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Nanocellulose from Agricultural Leftovers: Environmental Benefits, Properties, Applications, Extraction, Challenges, Opportunities, and Sustainability

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ABSTRACT: Nanocellulose derived from agricultural leftovers (waste) possesses high strength, low viscosity, biodegradability, and renewability. These characteristics render nanocellulose a promising material for diverse applications. This manuscript succinctly presents the significance of utilizing agricultural leftovers for nanocellulose production, the environmental advantages of this approach, an overview of nanocellulose and its properties, various applications of nanocellulose, the extraction process from agricultural leftovers, and the challenges and opportunities associated with nanocellulose in sustainable development. Nanocellulose sourced from agricultural leftovers is increasingly recognized as a sustainable raw material across multiple industries.

Keywords: agricultural waste, nanocellulose, eco-friendly, sustainability.

INTRODUCTION

Lignocellulosic biomass (abundantly available in agricultural waste) is an excellent source of nanocellulose. Lignocellulosic biomass is primarily composed of lignin, cellulose, and hemicellulose, and is an abundant bioresource that is often overlooked and underutilized (Pires *et al.*, 2019). Lignocellulosic biomass can be found in agricultural and industrial residues from lignocellulosic crops (Philippini *et al.*, 2020). The cellulose extracted from lignocellulosic biomass can be depolymerized, resulting in nanocellulose production in its nanometer-scale form, a unique bio-based material that holds immense promise due to its abundance, biodegradability, renewability, and low-cost nature. Nanotechnology offers the development of materials with unique physicochemical properties at the nanoscale, enabling advancements across various fields such as medicine, energy, and environmental applications (Bhagwan *et al.*, 2019). Nanofibers, as a specific form of nanomaterials, are characterized by their fibrous structure in nanoscale, lightweight nature, high surface-to-volume ratio, and customizable pore structures, making them highly suitable for dynamic applications including sensor making, water treatment, tissue engineering, and protective textiles (Cai *et al.*, 2012) and their ability to be produced from diverse polymeric materials and tailored for specific functions enhances their significance in technological and biomedical innovations (Cai *et al.*, 2012; Bhagwan *et al.*, 2019). Nanocellulose material offers exceptional properties and holds immense potential for various applications in different sectors (Philippini *et al.*, 2020).

Nanocellulose obtained from agricultural leftovers offers various advantages in terms of its mechanical and optical properties. Nanocellulose is one of the most promising nanometric biomaterials, due to its nanometer size and outstanding mechanical properties, and it has the potential to be utilized in a variety of engineering applications. Recently, there has been a strong emphasis on producing nanocellulose from agricultural wastes, offering numerous benefits, including the conversion of waste into valuable bio-products. Nanocellulose from agricultural waste minimizes the environmental pollution from waste disposal and encourages the circular economy, as well as providing a sustainable and economical approach. Traditionally, biomolecules are produced from lignocellulosic, starchy, and other agro-industrial byproducts. However, there is still a lot of potential for research and optimization in this field. The development of sustainable bio-refining approaches that utilize agricultural waste as a raw material for producing nanocellulose could greatly enhance the cost-effectiveness and scalability of the technology. The importance of utilizing nanocellulose from agricultural wastes lies in its numerous advantages and the positive impact on both the environment and various industries. A key advantage of using agricultural waste for nanocellulose is its abundance and renewability. The utilization of agricultural waste for nanocellulose production aligns with the principles of green chemistry and sustainability. Nanocellulose derived from agricultural wastes also presents an opportunity to create new revenue streams for farmers and agricultural industries. By valorizing agricultural waste and creating a marketable product from it, farmers can diversify their income sources and reduce the economic burden of waste management (Pavalaydon *et al.,* 2022). The versatile nature of nanocellulose allows for its use in various applications such as reinforcement in composites, barrier films, rheological modifiers, and even in biomedical and pharmaceutical fields.

The extraction of nanocellulose from agricultural wastes is an area of growing interest that offers many new possibilities and potential applications. The ongoing research, development, and use of nanocellulose are necessary to create opportunities for future profitability. With more sustainable and eco-friendly materials being developed, the use of agricultural waste to produce nanocellulose is becoming more significant than ever. A glimpse of some advantages of nanocellulose derived from agricultural waste is given in Fig. 1.

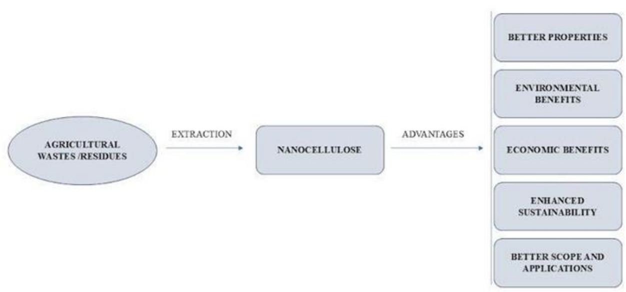

Fig. 1. Some benefits of nanocellulose derived from agricultural wastes.

THE ENVIRONMENTAL BENEFITS OF UTILIZING AGRICULTURAL LEFTOVERS

Reusing agricultural waste and making nanocellulose are two ways to help the environment. The goal is to minimize the contamination that results from incorrect disposal practices that are harmful to the land, water, and air. Through the process of turning agricultural waste into nanocellulose, sustainability can be achieved. Economic benefits and environmental advantages are also realized. Burning of agricultural waste is also reduced, resulting in the reduction of greenhouse gas emissions. Agricultural wastes used for nanocellulose production decrease the amount of waste that finally ends up filling the landfills and also help to minimize the pollution caused by improper waste disposal (Patti *et al.,* 2020). Through the utilization of collected agricultural waste for extracting nanocellulose (instead of discarding agricultural waste), pollution can be mitigated, principles of circular economy can be supported, and waste can be minimized (Pires *et al.,* 2019). Along with the reduction in expenditure on landfill releases, this also creates new opportunities for rural economic growth and jobs in the textile and agricultural industries. By reducing the quantity of garbage dumped, the nanocellulose made from waste will help in becoming less dependent on the environment (Pires *et al.,* 2019). Based on the fact that nanocellulose sourced from plants is an efficient replacement for petroleum-based materials, biological waste is promoted as it fosters renewable resource use. Industries can reduce their reliance on fuel and contribute to a more sustainable economy by using agricultural waste to produce nanocellulose (Philippini *et al.,* 2020). Making nanocellulose from agricultural waste is an economical option. It enables the use of a plentiful and easily accessible resource, decreasing the demand for costly raw materials. Nano-cellulose products can lead to lowering production costs and making them more affordable for a greater number of people. Compared to conventional goods, products based on nanocellulose are more environmentally friendly. Compared to goods based on oil, cellulose nanoparticles derived from agricultural waste need less energy and emit fewer carbon emissions (Patterson *et al.,* 2023). Its use in the textile industry offers distinct material advantages, including environmental friendliness, production of highly fire-retardant fabrics, and sustainability (Tavakoli *et al.,* 2022). Nanocellulose-based products can replace synthetic materials, which often come with environmental concerns (Pires *et al.,* 2019). For example, the production of synthetic fibers such as polyester and nylon requires the use of non-renewable resources and energy-intensive processes. By incorporating nanocellulose from agricultural waste into textiles, the reliance on synthetic materials and their associated environmental impacts can be reduced (Patti *et al.,* 2020).

UNDERSTANDING NANOCELLULOSE, ITS PROPERTIES, AND APPLICATIONS

Nanocellulose is the term for cellulose fibers that have been converted into very tiny spheres that are in the range of 1 nm to 100 nm (Pires *et al.,* 2019). These particles are equipped with features that find applications in almost all industries (Philippini *et al.,* 2020). Important features of nanocellulose are strength, transparency, biodegradability, renewability, and compatibility with chemicals. Nanocellulose exhibits attributes like robust tensile strength and stiffness. Using nanocellulose in composites can enhance product strength and durability (Pires *et al.,* 2019). The particles have a high length-to-diameter ratio, leading to unique mechanical and optical properties. This aspect ratio improves reinforcement and performance in different materials (Pandey *et al.,* 2010). Nanocellulose extracted from agricultural waste offers an environmentally friendly alternative to synthetic raw materials (Pires *et* *al.*, 2019). The utilization of agricultural wastes for producing nanocellulose holds significant importance for several reasons (Kumar *et al.*, 2020). Nanocellulose derived from agricultural wastes offers a range of benefits and applications because of its properties (Pires *et al.*, 2019). Such properties include increased strength and durability in different items, transparency and light scattering reduction for displays and touch screens, eco-friendliness in biodegradability and renewability, and a broad range of chemical acceptability for applications. Nanocellulose particles have a high aspect ratio that gives them special mechanical and optical properties, making them suitable for strengthening different materials. When used in composites, nanocellulose can improve the strength and longevity of products (Pandey *et al.*, 2010). Nanocellulose sourced from agricultural wastes also exhibits good chemical compatibility (Pires *et al.*, 2019), making it suitable for applications in medicine, electronics, environmental remediation, and energy storage (Pandey *et al.*, 2010). Transparency and low light scattering are the main qualities of this material that make it desirable for use in the production of touchscreens and displays for the electronics industry. It is suitable for situations where transparent materials are important because of its extraordinary transmission capabilities. The low-cost production of nanocellulose sourced from agricultural wastes is another significant advantage (Philippini *et al.*, 2020). By converting agro-waste into nanocellulose, a reduction in waste and ensuring a cleaner environment can be accomplished. The use of green materials has improved the functionality of the product and also supports environmental protection. Nanocellulose derived from agricultural residues is available, renewable, biodegradable, and cost-effective, and thus applies as a highly prospective nanomaterial that can be utilized in multiple sectors (Islam *et al.*, 2013).

Nanocellulose is used in eco-friendly, sustainable packaging. The manufacturing of coatings (having sufficient barrier properties) for coverings that require preservation against moisture, oxygen, and UV radiation can be produced out of nanocellulose. The cellulose nanofibers can act as biodegradable and renewable packing material. Nanocellulose has excellent barrier qualities and high thermal stability (Ncube *et al.*, 2020). Nanocellulose with increased thermal stability can be used as a very desirable material for packaging (Pires *et al.*, 2019). Nanocellulose is an environmentally sustainable material as it is capable of degrading itself in the natural environment and can reduce the usage of petroleum-based options in packaging solutions (Ncube *et al.*, 2020).

The development of nanoparticle-loaded oral films for poorly water-soluble drugs primarily involves employing nanoparticles or micro-particles to incorporate these drugs into the film matrix, thereby ensuring a uniform dispersion of water-insoluble drugs throughout the film, which is crucial for consistent dosing and efficacy (Kardile *et al.*, 2023). Nanocellulose from agricultural wastes holds promise in biomedical applications. The good chemical compatibility of nanocellulose makes it appropriate for medical applications. The exceptional mechanical properties, like high strength and stiffness, make nanocellulose suitable for various biomedical applications. The biodegradability of nanocellulose lines up with the increasing demand for sustainable and biocompatible materials in the biomedical sector. Nanocellulose can be used for drug delivery systems, wound healing materials, and tissue engineering scaffolds (Pires *et al.*, 2019).

The high transparency makes nanocellulose a valuable component in the development of renewable and transparent electronics. As sustainable electronic devices continue to grow, nanocellulose-based materials help in advancing the next generation of electronic displays and touchscreens. Nanocellulose can be incorporated into electronics as a substrate for flexible and transparent displays, sensors, and devices for energy storage. High surface area, high mechanical strength, and biodegradability make nanocellulose an ideal material for enhancing textile properties (Islam *et al.*, 2013).

When nanocellulose is added to fabrics, it enhances strength, lowers weight, and protects the fabrics from wrinkles and shrinking. Nanocellulose adds antibacterial properties to fabrics, preventing the growth of bacteria and odors. Nanocellulose can enhance the UV protection capabilities of fabrics, making them ideal for outdoor environments where protection against UV rays is important. Nanocellulose is a material that can enhance the flame resistance of textiles, making them safer and more durable against catching fire and spreading flames. Integration of nanocellulose into fabrics can enhance their functionality and performance (Patti *et al.*, 2020). Nanocellulose can improve the strength and durability of fabrics, making them more resistant to tearing and wearing out. Nanocellulose can also enhance the moisture-wicking properties of textiles, making them more comfortable to wear (Islam *et al.*, 2013). Nanocellulose can be a sustainable alternative to synthetic fibers (Patti *et al.*, 2020). Nanocellulose's high tensile strength, lightweight, and biodegradability make it an ideal material for producing eco-friendly textiles (Islam *et al.*, 2013).

Nanocellulose derived from agricultural wastes is employed in different industries such as packaging, automobile, construction, and electronics (Patti *et al.*, 2020). The flexible nanocellulose material is an excellent option for producing strong but lightweight parts for vehicles, hence, less fuel and fewer emissions are achieved. The nanocellulose application in construction materials leads to the betterment of their strength as well as thermal insulation capabilities (Pires *et al.,* 2019).

Agricultural waste-based nanocellulose holds great promise in agriculture. Nanocellulose improves soil health and fertility by enhancing water retention, nutrient absorption, and microbial activity. This can lead to increased crop yields and improved overall agricultural productivity. Nanocellulose-based nano-fertilizers transform the way nutrients are delivered to crops. Traditionally, fertilizers are applied to fields in large quantities, leading to nutrient leaching and pollution of water bodies. With nanocellulose-based nano-fertilizers, nutrients can be released slowly and controlled to match the plant's needs, reducing nutrient loss and minimizing environmental impact. The scope of nanocellulose produced from agricultural waste not only addresses the issue of waste management but also has significant implications for sustainable materials and agriculture. Water retention enhancement and nutrient absorption in agricultural soils can improve crop yields and minimize the dependence on synthetic fertilizers. Nanocellulose can act as a carrier for agrochemicals, allowing for controlled and targeted delivery of fertilizers and pesticides (Pires *et al.,* 2019). Applications of agricultural waste-based nanocellulose in various industries, particularly in agriculture, hold immense importance.

EXTRACTION OF NANOCELLULOSE FROM AGRICULTURAL LEFTOVERS

Discovering the wide range of potential applications for nanocellulose has been made possible by recent developments in the extraction of nanocellulose from agricultural waste (Pires *et al.,* 2019). The goal of these extraction methods is to break down the lignocellulosic framework of agricultural waste to extract the cellulose component, which may then be processed further to create nanocellulose. There are several established extraction procedures, each with specific benefits and drawbacks. The popular extraction methods are enzymatic hydrolysis, acid hydrolysis, and mechanical remedies like excessive-strain homogenization or ultrasonication (Philippini *et al.,* 2020). Nanocellulose may be extracted from agricultural waste using a variety of methods, each of which has a unique set of requirements that must be properly adjusted for optimal results (Pires *et al.,* 2019). Conventional extraction techniques, like mechanical treatments and acid hydrolysis, have obstacles in terms of their performance and yield. However, the latest advancements have led to the utilization of modern extraction techniques that surpass those obstacles, resulting in better yields and better pleasant nanocellulose. Enzymatic hydrolysis, for instance, is one such approach in which enzymes are used to break down cellulose fibers into nanoscale debris. This approach, among other things, increases the efficiency of cellulose production, which in turn reduces the use of harsh chemical compounds, thereby making it eco-friendly. Advanced extraction technology also employs nanoscale fibrillation, where cellulose fibers are automatically converted into nano-sized ones. Either high-strain homogenization or micro-fluidization is used to get the fibers fibrillated, resulting in cellulose nanocellulose of higher purity and a greater aspect ratio. The development of these advanced extraction methods is leading the way for the widespread utilization of nanocellulose derived from agricultural waste in various industries.

CHALLENGES AND OPPORTUNITIES IN NANOCELLULOSE PRODUCTION

The summary of various challenges and opportunities is given in Figure 2 for a quick preview before a detailed discussion in the subsequent paragraphs.

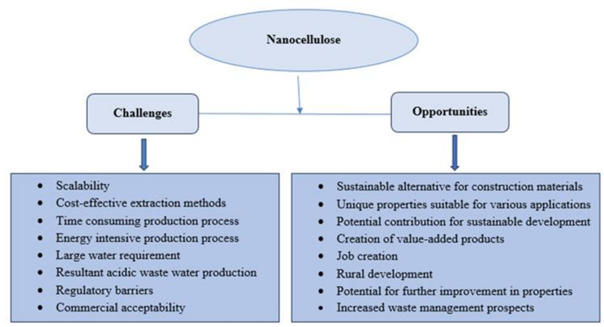

Fig. 2. A glimpse of some challenges and opportunities of nanocellulose.

The process of obtaining nanocellulose from waste biomass still has many advantages, even though some problems should also be addressed. A problem is in extracting cellulose from agricultural waste (Pires *et al.,* 2019). Since the structural complexity of lignocellulose is higher, special and cost-effective extraction techniques are required to purify and separate nanocellulose from the lignocellulose mixture. Different approaches, including mechanical, chemical, and enzyme ones, have been developed to extract nanocellulose. They require extra research to make full use of these techniques and improve their performance. The scaling up of nanocellulose production becomes a problem, particularly in the labs where it is generated from agricultural by-products (Philippini *et al.,* 2020). Regulatory barriers and commercial acceptability are among the issues impeding progress in this industry. It is essential to demonstrate the safety and efficacy of nanocellulose products derived from agricultural waste to gain approval from regulatory agencies and ensure consumer confidence.

The manufacture of nanocellulose has many problems that obstruct the practical application of nanocellulose. Some of the problems are related to its formation, the availability of various natural sources, and the diverse manufacturing techniques (Kryg *et al.,* 2024). The production of nanocellulose using the prevalent methods is a very time-consuming, energy-intensive process and is also subject to scaling challenges, thereby being confined to the laboratory-scale production (Kaur *et al.,* 2021). The production of nanocellulose requires a large amount of water, and the resulting acidic wastewater production is a cause of environmental concerns (Lindström and Aulin, 2014). The scalability of the manufacture of nanocellulose is held back on account of increased operational expenses and the large amount of time required for processing the nanocellulose (Lindström and Aulin, 2014).

Considering the problems associated with the production of nanocellulose, it is recommended to find out the progress made in the spinning of nanocellulose filaments and to define the necessary process for the effective production of nanocellulose (Balea *et al.,* 2021). For achieving commercial implementation, it is very much essential that the prevailing insufficiencies and other restrictions in the characterization of nanocellulose should be sorted out (Balea *et al.,* 2021; Pradhan *et al.,* 2022).

Despite these challenges, there are several opportunities for the production, advancement, expansion, and utilization of nanocellulose. Nanocellulose can come out as a sustainable and feasible material for numerous applications. Bacterial nanocellulose has shown itself to be used as a capable, sustainable alternative for construction materials (Alrubaie and Resan, 2023). Nanocellulose structures can be converted into bio-based triboelectric generators and sensors (Wu *et al.,* 2019). The nanocellulose material is endowed with many significant features that enable it to be used as an appropriate material for many applications (Khan *et al.,* 2021). Microalgae may be an inexpensive and scalable option for the production of nanocellulose (Ross *et al.,* 2021). Nanocellulose can be used in various applications, including pulp and paper production, tissue engineering, biodegradable food packaging, etc. (Sofiah *et al.,* 2023). The nanocellulose market was estimated to grow from USD 635.0 million in 2024 to USD 3.4 billion by 2032, at a compounded annual growth rate of compounded annual growth rate of 23.7% (Trache *et al.,* 2020). Since the possibility of nanocellulose production characterized by various features is there, the further exploration of various biomass sources

The opportunity to produce nanocellulose with various features can promote the exploration of unexplored biomass sources (Trache *et al.,* 2020). Nanocellulose can be used in producing fillings, crushes, chips, wafers, soups, gravies, and puddings, due to its rheological behavior concerning the various food-related applications (Serpa *et al.,* 2016). These opportunities highlight the potential of nanocellulose production to contribute to sustainable development, economic growth, and innovation across different sectors.

The properties of the cellulose nanocrystals can be improved by chemical modifications, physical adsorption, and functionalization strategies. These methods can improve their biocompatibility, stability, and targeted delivery capabilities. Such enhancement in the properties of nanocellulose has an encouraging future for nanocellulose in innovative medical applications, including cancer treatment and regenerative medicine, while also exploring its use in sensing and bio-imaging technologies. The chemical modifications made possible using methods like TEMPO-oxidation, click-chemistry, esterification, etc., enhance the properties of cellulose nanocrystals for drug delivery applications. TEMPO-oxidized cellulose nanocrystals and chitosan oligosaccharide, where primary alcohol moieties and amino groups of chitosan oligosaccharide react with carboxylic acid groups on oxidized cellulose nanocrystals using EDC (1-ethyl-3-(3-dimethylaminopropyl) carbodiimide, commercial grade) and N-hydroxysuccinimide as coupling agents (Akhlaghi *et al.,* 2013). Chitosan-based electrospun nanofibers are important due to their high surface area, biodegradability, biocompatibility, and ability to absorb fluids and molecules effectively, making them suitable for various applications such as intelligent packaging, smart packaging, and sensors (Qasim *et al.,* 2018). The future scope of chitosan-based electrospun nanofibers includes their potential applications in various fields such as intelligent packaging, sensors, water filtration, tissue engineering, and microbiological studies, especially in areas involving pH change detection (Begum *et al.,* 2023). Amino-functional nanofibrillated cellulose is prepared using click chemistry in aqueous solution, where reactive azido groups are introduced on the surface of the nanofibrillated cellulose and subsequently coupled to propargyl amine through copper-catalyzed azido-alkyne cycloaddition (Pahimanolis *et al.,* 2011). Esterification with titania nanoparticles involves binding titania nanoparticles, loaded with drugs, to nanocellulose through ester bonds, using butane tetracarboxylic acid as a spacer and sodium hypophosphite for crosslinking (Galkina *et al.,* 2015). These modifications help in improving the loading and release profiles of drugs when cellulose nanocrystals are used as carriers.

The modification of nanocellulose improves its printability and mechanical properties for use in bio-inks through several mechanisms. Modification techniques like the introduction of charged functional groups, blending with other polymers, modification of hydrogel components, and shear-thinning behavior have been used by various researchers. The addition of charged functional groups to the cellulose nanofibril interface improves the colloidal stability of hydrogels (Fall *et al.,* 2011). The colloidal stability of hydrogels is crucial for maintaining the viability of inks over time (Fall *et al.,* 2011). The blending of the nanocellulose with auxiliary materials such as alginate (Markstedt *et al.,* 2015; Jessop *et al.,* 2019), hyaluronic acid (Henriksson *et al.,* 2017; Nguyen *et al.,* 2017), and gelatin (Xu *et al.,* 2019) helps to improve the rheological properties of nanocellulose-based inks, thereby enhancing their printability. The use of carboxymethylcellulose as a dispersing/gelling agent can adjust the ink flow and elastic properties, contributing to better printability. Additionally, the cross-linking of modified carboxymethylcellulose with hydrazide-modified gelatin during 3D printing can further enhance the mechanical properties of the resulting hydrogels (Fall *et al.,* 2011). Shear-thinning and thixotropic behaviors are beneficial for the printing process, allowing for higher solid loadings at a given viscosity and storage modulus (Rees *et al.,* 2015). These modifications collectively contribute to improved printability and mechanical properties, making nanocellulose more suitable for bio-ink applications. The reason for choosing biodegradable polymers over synthetic materials is primarily due to their environmental benefits, such as reducing soil and water pollution caused by non-biodegradable plastics, and their eco-friendly nature (Anisha *et al.,* 2023). Biodegradable polymers like polyhydroxybutyrate (PHB) can decompose naturally, thereby minimizing hazardous environmental effects associated with traditional plastics (Anisha *et al.,* 2023). Various applications of biopolymers include their use in medical devices such as screws, plates for bones and cartilage, biodegradable sutures for dental implants, and tissue engineering applications due to their biocompatibility and biodegradability (Zaheer and kuddus, 2017). They are also utilized in food packaging for improved barrier performance and UV resistance as well as in agriculture to promote plant growth and crop protection (Bucci *et al.,* 2005). Biodegradable nanofibres are increasingly being considered for environmental applications, notably in water purification and filtration systems, because of their high surface area and porosity that enable effective removal of contaminants, making them promising candidates for sustainable water treatment solutions (Selvakumar *et al.,* 2020). The integration of biodegradable nanofibres into water purification technologies aligns with the global emphasis on environmentally friendly and efficient filtration methods (Selvakumar *et al.,* 2020).

Cellulose nanocrystals have emerged as promising materials in the field of drug delivery due to their unique properties and versatility. The effectiveness of cellulose nanocrystals in drug delivery systems can be significantly enhanced through various surface modification techniques. These modifications aim to improve the interaction of cellulose nanocrystals with drugs and biological systems, ultimately leading to more efficient targeting and delivery of therapeutic agents. Several surface modification techniques have been studied to enhance the drug delivery capabilities of cellulose nanocrystals. The cetyltrimethylammonium bromide (CTAB) surface modification method creates an amphiphilic nanostructure with a hydrophilic core and a lipophilic surface. This structure is particularly advantageous for accommodating hydrophobic drugs, thereby improving their solubility and delivery efficiency (Tortorella *et al.,* 2020). The chemical modifications, such as amination, esterification, oxidation, silylation, carboxymethylation, epoxidation, sulfonation, and thiol- and azido-functional capabilities, have been explored to introduce functional groups on the surface of cellulose nanocrystals, enhancing their properties for drug delivery applications (Tortorella *et al.,* 2020). Surface functionalization using chitosan oligosaccharides is another technique that has been investigated for drug delivery applications. This approach not only improves the biocompatibility of cellulose nanocrystals but also enhances their ability to target specific cells, such as cancer cells. By modifying the surface properties of cellulose nanocrystals, researchers aim to create more effective drug delivery systems that can selectively release therapeutic agents at the desired site of action (Akhlaghi *et al.,* 2013). Surface functionalization using chitosan oligosaccharides is another technique that has been investigated for drug delivery applications. This approach not only improves the biocompatibility of cellulose nanocrystals but also enhances their ability to target specific cells, such as cancer cells. By modifying the surface properties of cellulose nanocrystals, the creation of a more effective drug delivery system that can selectively release therapeutic agents at the desired site of action can be achieved (Akhlaghi *et al.,* 2013). The implications of these surface modifications extend beyond just drug delivery. The versatility of cellulose nanocrystals, combined with effective surface modifications, positions them as a valuable resource in the development of innovative drug delivery systems. The enhanced properties of modified cellulose nanocrystals can lead to improved mechanical stability and biocompatibility, making them suitable for various biomedical applications, including tissue engineering and biosensing. The effectiveness of surface modifications in enhancing the drug delivery capabilities of cellulose nanocrystals is evident through various techniques that improve their interaction with drugs and biological systems. The ongoing exploration of these modifications holds great promise for advancing the field of biomedical applications.

THE FUTURE OF NANOCELLULOSE IN SUSTAINABLE DEVELOPMENT

Various industries may benefit from agricultural waste-based nanocellulose production. The abundance and low-cost availability of agricultural waste make nanocellulose a highly desirable option for sustainable development. Not only does it provide opportunities for innovative bio-refining approaches and sustainable products, but it also contributes to waste management, reduces the negative environmental impact, and promotes a circular economy (Philippini *et al.,* 2020).

This helps in efficient waste management and creates new revenue streams for the agricultural and textile industries. The nanocellulose production from agricultural waste can address two crucial challenges, namely, waste management and sustainable materials development (Pires *et al.,* 2019). By utilizing agricultural waste, which is abundantly available and often disposed of in landfills or burned, nanocellulose production can effectively decrease the amount of agricultural waste in the environment. Nanocellulose offers several advantages that make it an attractive alternative to conventional materials. Nanocellulose helps in the enhancement of the mechanical strength and durability of biocomposites, leading to more sustainable and long-lasting materials (Pandey *et al.,* 2010). By utilizing agricultural waste to produce nanocellulose, the reliance on synthetic fertilizers is reduced, and the harmful ecological impact associated with the use of manmade materials can also be mitigated. This can lead to improved nutrient uptake, higher crop yields, and reduced soil degradation (Basavegowda and Baek 2021). The abundance of agricultural waste makes it a readily available and sustainable source for nanocellulose production. This helps to reduce the dependence on fossil fuels and other non-renewable resources, promoting sustainable economic growth (Mateo *et al.*, 2021).

A summary of attributes of agricultural wastes and the significance of nanocellulose, with a few nanocellulose applications, is given in Table 1.

Table 1: Attributes of agricultural wastes, significance, and some applications of nanocellulose.

Agricultural wastes	Nanocellulose	Some applications of nanocellulose
• Composed of lignin, cellulose, and hemicelluloses • Readily available • Sustainable source • Abundantly available • Biodegradability • Renewability • Low-cost • Underutilized • Applications in different sectors • Disposed of by burning or landfilling • Promotes environmental sustainability • Sustainable bio-refining approaches	• Good mechanical and optical properties • Excellent transparency • High aspect ratio and thermal stability • Good chemical compatibility • Low-cost production • Low light scattering and high surface area • Opportunities for economic growth and job creation • Biodegradability and renewability • Minimizing the disposal of agricultural waste • Contributes to a circular economy • Lower carbon footprint • Substitute for synthetic materials • Environment sustainability • Minimize the dependence on synthetic fertilizers • Sustainable and renewable alternative to traditional raw materials • Encourages environmental sustainability • Sustainable materials development • Opportunities for sustainable product development • Promotion of sustainable agricultural practices	• Displays and touchscreens • Environmental remediation • Energy storage • Films and coatings • Drug delivery system • Wound dressings • Tissue engineering scaffolds • Eco-friendly textiles • Vehicle components • Improves soil health and fertility • Nanocellulose-based nano-fertilizers • Sustainable packaging • Sustainable electronics

The manuscript discusses the production and applications of nanocellulose derived from agricultural waste, emphasizing its sustainability, biodegradability, and potential across various industries such as textiles, packaging, and biomedical fields. It highlights the environmental benefits of utilizing agricultural leftovers, the challenges in extraction methods, and the opportunities for innovation in nanocellulose technology. The document underscores the importance of promoting a circular economy and enhancing soil health while providing economic benefits to farmers through waste management.

The paper discusses the significance of nanocellulose derived from agricultural leftovers as a sustainable and eco-friendly material. Key points include:

• **Properties**: Nanocellulose exhibits high strength, low viscosity, biodegradability, and renewability.

• **Environmental Benefits**: Utilizing agricultural waste for its production reduces pollution and promotes a circular economy.

• **Applications:** It has diverse applications across industries such as textiles, packaging, pharmaceuticals, construction, and biomedical fields.

• **Extraction Methods**: The manuscript explores extraction processes like enzymatic hydrolysis and mechanical methods, highlighting the need for improved techniques.

• **Challenges and Opportunities:** While there are challenges in extraction, scalability, and regulatory acceptance, innovations in extraction and surface modifications can enhance their applications, particularly in drug delivery and bio-inks.

• **Economic Benefits**: Agricultural waste offers farmers economic advantages and contributes to sustainable development and innovation.

The paper highlights several future aspects related to nanocellulose, including:

• **Improved Extraction Methods:** There is a significant opportunity for advancement in the development of improved extraction methods to fully harness the benefits of nanocellulose.

- **Commercial Implementation**: Addressing the current insufficiencies and restrictions in the characterization of nanocellulose is essential for achieving commercial implementation.
- **Exploration of Biomass Sources**: Further exploration of various biomass sources for nanocellulose production can promote the development of materials with diverse features.
- **Economic Opportunities**: Using agricultural waste for nanocellulose production can create new opportunities for rural economic growth and jobs in the textile and agricultural industries.
- **Sustainability and Environmental Benefits**: The ongoing research and development of nanocellulose from agricultural waste are necessary to enhance sustainability and minimize environmental pollution.

CONCLUSIONS

In a period of growing concern about the Earth's sustainability, it is critical to develop new methods to use agricultural waste. Nanocellulose derived from agricultural waste has the potential to promote sustainable development. Nanocellulose contributes to waste management by minimizing the volume of agricultural waste that is released into the environment. Nanocellulose presents avenues for innovative bio-refining methods and sustainable products. The use of agricultural waste-derived nanocellulose has the potential to transform sectors such as farming, packaging, and pharmaceuticals. The exceptional properties of nanocellulose have made it an intriguing alternative to man-made materials for a wide range of uses, including bio-composites and packaging materials. Nanocellulose offers advantages by enhancing soil health, which presents an opportunity to boost agricultural productivity while reducing reliance on synthetic fertilizers, thereby alleviating their detrimental environmental impacts. Nanocellulose presents a compelling alternative material for a range of applications, such as biocomposites, packaging materials, and agricultural practices, providing enhanced thermal stability, mechanical strength, and soil fertility. The characteristics and potential of nanocellulose to improve material performance render it a compelling substitute for conventional synthetic materials. The advancements in extraction techniques have been crucial for the investigation of agricultural by-products. Recent advancements in extraction techniques have facilitated quicker and more efficient processes, leading to a broader range of applications across various industrial sectors. While ongoing exploration into the potential of nanocellulose continues, there remains a significant opportunity for advancement, particularly in the development of improved extraction methods to fully harness its benefits. Adopting new advancements is essential for realizing a sustainable and environmentally friendly future.

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