RASĀYAN *J. Chem.*
Vol. 17 | No. 1 |118-127| January - March | 2024
ISSN: 0974-1496 | e-ISSN: 0976-0083 | CODEN: RJCABP
http://www.rasayanjournal.com
http://www.rasayanjournal.co.in

A RECENT OVERVIEW ON AGRO WASTE BASED NANO CELLULOSE COMPOSITE AND ITS ENVIRONMENTAL APPLICATION: A SHORT REVIEW

Jim Nahurira, Revantkumar S. Gorfad and Suranjana V. Mayani✉
Department of Chemistry, Marwadi University, Rajkot-Morbi Road, P.O. Gauridad, Rajkot 360003, (Gujarat), India
✉Corresponding Author: suranjana.mayani@marwadieducation.edu.in

ABSTRACT

Nowadays, one of the most remarkable environmentally friendly materials available is nano cellulose (NC), or cellulose in several nanostructures. Nanocellulose materials are becoming more and more popular due to their remarkable and intriguing properties, which include their high aspect ratio, biocompatibility, renewability, abundance, and great mechanical capabilities. Numerous hydroxyl functional groups allow for a range of functionalization by chemical procedures, leading to the creation of various materials with adjustable characteristics. This review describes important advancements in the synthesis, modifications, and emerging uses of nanocellulose based on a study of the most recent studies.

Keywords: Nanocellulose; Cellulose Nano Bio Composite; Functionalization; Application.
RASĀYAN *J. Chem.*, Vol. 17, No.1, 2024

INTRODUCTION

Agro-waste, which includes leftover agricultural material and animal waste, is a byproduct of the food production process that is unusable and can be solid or liquid. A lignocellulose plant's cell wall primarily consists of cellulose.[1] The material has a significant quantity of microfibrilized and interconnected linear D-glucose units (1, 4). The structure of the fiber cell walls is shaped by the interaction between these Van der Waals forces and microfibrils. The word "nanocellulose" is used to describe cellulose with a single dimension in the nanoscale range.[2] The majority of places that produce nanocellulose are microorganisms, animals, and plants. However, Agricultural and wood waste have been proposed as the two primary substrates for nanocellulose production.[1] The lignocellulosic fibers obtained from agricultural waste are important because they are readily available, reasonably priced, renewable, and biodegradable. Plant fibers with a reasonably high cellulose content are selected for the production of nanocellulose biocomposites because they may effectively reduce environmental pollution, protect forest resources, and provide value to agricultural waste fibers.[3] Based on form and size, nanocellulose is divided into Bacterial Cellulose (BC), Cellulose Nano Crystals (CNC), and Cellulose Nano Fibers (CNF).[3] There are two distinct ways to extract CNC and CNF from the same cellulose source. Chemically, bleached wood or other cellulosic fibers can be hydrolyzed with an acid to create CNC, which are nano cellulose structures that range in size from 3 to 20 nm in width and 50 to 500 nm in length.[4] Chains with a breadth of 4 to 50 nm and a length of more than 500 nm can be formed mechanically from CNF without the need for chemical or biological processing.[3] Bacteria produce cellulose, which aggregates into a group of nanofibrils with a width of roughly 70–80 nm, to form BC. This process is bottom-up. As a result, the pellicle membrane can hold 60–700 times its dry weight in water.[3] Nanocellulose materials can be produced through a variety of procedures, effectively enhancing the qualities of finished products. The creation of Nano Cellulose-based composites that decompose with enhanced properties is the subject of extensive investigation.[5] In polymer compounds where CNC is used as a reinforcing filler, a three-dimensional H-bonded network may develop.[6] This network gives nano-bio composites the energy to withstand exterior strains which improves their mechanical behavior.[7]

EXPERIMENTAL

Agro waste Agro-based nanocellulose can be obtained from the following sources:

http://doi.org/10.31788/RJC.2024.1718655

From Forest Residues

Residues are produced during the use of timber, including logging refuse, sawdust, plywood, trash, and shavings. In 2018, approximately 1.1977 billion tons of forest refuse were generated globally. The percentage of deforestation in densely inhabited areas can reach 66%, with 34% being made up of leftover leaves and branches. Logging trash may be neglected and allowed to decay in the forest in sparsely populated areas.[8] As a result of defoliation, pruning, or replanting, trees naturally create a certain quantity of waste throughout the growing process, such as leaves, branches, and bushes. Pruning and replanting generate about 15.1 t/hm^2 of trash annually when considering a Cunninghamia lanceolate forest. It follows that forest residues serve as a significant source of biomass wastes for the synthesis of nanocellulose. The main morphologies of nanocellulose produced in this work are cellulose nanofiber (CNF) and cellulose nanocrystal, which each go through a variety of conditioning procedures, pretreatments, bleaching processes, and purifying steps (CNC). Use fossil fuels, maintain sustainable economic growth, and close the resource usage loop to minimize the effect on the ecosystem.[2]

From Agricultural Residues.

A similar mixture of lignin, cellulose, pectin, hemicellulose, and other minor components makes up agricultural residues as do those from forests, though their physical and chemical makeup can vary depending on the growth cycle, living conditions, and other factors.[2] Farming waste contains considerably lesser cellulose concentration than most forest remnants, but a greater quantity of lignin.[9] Other than agricultural products or fruits, agricultural cellulosic wastes include wheat straws, rice straws, maize stover, corn cobs, rice husks, and sugarcane bagasse.[10] Every year, around 998 million tonnes of various agricultural leftovers are produced worldwide, including butnot limited to important crop residues such as maize stover, wheat straws, and rose straws.[11] Low-value additions are a hallmark of the early stages of the exploitation of agricultural waste from agricultural processing. They are typically used in agriculture as compost conversion or fertilizer. In terms of material conversion, these uses have not yet attained their full potential from an economic and environmental standpoint.[2] From lignocellulosic agricultural wastes, different kinds of nanocellulose (CNC, CNF) can be created and utilized in a range of industries, consisting of biomedicine, cosmetics, and pharmaceuticals.[2] Agricultural waste is a good source of cellulose thatis sustainable and renewable, as can be seen in the aforementioned examples. The two primary types of nanocelluloses (NCs) are cellulose nanocrystals and nano Fibrillated Cellulose (NFC) (CNC). They are often considered superior substitutes for petroleum-based products and second-generation renewable resources. These materials have drawn increased attention because of their great mechanical strength and low density, both biodegradable and renewable qualities. Many studies in the literature have addressed the extraction of CNC and NFC from a variety of sources,such as agricultural waste and softwood or hardwood. This comprehensive study focuses on the properties of CNC and NFC that are exclusively extracted from industrial and agricultural waste using chemical, mechanical, and enzymatic techniques.[12]

From Industrial by-products

Commercial garbage from the manufacture of furniture, pulp and paper, printing, packaging, and food processing is another ideal recyclable cellulose resource for nanocellulose extraction. Because the chemical and structural composition of the feedstock varies, different extraction techniques are used to recover nanocellulose from industrial waste.[13] The food processing industries generate tonnes of residue, but they also leave behind a sizable amount of lignocellulosic waste that may be used to make high-value products.[14]

Synthesis Methods of Nanocellulose Composite

The remarkable properties of nanocellulose and its potential for future applications make the study of nanocellulose extraction from lignocellulosic biomass highly attractive, particularly when it comes to extraction from agricultural waste.[15] Before extracting nanocellulose, the lignocellulosic biomass is processed to remove non-cellulosic elements like lignin, hemicellulose, and other compounds. Then, using a variety of extraction techniques, nanocellulose is removed. Alkaline treatment is one of the traditional approaches to biomass treatment.[16] During the alkaline treatment, the amorphous hemicellulose polymer is eliminated to protect the lignin.[13] Holocellulose is combined with sodium hydroxide (4–20 weight percent) as an alkali for 1–5 hours.[17] The final product dried in an oven at 50 ^{0}C after being rinsed with distilled water until it attained a pH of neutral. This process produces fiber that is primarily made of cellulose.[15] Following this treatment for the biomass, the resulting product is bleached to increase the cellulose content.[17]

Methods for Extraction of Nanocellulose

Several methods can be used to extract nanocellulose. Different extraction methods provide different types and qualities of nanocellulose.[18] The three primary techniques for extraction are the mechanical process, enzymatic hydrolysis, and acid hydrolysis.[15] Acid hydrolysis is one of the most used methods for removing nanocellulose from cellulosic products.[19] Sulphuric acid is typically employed in acid hydrolysis.[20] This acid disperses nanocellulose as a stable colloid system and isolates the nanocrystalline cellulose because the sulfate ions have esterified the hydroxyl group.[21] The main problem with acid hydrolysis is that a lot of waste water is produced while washing the nanocellulose suspension. The essential step in the washing procedure is the addition of cold water, which is followed by centrifugation until a neutral pH is reached.[17] Temperature, acid concentration, and reaction time are the three main regulating elements that have a significant impact on nanocellulose properties.[22]

Fig.-1: Diagrammatic Representation of the P. Juliflora Nanocellulose Extraction Technique. Adapted as open access article[24]

Enzymes are utilized in the biological treatment procedure known as enzymatic hydrolysis to break down or change cellulose fibers. Although it is carried out in comfortable circumstances, the process takes a long time.[23] To solve this problem, enzymatic hydrolysis is employed in conjunction with other strategies. Enzymatic hydrolysis is used in combination with other techniques to address this issue. To maximize the accessible surface area, cellulose fibers were separated from wood chips by enzymatic hydrolysis with laccase following pretreatment with ionic solutions. The generated nanocellulose displayed higher thermal stability and crystallinity than natural wood fibers. The mechanical technique of separating cellulose fibrils breaks the cellulose fibers across their longitudinal dimension with severe shear stress, resulting in nano-fibrillated cellulose.[5] The three most used mechanical processes are high-pressure homogenization, ultrasonication, and ball milling.[23] The procedure for extracting nanocellulose from P. juliflora is shown in Fig.-1.[24]

RESULTS AND DISCUSSION

Environmental Significance During Synthesis and Preparation

When nanocellulose is prepared by acid hydrolysis, a significant amount of wastewater is createdduring the neutralization process. The wastewater generated harms the ecosystem. Because of itsnumerous special features and capacities, nanocellulose is one of the many sustainable functionalnanomaterials that is attracting interest for application in environmental remediation technologies.Typically, microorganisms or the degradation of naturally occurring polymers produce nanocellulose. There are differing opinions about the difficulties, the way ahead, and the most recent advancements in the major use the nanocellulose in environmental restoration. The characteristics and documented uses of nanocellulose as a photocatalyst, membrane, adsorbent, and flocculant are specifically examined.[17]

Positive Effects on the Environment

Numerous sectors, including biomedicine and pharmacy, nutritious foods and feeds, packaging, cosmetics, optoelectronic devices, and electronics have considerable potential for using nanocellulose. This is because it has a number of unique qualities, including non-toxicity, biocompatibility, a high capacity for adsorbing and holding onto water, and great mechanical properties. The advantages of nanocellulose's cost-effectiveness, which are derived from various biomass wastes, are particularly pronounced in a wider variety of raw material sources. Hence, using nanocellulose made from biomass waste to produce high-value commodities is essential for both economic growth and environmental preservation. The materials based on nanocellulosethat are created using the previously outlined techniques are recyclable, non-toxic, and carbon neutral. Because these materials work better when creating composite materials, it is anticipated that they will become green nanomaterials. By combining this nanomaterial with other organic orinorganic components, composite materials with a variety of applications in the modeling, packaging, human motions, electronics, optoelectronics, and sensing device industries may be created.[2] Figure-2 outlines the possible applications of nanocellulose for goods with considerablevalue.

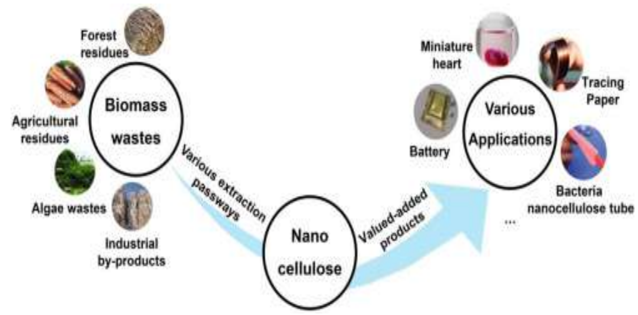

Fig.-2: The Potential Usages of Nanocellulose Towards the High Value-Added Products. Adapted as an Open Access article[18]

What are the Likely Effects of Their Use on Human Health?

The majority of studies indicate that there is no discernible impact on human health from agro-waste nanocellulose biocomposites. Its impacts on human health are negligible due to its biodegradability and low toxicity. Nano-crystalline cellulose (NCC) was tested for cell toxicity inhuman brain microvascular endothelial cells and found to be non-toxic. It can be employed as a carrier in the targeted administration of therapies The creation of biodegradable films utilizing nanocellulose may be a promising way to replace synthetic plastic packaging and provide a solution to health issues. In addition, it has several benefits in terms of tensile and physical qualities,as well as lowering health risks. With the addition of cellulose nanoparticles, the tensile and physical qualities of the biodegradable films and biodegradable composite films are enhanced andwater vapor permeability is decreased. There are four different ways to employ nanocellulose toproduce biodegradable materials: rice husk, other plant agricultural waste extracts, extracts, and biopolymer composite material for food packaging.[18]

Environmental Applications of Agro-Waste-Based Nano Cellulose Composite

Dye Removal from Water

Colors, oils, pesticides, pharmaceuticals, and a wide range of other organic chemicals can all be pollutants in water. The primary issue here will be the functionalized nanocellulose's adsorption of medications and pigments. Worldwide organic pigment pollution from sectors such as the textile industry is a serious threat to the environment. In addition to having a complicated aromaticstructure, organic dyes can be cationic, non-ionic, or anionic. Recent descriptions of relatedprocesses highlight the significance of the interactions of organic dyes with cellulose The efficacyof conventional dye removal techniques is constrained. Because of its excellent mechanical and thermal properties, biodegradability, nontoxicity, and other favorable characteristics, nanocellulose has been utilized to create membranes for removing color from wastewater. Its adaptation has also been made simple. Nanocellulose materials may be utilized to create high-efficiency membranes because it has more surface area and mechanical strength than bulkcellulose. The several surface OH groups are primarily to blame for this. Furthermore, nanocellulose has a tremendous ability to soak up a variety of contaminants, such as colors, because of its high aspect ratio and large population of active binding sites.[25] Through extraction with a hydrochloric and citric acid solution, methylene blue can be absorbed by carboxylated CNCs formed of microcrystalline cellulose, with an absorption proportional to the amount of carboxyl groups. Typically, nanocellulose with cationic functionality, such as CNC that has been amino-functionalized, is used to remove anionic dyes. The maximum amount of acid red GR that cationic CNCs can absorb is 556 mg/g, which is the result of successive ethylenediamine and sodium periodate oxidation reactivity. pH-dependent dissociation of functional groups limits the quantity of positively charged CNCs that may adsorb. In cationic CNFs produced by quaternization with epoxy trimethylammonium chloride (EPTMAC), experiments on the kinetic absorption of acid green 25 and Congo red 25 demonstrated recognition of up to 683 mg/g and 664 mg/g of each dye in less than a minute, respectively.[25] Water contaminants that are negatively charged, such as phosphate, nitrate, fluoride, and sulfate, are well-adsorbed by cationic CNFs. As expected, the capacity for adsorption of all the anions increased in proportion to the surface charge density of CNFs. Compared to monovalent ions F- and NO3-, cationic CNFs exhibited a greater affinity for multivalent ions PO_4^{3-} and SO^{2-}.[25] Dye removal in water can be proceeded by nanocellulose composites as shown in Fig.-3.

Fig.-3: Dye Removal in Water by Nanocellulose Composite. Adapted as an Open Access article[26]

Ismat Ara Eti *et al*. (2023) created a unique composite film made of cornflour, polyvinyl alcohol, and nanocellulose (CPCN). Nanocellulose was removed from the banana bract via a chemical process and then blended to create the composite film. The synthesized cornflour, polyvinyl alcohol, and nanocellulose (CPCN) were characterized using scanning electron microscopy (SEM) with EDX and Fourier-transform infrared spectroscopy (FTIR) to understand the surface shape and molecular interaction. Effects of pH, adsorbent dose, starting dye concentration, and contact duration were studied about the methylene blue dye's adsorption. At pH 10, the highest adsorption was discovered to be up to 63.13 mg/g Methylene blue, the adsorbent dose is 2 grams, a 150-ppm starting concentration, and a 120-minute contact time at the surrounding temperature (25 ° Celsius). This suggests an average adsorption capability of CPCN. Given that the Langmuir model fits the MB dye adsorption data well, the Freundlich and Langmuir adsorption isotherm models may be used to estimate the uptake of MB dye by CPCN. The deposited dye in the kinetic adsorption experiment adhered to the pseudo-second-order kinetic model and, for the CPCN, almost reached equilibrium at 120 minutes. Consequently, the CPCN presented an opportunity for application as an adsorbent in wastewater treatment.[27] Hairy nanocellulose, a type of biodegradable cellulose nanoparticle, has been created by M. Tavakolian *et al.* (2020).[26] By using periodate and chlorite in a two-step oxidation process, wood pulp can be converted into electrosterically stabilized nanocrystalline cellulose (ENCC), a particular kind of hairy nanocellulose that can adsorb large amounts of material and a high negative charge density. According to this investigation, the stoichiometry up to charge (1400 mg dye/g adsorbent), cationic dye methylene blue may be absorbed by ENCC; above this point, ENCC-dye complexes start to agglomerate. To show how the adsorption is impacted by other ions and how an ion- exchange mechanism can account for it, a model is developed. Low pH and high ionic strengths both reduce equilibrium dye removal. Amiralian *et al.* (2020) described the surface of nanofibers that were grafted with magnetic nanoparticles using in situ hydrolysis of metal precursor (iron oxide) at ambient temperature. The improved oxidation process, which was based on sulfate radicals, was subsequently carried out using the magnetic membrane as an economical, cost-effective catalyst. Rhodamine B (RhB), a typical hydrophilic organic dye used in industry, was successfully removed by the membranes by activating peroxymonosulphate (PMS).

At ambient temperature, 94.9% of the Rhodamine B was broken down in 300 minutes, showing that the magnetic nanocellulose membrane is very effective at catalyzing PMS to remove RhB.[28]

Ultrafiltration

Nanocellulose is used in both the filtration and ultrafiltration procedures due to their lower-size approaches. A key component of the ultrafiltration procedure is nanocellulose. Nanocellulose can be used in membranes or sheets referred to as ultrafiltration membranes or papers to accomplish the filtering process.[29] Such nanocellulosic-based sheets as well as membranes are made from nanocellulose derived from wood, microorganisms, and cellulose nanocrystals.[30] Nanocellulose has been produced in membrane form using two different techniques. To enhance the performance of that polymeric membrane, the first technique is adding this nanocellulose to specific polymer matrices. The polymer matrix needs to be completely dissolved in a solvent during the film-casting process, and the nano-cellulosic solution needs to be dispersed equally. The solvent casting procedure, the second strategy, yields the best porosity.[29]

Hazardous Metal Removal

Heavy metals are the main component released by chemical companies, industrial waste soils, household items, and oil spills. The use of nanocelluloses as water purification components for ecological safeguarding and cleaning has a lot of promise. Over the past two decades, they have been included in water treatment processes using state-of-the-art nanoengineering techniques. With the advent of novel nanotechnologies for the cleaning and purifying of wastewater, which might involve reverse osmosis, nanofiltration, photocatalytic degradation, ultrafiltration, adsorption, flocculation, absorption, antifouling, and disinfection, this review aims to give a general overview of the requirements for nanocellulose. At first, reports were made about the different ways that nanocellulose can be synthesized (mechanical, physical, chemical, and biological), as well as about its unique properties (sizes, geometries, and surface chemistry). A magnetic hybrid aerogel that can adsorb heavy metal ions from water and achieve controlled recovery under magnetic circumstances has been reported, combining ferroferric oxide (Fe_3O_4) nanoparticles with nanocellulose.[18,30] To eliminate the heavy metal chromium (Cr (VI)), it was discovered that the hybrid aerogel had good adsorption effectiveness of 22 mg/g with a mass ratio of ferroferric oxide to nanocellulose of 1:1. This offers a revolutionary method of water purification that mixes abundant nanocellulose with additional beneficial components.[31] Extensive extraction of plumbum and copper ions from the hybrid aerogel also produces good results. Shahnaz, Padmanaban, and Sharma: To eliminate the heavy metal ions Cr^{6+}, $Co^{3+,}$ and Cu^{2+} [32], the researchers employed chitosan aerogel and nanocellulose. Hazardous metal removal has been shown in Fig.-4.

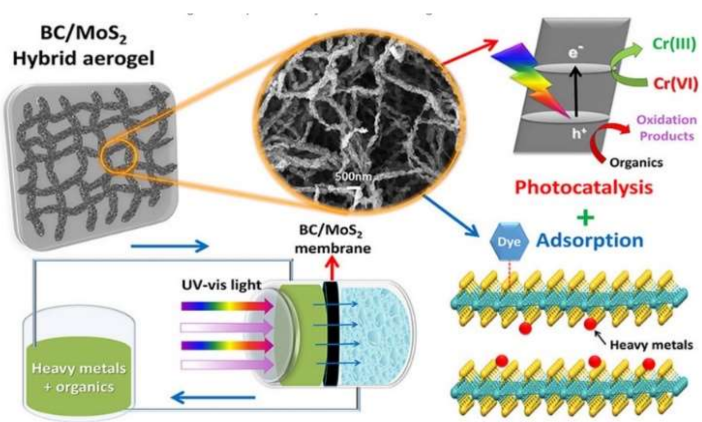

Fig.-4: Hazardous Metal Removal by Nanocellulose Biocomposites. Adapted as an Open Access Article.[33]

According to Reshmy *et al.* (2020), reducing cellulose dimension to nanometric levels greatly improves heavy metal adsorption from wastewater. For example, from contaminated water, nanocellulose consumed 5.98 % of Cr^{6+} ions and 62.40 % of Cr^{3+} ions, whereas microcellulose only adsorbed 42.02 % and 5.79 % of Cr^{3+} and Cr^{6+} ions, respectively.[34] The isotherm analysis demonstrated that the monolayer adsorption mechanism was followed by the adsorption process. The adsorbent's structure and shape may also have an impact on how much it can absorb. It was demonstrated that carboxylated NC-sodium alginate beads could adsorb 338.98 mg/g of Pb ions at a starting concentration of 400 ppm.[35] To boost the negative charges carried by the carboxylate ions and enhance mechanical stability, the carboxylated CNC is injected into the sodium alginate hydrogel. Li *et al.* (2018) carried out an experiment with CNF-PEI aerogel beads that was comparable to this one. Pb (II) and Cu (II) ions were removed in separate batch studies, and Both had exceptional removing ability, with Pb ions displaying a greater degree of selectivity.[37] Alipour *et al.* published work from 2020 that showed excellent Pb removal in a short amount of time, with 99.99 % removal observed when the adsorption was carried out under ideal conditions. Sulfur, amino, and oxide groups predominated in the process of Pb ion adsorption using a magnetic ZnO/nanocellulose composite modified by thiourea. The most straightforward explanation is that the anionic groups of the adsorbent attract those with positive charges Pb ions. When compared to the adsorbent that is currently on the market, the composite nano cellulose-based absorbent material showed a lot of promise.[37] When the conditions were right, the modified CNF that Bisla *et al.* (2020) synthesized to remove mercury ions had an exceptional removal performance that was further facilitated by the core functional groups of the CNF.[38] The most recent development in nanocellulose-based adsorbent was made possible by research conducted by Mo and associates (2021). They claimed that other metals (Zn, Cu, Cd, and Mn) might be removed as well, but at a pace that would be equivalent to other research that had been published. According to their claims, Pb ions can be removed by their wood-inspired aerogel adsorbent in around ten minutes. With an adsorption capacity of up to 571 mg/g, Pb ions can be eliminated. Graphene oxide (GO), Trimethylolpropanetris-(2-methyl-1-aziridine) propionate (TMPTAP), and TOCNF together have unique properties in their adsorbent that increase the number of active sites where metal ions can be bound, resulting in better adsorption performance.[39] The studies on Environmental remedies using Agro waste-based nanocellulose can be summarized in the following Table-1. Recovery and reusability of nanocellulose

Table-1: The Studies on Environmental Remedies using Agro Waste Based Nanocellulose

Cellulose source	Preparation method	Salient feature	Application	References
Peanut shell	Alkaline treatment and bleaching	Lignin and cellulose microcrystals (CMC)	Bioethanol production, crystal dye removal	[40]
Wheat straw pulp	Bleaching treatment, pressure sieve	Wheat pulp Nano cellulose	Lead (II) ions removal	[41]
Eucalyptus sawdust	Tetramethyl-1-piperidinyloxyl (TEMPO) oxidation	Nano-fibrillated cellulose (CNF)	Reinforcement in Papermaking	[42]
Forest residues (sawdust)	Acid hydrolysis	Nanocellulose based membranes	Heavy metal removal, dye removal	[25]
Oil palm biomass	TEMPO oxidation	Nanocellulose	Heavy metal removal	[30]
Reed fiber (wheat, corn, rice)	Acid hydrolysis	Nanocellulose	Food packaging, pharmaceutical applications	[12]
Rice husk, sugarcane bagasse	Acid hydrolysis	Nanocellulose	Biomedicine, packaging applications	[18]
Industrial waste cotton, sugarcane bagasse	Acid hydrolysis	Nanocellulose	Food packaging applications	[5]
Rice husk, wood	Acid hydrolysis	Cellulose nanocrystals	Membrane filtration, reinforcement	[3]
Rice husk	Alkaline treatments and Acid hydrolysis	Cellulose and cellulose nanocrystals	Re-inforcement filler	[17]

Recovery and Reusability of Nanocellulose

Only a few researchers have discussed the recovery and recyclability study in recent publications, even though many have raised the possibility of it. According to Mo *et al.* (2019),[43] they developed an NC-based aerogel adsorbent that demonstrated strong regeneration and desorption capacities for four cycles or more, reaching Over 80% of the Cu (II) ions are removed at that point. To speed up the desorption process, a magnetic component can be added to the NC adsorbent. Adsorption performance is expected to decline with each cycle; however, the effectiveness of metal removal is increased when magnetic components are included in the chemical composition since this increases the adsorbent's recovery percentage. A regrowth test for magnetic carboxylate CNC was developed, and the findings demonstrated that the CNC could sustain a Pb (II) ion removal rate of more than 80% throughout five consecutive adsorption-desorption cycles. Lu and associates (2016),[44] Chai *et al.'s* work from 2020 submitted the NC adsorbent crosslinked with PEI and glutaraldehyde (GA) to an alkali treatment for the desorption operation rather than an acid treatment because of the acidic character of their synthetic wastewater[5], even after the eighth cycle, the success of removal displayed an excellent performance. In summary: NC-based adsorbent is readily regenerable with the correct care, and the proportion of adsorbent recovery increases with the inclusion of magnetic compounds. More than eight cycles of the adsorption and then desorption process were carried out in this investigation, which showed outstanding metal removal effectiveness.

CONCLUSION

Advanced technology can be utilized to obtain nanocellulose from agricultural leftovers through other ecologically friendly procedures. A number of factors, including the choice of raw materials, methods of extraction, life cycle analysis, and product design, affect the development of sustainable applications. Because of its renewable, biocompatible, and biodegradable qualities, nanocellulose is attractive and has a numerous application. To effectively recover cellulose from agricultural waste, pretreatment is required. Yet, depending on the pretreatment procedure, it could be costly and present environmental risks. The need to create more economical methods stems from the fact that producing products based on nanocellulose is still costly and might not be possible in developing countries.[46-48] Furthermore, research is needed to develop composite nanocellulose-based adsorbents that can concurrently adsorb a wide variety of chemical species. The extraction procedure is still carried out on a small scale, thus more investigation is required to get it up to an industrial level. Finally, the process is time-consuming because of the necessary steps; automated solutions must be developed to avoid tedious procedures and human error. The simple developments in the synthesis, modification, and application of nanocellulose—specifically, cellulose nanocrystals—as building blocks for a range of inventive applications are discussed in this article. It offers data that stimulates more study in this field. Even though the literature on nanocellulose has been thoroughly examined over the past 20 years using a range of naturally occurring sources and methodologies, Certain issues still need to be resolved, specifically about surface and end-reducing modifications, the development of more affordable, energy-efficient extraction processes, and production upscaling. This nanomaterial is genuinely green because of its incredibly useful properties, which include enhanced mechanical properties, altered area of surface, customizable surface chemistry, anisotropic shape, and other essential aspects. Because of this, it is a great material with great promise for developing industries and numerous applications in the domains of biomedical engineering and material science. There is still potential for improvement and new applications of those that are already in use with the advent of affordable commercial sources of nanocellulose, which can be used in a variety of Industries that need materials with cutting-edge qualities.[49,50] In the future, this subject will be especially interesting. Further study is required to determine the viability of the finished products and get them onto the market. Notwithstanding the challenges mentioned above, we believe that developments in the upcoming generation of materials will lead to nanocellulose-based products that enhance people's quality of life.

ACKNOWLEDGEMENTS

The Authors are grateful to Marwadi University, Rajkot, Gujarat

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

Jim Nahurira https://orcid.org/0009- 0005-1443-2669
Revantkumar S. Gorfad https://orcid.org/0009-0009-9999-4634
Suranjana V. Mayani https://orcid.org/0000-0002-2624-3305

REFERENCES

1. S. P. Bangar and W.S. Whiteside, *International Journal of Biological Macromolecules*, **185,** 849 (2021), https://doi.org/10.1016/j.ijbiomac.2021.07.017
2. S. Yu, J. Sun, Y. Shi, Q. Wang, J. Wu and J. Liu, *Environmental Science and Ecotechnology,* **5,** 100077(2021), https://doi.org/10.1016/j.ese.2020.100077
3. A.B. Perumal, P. S. Sellamuthu, R.B. Nambiar, E.R. Sadiku and O.A. Adeyeye, *Green Biopolymers Nanocomposite,* **1**, 83(2019).
4. S. Beck-Candanedo, M. Roman and D.G. Gray, *Biomacromolecules,* **6**,1048(2005).
5. A. Dufresne *Current Opinion in Colloid and Interface Science*, **29,** 1(2017), https://doi.org/10.1016/j.cocis.2017.01.004
6. M. Mariano, C. Chirat, N. El. Kissi and Dufresne A, *Journal of Polymer Science Part B: Polymer Physics,* **54**, 2284(2016), https://doi.org/10.1002/polb.24139
7. E. Fortunati, M. Peltzer, I. Armentano, L. Torre, A. Jiménez and J.M. Kenny, *Carbohydrate Polymers,* **90**, 948(2012), https://doi.org/10.1016/j.carbpol.2012.06.025
8. T.H. Fleming and W.J. Kress, *Ornaments Life,* **1**, 63 (2015).
9. F. A. Ximenes, W.D. Gardner and A. Kathuria, *Forest Ecology and Management,* **256,** 335(2008), https://doi.org/10.1016/j.foreco.2008.04.037
10. T. Kätterer, M.A. Bolinder, O. Andrén, H. Kirchmann and L. Menichetti, *Agriculture Ecosystems & Environment,* **141**, 184 (2011), https://doi.org/10.1016/j.agee.2011.02.029
11. F. Obi, B. Ugwuishiwu, J. Nwakaire, *Nigerian Journal of Technology*, **35**, 957(2016), https://doi.org/10.4314/njt.v35i4.34
12. A. García, A. Gandini, J. Labidi, N. Belgacem and J. Bras, *Industrial Crops and Products*, **93**, 26(2016), https://doi.org/10.1016/j.indcrop.2016.06.004
13. A. Mandal and D. Chakrabarty, *Carbohydrate Polymers,* **86,** 1291(2011), https://doi.org/10.1016/j.carbpol.2011.06.030
14. J.O. Alves, J.A. Soares Tenório, C. Zhuo and Y.A. Levendis, *Journal of Materials Research and Technology***, 1**, 31(2012).
15. P. Phanthong, P. Reubroycharoen, X. Hao and G. Xu, *Carbon Resources Conversion,* **1,** 32(2018), https://doi.org/10.1016/j.crcon.2018.05.004
16. M.K.M. Haafiz, A. Hassan, Z. Zakaria and I.M. Inuwa, *Carbohydrate Polymers,* **103**, 119(2014).
17. N. Johar, I. Ahmad and A. Dufresne, *Industrial Crops Production*, **37**, 93(2012)
18. R. Si, J. Pu, H. Luo, C. Wu and G. Duan, *Polymers*, **14(24),** 5479(2022), https://doi.org/10.3390/polym14245479
19. R.J. Moon, A. Martini, J. Nairn, J. Simonsen and J. Youngblood J, *Journal of Chemical Society Reviews,* **40**, 3941(2011).
20. D. Bondeson, A. Mathew and K. Oksman, *Cellulose,* **13** ,171(2006).
21. K. Das, D. Ray, N.R. Bandyopadhyay, T. Ghosh, A.K. Mohanty and M. Misra, *Cellulose*, **16**, 783(2009).

22. N. Lavoine, I. Desloges, A. Dufresne and J. Bras J, *Carbohydrate Polymers*, **90**, 73(2012), http://dx.doi.org/10.1016/j.carbpol.2012.05.026
23. H.P.S.A. Khalil, Y. Davoudpour, N. Islam, A. Mustapha, K. Sudesh, Dungani *et al., Carbohydrate Polymers,* **99**, 649(2014), https://doi.org/10.1016/j.carbpol.2013.08.069
24. L. Valencia, V. Arumughan, B. Jalvo, H.J. Maria, S. Thomas and A.P. Mathew, *ACS Omega,* **4,** 4330(2019), https://doi.org/10.1021/acsomega.8b02685
25. H. Voisin, L. Bergström, P. Liu and A.P. Mathew, *Nanomaterials*, **7(3),** 57(2017).
26. M. Tavakolian, H. Wiebe, Md. A. Sadeghi and T.G.M. Van de Ven, *ACS Applied Material Interfaces*, **12(4)**, 5040(2020).
27. I.A. Eti, M. Khatun, M.A. Khatun, Md. O. Rahman, K.M. Anis-Ul-Haque and Md. J. Alam, *Advanced Polymer Technol*ogy, 1 (2023).
28. N. Amiralian, M. Mustapic, Md. S.A. Hossain, C. Wang, M. Konarova, Tang *et al., Journal of Hazarodous Material,* **394,** 122571(2020), https://doi.org/10.1016/j.jhazmat.2020.122571
29. M. L. Hassan, S.M. Fadel, R. E. Abouzeid, W.S. Abou Elseoud, E.A. Hassan, Berglund *et al*., *Scientific Reports,* **10**, 1(2020).
30. A. Dpeursinge, D. Racoceanu, J. Iavindrasana, G. Cohen, A. Platon, P.A. Poletti *et al., Artificial Intelligence in Med*icine, **229**, 1118(2010).
31. J. Wei, Z. Yang, Y. Sun, C. Wang, J. Fan, G. Kang *et al., Journal of Material Sci*ence, **54**, 6709(2019).
32. M.N.F. Norrrahim, N. Azilah, M. Kasim, V.F. Knight, M. Syukri, M. Misenan *et al*., *Nanocellulose as an adsorbent for heavy metals, Elsevier Ltd.* (2022).
33. E.P. Ferreira-Neto, S. Ullah, T.C.A. da Silva, R.R. Domeneguetti, A.P. Perissinotto and F.S. de Vicente, *ACS Applied Material Interfaces*, **12**, 37(2020).
34. R. Reshmy, E. Philip, A. Madhavan, A. Pugazhendhi, R. Sindhu, R. Sirohi *et al*., *Journal of Hazardous Material,* **424**, 127516(2022), https://doi.org/10.1016/j.jhazmat.2021.127516
35. Z. H. Hu, A. M. Omer, X. Ouyang and D. Yu, *International Journal of Biological Macromolecules,* **108,** 149(2018).
36. J. Li, K. Zuo, W. Wu, Z. Xu, Y. Yi, Y. Jing *et al*., *Carbohydrate Polymers*, **196** 376(2018).
37. A. Alipour, S. Zarinabadi, A. Azimi and M. Mirzaei, *International Journal of Biological Macromolecules***, 151,** 124(2020), https://doi.org/10.1016/j.ijbiomac.2020.02.109
38. V. Bisla, G. Rattan, S. Singhal and A. Kaushik, *International Journal of Biological Macromolecules,* **161**, 194(2020), https://doi.org/10.1016/j.ijbiomac.2020.06.035
39. L. Mo, H. Pang, Y. Lu, Z. Li, H. Kang, M. Wang *et al*., *Journal of Hazardous Material*, **415,** 125612(2021).
40. P. Ganguly, S. Sengupta, P. Das and A. Bhowal, *Fuel*, **280**, 118581(2020).
41. T. Suopajärvi, H. Liimatainen, M. Karjalainen, H. Upola and J. Niinimäki, *Journal of Water Process Engineering,* **5,** 136(2015).
42. M.E. Vallejos, F. E. Felissia, M.C. Area, N.V. Ehman, Q. Tarrés and P. Mutjé P, *Carbohydrate Polymers* **139**, 99(2016).
43. L. Mo, H. Pang, Y. Tan, S. Zhang and J. Li, *Chemical Engineering Journal,* **378,** 122157(2019).
44. J. Lu, R.-N. Jin, C. Liu, Y-F., Wang and X. Ouyang, *International Journal of Biological Macromolecules*, **93** 547 (2016).
45. F. Chai, R. Wang, L.Yan, G. Li, Y. Cai and C. Xi, *Carbohydrate Polymers* **245**, 116511(2020).
46. J. Chen, R. Yang, Z. Zhang Z and D. Wu, *Journal of Hazardous Material,* **421**, 12681 (2022), https://doi.org/10.1016/j.jhazmat.2021.126817
47. R. Reshmy, T.A.P. Paulose, E. Philip, D. Thomas, A. Madhavan, Sirohi *et al., Fuel*, **311**, 122575(2022).
48. N. R. Savadekar and S.T. Mhaske, *Carbohydrate Polymers*, **89,** 146(2012).
49. E. Bahcegul, H. Ezgi, N. Ozkan and U. Bakir, *Bioresource Technology*, **103**, 440(2012).
50. A. Tshikovhi, S. B. Mishra and A.K. Mishra, *International Journal of Biological Macromolecules,* **152**, 616(2020).

[RJC- 8655/2024]