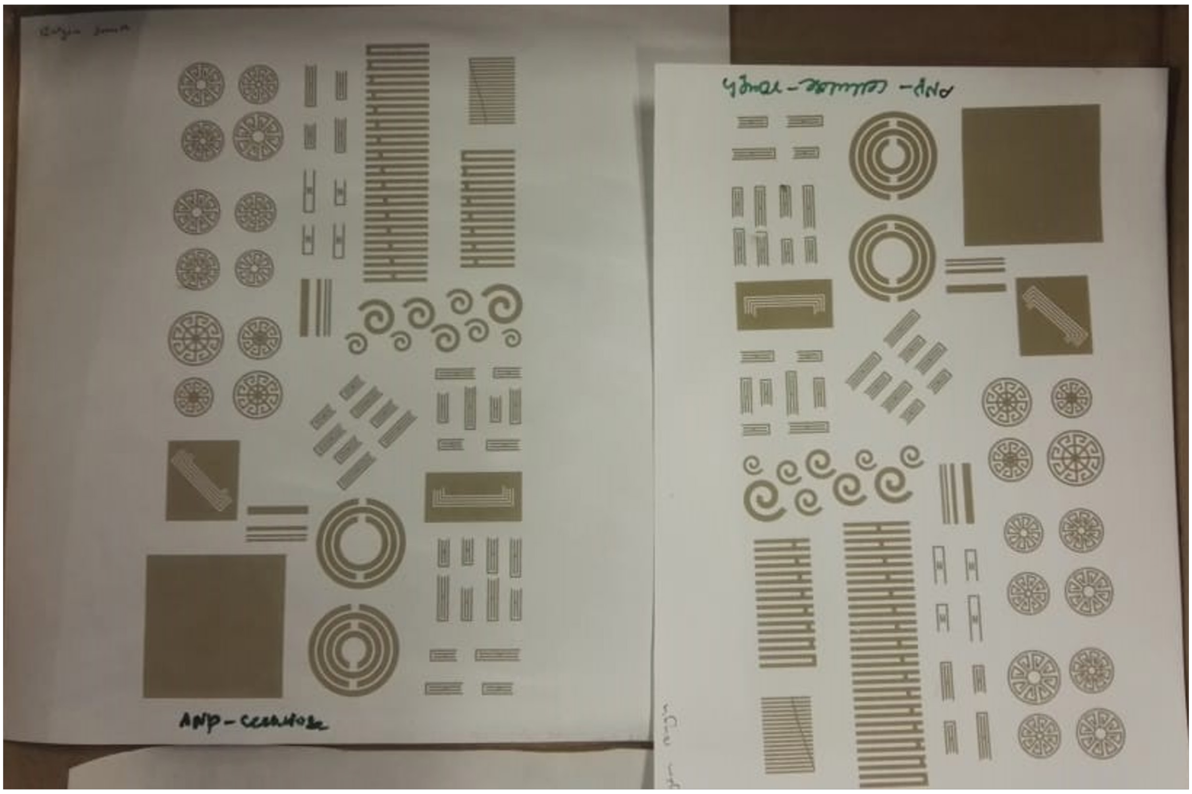

Figure 13. The printed circuits on the spray-coated nanocellulose films

4.2. Bismuth-based nanocellulose composite

Bismuth-based nanocellulose composites are advanced materials that combine the unique properties of bismuth with the versatility and sustainability of nanocellulose. Bismuth, a heavy metal with low toxicity, is known for its high density, low melting point, and excellent radiation shielding properties. On the other hand, nanocellulose, derived from renewable sources like wood pulp, offers high strength, lightweight, and biodegradability. When combined, bismuth-based nanocellulose composites exhibit improved mechanical strength, thermal stability, and radiation shielding capabilities. These composites have potential applications in various fields such as healthcare, aerospace, and environmental protection. In the healthcare sector, bismuth-based nanocellulose composites can be used in diagnostic imaging, drug delivery systems, and tissue engineering due to their biocompatibility and radiation-shielding properties. In aerospace, these composites can be utilized for lightweight structural components and radiation protection for space missions. Additionally, in environmental protection, they can help in developing eco-friendly packaging materials and wastewater treatment systems. Overall, bismuth-based nanocellulose composites represent a promising avenue for the development of innovative and sustainable materials with a wide range of applications. **Figure 14** shows the spraying of the bismuth-based nanocellulose composite, an antimicrobial barrier material. In addition to their barrier performance, these composites can be used as anti-microbial packaging materials, biomedical bandages, and surface coatings. Phenol bismuth bis(diphenyl phosphinate) is added to a nanocellulose suspension as a broad-spectrum antimicrobial agent to make composites [21]. The anti-microbial zone of the composite loaded with 5 weight percent bismuth was determined to be 15 mm through the use of a disc diffusion test. This zone of inhibition was found to be effective against gram-negative microorganisms such as *Escherichia coli* (*E. coli*) and *Pseudomonas aeruginosa* (*P. aeruginosa*), as well as gram-positive bacteria such as *Staphylococcus aureus* (*S. Aureus*), and anti-microbial resistant pathogens, specifically Vancomycin-resistant Enterococcus (VRE) and Methicillin-resistant *Staphylococcus aureus* (MRSA). The addition of diphenyl phosphinate, or phenyl bismuth bis, did not affect the operation time for the spraying process, which is independent of suspension concentration. A bifunctional coating with barrier and antimicrobial qualities can be created by spraying a suspension of bismuth and nanocellulose onto paper substrates [22].

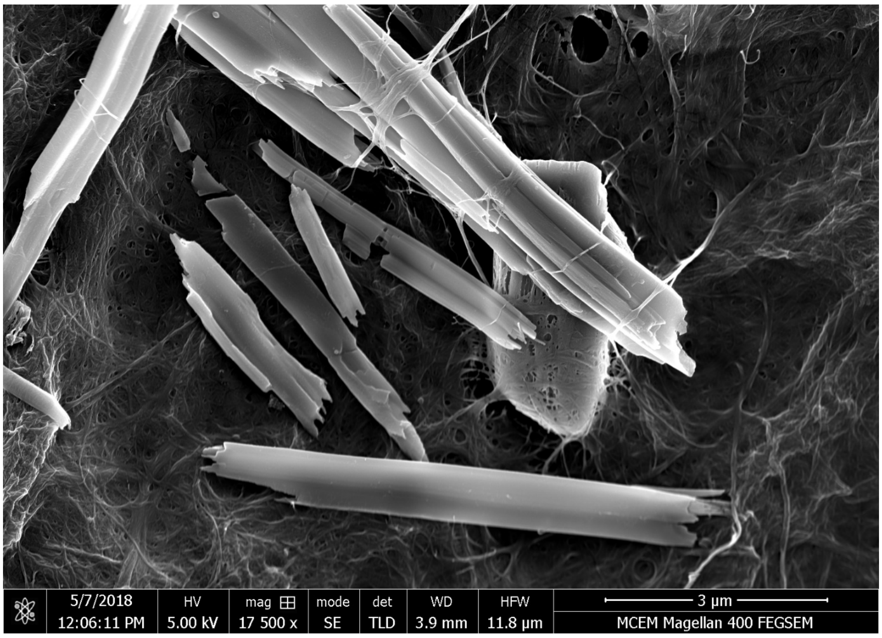

Figure 14. Bismuth-based nanocellulose composite prepared via spray coating

4.3. Silver nanowires-nanocellulose composites

AgNWs, or silver nanowires, are a kind of one-dimensional nanostructure that can have diameters of 10 to 200 nm and lengths of 5 to 100 µm. The spray-coated nanocellulose film was mixed with silver nanowires to form a conductive composite that could be used for many purposes. This technique produced a conductive surface on the spray-coated nanocellulose films by applying the silver wire metallization process to the base substrates. The adhesion between spray-coated nanocellulose film and silver nanowires was very challenging to prepare the conductive surface. There are several applications for this composite as an electrode [23]. Silver nanowires-nanocellulose composites are innovative materials that combine the electrical conductivity of silver nanowires with the mechanical properties of nanocellulose. These composites have garnered interest in various applications due to their unique combination of properties. The silver nanowires provide excellent electrical conductivity, making these composites suitable for use in flexible electronics, touchscreens, and sensors. The nanocellulose, on the other hand, offers mechanical strength and flexibility, enhancing the overall durability of the composite material. The synergy between silver nanowires and nanocellulose in these composites allows for the development of lightweight and flexible conductive materials with potential applications in wearable electronics, printed electronics, and energy storage devices. Furthermore, the use of nanocellulose, a sustainable and biodegradable material, in these composites aligns with the growing demand for environmentally friendly alternatives in various industries. Overall, silver nanowires-nanocellulose composites hold promise for advancing next-generation electronics and materials by offering a unique blend of electrical conductivity, mechanical strength, flexibility, and sustainability.

4.4. Biomedical device

Antimicrobial agents, such as antibiotics, and nano clay were incorporated into the spray-coated nanocellulose film as a base substrate to repair dermal wounds. The most well-known renewable, recyclable, and nanocomposite material is cellulose nanofiber. To increase the cellulose nanofiber film's mechanical strength and liquid absorption, spray-coated cellulose nanofiber was integrated with silver nanoparticles and montmorillonite (MMT). For improved wound closure, AgNPs exhibit strong antioxidant and antimicrobial activity. Using 3T3 fibroblast cells, the MTT assay was used to assess the composite's cell viability. It was found that the plant extract and AgNPs had antidiabetic assay results of 56% and 61%, respectively. Because CNF-MMT-AgNPs are cost-effective and have good biocompatibility, they can be used to repair soft tissue in a variety of wounds [24].

4.5. Nanocellulose-MMT composite

Through the use of spray coating, a smooth montmorillonite-cellulose nanofiber composite that serves as a green barrier material has been created. The effect of MMT loading into the suspension of cellulose nanofibers for the production of nanocomposite is significant, independent of the operation time, and ideal for process scaling up. The spray-coated nanocomposites' barrier, surface, and topography were comparable to those of the nanocomposites made using vacuum filtration, a traditional technique. The spray-coated nanocomposites' air permeance and water vapor permeability were successfully attained to verify that the green materials were, in fact, barrier materials. WVP was elevated as a result of MMT clays aggregating on a higher MMT in the nanocomposite. This indicates that spray coating is a highly effective method for creating sustainable nanocomposites as a substitute for synthetic plastics. The morphology and topography of the spray-coated pure nanocellulose film and nanocellulose-MMT composite are shown in **Figures 15** and **16**. The nanocellulose-MMT composite's SEM micrograph demonstrated how the MMT was properly positioned within the cellulose fibrous matrix, creating a tortuous pathway that facilitates the passage of gases and water vapor. Consequently, the composite's barrier performance outperformed that of pure nanocellulose films [17, 25].

Nanocellulose-MMT composite refers to a material formed by combining nanocellulose, which is derived from cellulose fibers broken down into nanoscale dimensions, with montmorillonite (MMT), a type of clay mineral. The combination of these two materials offers a range of desirable properties, making the composite suitable for various applications. Some key points about nanocellulose-MMT composites are as follows. Enhanced mechanical properties: The addition of MMT to nanocellulose can improve the mechanical properties of the composite, such as strength, stiffness, and toughness. This enhancement is particularly significant in materials like bioplastics, where reinforcing agents are needed. Barrier properties: MMT is known for its excellent barrier properties against gases and liquids. When incorporated into nanocellulose matrices, it can enhance the barrier performance of the composite, making it suitable for packaging applications where moisture and gas barrier properties are crucial. Thermal stability: MMT can also improve the thermal stability of nanocellulose-based materials. This is important for applications where heat resistance is required, such as in automotive or aerospace industries. Biodegradability and sustainability: Both nanocellulose and MMT are derived from natural sources and are biodegradable. Combining them into a composite material maintains the sustainability of the final product, making it an attractive option for environmentally conscious applications. Potential applications: Nanocellulose-MMT composites have a wide range of potential applications, including packaging materials, coatings, biomedical devices, structural materials, and environmental remediation. Processing methods: Various methods can be used to prepare nanocellulose-MMT composites, including solution casting, melt mixing, and in situ polymerization. The choice of method depends on the desired properties of the final product and the compatibility of the materials. Overall, nanocellulose-MMT composites represent a promising class of materials with diverse properties and applications, offering a combination of mechanical strength, barrier properties, thermal stability, and sustainability.

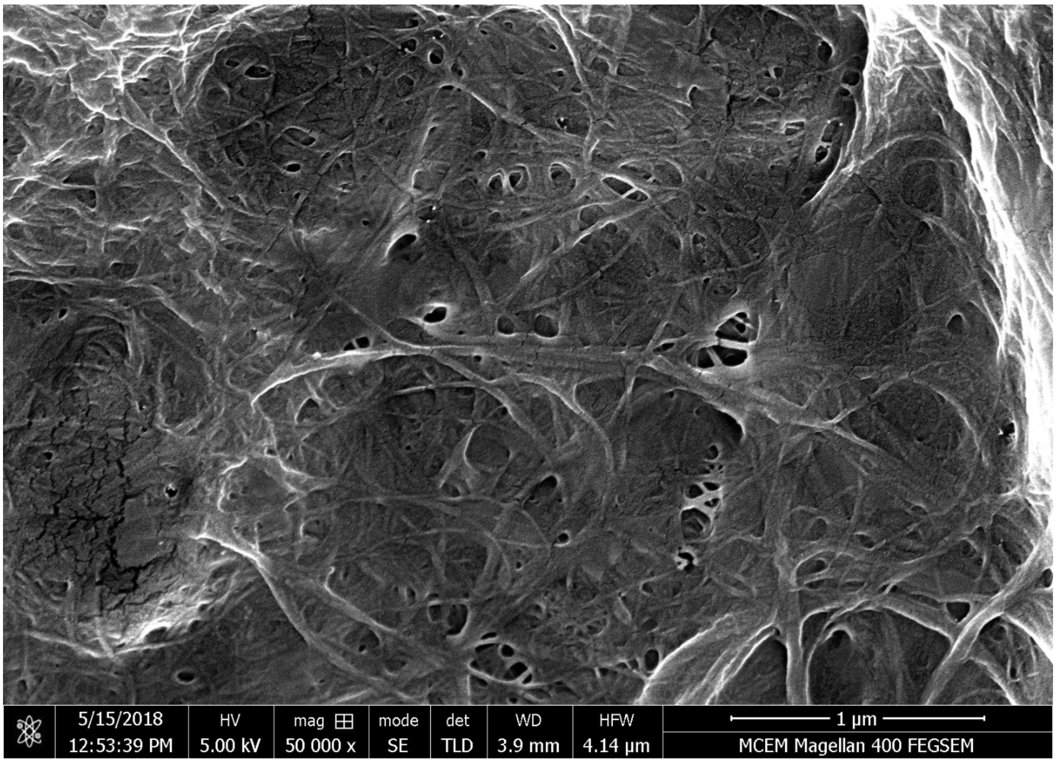

Figure 15. Pure nanocellulose film via spray coating

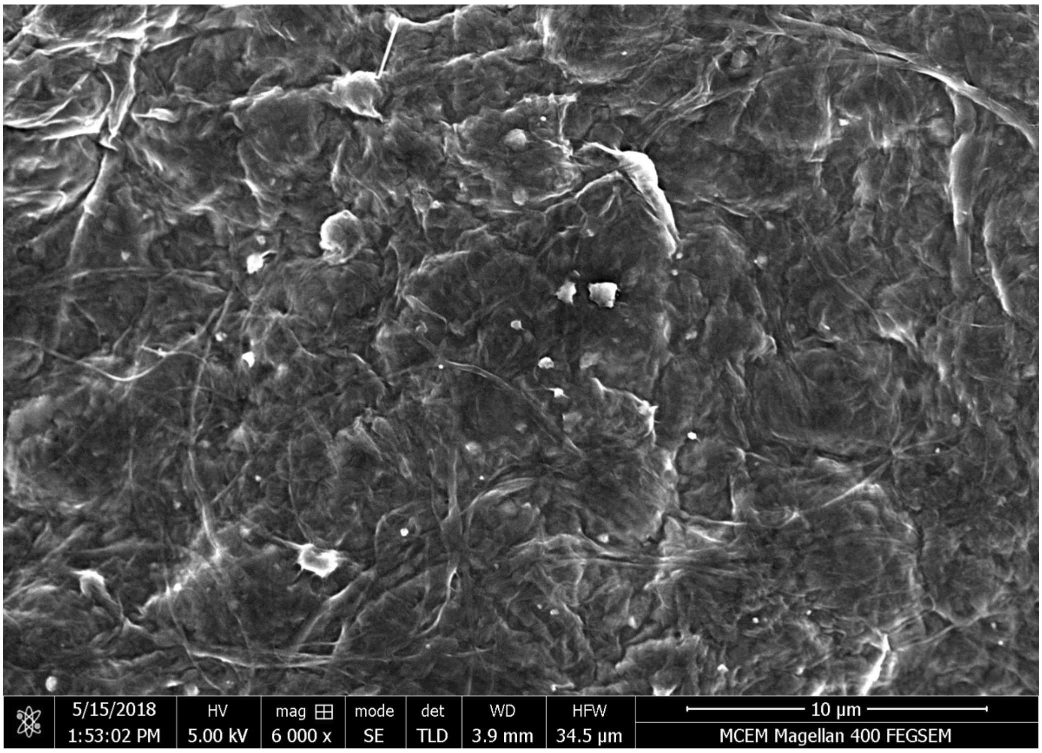

Figure 16. Nanocellulose-MMT composite prepared via spray coating

4.6. Spray-coated nanocellulose as layers for membrane development

Depth-type composite filters were implemented to remove various contaminants from wastewater via mechanical entrapment and adsorption. Adsorption of one type of charged contaminants and microparticle filtration are treated via depth filtration. The cellulose nanofiber (CNF) layer spray-coated on the surface of the filters was a perfect fit for depth filtration. The depth filter was fabricated with cellulose, perlite, and PAE via both vacuum filtration and spray coating to form a base sheet. The performance of CNF top coating has a molecular weight cut-off of up to 80% for two different molecular weights. Furthermore, the removal of positively charged contaminants increased significantly after adding the CNF layer. The coating of the layer via spray coating is also robust in terms of getting adequate internal strength within the interface of the base sheet and top layer. The concept of top barrier coating is a promising and easy method to alter the filter performance and is used in membrane fabrication for wastewater treatment [26].

Using spray-coated nanocellulose layers for membrane development is an innovative approach that leverages the unique properties of nanocellulose for various membrane applications. Below are how it works and why it is advantageous. Uniform coating: Spray coating allows for the uniform deposition of nanocellulose onto a substrate, ensuring consistent membrane quality and performance. This uniformity is crucial for membranes, especially in filtration applications where even distribution of pores is essential for efficient separation. Controlled thickness: By adjusting spray parameters such as spray rate, nozzle size, and spray distance, researchers can control the thickness of the nanocellulose layers. This control enables the customization of membrane properties, such as permeability and selectivity, to meet specific application requirements.

Pore size control: Nanocellulose-based membranes can be engineered to have precise pore sizes by controlling the concentration and distribution of nanocellulose during the spray-coating process. This tunability is valuable for tailoring membranes for different filtration tasks, from microfiltration to nanofiltration.

Enhanced mechanical strength: Nanocellulose possesses excellent mechanical properties, including high strength and flexibility. Incorporating nanocellulose layers into membranes can improve their mechanical integrity, making them more robust and durable, which is advantageous for long-term membrane performance. Biocompatibility and sustainability: Nanocellulose is derived from renewable sources and is biocompatible, making it an attractive material for membrane development, particularly in biomedical applications such as tissue engineering and drug delivery. Additionally, nanocellulose-based membranes are environmentally friendly and biodegradable. Versatility: Spray-coated nanocellulose layers can be applied to various types of substrates, including porous supports, polymer films, and other membrane materials. This versatility allows for the integration of nanocellulose into existing membrane technologies, expanding their potential applications. Potential applications: Nanocellulose-based membranes have diverse applications, including water purification, gas separation, food processing, and biomedical applications. The ability to tailor membrane properties through spray-coating techniques enhances their suitability for specific tasks within these fields. In summary, using spray-coated nanocellulose layers for membrane development offers numerous advantages, including uniform coating, controlled thickness, and pore size, enhanced mechanical strength, biocompatibility, sustainability, versatility, and a wide range of potential applications. This approach holds great promise for advancing membrane technology in various industries.

5. Recommendations

The final films' level of smoothness will differ significantly between spray-coating iterations. Robotic arms can automate the application of power, the distance between the spray nozzle and the substrate, and the coating rate, which will greatly improve the accuracy of how to achieve incredibly smooth surfaces. The concentration of the polymer and solvent, as well as the surroundings in which the experiment is conducted, can all be used to control the size of the pores. Even more notable outcomes for the films that serve as the foundation for printed electronics may arise from the consistency and reproducibility of the reaction conditions. It has the potential to scale up for conventional scale production of nanocellulose film, based on proof of concept and laboratory-scale experiments on spray coating. Professional spray coating equipment is becoming more sophisticated to better handle high NC suspension and produce uniformly high-quality nanocellulose films.

6. Conclusion

In conclusion, the application of spray-coated barrier layers and nanocellulose film on paper substrates is the main focus of the spray-coating concept, which was developed to create smooth nanocellulose films. One of the most important factors influencing the material's performance in the creation of different cellulose-based functional materials, like flexible and printed electronics, is the smoothness of the spray-coated nanocellulose film. The use of nanocellulose films as high-performance barrier materials and a possible replacement for packaging made of synthetic plastic is expanded by spray coating. The process of creating nanocellulose film by spray coating takes less than a minute. When compared to vacuum filtration, this method offers excellent potential for rapidity with nanocellulose films. Spray-coated wet film requires more than 24 hours to dry in a controlled laboratory setting using air drying. Since it is outside the purview of the current work to improve the drying process on the wet film, it will be the focus of future research projects. The process of spraying a film serves as evidence for the concept, and the quality of the film produced through this method is contrasted with that of vacuum filtration. The shiny films created by spraying nanocellulose onto the polished impermeable surface could serve as a platform for a variety of sustainable functional devices.

Disclosure statement

The authors declare no conflict of interest.

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