Innovation and Integrative Research Center Journal
ISSN: 2584-1491 | www.iircj.org
Volume-4 | Issue-2 | February-2026 | Page 06-24

# Nanocellulose from Sugarcane Bagasse: Fundamental Aspects and Advanced Applications

Dr. Arvind Kumar Pandey
Department of Organic Chemistry Devision, National Sugar Institute, Kalyanpur, Kanpur-208017, India

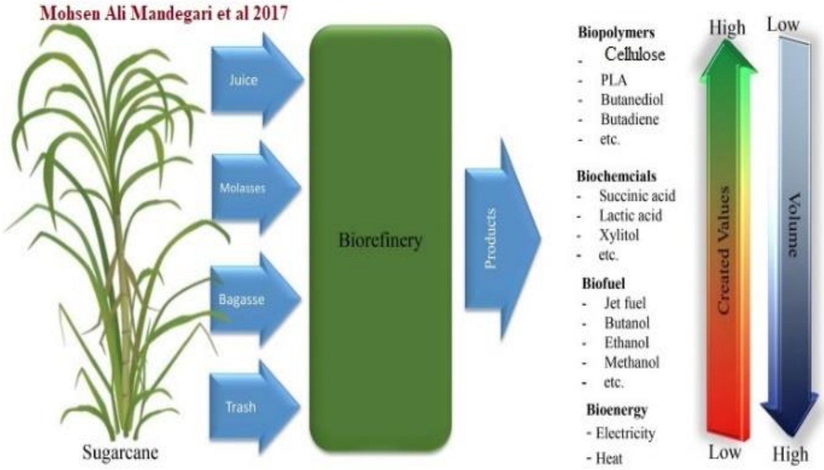
## Abstract:

Agro-industrial residues such as sugarcane bagasse can be exploited as suitable and low-cost feedstocks for the development of nanocellulose and advanced bio-based biomaterials. Here we critically review recent advances in sugarcane bagasse conversion to nanocellulose, focusing on feedstock composition, structural recalcitrance and variability associated with cultivar and processing conditions. This is discussed with respect to structure-property-application relationships and with a brief contextual comparison to bacterial nanocellulose, which differs in its structural characteristics from cellulose nanocrystals and cellulose nanofibrils. We analyze sustainable pretreatment, extraction, surface functionalization, and composite engineering strategies to illustrate enhancements in dispersion, interfacial compatibility and multifunctionality. Important application areas such as food packaging, polymer-based nanocomposites, biomedical engineering, water treatment and new energy applications are highlighted in conjunction with technology readiness levels and scale-up perspectives. Finally, challenges pertaining to standardization, cost minimization, continuous processing and regulatory acceptance are presented and future avenues addressing functional nanocellulose and smart materials are suggested.

**Keywords;** Sugarcane bagasse, Nanocellulose, Cellulose nanocrystals, Sustainable materials, Biorefinery

## Introduction:

Bagasse, the waste of sugarcane when it passes through its extraction in factories, is one of the most widely produced agro-industrial by-products owing to the vast global scale of sugar production (in 2018-19 alone, 270 metric billion tons). Bagasse is reported to represent 25-35 % of processed sugarcane mass, leading to the production of significant amounts yearly particularly in large sugar-producing regions like Brazil, India, China and Southeast Asia (Pandey et al., 2000; Hiranobe et al., 2024).

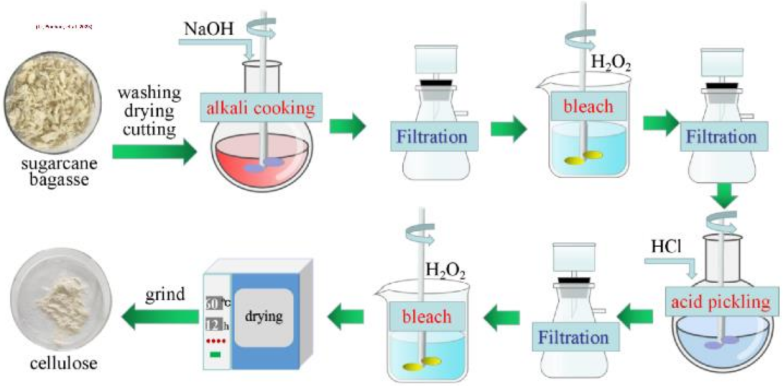

Mohsen Ali Mandegari et al 2017

Historically, the most common use of sugarcane bagasse has been as a fuel for cogeneration of heat and electricity in sugar mills that help achieve energy self-sufficiency but limit bagasse to a low-value end-use (Matsueda and Antunes, 2024). Although bagasse has high cellulose and a relatively suitable lignocellulosic structure, previous reports have shown that it is under-utilized and/or inefficiently valorized, leading to its low conversion degree into HVPs (Hiranobe et al. 2024).Alternative and sustainable utilization pathways of sugarcane have thus received growing interest in recent years, including its conversion to biofuels, production of biochemicals, adsorbent preparation, bio-coagulation for water treatment and advanced materials (Iwuozor et al., 2023; Sylvere et al., 2025). This new approach to valorization seeks to convert sugarcane bagasse from a low-value, predominantly energy-based residue to a multi-functional renewable feedstock that enables circular economy approaches and resource-efficient development in the wider global sugar industry (Matsueda and Antunes, 2024; Sylvere et al., 2025).

Nanocellulose has gained considerable scientific and technological attention owing to its renewable source, nanoscale size, and exceptional physicochemical properties arising from the hierarchical structure of cellulose. Nanocellulose, particularly cellulose nanocrystals and cellulose nanofibrils have been widely researched as they can be derived from various lignocellulosic residues that contribute to higher crystallinity, high tensile strength, large surface area and less density (Trache et al., 2017; Kaur et al., 2021) are an effective reinforcing material for advanced composites. A wide range of chemical modifications can be achieved by activating surface hydroxyl groups, enabling tailored tuning of the charge and hydrophilicity of the surface while optimizing interfacial interactions crucial for polymer matrix and functional system compatibility (Yi et al., 2020).

These inherent characteristics of nanofibers, along with biodegradability, biocompatibility, and non-toxicity, have pushed the range of applications toward high value sectors as biomedical scaffolds (Hong et al., 2020a), drug delivery systems (Wang et al. n.d.), wound dressing materials (Ha et al., 2021; Khalili et al., 2022), barrier films (Kaur et al., 2019; Xue yunyun e Xie Tie GPS;. Tiago Dos Santos Cruz e], and sustainable packaging materials (Randhawa et al., 2022; Kaur et al., 2021). Therewith, with the encounter of premium material performance and sustainability-driven design, nanocellulose has emerging as a platform material enabling the transition to bio-based and circular material economies (Trache et al., 2017; Yi et al., 2020).

A recent review covers the fundamentals of nanocellulose and discusses its manufacturing routes, physicochemical properties as well as a wide array of nanocellulose applications, such as in composites, coatings systems, biomedical applications, environmental systems (Trache et al., 2020; Oraon et al., 2022; Jose et al., 2025). Although these studies directly-down ascertain nanocellulose as a versatile and high-performance bio-based nanomaterial, they further highlight remaining challenges in terms of scale up manufacture, energy intensity, cost competitiveness, material standardization and process sustainability that presently restricts widespread industrial implementation (Jose et al., 2025; Oraon et al., 2022).

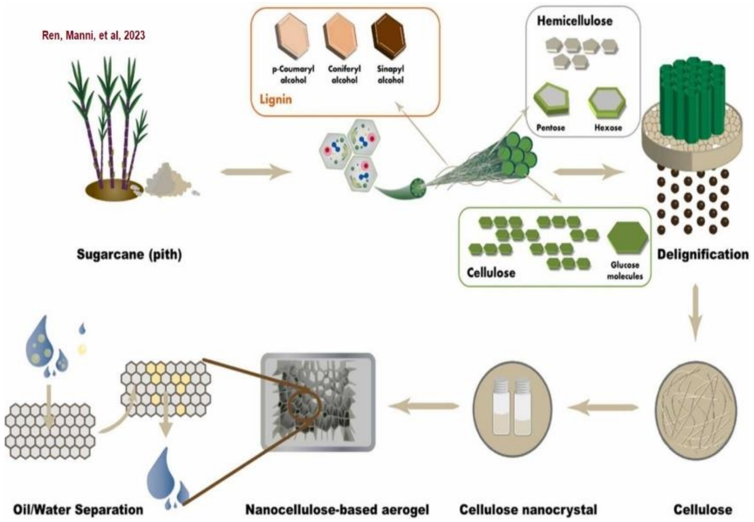


Furthermore, a number of the reviews focus on general nanocellulose platforms or application-specific developments with a relative lack of integration regarding feedstock-driven valorization strategies, alignment with circular bioeconomy principles and sustainability metrics throughout the entire material life cycle (Shak et al., 2018; Trache et al., 2020). New perspectives further emphasize the increasing relevance of functionalized and intelligent cellulosic nanomaterials and outline a shift from proof-of-concept demonstration to application-driven material redesign with respect to environmental & social requirements (Singh et al., 2025). Once again, in this context, the present review provides a concise definition of scope that critically interlinks not only sustainable production pathways and structure-property-application correlations of nanocellulose but also discusses advanced functional utilizations of nanocellulose, providing a solid roadmap evaluating current technological bottlenecks, sustainability consideration aspects as well important future research directions required for successful translation into industrial scale (Jose et al., 2025; Oraon et al., 2022).

## Sugarcane Bagasse as Feedstock

The suitability of sugarcane bagasse as a substrate for advanced materials and biorefinery applications depends on its chemical composition, microstructure and semitrictness. Bagasse has been largely characterized, revealing its composition as mainly cellulose surrounded by hemicellulose and lignin forming strong lignocellulosic structures of lignocelluloses- carbohydrate complexes (LCC) that restrict enzymatic admission and chemical reactivity (Rezende et al., 2011; Zhang et al., 2020).

This resilient structure necessitates productive pretreatment approaches, incorporating an amalgamation of chemical and enzymatic treatments leading to a substantial increase in the accessibility of cellulose and its efficiency for conversion during downstream operations (Thite and Nerurkar, 2019; Ntunka et al., 2025). The cellulose extraction optimization studies do confirm the central importance of the pretreatment severity and processing parameters conducive to its yield, crystallinity, and final purity in determining for what downstream applications it will be useful as a material or for whether it will be suitable for biochemical uses (Melesse et al., 2022).



In addition, sugarcane bagasse is highly heterogeneous regarding its physicochemical properties due to cultivar and growth season, as well milled conditions that are directly related to composition and process performance (Benjamin et al., 2014). Due to its renewable nature and mechanical properties that can be tailored with appropriate processing, sugarcane bagasse has also been recognized as a promising sustainable reinforcement and composite material (Kusuma et al., 2024); thus, emphasizing its potential for the development of circular and green materials feedstock.

## Nanocellulose Types and Structure

Nanocellulose describes a family of nanoscale cellulose-based substances; nanocellulose is categorised primarily into three types, namely cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs) and bacterial nanocellulose (BNC), with each type being fractionated based on distinct structural properties which play an important role in determining their physicochemical behaviour and performance once applied (Trache et al., 2020; Thomas et al., 2020). Crystalline nanocellulose (CNC) are straight, rod-like particles that primarily result from acid hydrolysis and have high crystallinity, low flexibility and high elastic modulus; these properties have led CNC to be an effective reinforcing agent in polymer nanocomposites (Vanderfleet and Cranston, 2021; Mondal, 2018). On the other hand, CNFs comprise of long, flexible and highly entangled fibrillar networks with crystalline and amorphous regions that afford high aspect ratios with excellent hydrogen-bonding ability as well as film-forming and rheological properties (Kaur et al., 2021). Due to these structural differences, different structure-property relationships exist as CNCs mainly enhance stiffness and strength, whereas CNFs has been shown to contribute to toughness, barrier properties and network integrity in composite- and film-based systems (Chen et al., 2019; Mondal, 2018). Although bacterial nanocellulose is not traditionally well represented amongst the biomass valorization routes, it provides a high-purity, narrowly defined nanofibrillar network free from

Innovation
and Integrative Research Center Journal

both lignin and hemicellulose which can be an important reference material for applications requiring refined properties (Geiss et al., 2025; Trache et al., 2020). Considerations of structural features and programmability that can affect nanocellulose functionality are increasingly supported by comparative characterization studies indicating that crystallinity, aspect ratio, and surface chemistry define a trinary landscape in which each phase contributes collectively to the emergent behavior of cellulosic nanoparticles (Thomas et al., 2020; Vanderfleet and Cranston, 2019). Controlled production routes thus allow us to selectively tailor the structure of nanocellulose materials to achieve performance criteria suitable for numerous applications.

## Properties of Nanocellulose

Nanocellulose (including cellulose nanocrystals, CNCs and cellulose nanofibrils CNFs) stands out for its peculiar combination of high stiffness/strength-to-weight properties, large specific surface area as well as densely hydroxyl-rich surfaces that provide a potential for abundant hydrogen-bonding and versatile chemical functionalization while being renewable, biodegradable and generally biocompatible (Li et al., 2015; Serpa et al., 2016; Trache et al., 2020). CNCs typically give high crystallinity and stiff rod-like structure, while CNFs form a tangled inter-grown networks leading to great reinforcement capability and tunable viscoelastic property; therefore, the nanocellulose suspensions show significant shear-thinning, yield stress formation, gelation, and thixotropy, important features for their coating/printing/processing performance (Hubbe et al., 2017; Thomas et al., 2020).

Innovation and Integrative Research Center Journal

Such structural features are reflected as superior tensile modulus/strength and microstructural coherence in polymer and biopolymer matrices, when dispersion and interfacial interactions were well-controlled (Chen et al., 2019; Thomas et al., 2020). Nanocellulose improves barrier properties (e.g., oxygen, aroma), via the generation of tortuous diffusion pathways and as a densifying agent of film microstructures-an advantage exploited in packaging and edible/biodegradable film concepts, extensively (Li et al., 2015; Xu et al., 2024). Crucially, this performance is highly process-dependent with production routes and surface chemistry (charge, sulfate/oxidized groups etc.) controlling colloidal stability, rheology and end-use behaviour which drives property-tailored CNC/CNF design (Vanderfleet & Cranston, 2021; Kaur et al., 2021; Randhawa et al., 2022; Dufresne, 2019).


(Shaikh, Kaleemullah, et al, 2024)

Innovation and Integrative Research Center Journal

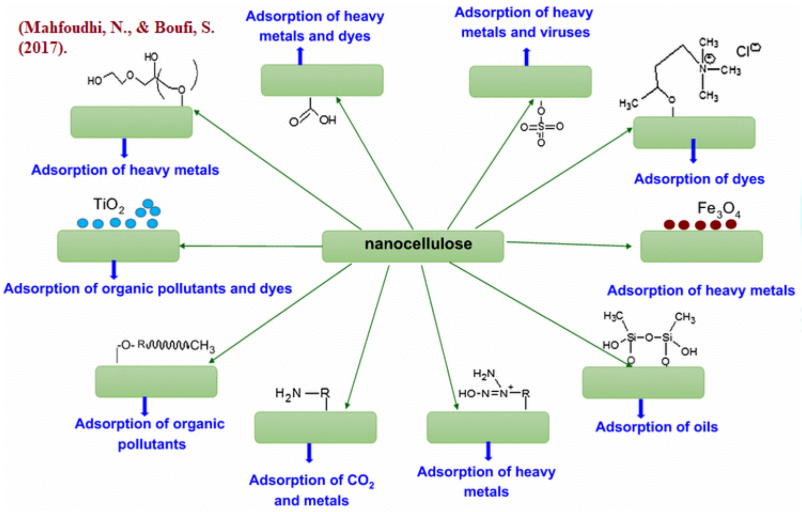
## Surface Functionalization and Composite Engineering

The inherently hydrophilic nature of nanocellulose additionally promotes strong hydrogen bonding between individual nanoparticles which greatly limits its dispersion and interfacial interaction within a wide range of polymer matrices, especially those that are semi-polar or hydrophobic; consequently, surface functionalization remains the most important tactic for improving the capability of nanocellulose to be integrated into a matrix. Chemical modification, consisting of different approaches like esterification, etherification, oxidation and silanization have shown significant effectiveness to modify the surface chemistry of nanocellulose by incorporating hydrophobic or reactive functional groups into them which ensured matrix affinity and load transfer efficiency improvement (Eyley et al., 2014; Thakur et al., 2021; Dufresne, 2019). Sophisticated strategies such as polymer grafting (“grafting-to” and “grafting-from”) allow for precise control of interfacial architecture and dispersion of nanofiller within the matrix, leading to a significant enhancement in mechanical strength, thermal stability, and durability of nanocellulose-based nanocomposites (Ghasemlou et al., 2021; Chakrabarty and Teramoto, 2018).

The notion of interface-driven design only gets more relevant to the balance between stiffness, toughness and lightweighting for high-performance applications (Armioun, 2025).

Along the classical polymer reinforcements, recent composites design moves toward hybrid nanocelluloses systems whereby its incorporation with secondary functional fillers similar to metal oxides, metal-organic frameworks, lignin or conductive phases allows cladding with multifunctionality (Oprea and Voicu, 2020; Zhou, 2021). This fundamentally changes the role of nanocellulose from merely a passive reinforcing agent (filler and strengthener for composite materials) to an active functional scaffold in biomedical devices, water purification degrading devices, flexible electronics, energy storage systems (Randhawa et al., 2022; Lasrado et al., 2020; Basheer et al., 2025).

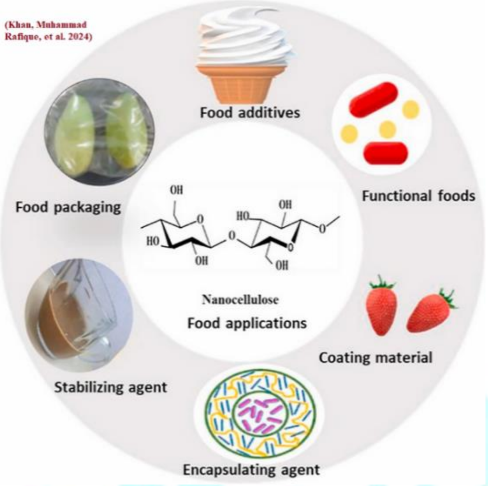
Homogeneous dispersion and strong interfacial bonding in those hybrid materials, therefore, require proper tuning of surface chemistry, processing conditions and interactions filling material-matrix concepts recently implemented into design guides for bio-based sustainable but application-oriented nanocellulose composites (Ahmed et al., 2026; Dufresne, 2019). Collectively, these advancements support the notion that well-reasoned surface functionalization and interface engineering will be integral to harnessing the maximum potential of nanocellulose for next-generation composites with value-added applications.


(Mahfoudhi, N., & Boufi, S. (2017).

## Advanced Applications

### Packaging & Food Science

Nanocellulose is one of the most prospective bio-based materials for food packaging applications because of its excellent film formation ability, mechanical strength, low permeability to gases and renewable biocompatibility. Nanocellulose-based composite films have been extensively reviewed and found to possess high strength, stiffness and barrier properties such as permeability against oxygen and aroma compounds in comparison to conventional biopolymer films, thereby making them promising alternatives for petroleum derived packaging materials (Li et al., 2015; Serpa et al., 2016; Xu et al., 2024). Cellulose nanofibrils or nanocrystals form a dense hydrogen-bonded network, creating tortuous diffusion pathways for gases that enhance shelf-life and food quality. Additionally, nanocellulose is easily processable with biopolymers including starch, proteins, and polysaccharides to provide flexibility, transparency and moisture sensitivity needed for different packaging formats (Serpa et al., 2016; Xu et al., 2024).


(Khan, Muhammad Rafique, et al. 2024)

Besides passive barrier improvement, nanocellulose-based films have been widely investigated as active and functional food packaging systems. Controlled release of antimicrobial agents, antioxidants, or bioactive compounds in nanocellulose matrices enhances food safety. It is noteworthy that nanocellulose obtained from sugarcane bagasse was already used to develop bio-based antimicrobials active packaging films in which nisin incorporation provided powerful antibacterial activity without compromising mechanical and barrier properties (Yang et al., 2020). These hybrid systems are demonstrating the capacity of nanocellulose to act as a structural matrix as well as an active agent carrier. Consequently, these evaluations have further highlighted that nanocellulose-based composite films are in line with current sustainability and circular economy objectives in the food packaging area even if issues related to moisture sensitivity, large-scale processing and regulatory clearance continue to be fundamental aspects for their commercial implementation (Li et al., 2015; Xu et al., 2024).

**Polymer Nanocomposites & Reinforcement**

Due to its high elastic modulus, large specific surface area and strong interfacial hydrogen-bonding ability that facilitate the stress transfer in polymer matrix (Ilyas et al., 2018), nanocellulose has been widely studied as an reinforcing agent in polymer nanocomposites. Cellulose nanocrystals and cellulose nanofibers have been reported to significantly improve mechanical strength, stiffness, and thermal stability of thermoset and thermoplastic polymers at low loading levels. Morphological and structural studies proved a uniform dispersion of cellulose nanofibers in epoxy-based systems, resulting in superior tensile and flexural properties with increased interfacial adhesion (Saba et al. 2017). These results highlight the effectiveness of nanoscale dispersion and matrix-filler interactions in producing high-performance polymer nanocomposites.

In recent years, the multifunctional capability of such composites has been enhanced and many studies have found cellulose-based materials from renewable resources (e.g., sugarcane bagasse) to be very promising. Nanocellulose extracted from bagasse have been successfully incorporated into polymer matrices to develop the combination of biodegradable and antimicrobial nanocomposites (Reshmy et al., 2021). The use of natural additives with nanocellulose improved tensile strength and barrier properties whilst also contributing to antimicrobial activity, confirming the potential for development of high value-added sustainable nanocomposites for applications in food packaging and related areas. Together these studies validated that nanocellulose is a versatile reinforcement phase with the ability to enhance mechanical performance whilst promoting sustainable and functionality-enhanced polymer materials (Ilyas et al., 2018; Reshmy et al., 2021).

### Biomedical Engineering

Due to its biocompatibility, high moisture retention capacity, tunable mechanical properties and structural resemblance with native extracellular matrix (ECM), this material has drawn great interest in the field of tissue engineering and regenerative medicine (Rai and Dhar, 2022). Plant-based nanocellulose and bacterial cellulose have been used as scaffold materials, hydrogels and drug delivery system. For instance, nanocellulose derived from sugarcane bagasse has shown considerable prospects in bone tissue engineering; injectable hydrogel scaffolds based on this nanocellulose and calcium ions have displayed high mechanical integrity, porosity, and bioactivity as well as cell attachment and support for bone regeneration (Kamel et al., 2023). This type of systems illustrates the double benefit of exploiting agro-waste-based nanocelluloses and at the same time satisfying key requirements in terms of biomedical performance.

Apart from plant-derived sources, bacterial cellulose-based scaffolds are extensively studied for soft and hard tissue engineering applications owing to their high purity, nanoscale fibrous network and good mechanical stability under physiological conditions (Ujjwal & Slaughter, 2025). Strategies for surface modification and functionalization also broaden the biomedical utility of the nanocellulose by allowing targeted drug delivery, improved cell-material interaction, and controlled release of bioactive molecules (Tortorella et al., 2020). Such recent reviews have highlighted the importance of customizing surface chemistry, stiffness and degradation behavior with respect to tissue-specific needs while avoiding immune responses (Rai and Dhar 2022; Tortorella et al. 2020). Together, these studies emphasize nanocellulose as a generalized and sustainable biomaterial platform suitable for sophisticated biomedical applications from tissue scaffolds and wound dressings to nanomedicine and regenerative therapies.

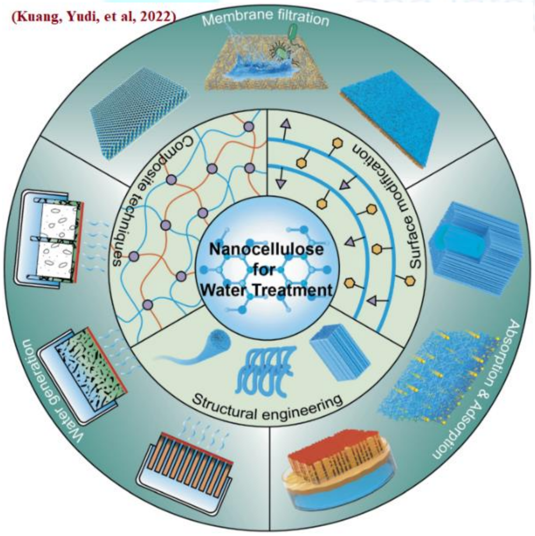
**Water Treatment & Remediation**

Shak et al. (2018) and Salama et al. (2021) reported that nanocellulose has become a promising and eco-friendly material for water treatment and environmental remediation because of its high specific surface area, large number of hydroxyl groups on the surface, tunable surface chemistry, and excellent dispersion in water. These inherent properties allow nanocellulose-based materials to interact effectively with different types of water pollutants through adsorption, ion exchange, and surface complexation mechanisms. Recent studies show that nanocellulose can be developed into different functional forms such as aerogels, membranes, and hybrid composites for removing dyes, heavy metals, pharmaceuticals, and harmful microorganisms from water (Sulbarán-Rangel, 2022; Salama et al., 2021).

Innovation and Integrative Research Center Journal

Surface functionalization along with hybridizing the nanomaterials with inorganic nanomaterials can enhance the efficiency of nanocellulose for water remediation, offering more than just ordinary adsorption. Nanocellulose made from sugarcane bagasse especially has been successfully utilized as a biotemplate to prepare nickel oxide nanoparticle-decorated composites. The obtained composites demonstrated significant removal efficiency for organic dyes via the combined processes of adsorption and photocatalytic degradation mechanisms (Mohammed et al., 2024). Such hybrid materials achieved higher removal rate, reusability and structural stability than pure nanocellulose. In addition, comprehensive reviews emphasize the significant potential of nanocellulose in modern water treatment technologies including photocatalysis, disinfection, antifouling membranes and

(Kuang, Yudi, et al, 2022)

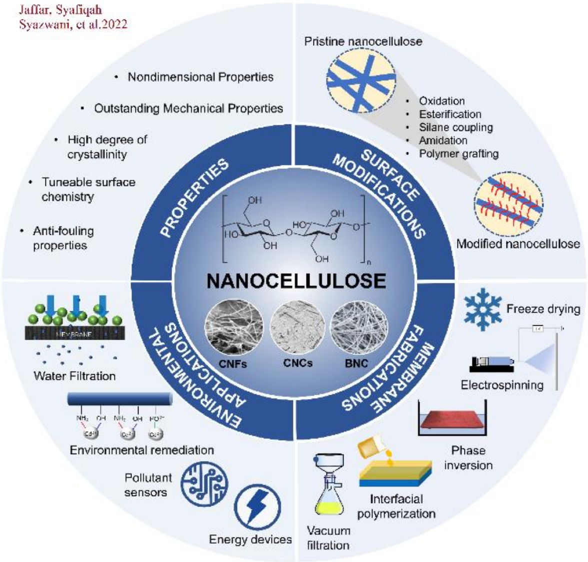


nanofiltration with promising prospects as a viable material for sustainable next-generation water purification systems (Shak et al., 2018; Salama et al., 2021).

**Energy & Technology Readiness**

The exploration of sugarcane bagasse-derived carbonaceous and nanocellulosic materials for energy storage and conversion applications is growing, showing great promise to overcome the increasing demand for sustainable and low-cost electrode materials. Recent research has shown that activated carbon derived from sugarcane bagasse possesses high surface area, suitable pore size distribution, and excellent electrical conductivity adequate for its dual application in environmental remediation as well as electrochemical energy storage systems (Somyanonthanakun et al., 2023). Activated carbon derived from bagasse, for example, has demonstrated electrochemical performance as supercapacitor electrodes with high specific capacitance values combined with good rate capability and cycling stability that indicates the possibility of transforming waste material from the sugar industry into high performance functional energy materials (Rajivgandhi et al., 2025). These developments show the promise of sugarcane bagasse as a scalable feed stock for next-generation, low-carbon energy technologies.

The technology readiness level (TRL) of nanocellulose-based energy and functional materials is still limited due to production economics, scalability, and process integration issues despite promising lab-scale performances. Various techno-economic analyses highlight aspects like energy-intensive fibrillation, chemical recovery, water consumption and the variable nature of feedstock quality that are major determinants of commercial nanocellulose production in terms of economic viability (Clauser et al., 2022). Recent scale-up studies on bacterial cellulose produced from various industrial and agro-wastes, however, show that well-optimized bioprocessing as well as waste feedstock utilization coupled with integrated downstream processing can help achieve a tenfold or more improvement in


Jaffar, Syafiqah Syazwani, et al.2022

economics for the production process relative to traditional processes, bringing nanocellulose technologies within reach of industrial commercialization (Mukherjee et al., 2025). In aggregate, these results imply that sugarcane bagasse-derived materials possess a strong potential for energy applications; however, ongoing innovations in process intensification, techno-economic analysis, and supply-chain integration will be critical to enabling technologies based on sugarcane bagasse to transition from pilot-scale demonstrations into commercially viable energy alternatives.

## Challenges and Future prospectives

The diversity of studies and applications mentioned above showcases that nanocellulose is a very promising material, leading to rapid developments in both academic research and industrial applications. Among the most significant problems are the absence of standardized nomenclature, grades, and dispersibility for nanocellulose as well as requirements for detailed toxicological and long-term environmental studies to promote regulatory acceptance (Dufresne, 2019; Trache et al., 2020). From a manufacturing aspect, elevated production costs due to energy-demanding fibrillation techniques, large water consumption, chemical utilization and complex downstream processing still act as a major obstacle towards commercialization (Clauser et al., 2022). Overcoming these bottlenecks will need to be tackled by (i) process intensification, (ii) identification of low-energy pretreatment routes, and (iii) prevention of nanocellulose production being merely a follow-up step in biorefinery settings to enhance economic feasibility in general terms (Vanderfleet and Cranston, 2021; Thakur et al., 2021).

Moreover, the shift from batch processes at laboratory scale to continuous manufacturing systems and from effective solvent and reagent recovery represents a new frontier that is now commonly seen as key to reducing operational costs and environmental footprints (Thomas et al., 2020). In the future perspective, further studies are anticipated to innovate in new-generation nanocellulose materials including next-generation and multifunctional nanocellulose surface-modified with specific moieties, intelligent and stimuli-responsive composites as well as rheology-engineered formulations for innovative manufacturing techniques like 3D printings which overall expand the arena of usage of nanocelluloses beyond their innate reinforcement functionalities (Thakur et al., 2021; Vanderfleet and Cranston, 2021). Coordinating progress in materials science, process engineering and sustainability assessment to overcome these challenges successfully will be vital in scaling nanocellulose technologies into market-ready solutions within a circular bioeconomy.

## Conclusion

It is expected that sugarcane bagasse in the context of circular bioeconomy will be one of the most promising sustainable feedstocks for nanocellulose and advanced bio-based materials production. This review highlights that while challenges related to feedstock variability and structural recalcitrance will remain, developments in pretreatment, extraction, and surface functionalization have made it possible to produce cellulose nanocrystals and nanofibrils with tailor-made properties. strong structure-property correlations of bagasse-derived nanocellulose also play a significant role in their effective incorporation into various applications including food packaging, polymer nanocomposites, biomedical engineering, water treatment as well as new energy technologies. While promising laboratory results are very encouraging, transitioning to industrial implementation will require addressing key challenges in standardization, cost reduction and the intensification and continuous manufacture of the processes. Future work will need to involve the co-location of nanocellulose production with sugarcane biorefineries, improved techno-economic options and building functional and smart nanocellulose platforms amenable to advanced manufacturing methods. Overall, sugarcane bagasse based nanocellulose is a versatile and scalable solution platform that holds great potential to drive sustainable materials innovation and industrial transformation.

Innovation
and Integrative Research Center Journal

## References

Ahmmed, A. S., Tadesse, M. G., Abtew, M. A., & Bräuning, M. (2026). Nanocellulose-Based Sustainable Composites for Advanced Flexible Functional Devices: Progress, Challenges, and Opportunities. *Sustainability*.

Antony Jose, S., Cowan, N., Davidson, M., Godina, G., Smith, I., Xin, J., & Menezes, P. L. (2025). A comprehensive review on cellulose nanofibers, nanomaterials, and composites: manufacturing, properties, and applications. *Nanomaterials*, *15*(5), 356.

Armioun, S. (2025). *Engineering Sustainable Composites for Lightweight Automotive Applications: Experimental and Theoretical Insights on Hybrid Fibre-reinforced Polymers* (Doctoral dissertation, University of Toronto (Canada)).

Basheer, J., Uthaman, A., Lal, H. M., Thomas, S., Gopakumar, D. A., & George, J. J. (2025). Nanocellulose: A sustainable functional construct for the remediation of heavy metal ions from water. *Journal of Thermoplastic Composite Materials*, *38*(1), 371-404.

Benjamin, Y., Görgens, J. F., & Joshi, S. V. (2014). Comparison of chemical composition and calculated ethanol yields of sugarcane varieties harvested for two growing seasons. *Industrial crops and products*, *58*, 133-141.

Chakrabarty, A., & Teramoto, Y. (2018). Recent advances in nanocellulose composites with polymers: A guide for choosing partners and how to incorporate them. *Polymers*, *10*(5), 517.

Chen, Q., Liu, Y., & Chen, G. (2019). A comparative study on the starch-based biocomposite films reinforced by nanocellulose prepared from different non-wood fibers. *Cellulose*, *26*(4), 2425-2435.

Clauser, N. M., Felissia, F. F., Area, M. C., & Vallejos, M. E. (2022). Technological and economic barriers of industrial-scale production of nanocellulose. In *Green nanomaterials for industrial applications* pp. 21-39.

Dufresne, A. (2019). Nanocellulose processing properties and potential applications. *Current Forestry Reports*, *5*(2), 76-89.

Dufresne, Alain. "Nanocellulose processing properties and potential applications." *Current Forestry Reports* 5.2 (2019): 76-89.

Eyley, S., & Thielemans, W. (2014). Surface modification of cellulose nanocrystals. *Nanoscale*, *6*(14), 7764-7779.

Geiss, O., Bianchi, I., Blazevic, I., Bucher, G., El-Hadri, H., Fumagalli, F., ... & Barrero-Moreno, J. (2025). Characterisation of Nanocellulose Types Using Complementary Techniques and Its Application to Detecting Bacterial Nanocellulose in Food Products. *Nanomaterials*, *15*(20), 1565.

Ghasemlou, M., Daver, F., Ivanova, E. P., Habibi, Y., & Adhikari, B. (2021). Surface modifications of nanocellulose: From synthesis to high-performance nanocomposites. *Progress in Polymer Science*, *119*, 101418.

Hiranobe, C. T., Gomes, A. S., Paiva, F. F., Tolosa, G. R., Paim, L. L., Dognani, G., ... & Cabrera, F. C. (2024). Sugarcane bagasse: Challenges and opportunities for waste recycling. *Clean technologies*, *6*(2), 662-699.

Hubbe, Martin A., et al. "Rheology of nanocellulose-rich aqueous suspensions: a review." *BioResources* 12.4 (2017): 9556-9661.

Ilyas, R. A., Sapuan, S. M., Sanyang, M. L., Ishak, M. R., & Zainudin, E. S. (2018). Nanocrystalline cellulose as reinforcement for polymeric matrix nanocomposites and its potential applications: a review. *Current Analytical Chemistry*, *14*(3), 203-225.

Iwuozor, K. O., Adeniyi, A. G., Emenike, E. C., Ojeyemi, T., Egbemhenghe, A. U., Okorie, C. J., ... & Saliu, O. D. (2023). Prospects and challenges of utilizing sugarcane bagasse as a bio-coagulant precursor for water treatment. *Biotechnology Reports*, *39*, e00805.

Jaffar, Syafiqah Syazwani, et al. "Recent development and environmental applications of nanocellulose-based membranes." *Membranes* 12.3 (2022): 287.

Kamel, R., El-Wakil, N. A., & Elkasabgy, N. A. (2023). Injectable hydrogel scaffolds composed of Nanocellulose derived from sugarcane bagasse and combined with calcium for Bone regeneration. *Research Journal of Pharmacy and Technology*, *16*(7), 3439-3450.

Kaur, Prabhpreet, et al. "Nanocellulose: resources, physio-chemical properties, current uses and future applications." *Frontiers in Nanotechnology* 3 (2021): 747329.

Khan, Muhammad Rafique, et al. "A review study on derivation of nanocellulose to its functional properties and applications in drug delivery system, food packaging, and biosensing devices." *Polymer Bulletin* 81.11 (2024): 9519-9568.

Kuang, Yudi, et al. "Nanocellulose for Water Treatment Applications." *Emerging Nanotechnologies in Nanocellulose*. Cham: Springer International Publishing, 2022. 301-333.

Kusuma, H. S., Permatasari, D., Umar, W. K., & Sharma, S. K. (2024). Sugarcane bagasse as an environmentally friendly composite material to face the sustainable development era. *Biomass Conversion and Biorefinery*, *14*(21), 26693-26706.

Lasrado, D., Ahankari, S., & Kar, K. (2020). Nanocellulose-based polymer composites for energy applications—a review. *Journal of Applied Polymer Science*, *137*(27), 48959.

Li, F., Mascheroni, E., & Piergiovanni, L. (2015). The potential of nanocellulose in the packaging field: a review. *Packaging Technology and Science*, *28*(6), 475-508.

Li, Fuchao, et al. "Synthesis of cellulose-poly (acrylic acid) using sugarcane bagasse extracted cellulose fibres for the removal of heavy metal ions." *International Journal of Molecular Sciences* 24.10 (2023): 8922.

Mahfoudhi, Norhene, and Sami Boufi. "Nanocellulose as a novel nanostructured adsorbent for environmental remediation: a review." *Cellulose* 24.3 (2017): 1171-1197.

Matsueda, Y., & Antunes, E. (2024). A review of current technologies for the sustainable valorisation of sugarcane bagasse. *Journal of Environmental Chemical Engineering*, *12*(6), 114900.

Melesse, G. T., Hone, F. G., & Mekonnen, M. A. (2022). Extraction of cellulose from sugarcane bagasse optimization and characterization. *Advances in materials science and engineering*, *2022*(1), 1712207.

Mohammed, K. S., Atlabachew, M., Abdu, B., & Desalew, A. A. (2024). A nanocellulose from sugarcane bagasse as a template for nickel oxide nanoparticles for removal of organic dyes from aqueous solution. *Scientific Reports*, *14*(1), 31684.

Mohsen Ali Mandegari, Somayeh Farzad, Johann F. Görgens, Recent trends on techno-economic assessment (TEA) of sugarcane biorefineries, Biofuel Research Journal 15 (2017) 704-712

Mondal, S. (2018). Review on nanocellulose polymer nanocomposites. *Polymer-Plastics Technology and Engineering*, *57*(13), 1377-1391.

Mukherjee, P., Kamble, R. D., Krishnan, J. B., Sivaprakasam, S., & Sekharan, S. (2025). Bacterial cellulose production, scale-up, and applications: a techno-economic study of industry-ready bacterial cellulose production from industrial and agro wastes. *Cellulose*, 1-30.

Ntunka, M. G., Makhathini, T. P., Khumalo, S. M., Bwapwa, J. K., & Tshibangu, M. M. (2025). Recent Developments in the Valorization of Sugarcane Bagasse Biomass via Integrated Pretreatment and Fermentation Strategies. *Fermentation*, *11*(11), 632.

Oprea, M., & Voicu, S. I. (2020). Recent advances in composites based on cellulose derivatives for biomedical applications. *Carbohydrate Polymers*, *247*, 116683.

Oraon, R., Rawtani, D., Singh, P., & Hussain, C. M. (Eds.). (2022). *Nanocellulose materials: Fabrication and industrial applications*. Elsevier.

Pandey, A., Soccol, C. R., Nigam, P., & Soccol, V. T. (2000). Biotechnological potential of agro-industrial residues. I: sugarcane bagasse. *Bioresource technology*, *74*(1), 69-80.

Rai, R., & Dhar, P. (2022). Biomedical engineering aspects of nanocellulose: A review. *Nanotechnology*, *33*(36), 362001.

Rajivgandhi, P., Thirumal, V., Sekar, A., & Kim, J. (2025). Sustainable Sugarcane bagasse-derived activated carbon for high-performance symmetric supercapacitor devices applications. *Nanomaterials*, *15*(13), 1028.

Randhawa, A., Dutta, S. D., Ganguly, K., Patil, T. V., Patel, D. K., & Lim, K. T. (2022). A review of properties of nanocellulose, its synthesis, and potential in biomedical applications. *Applied Sciences*, *12*(14), 7090.

Ren, Manni, et al. "Characterization of cellulose nanocrystals prepared by different delignification methods and application of ultra-light, hydrophobic aerogels as oil absorbent in food systems." *Industrial Crops and Products* 197 (2023): 116653.

Reshmy, R., Madhavan, A., Philip, E., Paul, S. A., Sindhu, R., Binod, P., ... & Pandey, A. (2021). Sugarcane bagasse derived nanocellulose reinforced with frankincense (Boswellia serrata): Physicochemical properties, biodegradability and antimicrobial effect for controlling microbial growth for food packaging application. *Environmental Technology & Innovation*, *21*, 101335.

Rezende, C. A., De Lima, M. A., Maziero, P., deAzevedo, E. R., Garcia, W., & Polikarpov, I. (2011). Chemical and morphological characterization of sugarcane bagasse submitted to a delignification process for enhanced enzymatic digestibility. *Biotechnology for biofuels*, *4*(1), 54.

Saba, N., Mohammad, F., Pervaiz, M., Jawaid, M., Alothman, O. Y., & Sain, M. (2017). Mechanical, morphological and structural properties of cellulose nanofibers reinforced epoxy composites. *International journal of biological macromolecules*, *97*, 190-200.

Salama, A., Abouzeid, R., Leong, W. S., Jeevanandam, J., Samyn, P., Dufresne, A., ... & Barhoum, A. (2021). Nanocellulose-based materials for water treatment: adsorption, photocatalytic degradation, disinfection, antifouling, and nanofiltration. *Nanomaterials*, *11*(11), 3008.

Serpa, A., et al. "Vegetable nanocellulose in food science: A review." *Food Hydrocolloids* 57 (2016): 178-186.

Serpa, A., Velásquez-Cock, J., Gañán, P., Castro, C., Vélez, L., & Zuluaga, R. (2016). Vegetable nanocellulose in food science: A review. *Food Hydrocolloids*, *57*, 178-186.

Shaikh, Kaleemullah, et al. "Nanocellulose: Fundamentals and Applications." *Nanocellulose-Sources, Preparations, and Applications*. IntechOpen, 2024.

Shak, K. P. Y., Pang, Y. L., & Mah, S. K. (2018). Nanocellulose: Recent advances and its prospects in environmental remediation. *Beilstein journal of nanotechnology*, *9*(1), 2479-2498.

Singh, A., Kaur, S., Thakur, H., Rashi, Kashyap, S., Lyudmila, A., & Mudgal, G. (2025). Unveiling the transformative power of smart cellulosic nanomaterials: revisiting potential promises to sustainable future. In *Functionalized cellulose materials: sustainable manufacturing and applications* (pp. 1-42). Cham: Springer Nature Switzerland.

Somyanonthanakun, W., Greszta, A., Roberts, A. J., & Thongmee, S. (2023). Sugarcane bagasse-derived activated carbon as a potential material for lead ions removal from aqueous solution and supercapacitor energy storage application. *Sustainability*, *15*(6), 5566.

Sulbarán-Rangel, B. (2022). Nanocellulose-based materials in the removal of contaminants from water. *Polym. Sci. Peer Rev. J*, *3*, 1-4.

Sylvere, N., Omar, T., Youness, A., El Farissi, L., & Lina, G. (2025). Innovative applications of sugarcane bagasse in the global sugarcane industry. *Processes*, *13*(12), 3796.

Thakur, V., Guleria, A., Kumar, S., Sharma, S., & Singh, K. (2021). Recent advances in nanocellulose processing, functionalization and applications: A review. *Materials Advances*, *2*(6), 1872-1895.

Thite, V. S., & Nerurkar, A. S. (2019). Valorization of sugarcane bagasse by chemical pretreatment and enzyme mediated deconstruction. *Scientific reports*, *9*(1), 15904.

Thomas, Paul, et al. (2020): "Comprehensive review on nanocellulose: Recent developments, challenges and future prospects." *Journal of the mechanical behavior of biomedical materials* 110 103884.

Tortorella, S., Vetri Buratti, V., Maturi, M., Sambri, L., Comes Franchini, M., & Locatelli, E. (2020). Surface-modified nanocellulose for application in biomedical engineering and nanomedicine: A review. *International journal of nanomedicine*, 9909-9937.

Trache, D., Hussin, M. H., Haafiz, M. M., & Thakur, V. K. (2017). Recent progress in cellulose nanocrystals: sources and production. *Nanoscale*, *9*(5), 1763-1786.

Trache, D., Tarchoun, A. F., Derradji, M., Hamidon, T. S., Masruchin, N., Brosse, N., & Hussin, M. H. (2020). Nanocellulose: from fundamentals to advanced applications. *Frontiers in chemistry*, *8*, 392.

Trache, Djalal, et al. "Nanocellulose: from fundamentals to advanced applications." *Frontiers in chemistry* 8 (2020): 392.

Ujjwal, R. R., & Slaughter, G. (2025). Advances in Bacterial Cellulose-Based Scaffolds for Tissue Engineering. *Journal of Biomedical Materials Research Part A*, *113*(4), e37912.

Vanderfleet, O. M., & Cranston, E. D. (2021). Production routes to tailor the performance of cellulose nanocrystals. *Nature Reviews Materials*, *6*(2), 124-144.

Xu, Y., Wu, Z., Li, A., Chen, N., Rao, J., & Zeng, Q. (2024). Nanocellulose composite films in food packaging materials: a review. *Polymers*, *16*(3), 423.

Xu, Yanting, et al. "Nanocellulose composite films in food packaging materials: a review." *Polymers* 16.3 (2024): 423.

Yang, Y., Liu, H., Wu, M., Ma, J., & Lu, P. (2020). Bio-based antimicrobial packaging from sugarcane bagasse nanocellulose/nisin hybrid films. *International Journal of Biological Macromolecules*, *161*, 627-635.

Yi, T., Zhao, H., Mo, Q., Pan, D., Liu, Y., Huang, L., ... & Song, H. (2020). From cellulose to cellulose nanofibrils—a comprehensive review of the preparation and modification of cellulose nanofibrils. *Materials*, *13*(22), 5062.

Zhang, Q., Wan, G., Li, M., Jiang, H., Wang, S., & Min, D. (2020). Impact of bagasse lignin-carbohydrate complexes structural changes on cellulase adsorption behavior. *International journal of biological macromolecules*, *162*, 236-245.

Zhou, S. (2021). *Nanocellulose and Metal-Organic Framework-Based Composites: Synthesis, Characterization, and Applications* (Doctoral dissertation, Acta Universitatis Upsaliensis).