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Methods for Fabrication of Self/Free Standing Nanocellulose (NC)-Nano Montmorillonite (N-MMT) Composite Films/Sheets — A Review

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Abstract: Plastic pollution looms large as a formidable foe to the environment. Enter cellulose nanofibers, the shining stars in the quest for innovative, eco-friendly paper-based packaging that is not just renewable, but also recyclable and biodegradable. These cellulose wonders boast impressively low oxygen permeability, but when it comes to water vapor, they fall short compared to traditional packaging plastics like LDPE. To tackle this challenge, researchers have been crafting composites by blending cellulose nanofibers with inorganic nanoparticles, such as Montmorillonite clay, which helps to curb water vapor permeability. However, this clever addition comes with a catch — it further complicates the already tricky drainage process during layer formation via vacuum filtration. This review delves into the complex world of nano cellulose-nano-MMT (Montmorillonite) composites, examining their preparation processes, unique characteristics, wide-ranging uses, and their significant contribution to promoting circular economy principles. By combining cellulose nanomaterials with MMT, a synergistic approach is taken to develop a new composite material with improved mechanical, thermal, and barrier properties. Various fabrication techniques are explored, including solution blending, spray coating, vacuum filtration, allowing for customized design and optimization of the composite material. The review discusses how the nano cellulose-MMT composite demonstrates enhanced mechanical strength, thermal stability, and barrier properties, positioning it as a sustainable option compared to traditional materials. The review also showcases the diverse applications of these nano-composites in fields like packaging, biomedical devices, and environmental cleanup, emphasizing their alignment with circular economy principles. By examining the entire life cycle of these composites, from production to use and eventual disposal or recycling, the review underscores their role in supporting a circular economy. In light of the ongoing efforts by the scientific community and various industries to identify environmentally sustainable solutions, it is imperative to comprehend the synthesis, properties, and applications of nano cellulose-MMT composites. This understanding is essential for advancing sustainable processing for green material development.

Keywords: Nanocellulose (NC); Nano-montmorillonite (MMT); Vacuum filtration; Spray coating; Mechanical properties; Barrier properties; Application

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1. Introduction

With increasing environmental concerns about traditional packaging materials, there is a rising interest in exploring sustainable alternatives, with cellulose emerging as a compelling option. Cellulose-based packaging materials, derived from plant sources, offer a renewable and biodegradable solution to reduce the ecological impact of conventional plastics. Cellulose has advantages such as being abundant in nature, biocompatible, and suitable for various applications, making it a promising eco-friendly alternative to reduce reliance on non-renewable resources and promote environmentally conscious packaging solutions. Nanocellulose is also gaining attention as a groundbreaking solution for sustainable packaging. Derived from natural sources, nanocellulose has unique properties at the nanoscale, providing enhanced strength, flexibility, and biodegradability. The exploration of nanocellulose as a packaging material offers renewable origins, eco-friendly attributes, and diverse applications in the packaging industry, presenting an innovative avenue toward sustainable packaging solutions that balance functionality, environmental responsibility, and resource efficiency. Nano cellulose, sourced from renewable materials, presents a compelling solution due to its unique nanoscale properties that enhance strength and barrier characteristics, addressing the limitations of traditional materials. As awareness of environmental issues increases globally, the importance of incorporating nanocellulose in packaging becomes clear. With its eco-friendly nature, biodegradability, and potential to revolutionize the industry, nanocellulose plays a vital role in meeting the demand for environmentally responsible packaging solutions, promoting a balanced relationship between human activities and the environment.

The unique blend of nanocellulose and nano inorganics provides a wide array of functions. Nanocellulose is recognized for its exceptional surface area and high aspect ratio, and when combined with the diverse characteristics of nano inorganics, it creates composites with multiple functionalities. For example, integrating metallic nanoparticles can give the composites electrical conductivity, enabling potential applications in electronic devices and sensors. Likewise, incorporating antimicrobial nano inorganics can boost the composites' ability to resist bacterial growth, making them suitable for use in healthcare, food packaging, and other hygiene-sensitive environments [1]. Another important aspect of these composite materials is their ability to be adjusted. Scientists and businesses require composites that can have their properties controlled to customize them for specific uses. The makeup, dimensions, and distribution of both nanocellulose and nano-inorganics are crucial in determining the final properties of the composites [2]. Being able to precisely manage these factors enables customization based on the intended application. Whether it involves enhancing mechanical strength, thermal conductivity, or optical characteristics, the adjustability of these composites makes them flexible and suitable for a wide range of industrial needs.

The process of producing nanocellulose from wood pulp is an intriguing and innovative method that has attracted significant attention in the field of materials science. Understanding the complex steps involved in converting conventional wood pulp into nanocellulose, a nanomaterial with outstanding mechanical, thermal, and optical characteristics, is crucial. The process begins with selecting a suitable cellulose source, typically wood pulp from softwood or hardwood trees. Wood pulp is a plentiful and renewable raw material for nanocellulose production, meeting the increasing demand for sustainable and environmentally friendly materials. The cellulose fibers in wood pulp form the basis for the subsequent extraction of nanocellulose [3].

The initial stage of production involves reducing the large cellulose fibers into nanoscale sizes, which can be done through mechanical methods like high-pressure homogenization, micro-fluidization, or grinding. These techniques apply shear forces to break down the cellulose fibers into smaller fibrils, resulting in nanocellulose with decreased dimensions. Alternatively, chemical treatments like acid hydrolysis or enzymatic hydrolysis can also be used to break down cellulose fibers. Acid hydrolysis uses strong acids to target the amorphous regions of cellulose, producing crystalline nanocellulose. Enzymatic hydrolysis, on the other hand, employs enzymes to catalyze the breakdown of cellulose into nanoscale components. The choice between these methods depends on factors such as the desired properties of the nanocellulose and the specific application needs [4].

Purification steps following the breakdown process are essential to eliminate impurities and by-products. Common methods like filtration and centrifugation are used to separate nanocellulose from residual chemicals and contaminants. The resulting nanocellulose is typically in a gel or suspension form, requiring further processing to obtain a dry, usable material. Drying is a crucial step in nanocellulose production as it affects the final characteristics of the material. Various techniques such as freeze-drying, spray-drying, or air-drying are employed to remove water and produce a dry nanocellulose product. The choice of drying method can impact the nanocellulose's morphology and properties, underscoring the importance of careful consideration during this phase. The production of nanocellulose from wood pulp demonstrates the interdisciplinary nature of materials science, drawing on knowledge from chemistry, biology, and engineering. Researchers are continually exploring innovative methods to improve the efficiency and sustainability of the production process. Furthermore, advancements in nanotechnology have enabled the integration of nanocellulose into a wide range of applications, including biomedical devices, packaging materials, and reinforcement in composite materials [5].

Nanocellulose composites significantly contribute to the circular economy by enhancing the efficiency of material recycling. Unlike traditional composites, which often present challenges in separation and recycling due to their complex structures, nanocellulose composites are designed with recyclability in mind [6]. The uniform and homogenous distribution of nanocellulose within the matrix facilitates easier separation during the recycling process [7]. This streamlined recycling operation not only ensures the quality of recycled materials but also promotes a closed-loop system where materials can be reused without significant degradation. Consequently, nanocellulose composites play a pivotal role in advancing sustainable practices and reducing environmental impact by supporting a more efficient and effective recycling framework. In addition to improved recyclability, nanocellulose composites play a pivotal role in waste reduction. By incorporating nanocellulose into bio-based and biodegradable matrices, these composites contribute to the development of sustainable packaging materials [8]. Such materials provide a viable alternative to conventional, non-biodegradable packaging, effectively addressing the growing concerns surrounding plastic waste. The adoption of nanocellulose composites in packaging solutions not only reduces reliance on fossil-fuel-derived plastics but also mitigates the environmental impact associated with plastic pollution. This advancement aligns with the principles of a circular economy by promoting the use of renewable resources and enhancing the end-of-life management of packaging materials, ultimately fostering a more sustainable and eco-friendly approach to waste management.

Furthermore, nanocellulose composites have the potential to revolutionize the electronics and automotive industries, both of which have significant environmental footprints. By incorporating nanocellulose into conductive composites, these materials can be utilized in electronic devices, sensors, and lightweight components for vehicles [9]. This incorporation enhances the efficiency of electronic devices by providing superior conductive properties and promoting the development of flexible and lightweight electronics. In the automotive sector, using nanocellulose composites for lightweight components helps reduce the overall weight of vehicles, contributing to energy savings and reduced carbon emissions. This weight reduction translates into improved fuel efficiency and lower greenhouse gas emissions, aligning with global efforts to mitigate climate change and promote more sustainable industrial practices. Through these advancements, nanocellulose composites support the transition towards more environmentally friendly technologies and sustainable development in these critical sectors.

Nanocellulose composites hold great promise as a sustainable solution for the circular economy [10]. Their versatility, recyclability, and ability to enhance the properties of various materials position them as key contributors to a more sustainable and resource-efficient future. These composites can be tailored for diverse applications, ranging from packaging and electronics to automotive and construction industries, showcasing their wide-ranging impact on sustainability. The challenges and opportunities presented by nanocellulose composites allow for meaningful contributions to the advancement of circular economy practices and the development of greener technologies. Their use promotes the efficient recycling of materials and waste reduction, supports the creation of biodegradable and bio-based products, and enhances the performance of high-tech applications. Collectively, these factors make nanocellulose composites integral to driving innovation and sustainability, ultimately fostering a more circular and eco-friendly economy.

2. Fabrication of nanocellulose: MMT composite

Nanocellulose and montmorillonite (MMT) composites offer a unique combination of properties that make them suitable for a wide range of applications. Nanocellulose provides high mechanical strength, flexibility, and biodegradability, while MMT, a type of clay mineral, offers excellent barrier properties, thermal stability, and reinforcement. The synergy between these materials results in composites with enhanced mechanical, thermal, and barrier properties.

2.1. Dip coating

Dip coating is a versatile and straightforward method used to prepare nanocellulose-montmorillonite (MMT) composites. This technique involves immersing a substrate into a suspension of nanocellulose and MMT, followed by controlled withdrawal to form a thin, uniform coating. The dip coating method is a widely used technique in material science for creating thin films and coatings on various substrates. It is valued for its versatility, cost-effectiveness, and ability to produce uniform, homogeneous films with controlled thickness. This method applies to a broad range of materials and substrate shapes, making it suitable for various industrial applications. The dip coating technique is a versatile and cost-efficient method utilized in the field of material science to produce thin films and coatings on diverse substrates [11]. This process entails immersing a substrate into a liquid solution, enabling uniform coating upon withdrawal. A notable advantage of dip coating is its simplicity and capacity to generate thin, consistent films with regulated thickness. The procedure commences with the formulation of a solution containing the desired coating material, such as polymers or nanoparticles. Subsequently, the substrate is immersed in the solution, and through precise control of the withdrawal rate, a thin and uniform film is deposited onto the substrate’s surface. The dip coating method is highly adaptable and can be employed with various materials and substrate geometries, rendering it suitable for a broad spectrum of applications in industries like electronics, optics, and biomedicine. The efficacy of this technique lies in its capability to achieve even coatings with meticulous thickness control, rendering it an indispensable tool for researchers and engineers aiming to enhance material characteristics and explore novel applications.

The development of a nanocellulose-MMT composite using the dip coating technique represents an innovative advancement in the field of nanomaterial science. Nanocellulose, sourced from renewable materials such as wood pulp, exhibits remarkable mechanical attributes, including high strength and low density. Montmorillonite (MMT), a naturally occurring clay mineral, enhances the composite's versatility owing to its distinctive properties. The dip coating method is utilized as a cost-effective and efficient approach for producing thin films with enhanced characteristics. This process entails submerging a substrate into a solution containing nanocellulose and MMT, followed by a controlled withdrawal to achieve a uniform coating.

2.2. Spin Coating

Spin coating is a widely used technique in material science for creating thin films with uniform thickness on flat substrates. This method is particularly effective for producing nanocomposite films, such as those combining nanocellulose and montmorillonite (MMT), which are valued for their enhanced mechanical, thermal, and barrier properties. Spin coating is a commonly utilized and adaptable method within the field of material science for producing thin films of controlled thickness on even substrates. This technique involves the application of a liquid solution or dispersion onto the center of a rotating substrate, typically a silicon wafer or glass slide. The rapid rotation of the substrate results in the radial spreading of the liquid due to centrifugal force. Upon evaporation of the solvent, a thin and uniform film is generated. Spin coating is valued for its straightforwardness, efficiency, and repeatability. By adjusting the rotational speed and duration, the desired thickness and uniformity of the coating can be achieved. This approach is particularly effective for materials such as polymers, organic semiconductors, and nanoparticles. The thin films produced through spin coating have diverse applications in fields like electronics, optics, and photovoltaics [12]. While spin coating is well-suited for flat substrates, its limitations are evident when working with non-flat or three-dimensional surfaces. Nevertheless, spin coating remains a crucial technique in thin film production, offering precise management over film thickness and quality.

The synthesis of a nanocellulose-MMT composite using the spin coating method presents a novel approach to nanomaterial fabrication. Nanocellulose, sourced from renewable materials such as wood pulp, exhibits outstanding mechanical properties and biocompatibility. Montmorillonite (MMT), a natural clay mineral, imparts distinctive characteristics to the composite. Spin coating is utilized as an effective and regulated process for applying thin films onto planar substrates. During this procedure, a solution comprising nanocellulose and dispersed MMT nanoparticles is meticulously dispensed onto a rotating substrate, typically a silicon wafer or glass slide. The rapid rotation of the substrate generates centrifugal forces, ensuring uniform distribution of the solution and enabling the development of a thin composite film as the solvent evaporates. The spin coating method offers benefits including precise management of film thickness, high reproducibility, and a relatively straightforward configuration.

The nanocellulose-MMT composite fabricated via spin coating demonstrates distinctive characteristics resulting from the combined effects of its components. The precise manufacturing process yields a uniform and firmly attached coating, indicating potential enhancements in mechanical strength and functionality. These attributes position the composite as a promising candidate for utilization in diverse fields such as flexible electronics, sensors, and biomedical devices [13]. The versatility and scalability of the spin coating technique further enhance the feasibility of incorporating this nanocomposite into various technological innovations. Despite potential challenges associated with non-planar or three-dimensional substrates, spin coating remains a valuable method for researchers seeking to customize nanomaterial properties for specific applications.

Ongoing investigation into the application of spin coating for nanocellulose-MMT composites shows potential for advancing materials science and fostering the development of sustainable, high-performance technologies.

2.3. Hot pressing

Hot pressing is a widely used method in material science for fabricating composites, including those made from nanocellulose and montmorillonite (MMT). This technique involves applying heat and pressure to form dense, uniform composites with enhanced mechanical properties. Hot pressing is particularly effective for consolidating and densifying materials, making it suitable for creating high-performance nanocellulose-MMT composites.

The hot-pressing technique is a widely utilized method in the field of materials science for compacting powders into solid and dense forms. This process involves the application of heat and pressure to a powdered material contained within a die or mold. Initially, the material is placed in the mold, followed by the application of pressure while simultaneously heating the assembly. The combination of elevated temperature and pressure enables the powder to densify, resulting in a compact and cohesive structure. This method is particularly effective in the production of ceramic, metal, and composite materials with enhanced mechanical properties [14]. The heat not only facilitates the rearrangement of particles but also encourages diffusion, aiding in particle bonding. The hot-pressing technique offers advantages in producing high-density components with reduced porosity, thereby improving mechanical strength and thermal conductivity. While this method is robust for specific applications, it is crucial to consider the material's compatibility with the elevated temperatures involved, and adjustments in processing parameters may be required based on the unique properties of the powder being pressed. In conclusion, hot pressing serves as a versatile approach to material processing, providing a controlled method for producing dense and well-consolidated materials suitable for a variety of engineering and industrial applications.

The interaction between nanocellulose and MMT is enhanced by the hot-pressing technique, where increased temperature promotes particle reorganization and adhesion. The use of pressure aids in consolidating the composite material, leading to a dense and cohesive structure. Employing hot-pressing offers advantages in manufacturing components of high density with minimized porosity, thereby improving mechanical resilience and thermal conduction [15]. Precise control over temperature and pressure parameters is essential for customizing the characteristics of the nanocellulose-MMT composite. The hot-pressing technique is widely applicable in various industrial sectors, such as the manufacturing of advanced materials used in structural components, electronics, and biomedical devices [16]. It is crucial to assess the thermal compatibility of nanocellulose and MMT with the high temperatures involved in this method. Furthermore, adjustments to processing parameters may be necessary to optimize the properties of the composite based on the unique characteristics of the nanomaterials. The versatility of the hot-pressing method in customizing nanocellulose-MMT composites for specific applications highlights its importance in the progression of materials science and the creation of sustainable and high-performance materials.

2.4. Layer-by-layer assembly

Layer-by-layer (LbL) assembly is a versatile and precise technique used for fabricating multilayered thin films and coatings with controlled architecture at the nanoscale. This method involves the sequential deposition of alternating layers of materials, such as nanocellulose and montmorillonite (MMT), to create composites with enhanced mechanical, thermal, and barrier properties. LbL assembly allows for fine-tuning of the composite structure, making it suitable for a wide range of applications. Layer-by-layer assembly is a highly versatile and precise technique within the realm of materials science, involving the sequential deposition of alternating layers of materials with opposite charges onto a substrate [17]. This method allows for the controlled fabrication of thin films with specific properties, rendering them applicable across a diverse array of fields. Typically, the process commences with immersing a substrate in a solution containing a positively charged material, followed by the deposition of a negatively charged material. This layering sequence is repeated iteratively, facilitating the creation of intricate and customizable multilayer structures. The selection of materials utilized can encompass polymers, nanoparticles, or biological macromolecules, thereby offering flexibility in crafting coatings with tailored functionalities. Notably, LbL assembly is recognized for its capacity to generate coatings on various substrates, including objects with complex geometries and three-dimensional shapes. The thickness and composition of the resultant multilayered film can be precisely regulated by adjusting parameters such as solution concentration, pH, and deposition duration. The adaptability and tunability of this method establish Layer-by-layer assembly as a valuable tool in diverse fields like electronics, sensors, drug delivery, and tissue engineering, presenting a sophisticated means of customizing material properties at the nanoscale [18].

The fabrication of a nanocellulose-MMT composite using the Layer-by-Layer (LbL) assembly technique represents a sophisticated and precise methodology within the field of materials science, enabling the stepwise deposition of nanoscale layers with enhanced properties. Nanocellulose, sourced from sustainable origins, offers notable mechanical strength and biocompatibility, while Montmorillonite (MMT), a natural clay mineral, contributes distinctive attributes to the composite material. The LbL assembly process entails the repetitive deposition of oppositely charged substances onto a substrate, leading to the formation of a multi-layered architecture. In the context of the nanocellulose-MMT composite, the procedure commences with a substrate immersed in a solution containing either positively charged nanocellulose or negatively charged MMT. Subsequently, the substrate is alternately submerged in solutions containing oppositely charged constituents, facilitating the sequential accumulation of nanocellulose and MMT layers.

The LbL assembly technique offers a high degree of flexibility in regulating the thickness and composition of composites through the manipulation of factors such as solution concentration, pH, and deposition duration [19]. The utilization of this method in creating nanocellulose-MMT composites presents significant potential for a wide range of applications, including but not limited to flexible electronics, sensors, and drug delivery systems. The precise layering process allows for the customization of mechanical, thermal, and barrier characteristics, rendering it suitable for advanced materials with specific functionalities. Moreover, the adaptability of the LbL assembly approach to diverse substrates, encompassing intricate geometries and three-dimensional configurations, further broadens its utility. Despite potential challenges in optimizing parameters for large-scale manufacturing, the LbL assembly method remains a valuable tool for designing nanocomposites with finely tuned properties, thereby contributing to the development of sustainable and high-performance materials within the domain of nanotechnology.

2.5. Roll-to-roll coating

Roll-to-roll (R2R) coating is an advanced manufacturing technique used to produce large-area thin films and coatings continuously and cost-effectively. This method is particularly suited for fabricating nanocellulose-MMT composites, which benefit from the scalability and uniformity provided by R2R processes. By combining nanocellulose's renewable nature and MMT's excellent barrier properties, R2R coating can create high-performance, sustainable materials for various applications.

The roll-to-roll (R2R) coating technique is a highly efficient and scalable method utilized in materials processing, particularly for the large-scale production of flexible thin films. This continuous manufacturing approach involves the application of a liquid coating onto a flexible substrate, typically in the form of a continuous roll. The process occurs as the substrate progresses through a sequence of rollers, each serving a specific function such as coating, drying, and curing. R2R coating offers the advantage of accommodating a diverse range of materials, including polymers, metals, and nanoparticles, on flexible substrates like plastic or paper [20]. Widely employed in sectors such as electronics, photovoltaics, and flexible packaging, this method is favored for its high throughput and cost efficiency. It ensures uniform thickness and excellent reproducibility, facilitating the mass production of materials with consistent properties. While excelling in continuous and high-volume manufacturing, the optimization of parameters such as coating speed, viscosity, and drying conditions is essential for achieving desired film characteristics. The roll-to-roll coating technique, characterized by its versatility and effectiveness, plays a pivotal role in the production of flexible materials for diverse applications within the dynamic domain of advanced manufacturing.

The synthesis of a nanocellulose-MMT composite using the roll-to-roll (R2R) coating technique presents a high-throughput and scalable method for nanomaterial production. Nanocellulose, sourced from renewable origins, imparts impressive mechanical properties and biocompatibility to the composite, while montmorillonite (MMT), a natural clay mineral, contributes distinct characteristics. The R2R coating process entails the continuous application of a liquid coating onto a flexible substrate, typically in the form of a continuous roll, as it traverses a series of rollers. In the context of the nanocellulose-MMT composite, the liquid coating consists of a well-dispersed blend of nanocellulose and MMT nanoparticles. The uninterrupted and effective nature of R2R coating ensures consistent deposition of the composite onto the flexible substrate, facilitating the large-scale production of thin films.

The adaptability of the R2R coating method allows for the creation of nanocellulose-MMT composites with varying thickness and composition by adjusting parameters like coating speed, viscosity, and drying conditions. The nanocellulose-MMT composite fabricated through the R2R coating process shows significant potential for use in flexible electronics, packaging, and biomedical devices. The continuous and high-throughput characteristics of R2R coating align with the requirements of industrial-scale manufacturing, rendering it a valuable technique for developing nanocomposites with customized properties. While challenges related to optimizing coating parameters may emerge, the R2R coating method emerges as a crucial approach in advancing nanomaterial synthesis, contributing to the production of sustainable and high-performance materials across diverse sectors [21]. The scalability and effectiveness of R2R coating position it as a pivotal tool in the incorporation of nanocomposites into practical applications.

2.6. Vacuum filtration

Vacuum filtration is a simple and effective technique used to fabricate composite materials, including those made from nanocellulose and montmorillonite (MMT). This method involves the use of vacuum pressure to drive a liquid suspension through a porous filter, depositing solid components onto the filter surface. Vacuum filtration is particularly advantageous for creating dense, well-organized nanocomposite films with controlled thickness and uniform distribution. The vacuum filtration technique is a commonly utilized method in laboratory and industrial settings for the separation of solids from liquids [22]. This process involves the application of reduced pressure to facilitate the passage of a liquid through a filter, leaving solid particles retained on the filter paper or membrane. Typically, the setup includes a Buchner funnel connected to a vacuum pump and a flask for collecting the filtrate. By pouring the solid-liquid mixture onto the filter paper and applying vacuum pressure, the filtration process is expedited as the liquid is rapidly drawn through the filter, while the solid particles are retained. Vacuum filtration is particularly beneficial for tasks requiring the separation of fine precipitates or the concentration of a liquid by eliminating excess solvent. This method finds extensive application in chemistry, microbiology, and the pharmaceutical industry for activities such as crystal isolation, compound purification, and biological sample collection. The vacuum filtration method's simplicity, speed, and efficiency render it an indispensable tool for various research and industrial purposes.

The fabrication of a nanocellulose-MMT composite using the vacuum filtration method presents a straightforward and effective approach in materials science, combining the favorable attributes of nanocellulose and montmorillonite (MMT). Nanocellulose, derived from sustainable sources, contributes remarkable mechanical strength and biocompatibility, while MMT, a natural clay mineral, imparts distinctive characteristics to the composite. The vacuum filtration process involves the separation of solids from liquids through reduced pressure, employing a Buchner funnel connected to a vacuum pump. In the production of the nanocellulose-MMT composite, a suspension containing nanocellulose and MMT nanoparticles is poured onto the filter paper. The application of vacuum accelerates the filtration, drawing the liquid through the filter and leaving the solid composite material on the filter paper.

The simplicity and efficiency of the vacuum filtration method make it an appealing choice for manufacturing nanocomposites. The isolated composite material can be conveniently recovered from the filter paper, and the process is adaptable for scaling up production volumes. The nanocellulose-MMT composite generated through vacuum filtration exhibits potential for diverse applications, including the creation of lightweight, high-strength materials and environmentally friendly packaging. The adjustability of the composite's properties by varying the nanocellulose to MMT ratio allows for versatility in its utilization. Despite the straightforward nature of the vacuum filtration method, its effectiveness in producing nanocomposites with controlled characteristics underscores its importance in advancing materials science [23].

2.7. Spray coating

Spray coating is a highly adaptable and effective technique utilized in the fabrication of thin films and coatings through the atomization of a liquid solution, which is subsequently deposited onto a substrate. This method is particularly advantageous for the production of free-standing nanocellulose-MMT composites that exhibit uniform thickness and desirable characteristics. Additionally, spray coating is well-suited for the generation of large-area films and can be readily scaled for industrial applications. As a widely employed technique in materials science, the spray coating process entails the atomization of a liquid solution or dispersion into fine droplets, which are directed towards a substrate via a nozzle. Upon contact with the substrate, these droplets coalesce to form a uniform coating as the solvent evaporates. The spray coating method presents numerous benefits, including its simplicity, cost-effectiveness, and capability to coat complex and irregularly shaped surfaces. This methodology exhibits significant scalability, rendering it appropriate for both laboratory-scale investigations and extensive industrial manufacturing. The thickness of the deposited film can be regulated by modifying parameters such as the distance of the spray nozzle, the concentration of the solution, and the duration of the spraying process. Spray coating is utilized across a range of disciplines, including electronics, optics, and the coating of medical devices. The synthesis of a nanocellulose-montmorillonite (MMT) composite via the spray coating technique represents a novel and effective methodology for the production of nanomaterials, leveraging the distinctive attributes of both nanocellulose and MMT. Nanocellulose, which is sourced from renewable materials, imparts remarkable mechanical strength and biocompatibility to the composite, whereas MMT, a naturally occurring clay mineral, contributes unique properties. The spray coating process entails the atomization of a liquid solution or dispersion containing nanocellulose and MMT into fine droplets, which are subsequently directed onto a substrate through a nozzle. Upon contact with the substrate, these droplets coalesce to form a uniform coating as the solvent evaporates.

The spray coating technique exhibits significant versatility, enabling precise regulation of the thickness and distribution of the nanocellulose-MMT composite across a variety of surfaces, including those with complex and irregular geometries. The nanocellulose-MMT composite generated via spray coating presents considerable potential for applications in multiple domains, such as advanced packaging, electronics, and biomedical devices. The process's efficiency and scalability are well-suited to meet the requirements of industrial-scale production, rendering it a compelling approach for the fabrication of nanocomposites with customized properties [24]. Ongoing investigations into innovative methodologies, including spray coating, play a crucial role in the advancement of sustainable and high-performance materials capable of addressing contemporary challenges across various industries.

Spray coating represents an effective technique for the fabrication of nanocomposites, facilitating meticulous regulation of film thickness and uniformity. In this methodology, cellulose nanofibers (CNF) are integrated with montmorillonite (MMT) clay, and the resultant suspension is spray-coated onto a stainless-steel substrate to yield free-standing nanocomposite films. CNF is derived from the mechanical or chemical treatment of cellulose sources, resulting in fibers characterized by high aspect ratios and superior mechanical properties. MMT is a type of clay that, upon exfoliation, enhances the barrier properties and mechanical strength of the composite. Composite suspension preparation: CNF and MMT (Cloisite Na++) are dispersed in water or an appropriate solvent to form a homogeneous suspension. This dispersion is achieved through sonication or mechanical stirring to ensure uniform mixing and exfoliation of MMT. The concentration of CNF and MMT in the suspension is adjusted according to the desired final properties of the nanocomposite film. Spray coating apparatus: An airbrush or spray gun is employed to atomize the CNF-MMT suspension. The nozzle size and spray pressure are calibrated to produce a fine mist and ensure uniform deposition. Substrate: A stainless-steel plate measuring 220 mm x 220 mm serves as the temporary substrate. The plate is meticulously cleaned to promote good adhesion of the initial layers and facilitate the subsequent removal of the final film. Spraying: The suspension is applied to the stainless-steel plate in a controlled manner, involving multiple passes to gradually build up the film thickness while ensuring uniformity and consistency. Drying and consolidation: Following the spraying process, the coated plate is dried at room temperature or in an oven to eliminate the solvent. Careful control of the drying process is essential to prevent cracking or warping of the film. Film thickness: The resulting nanocomposite film exhibits a thickness ranging from approximately 81.7 μm to 135.8 μm, contingent upon the number of layers applied and the concentration of the suspension. Basis weight: The basis weight of the film varies from about 70 g/m^2 to 100 g/m^2, influenced by the suspension concentration and the thickness of the applied layers. Film removal: Upon complete drying and consolidation, the film is carefully peeled from the stainless-steel plate, resulting in a free-standing nanocomposite film. The smooth surface of the stainless-steel substrate aids in the easy release of the film. Properties and applications: Mechanical properties: The incorporation of MMT into the CNF matrix significantly enhances the mechanical properties of the composite, resulting in increased tensile strength and stiffness. Barrier properties: The nanocomposite film demonstrates excellent barrier properties against gases and moisture, rendering it suitable for packaging applications that necessitate extended shelf life and reduced permeability. Uniformity and control: The spray coating technique allows for precise control over film thickness and uniformity, ensuring consistent material properties across extensive areas. Scalability: This method is scalable, making it appropriate for the industrial production of nanocomposite films with controlled thickness and properties.

Figure 1 shows the spray-coated nanocellulose-MMT composite and can be used as green packaging material. Spray coating was used to create MMT-CNF composites that were uniform, flexible, and foldable. Through the adjustment of MMT content in 2% weight CNF suspension, from 0 to 75%, the properties of the composites were customized. For every kind of composite film, the air and water vapor permeability (WVP) characteristics of the composites were assessed through spraying. By measuring the thickness, spray-coated cellulose nanofiber MMT composites were found to have good consistency. As the MMT component was raised from 5% to 75%, the composites' colors became more yellowish in the Closite Na++ MMT composite, reddish in the Closite Ca++ MMT composite, and light grey in the Closite 116 MMT composite. This is because of the MMT absorption spectra in the nanocomposites, which have also been noted. Spray coating and modifying MMT loading in CNF suspension produce a finished product that is colored and smooth.

The rough surfaces of the pure cellulose nanofiber film and the spray-coated 30% and 10% MMT-CNF composites are depicted in **Figure 2**. The photographs demonstrate the uniform distribution of MMT platelets across the rough surface of the spray-coated nanocomposite. The nanocomposite, which is prominently incorporated and impregnated in the cellulose fiber network, has MMT particles on its surface. It is possible to say that MMT is impregnated into the pore of cellulose nanofiber because its size ranges from 300 to 1000 nm.

The smooth side of the composites is shown in **Figure 3**, which also verifies the MMT distribution in the composites. In the composites with spray coating, MMT was layered. The barrier performance of the composites was impacted by the MMT stacking, which will be covered in more detail later in the paper. By mimicking the smoothness of the aforementioned stainless-steel plate, the CNF-MMT suspension sprayed on the stainless steel creates a smooth film.

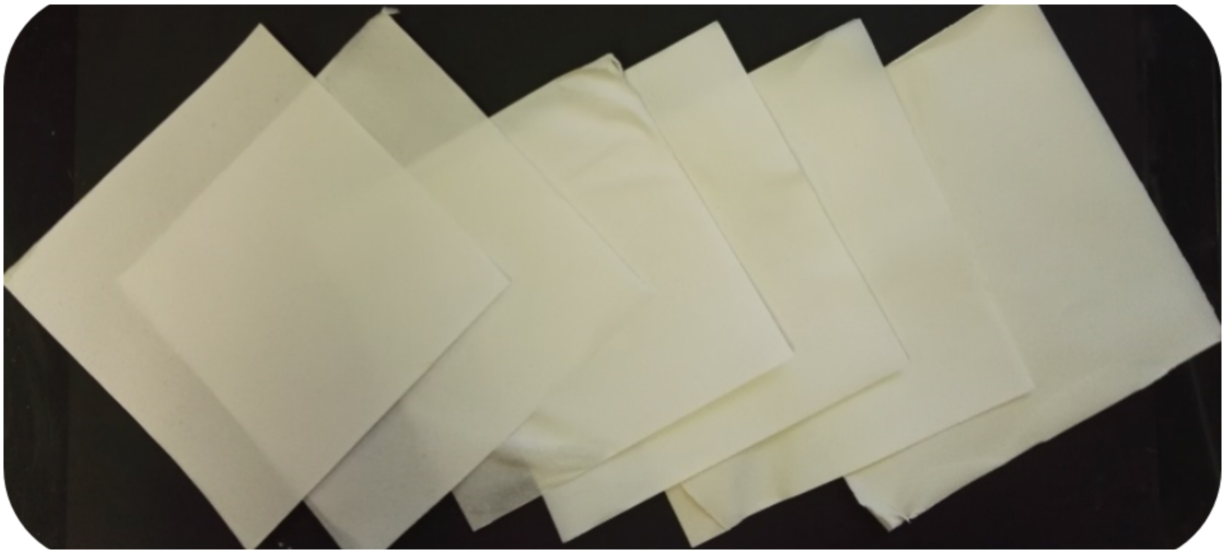

Figure 1. Spray-coated nanocomposites prepared via spraying cellulose nanofiber; MMT produced from spraying of CNF; Closite Na++ suspension on the stainless-steel plate. The size of cellulose nanofiber composite is 220 mm x 220 mm and thickness varies from 81.7 μm to 135.8 μm. The basis weight of the film varies from 70 g/m^2 to 100g/m^2 [25].

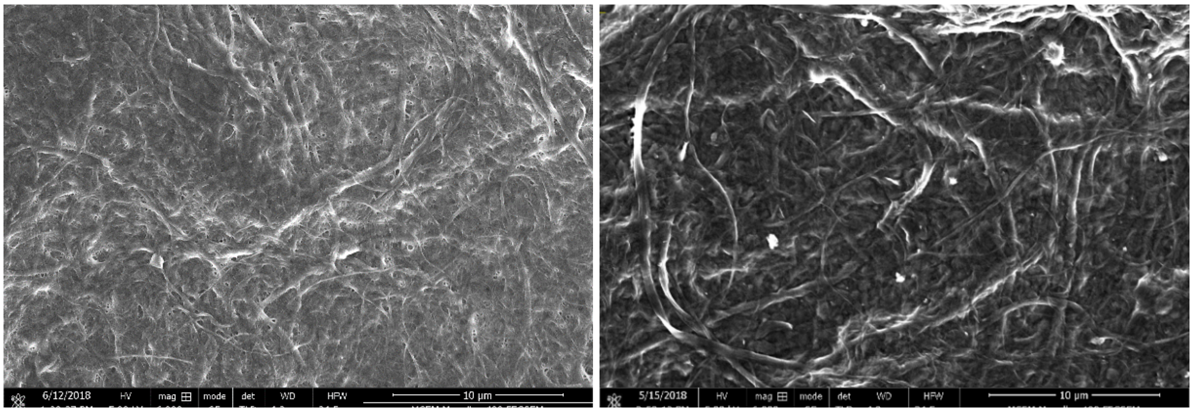

Figure 2. Spray-coated CNF-MMT Composite (Rough side) and CNF film (Rough side); Pure cellulose nanofibre (Left) and 30% MMT-CNF composite (Right) [25].

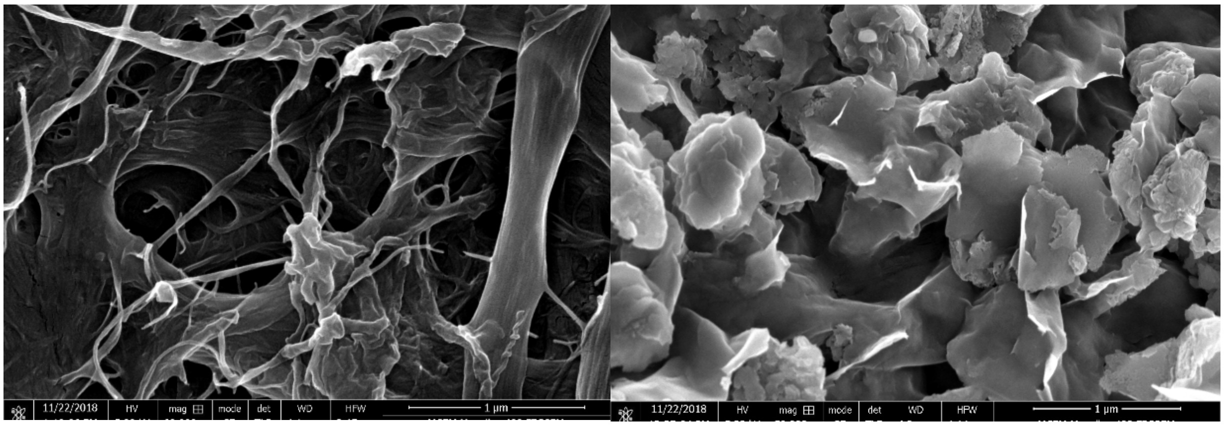

Figure 3. The smooth side of NC-MMT composites via spray coating; Pure cellulose nanofibre film (Left) and 30% MMT-CNF composite (Right) [25].

3. Surface morphology and topography of spray-coated nanocomposites

In the margins of the spray-coated nanocomposites, stacks of MMT were shown to aggregate. NC fibrils have an average diameter of 70 nm, a wide range of fiber diameters, an average fiber length of 8 μm, and an average aspect ratio of 142 ± 28. MMT particles ranged in length from 300 to 1000 nm. Because of the huge aspect ratio of the nanocellulose fibrils, the MMT platelets were exfoliated between them.

The surface morphology and topography of nanocomposite films are critical factors influencing their mechanical, barrier, and optical properties. For spray-coated nanocellulose-MMT nanocomposites, the interplay between cellulose nanofibers (CNF) and montmorillonite (MMT) significantly affects the film's final characteristics. Advanced imaging and analytical techniques are employed to study these properties and optimize the fabrication process. Surface morphology: Scanning Electron Microscopy (SEM): Resolution and magnification: SEM provides high-resolution images at various magnifications, revealing detailed surface features and the distribution of CNF and MMT. Surface features: SEM images typically show the network structure of CNF, with MMT platelets dispersed within the matrix. The surface may exhibit a rough texture due to the fibrous nature of CNF and the layered structure of MMT. The surface morphology and topography of spray-coated nanocellulose-MMT nanocomposites play a crucial role in determining their properties and performance. Nanocellulose and montmorillonite (MMT) are two important components that can enhance mechanical, thermal, and barrier properties when combined in a nanocomposite. The spray-coating process allows for the uniform deposition of nanocellulose-MMT nanocomposites onto a substrate, resulting in a thin film with specific surface features. Surface morphology refers to the shape, size, and distribution of particles on the coated surface, while topography refers to the overall surface texture and roughness. Analyzing the surface morphology and topography of these nanocomposites can provide valuable insights into their adhesion, durability, and functionality. Techniques such as scanning electron microscopy (SEM), atomic force microscopy (AFM), and profilometry are commonly used to characterize the surface of nanocomposite coatings. Understanding the surface features of spray-coated nanocellulose-MMT nanocomposites is essential for optimizing their performance in various applications, such as packaging materials, coatings, and biomedical devices. This research can lead to the development of advanced materials with tailored properties for specific industrial needs.

4. Properties of composites

Nanocellulose-MMT composites combine the unique properties of cellulose nanofibers (CNF) and montmorillonite (MMT) clay, resulting in materials with enhanced mechanical, barrier, thermal, and other functional properties. These composites are gaining attention for their potential applications in various fields, including packaging, electronics, and biomedicine.

4.1. Mechanical properties

Nanocellulose-MMT nanocomposites exhibit enhanced mechanical properties due to the combination of the unique characteristics of nanocellulose and montmorillonite clay. The intercalation of nanocellulose fibrils within the layered structure of montmorillonite clay leads to improved mechanical strength, stiffness, and toughness of the composite material. The high aspect ratio and large specific surface area of nanocellulose contribute to the reinforcement of the nanocomposite, leading to increased tensile strength and modulus. The hydrogen bonding between the hydroxyl groups of nanocellulose and the surface functional groups of montmorillonite enhances the interfacial adhesion, resulting in better stress transfer between the phases and improved mechanical properties. Moreover, the excellent barrier properties of nanocellulose and montmorillonite clay help to prevent crack propagation and enhance the overall toughness of the nanocomposite material. These synergistic effects result in nanocellulose-MMT nanocomposites with superior mechanical performance compared to conventional polymer composites. Overall, nanocellulose-MMT nanocomposites have great potential for various applications requiring high mechanical performance, such as in structural materials, packaging, and biomedical devices.

The mechanical characteristics of nanocellulose-MMT (Montmorillonite) composites are a significant focus in the field of materials science due to the synergistic effects resulting from the combination of nanocellulose and MMT components. Nanocellulose, sourced from renewable origins, demonstrates exceptional mechanical strength due to its nano-sized fibrillar structure and high aspect ratio. When combined with MMT, a natural clay mineral, the resulting composite displays a distinctive set of properties. The presence of MMT, known for its inherent strength and reinforcement capabilities, further enhances the mechanical properties of the composite material. The interaction between nanocellulose and MMT at the nano level facilitates efficient stress transfer within the composite, leading to improved tensile strength, modulus, and toughness.

The mechanical performance of nanocellulose-MMT composites can be customized by adjusting the ratio of nanocellulose to MMT, enabling precise optimization of mechanical properties based on specific application needs. The composite's tensile strength benefits from the strong interfacial adhesion between the nanocellulose and MMT phases, resulting in a synergistic reinforcement effect [26]. Moreover, the incorporation of MMT nanoparticles enhances stiffness and impact resistance, making the composite suitable for applications requiring superior mechanical performance.

The resulting nanocellulose-MMT composite, with its improved mechanical properties, shows potential for various applications. From lightweight structural elements to advanced materials in the aerospace and automotive sectors, the composite's enhanced strength and toughness position it as a viable alternative to traditional materials. Additionally, the biocompatibility of nanocellulose opens up possibilities for applications in biomedical devices and tissue engineering, where mechanical performance is critical for implant materials.

Nanocellulose-MMT composites exhibit enhanced mechanical characteristics, making them suitable for diverse fields. The inclusion of MMT led to an increase in the tensile strength of LMP-CMC-MMT nanocomposite films, indicating the formation of hydrogen bonds between MMT and the polymer matrix. Similarly, Ul-Islam observed improvements in tensile strength and thermal stability in BC-MMT composites, attributing these enhancements to the presence of MMT [27]. Silvério noted elevated mechanical properties in MC/WSH 30 nanocomposite films, suggesting that the mechanical percolation of cellulose nanocrystals and the formation of a continuous network contributed to these advancements [28]. Additionally, Wu demonstrated the potential of nanocellulose-MMT composites by achieving exceptionally high mechanical and oxygen barrier properties in TOCN/MTM composite films [29]. Together, these studies emphasize the crucial role of MMT in enhancing the mechanical properties of nanocellulose-based composites.

4.2. Barrier properties

Nanocellulose montmorillonite (MMT) nanocomposites exhibit improved barrier properties due to the combined effects of the nanocellulose and the MMT clay. Nanocellulose, with its high aspect ratio and strong hydrogen bonding, forms a dense network structure that can hinder the passage of gases and liquids. On the other hand, MMT clay has a layered structure with high aspect ratio platelets that can act as a physical barrier to the diffusion of molecules. When these two materials are combined in a nanocomposite, they work synergistically to enhance the barrier properties. The nanocellulose can fill the gaps between the MMT platelets, increasing the tortuosity of the diffusion path for molecules. This results in improved gas barrier properties, moisture barrier properties, and even UV-blocking capabilities. Overall, nanocellulose-MMT nanocomposites have great potential in various applications where superior barrier properties are required, such as in packaging materials, coatings, and barrier films.

The barrier characteristics of composite materials combining nanocellulose and montmorillonite (MMT) are a significant factor in their utilization across diverse industries. These composites, resulting from the combined effects of nanocellulose and MMT, display exceptional barrier properties against gases, liquids, and environmental elements. Various research studies have contributed to the comprehension and enhancement of these barrier properties. For example, Yu illustrated that the incorporation of MMT in LMP-CMC-MMT nanocomposite films significantly enhanced the barrier properties, particularly in preventing gas permeation. Similarly, Ul-Islam documented improved barrier properties, especially against liquid permeation, in BC-

MMT composites [27]. Silvério noted enhanced barrier properties in MC/WSH 30 nanocomposite films, attributing this enhancement to the mechanical percolation of cellulose nanocrystals and the establishment of a continuous network [28]. The integration of MMT has been pivotal in achieving superior barrier properties in nanocellulose-based composites, enhancing their suitability for applications in packaging, where safeguarding against external factors is critical. The advancements in barrier properties not only ensure the preservation of the composite's structure but also broaden its potential applications in areas such as food packaging, healthcare, and environmental conservation. In summary, nanocellulose-based materials, including those incorporating MMT, exhibit outstanding barrier properties, positioning them as promising options for sustainable packaging materials.

The WVP of the spray-coated NFC-MMT composite sheets is displayed in **Figure 4**. In this instance, the vacuum-filtered NFC-MMT composite sheets were also compared with the WVP values. 95% confidence intervals are shown by the error bars. As illustrated in **Figure 4**, the initial average WVP of a spray-coated, unhomogenized pure NFC sheet was found to be 2.5 x 10–11 g/m.s.Pa. This value is comparable to the water vapor permeability of pure NFC sheets created by spraying for packaging applications. In this case, it was demonstrated that adding 5 weight percent MMT loading would reduce this WVP by over half, to 1.2 x 10–11 g/m.s.Pa. However, at a 30% MMT loading, the WVP rose above this loading to a maximum of 3.3 x 10–11 g/m.s.Pa. The excessive MMT agglomeration is the cause of this.

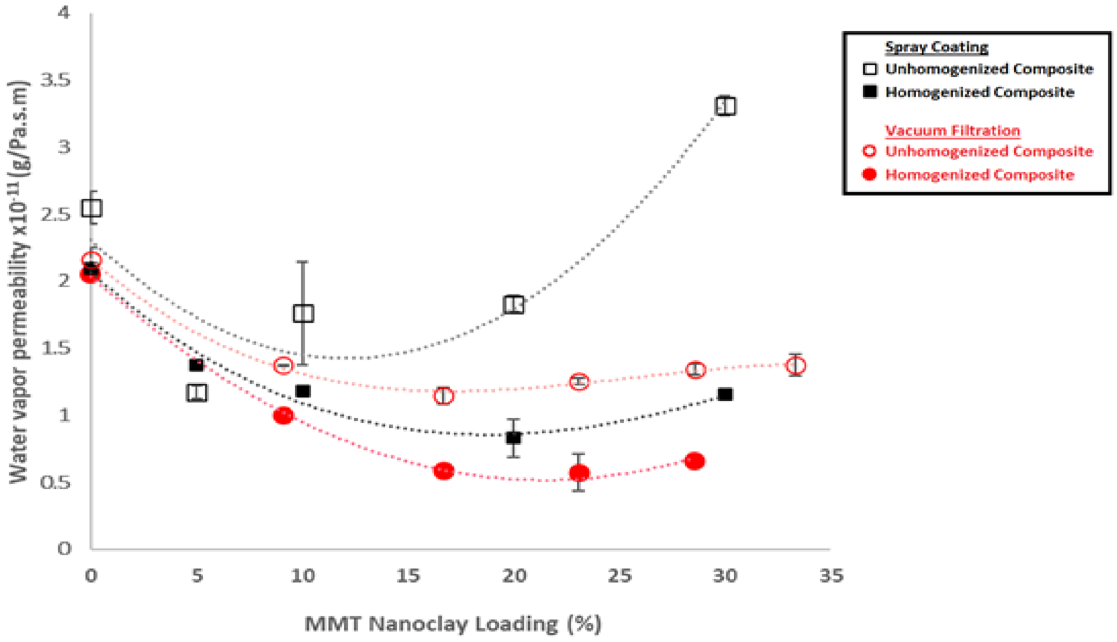

Figure 4. Water vapor permeability of spray-coated and vacuum-filtered NFC-MMT sheets containing the same amount of NFC with varying MMT loading for the NFC content [25].

It is interesting to note that with larger MMT loadings, homogenizing the MMT and NFC suspensions before spray coating significantly improved the WVP results. **Figure 3** illustrates the average weight loss pressure (WVP) of a spray-coated homogenized NFC-MMT composite sheet at an optimal loading of 20%

MMT, which was 0.8 x 10–11 g/m.s.Pa. The bigger MMT particles are thought to be broken down and delaminated during the homogenization process, which increases their effective surface area. As a result, the MMT distribution becomes more uniform throughout the NFC matrix, increasing the pathway's overall tortuosity and allowing water vapor to permeate.

Nanocellulose/MMT (montmorillonite) nanocomposites exhibit excellent barrier properties against water vapor due to their unique structure and composition. The nanocellulose component, derived from cellulose fibers, provides a high aspect ratio and a large surface area, allowing for efficient water vapor barrier properties. The MMT component, a type of clay mineral, further enhances the barrier properties by forming a tortuous path for the diffusion of water vapor molecules. The synergistic combination of nanocellulose and MMT in the nanocomposites results in improved mechanical strength and barrier performance compared to pure materials. The nanocellulose fibers form a reinforcement network within the MMT matrix, leading to enhanced barrier properties against water vapor transmission. These nanocomposites are promising materials for various applications requiring high-performance water vapor barriers, such as packaging, coatings, and films. The nanocellulose/MMT nanocomposites offer the potential to significantly reduce moisture ingress and enhance the shelf life of products while maintaining eco-friendly and sustainable characteristics due to the biodegradability of nanocellulose. Overall, the unique structure and combination of nanocellulose and MMT in nanocomposites make them attractive materials for developing advanced water vapor barrier solutions in a range of industrial applications.

5. Application of the composites

Nanocellulose-MMT (montmorillonite) nanocomposites have various applications due to their unique properties. These materials combine the strength and renewability of nanocellulose with the enhanced mechanical, thermal, and barrier properties provided by MMT. Nanocellulose-MMT nanocomposites have shown great potential in packaging applications due to their unique properties. Nanocellulose, derived from renewable sources, offers high strength, biodegradability, and barrier properties, making it an attractive alternative to traditional packaging materials. When combined with montmorillonite (MMT) nanoparticles, the resulting nanocomposites exhibit enhanced mechanical strength and barrier properties. In packaging applications, nanocellulose-MMT nanocomposites can be used to create sustainable and environmentally friendly packaging materials. These materials can provide excellent oxygen and water vapor barrier properties, prolonging the shelf life of food products and reducing food waste. Additionally, the high strength of nanocellulose-MMT nanocomposites can improve the durability and protective capabilities of packaging, ensuring the safe transportation and storage of goods. Furthermore, the biodegradability of nanocellulose-MMT nanocomposites offers a more sustainable solution to the growing issue of plastic waste in the packaging industry. By utilizing these advanced materials in packaging applications, manufacturers can reduce their environmental impact and meet the increasing consumer demand for eco-friendly packaging solutions.

In the medical field, these composites can be employed for drug delivery systems. The unique properties of nanocellulose and montmorillonite can be harnessed to create controlled-release systems for pharmaceuticals. Nanocellulose-MMT nanocomposites have promising biomedical applications due to their unique properties. These nanocomposites exhibit excellent mechanical strength, biocompatibility, and tunable surface characteristics, making them suitable for various biomedical applications. In tissue engineering, nanocellulose-MMT nanocomposites can be used as scaffolds to support cell growth and tissue regeneration. Their nanoscale structure closely mimics the extracellular matrix, promoting cell adhesion and proliferation. Furthermore, the presence of MMT nanoparticles can enhance the mechanical properties of the nanocellulose scaffolds, making them more robust and suitable for load-bearing applications. In drug delivery systems, nanocellulose-MMT nanocomposites can be used to encapsulate and deliver therapeutic agents to specific targets in a controlled manner. The high surface area of nanocellulose allows for efficient drug loading, while the MMT nanoparticles can help control the release rate of the drug. Moreover, the biocompatibility of nanocellulose-MMT nanocomposites ensures minimal immune response and toxicity, making them safe for use in biomedical applications. Overall, these nanocomposites hold great potential for advancing healthcare technologies and improving patient outcomes.

The addition of nanocellulose/MMT composites to paper products can improve their strength, durability, and water resistance. This can lead to the development of high-performance paper for various applications. Nanocellulose montmorillonite (MMT) nanocomposites have shown significant potential in enhancing the properties of paper and pulp products. The addition of nanocellulose to paper can improve its strength, flexibility, and barrier properties, making it more durable and suitable for various applications. MMT nanoparticles further enhance these properties by providing increased thermal stability, water resistance, and improved barrier against gases and liquids. In the paper industry, nanocellulose-MMT nanocomposites can be used as additives to produce specialty papers for packaging, filters, and other high-performance applications. These nanocomposites can also reduce the amount of virgin fibers required in paper production, promoting sustainability and reducing production costs. Additionally, the improved properties of nanocellulose-MMT nanocomposites can lead to the development of innovative paper and pulp products with enhanced performance characteristics. Overall, the application of nanocellulose-MMT nanocomposites in the paper and pulp industries offers a promising avenue for improving product quality, reducing environmental impact, and exploring new possibilities for advanced materials.

Nanocellulose montmorillonite nanocomposites have gained interest for applications as coatings and films due to their unique properties. These nanocomposites offer improved mechanical strength, barrier properties, and thermal stability compared to traditional materials. In coatings, nanocellulose-MMT nanocomposites can provide enhanced durability, wear resistance, and corrosion protection. They can be used to create thin, transparent coatings that protect surfaces while also offering aesthetic benefits. These coatings can be applied to various substrates including metals, plastics, and wood. In films, nanocellulose-MMT nanocomposites can be used as packaging materials, providing improved barrier properties against oxygen, moisture, and UV radiation. These films can extend the shelf life of food products and prevent the degradation of sensitive materials. They can also be used in electronic devices as flexible substrates due to their mechanical flexibility and strength. Overall, the application of nanocellulose-MMT nanocomposites as coatings and films offers a sustainable and eco-friendly alternative to traditional materials, with potential applications in various industries such as packaging, automotive, electronics, and construction.

Nanocellulose-MMT nanocomposites have shown promise in environmental remediation due to their unique properties. These materials combine the advantages of nanocellulose, such as high strength and biodegradability, with the enhanced adsorption capabilities of montmorillonite clay. Purification: Nanocellulose-MMT nanocomposites can effectively remove heavy metals, dyes, and organic pollutants from water through adsorption processes. Their large surface area and high porosity make them efficient in capturing and trapping contaminants. Soil remediation: These nanocomposites can be used to remediate soil contaminated with heavy metals, pesticides, and other pollutants. They can help in immobilizing contaminants and reducing their leaching into groundwater, thus minimizing environmental impact. Air filtration: Nanocellulose-MMT nanocomposites can also be used in air filtration systems to remove volatile organic compounds (VOCs) and other air pollutants. Their high adsorption capacity makes them effective in capturing and trapping harmful substances. Biodegradability: One of the key advantages of nanocellulose-MMT nanocomposites is their biodegradability, making them environmentally friendly and sustainable for use in remediation applications. Overall, the application of nanocellulose-MMT nanocomposites in environmental remediation shows great potential for addressing pollution challenges and promoting a cleaner and healthier environment.

6. Recyclability of composites

Nanocellulose-MMT (Montmorillonite) nanocomposites exhibit promising recyclability due to their unique combination of properties. The nanocellulose component provides high strength, stiffness, and biodegradability, while MMT clay offers barrier properties, thermal stability, and flame resistance. In terms of recyclability, these nanocomposites can be potentially recycled through various methods such as mechanical reprocessing, dissolution, or chemical recycling. Mechanical reprocessing involves breaking down the nanocomposites into smaller pieces and reforming them into new materials. Dissolution methods may involve using solvents to dissolve the matrix and separate the components for reuse. Chemical recycling techniques may involve breaking down the components into their original building blocks for further processing. The recyclability of nanocellulose-MMT nanocomposites is still an area of active research, with efforts focused on developing efficient and cost-effective recycling methods while maintaining the properties and performance of the materials. Overall, the recyclability of these nanocomposites holds great potential for reducing waste and promoting sustainability in various industries. Nanocellulose-montmorillonite nanocomposites offer significant potential for improving the sustainability of materials used in various industries, including packaging, construction, and biomedical applications. One critical aspect of their environmental impact is their recyclability.

7. Conclusion

In summary, this review offers a thorough examination of nano cellulose-MMT composites, elucidating their manufacturing techniques, unique characteristics, and diverse uses. The combination of cellulose nanomaterials with MMT leads to a new composite material with improved mechanical, thermal, and barrier properties. The range of production methods discussed enables customized design and enhancement, demonstrating the adaptability of these composites. The increased mechanical durability, thermal resistance, and barrier features displayed by the nano cellulose-MMT composite position it as an eco-friendly substitute for traditional materials. The review emphasis on circular economy principles reflects a growing recognition of sustainable material cycles. The incorporation of these composites supports the imperative to minimize waste and encourage recycling, contributing to a circular economy. The various applications outlined in the chapter, including packaging, medical devices, and environmental cleanup, highlight the versatility of nano cellulose-MMT composites. The attention to the complete life cycle of these composites, from production to use and eventual disposal or recycling, underscores their role in sustainable material innovation and resource management. As the scientific community and industries increasingly prioritize environmentally friendly solutions, the information presented in this paper becomes crucial. Grasping the manufacturing processes, characteristics, and uses of nano cellulose-MMT composites is vital for advancing sustainable practices and addressing the resource management challenges in the quest for a more environmentally aware future.

Disclosure statement

The author declares no conflict of interest.

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