



Algae-derived Nanocellulose: A Sustainable Resource for Advanced Material Applications

M. Priya and S. Pandi Prabha*

Department of Biotechnology, Sri Venkateswara College of Engineering, Sriperumbudur, Chennai, TN, India

Received: 23.06.2025 Accepted: 16.08.2025 Published: 30.09.2025

*prabha@svce.ac.in



ABSTRACT

In recent years, research efforts have increasingly focused on the development of products derived from biodegradable materials. Among these, nanocellulose has emerged as a highly promising green material, gaining traction across a variety of industries due to its remarkable properties. Its advantageous attributes, including a high aspect ratio, biocompatibility, renewability, and exceptional mechanical strength, have captured widespread interest. With the rapid growth in industrial production, some companies are now manufacturing nanocellulose on a scale of tons per day, signaling its growing commercial viability across various sectors. These cellulose-based nanomaterials possess unique structural features that enable surface chemistry modifications, thereby advancing the development of composites, films, and coatings. Moreover, they have demonstrated significant potential in engineering and biomedical applications. Nanocellulose can be sourced from plants, bacteria, and algae, and is classified into cellulose nanocrystals (CNCs), cellulose nanofibers (CNFs), and bacterial nanocellulose (BNC). The remarkable attributes of algae-derived nanocellulose are primarily linked to its exceptional purity and unparalleled quality. Algae biomass offers distinct advantages over conventional lignocellulosic sources for nanocellulose production, particularly in terms of availability, ease of processing, and material quality. However, its utilization remains limited compared to lignocellulose-based alternatives. This review presents an in-depth exploration of extraction methodologies for algal nanocellulose and its versatile applications across a wide range of industries.

Keywords: Nanocrystals; Nanofibers; Bacterial nanocellulose; Composites; Macroalgae.

1. INTRODUCTION

Many researchers are interested in utilizing environment-friendly and non-depletable materials for various purposes, as these serve as alternative solutions to the energy crisis, environmental degradation, global warming, and the ever-dwindling supply of non-renewable resources. Given their widespread availability from various sources, many materials have emerged as promising options. Cellulose is the most abundant renewable molecule derived from the Earth (Hoeng *et al.* 2016). The biomaterials industry has taken notice of cellulose, a plentiful, renewable, naturally occurring biopolymer that may be used to create products that are both environmentally friendly and biocompatible. The origin of this polymer, which can be derived from a wide range of living species, affects factors including the structure and characteristics of cellulose (Raju *et al.* 2023). It can be obtained from various sources like plants, algae, and bacteria. The extraction of cellulose from such sustainable sources and its usage in diverse eco-friendly products are the subject of extensive research (Zaki *et al.* 2021). Many research organizations are driven by the need to find new applications and enhance the qualities of the materials based on nanocellulose (Trache *et al.* 2020). The demand for nanocellulose is driven by both environmental concerns

related to greater product sustainability in the market and the shift towards bio-based products due to resource scarcity (Tafete *et al.* 2022). It has been used in a variety of applications, including membrane filtration, the chemical industry as a viscosity modifier, biomedicine, mechanical reinforcement of matrices, and food packaging (Kaur *et al.* 2021). The highly interdependent hydroxyl groups in cellulose materials give them a great propensity to self-associate and create an extensive network through intramolecular and intermolecular hydrogen interactions (Ahankari *et al.* 2021). The advantages of nanocellulose-based biomedical materials, such as their low cost, biodegradability, biocompatibility, exceptional mechanical qualities, availability, sustainability, and low cytotoxicity, have attracted a lot of attention (Jorfi *et al.* 2015). Advancements in cellulose research have been achieved through the utilization of various analytical techniques, including crystallography and microscopy. The methods used for studying the complex system have been varied, leading to an extensive body of literature to understand all the aspects of the system (O'Sullivan *et al.* 1997). The intricate structure of native cellulose fibers profoundly influences processes such as plant growth and chemical or enzymatic conversion of cellulosic biomass, the innovation of novel materials, and the understanding of the physical characteristics of various cellulose-based

materials (Nishiyama *et al.* 2009). The isolated celluloses have recently gained attention as a potential candidate for the development of advanced bio-based materials, particularly for films or composites, due to the abundance of resources and inherent renewability, sustainability, and biocompatibility, as well as excellent chemical and physical properties (Zhao *et al.* 2017).

Nanocellulose, owing to its numerous appealing characteristics, has become a significantly influential eco-friendly product in the market, making it a highly promising nanomaterial. A multitude of recently published reviews have centered on the preparation techniques of nanocellulose, as well as its characterization and applications in polymer composites (Hakim *et al.* 2023). In 2021, the nanocellulose market held a value of USD 346 million, a figure anticipated to surge to USD 963 million by 2026, reflecting a robust compound annual growth rate of 22.7%. Escalating environmental apprehensions, coupled with the market's impetus for heightened sustainability in product advancement, are driving the imperative incorporation of nanocellulose. Furthermore, the increasing scarcity of resources is redirecting demand toward biomaterial products, marking a substantial expansion in the nanocellulose market (Norizan *et al.* 2022). At present, the energy-intensive nature of producing plant-based nanocellulose - both cellulose nanofibers (CNFs), and cellulose nanocrystals (CNCs) on a large scale raises concerns about its potential environmental consequences. On the other hand, while notable advancements have been made, the production of bacterial nanocellulose (BNC) remains constrained due to the expensive requirements for bacterial cultivation support and its relatively modest yield (Ong *et al.* 2023). The search for equilibrium lies in adjusting the morphologies and surface properties of nanocomposite-based (NC) materials to achieve a harmonious blend of fresh functionalities and intrinsic characteristics. Concurrently, there's a need to advance the synthesis and production techniques for NC assemblies, making them scalable and competitive in the commercial realm (Ghilan *et al.* 2023).

1.1 Cellulose Structure

With the rising demand for sustainable and eco-friendly materials, biodegradable polymer composites reinforced with natural fibers are being increasingly utilized in areas such as packaging, automotive components, construction, and biomedical devices (Ramamurthy *et al.* 2025). Plants' primary structural component, cellulose, is becoming more important as a renewable chemical resource to replace products based on petroleum. Microfibrils make up the plant fibers, serving as composites, which serve as a reinforcing element for the matrix consisting of lignin and hemicellulose (Thomas *et al.* 2020). The cell wall is present around every cell, and also forms a continuous,

dynamic network throughout the entire plant. The secondary wall is the main location of the linear polymer cellulose, which is made of glucose monomer (Khalil *et al.* 2014). The involvement of the monomer's hydroxyl groups and their ability to create hydrogen bonds significantly influence the arrangement of crystalline packing, thereby dictating the physical characteristics of cellulose (John *et al.* 2008). The linear homopolysaccharide that makes up cellulose is made up of d-glucopyranose units that are connected by 1-4-linkages (Ram *et al.* 2022).

Cellobiose serves as the repeating unit of the naturally occurring linear molecule cellulose, which is composed of D-anhydroglucopyranose subunits linked by glycosidic linkages (Park *et al.* 2010). A single glucose unit is a hexose, and depending on where the hydroxyl groups are located, it can adopt one of the two forms (α or β). Hydrogen bonds allow single-molecule cellulose chains to join together to produce cellulose microfibrils with crystalline, paracrystalline, and amorphous areas (Huber *et al.* 2012). Depending on the cellulose source, the degree of polymerization (DP), or quantity of glucose units, can reach 20,000 (Klemm *et al.* 2018).

1.2 Cellulose Sources

One of the most prevalent biopolymers is cellulose, which is found in a wide variety of plant-based materials like wood, cotton, hemp, and other building blocks for plants. Cellulose also acts as the main structural reinforcement for plants. Furthermore, tunicates, algae, and some bacteria produce cellulose (Khalid *et al.* 2021).

1.3 Algae as a Source of Cellulose

As the algae industry and algae biorefinery technologies continue to expand, there is an increasing demand for high-value applications of biopolymers derived from algae. Among these, their use in biomedical applications holds significant promise, yet presents considerable challenges for practical implementation (Beaumont *et al.* 2021). Cellulose derived from diverse seaweed species exhibits properties comparable to those obtained from lignocellulosic sources. Although its relatively low abundance in seaweed biomass presents a limitation, the negligible or absent lignin content offers a significant advantage. Consequently, seaweed-derived cellulose holds considerable potential for a wide range of industrial applications. The cellulose content and its extraction from diverse seaweed species have been comprehensively reported across multiple studies (Baghel *et al.* 2021; Baghel *et al.* 2014; Siddhanta *et al.* 2013). Marine seaweeds, commonly referred to as algae, represent an abundant source of diverse biologically active compounds, underscoring their significance in various applications. Despite their potential as

carbohydrate sources, cellulose, the primary structural polysaccharide in algal cell walls, has received comparatively less attention. Notably, the cellulose content in seaweed varies widely, ranging from 1% to 13% by weight (Bogolitsyn *et al.* 2024). It is now widely known that algae also make cellulose microfibrils, despite the fact that cellulose is typically linked with lignocellulosic materials (Trache *et al.* 2017). A specific class of biomacromolecule known as polysaccharides is present in marine algae as part of their cell walls. The fibrous skeleton and amorphous embedding matrix that make up algae cell walls give them their structural complexity and heterogeneity (Xu *et al.* 2017). Algal cellulose has a high degree of crystallinity, which can reach 95% or higher. It has been discovered that the cellulose microfibril architectures of various algae species differ based on the production process (Mishra *et al.* 2018). Higher polysaccharide content in macroalgae has been widely observed, and it is utilized in many of the current industrial applications. Microalgal polysaccharides have been less explored for bioactive applications, despite exhibiting a faster growth rate and a simpler cultivation and extraction technique than macroalgal biomass (Patel *et al.* 2022).

1.4 Macroalgae

Seaweeds, which are simply marine macroalgae, are the most practical and ideal source for cellulose extraction because the majority of their cell walls are formed of cellulose fiber (Zainuddin *et al.* 2021). Brown algae (*Phaeophyceae*), red algae (*Rhodophyceae*), and green algae (*Chlorophyceae*) are three major classes into which marine macroalgae can be divided based on coloration and chemical framework (Kraan, 2013). Macroalgal cell walls, found in green, red, and brown seaweeds, consist of a cellulose-based fibrillar skeleton embedded in a polysaccharide-rich matrix primarily alginates and fucoidans in brown algae, sulfated galactans such as agar and carrageenan in red algae, and class-specific polysaccharides in green algae (Stiger *et al.* 2016). Due to their high carbohydrate content, various studies have shown that red algae, like *Gelidium*, appear to be a more attractive alternative for the manufacture of cellulose nanomaterials (Jeong *et al.* 2012). Brown algae contain multiple polysaccharides, with cellulose being one of the crucial linear polysaccharides utilized in the industry. In comparison to terrestrial plants, brown algae exhibit a lower quantity of lignin (Sterner and Edland, 2016). Green algae have cell walls made up of collections of polymers that remarkably resemble cellulose, pectins, hemicelluloses, and arabinogalactan proteins. These algae produce sulfated polysaccharides, a process that many other marine organisms also use to adapt to their environments (Domozych *et al.* 2012). Various studies reported the properties of nanocellulose derived from algae with other sources. Marine green algae from the *Cladophorales* possess cell walls abundant in native cellulose composed

of elementary fibrils (10–30 nm) characterized by exceptionally high crystallinity, substantial specific surface area in the dry state, and outstanding mechanical and rheological properties (Mihiranyan, 2011). Studies on fibroblast adhesion and viability have shown that TEMPO-modified *Cladophora* cellulose exhibits significant potential for tissue engineering applications, whereas for wood-derived nanofibrillated cellulose, cytocompatibility is primarily achieved through cationic modification (Hua *et al.* 2014). *Cladophora*-derived nanocellulose, owing to its higher crystallinity, porosity, and lower hygroscopicity compared to wood-derived NFC, exhibits distinct dielectric responses influenced by water mobility and frequency, highlighting its potential for high-power electrical insulation applications (Bras *et al.* 2015). Nanocellulose derived from non-wood sources such as cattail fibers and red algae exhibit higher crystallinity, greater thermal stability, and enhance the mechanical properties of bio-composites more effectively than wood-derived nanocellulose (Van-Hai *et al.* 2015).

1.5 Microalgae

In contrast to the enormous diversity of microalgal species, there are surprisingly few species that contain cellulose that have undergone extensive research. A strong, multilayered bag of crosslinked polymers makes up the most prevalent form of microalgal cell wall (Ross *et al.* 2021). The primary components of microalgae polysaccharides are heteropolymers of galactose, xylose, and glucose, which are joined by glycosidic linkages. Numerous enzymes are involved in the synthesis and modification of polysaccharides, which is a reflection of these complicated structures (Chanda *et al.* 2019). Due to challenges in obtaining clean samples and the intricacy of their chemical composition, very few structures of microalgal polysaccharides have been determined (Le *et al.* 2017). The polysaccharide structure of the red microalgae is more complex than that of the seaweeds' cell-wall polysaccharides, which are distinguished by an organized structure made up of repeating disaccharide blocks (Arad and Levy-Ontman, 2010). Depending on the growing method, the metabolism of microalgal cells may result in high-value polysaccharides constituting up to 70% of the dry weight of the cell (Colusse *et al.* 2022).

2. NANOCELLULOSE AND ITS TYPES

Nanostructured cellulose, often called nanocellulose, is acquired through the isolation of cellulose at the nanoscale, thus efficiently eliminating most of the imperfections linked to the hierarchical structure (Du *et al.* 2017). Essentially, it can be divided into three types: CNCs, CNFs, and BNCs. CNF consists of elongated fibers with extremely small lengths and diameters within the nanoscale range (Jacob *et al.* 2022). CNC is highly crystalline nanocellulose that resembles a

rod that is frequently produced through acid hydrolysis by removing amorphous areas from native cellulose (Serpa *et al.* 2016). BNCs are continuous fibers with a diameter of up to 100 nm that come together to form macroscopic mesh-like structures with great crystallinity and purity (Čolić *et al.* 2020). Table 1 concisely outlines the nanocellulose varieties, their structure, dimensions, and the percentage of crystallinity (Liu *et al.* 2021).

Table 1. Types of nanocellulose

Types of Nanocellulose	Dimensions	Morphology	Properties
CNFs	Diameter <100 nm Length: micrometer range	Long chain	Crystallinity: 50-65 % Aspect ratio: 60-100
CNCs	Diameter: 1 - 100 nm Length: 5 - 200 nm	Rod/Needle	Crystallinity: 72-80 % Aspect ratio: 10-50
BNC	Diameter: 20 - 100 nm Length: micrometer range	Twisted ribbon	Crystallinity: 75-80 % Aspect ratio: 0-50

2.1 Cellulose Nanocrystals

The most widely used form of nanocellulose is called CNCs, which are mostly created by hydrolyzing the amorphous portion of cellulose fibers. Typically, cellulose's amorphous sections are dissolved by strong sulfuric acid, leaving the crystalline regions unaffected (Charreau *et al.* 2020). The sulphate groups stay attached to the surface of the fibers as contaminants, even though this process creates a stiff, rod-like CNC with over 90% purity. CNCs typically range in size from 200 to 500 nm in length to 3-35 nm in diameter (Nasir *et al.* 2017).

2.2 Cellulose Nanofibers

As opposed to CNCs, CNFs require far less severe chemical cleavage in the cellulose chain's molecular structure, making their manufacture much easier. CNF is an excellent positive component for the improvement of polymer materials since it often has a high aspect ratio (Huang *et al.* 2019). Cellulose fibers are physically separated to create CNFs using processes like grinding, homogenization, and ultrasonication. In addition to mechanical separation techniques, chemical techniques such as TEMPO oxidation and acid or alkali treatment can also be used to create CNFs (Reshmy *et al.* 2021). Individual CNFs can occasionally be created using a combination of mechanical and chemical techniques. The typical range for the diameter of CNFs is 5 to 60 nm, depending on the type of raw materials (Zhang *et al.* 2020).

2.3 Bacterial Nanocellulose

The cellulose produced by bacteria is also referred to as 'bacterial nanocellulose,' 'microbial cellulose,' or 'biocellulose'. Due to its non-toxicity and high biocompatibility, BNC is generating significant interest in a variety of applications, particularly in the medical field (Niyazbekova *et al.* 2018). When compared to cellulose derived from plants, cellulose made from bacterial sources has a number of advantages due to its lack of extra contaminants (Abitbol *et al.* 2016). BNC can store 400 times its weight in water compared to its dry weight. Numerous microbial strains, including *Komagataeibacter xylinus*, *Achromobacter*, and *Sarcina ventriculi*, have been recognized as cellulose producers, thriving on diverse carbon sources, which include biomass waste (Chandana *et al.* 2022).

Bacteria are grown in nutrient-rich aqueous conditions containing supplies of low-molecular-weight nitrogen and carbon, and they extrude a highly porous network of BNC (Kedzior *et al.* 2021).

3. ISOLATION OF NANOCELLULOSE

Before being turned into nanocellulose, the majority of cellulose is separated from untreated cellulose pulp that contains hemicelluloses and lignin (Wei *et al.* 2014). Pure cellulose extraction entails multi-stage methods that include enzymatic, mechanical, and chemical treatments. Purified cellulose is directly acid-hydrolyzed to produce CNCs, whereas a variety of mechanical processes produce CNFs (Reshmy *et al.* 2020). Pretreatment of untreated cellulosic biomass and conversion of pretreated biomass into cellulose nanoparticles are the two steps required to produce nanocellulose from lignocellulosic biomass (Mondal *et al.* 2018). Fig. 1 illustrates the synthesis of nanocellulose from algae biomass.

In general, it was found that mechanical treatment is the primary treatment utilized to make CNFs, whereas it is also used to produce CNC in the post-treatment and purification step. The cellulose pulp is frequently disintegrated mechanically to create minute particles (Saud *et al.* 2022). In contrast to mechanical disintegration, chemical treatment separates the amorphous region into tiny fibers while leaving the crystalline regions intact. Acid hydrolysis is a widely used technique for removing CNC from cellulose (Salas *et al.* 2014). Prior to mechanical disintegration of cellulose, enzymatic hydrolysis of cellulose is a frequently used technique in the production of nanocellulose. Due to its morphologies, enzyme-produced nanocellulose typically has more high-value uses (Ribeiro *et al.* 2019).

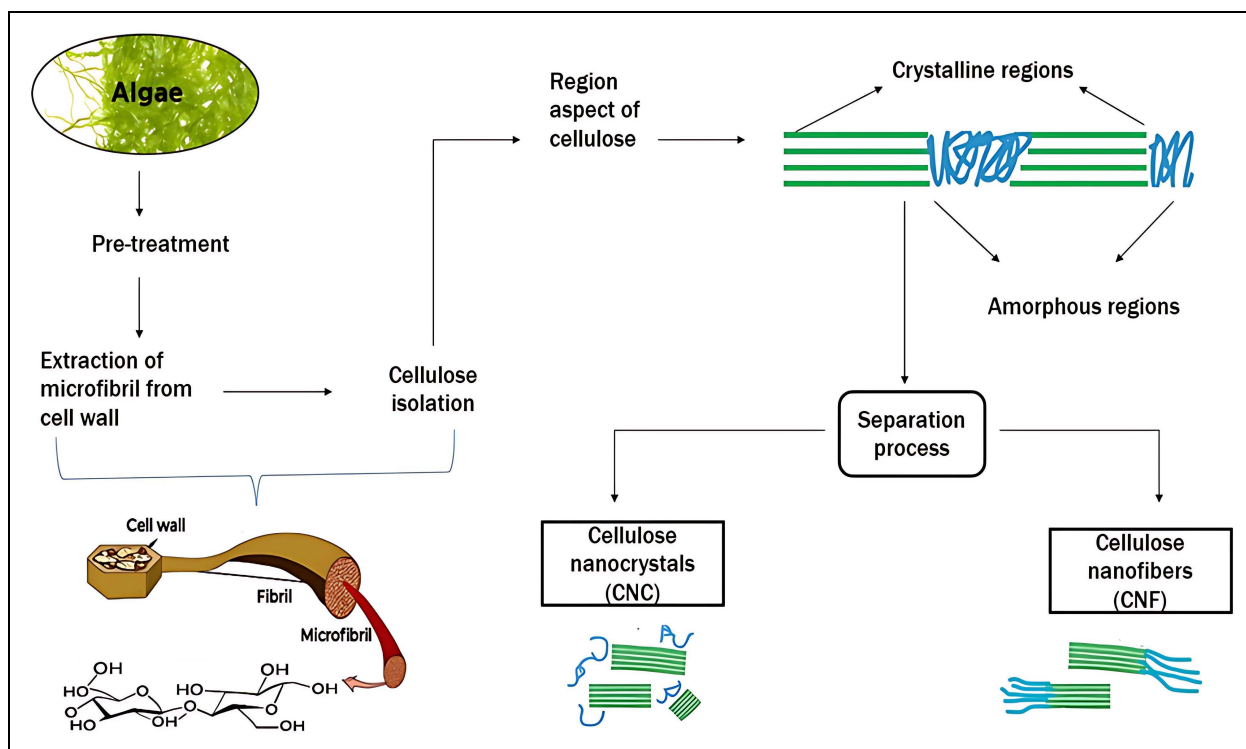


Fig. 1: Schematic outline of the Synthesis of Nanocellulose

3.1 Algal Nanocellulose

Given the ongoing economic challenges and the increasing demand for cellulose materials, it becomes imperative to seek out alternative sources of cellulose and develop extraction processes that are both more sustainable and efficient (Hafid *et al.* 2021). Multicellular marine organisms known as macroalgae or seaweed harbor large quantities of diverse polysaccharides like agar, alginates, fucoidan, carrageenan, agarose, and cellulose. With the rising

market demands, the production of nanocellulose derived from macroalgae has witnessed growth in recent years, paralleling the increased macroalgae production (Yahya *et al.* 2023). The characteristics of cellulose derived from seaweed exhibit variations based on the source species. Cellulose fibers obtained from different seaweed species are documented to possess distinct lengths and widths (Salem and Ismail. 2022). Table 2 presents the primary techniques used for extracting algal nanocellulose.

Table 2. Extraction methods for the production of algal nanocellulose

Algae	Type of Nanocellulose	Extraction Method	Conclusion	Reference
<i>Nannochloropsis oceanica</i>	CNF	TEMPO oxidation	The resulting CNFs had diameters measuring only a few nanometers. The tensile strength of these CNFs can serve as an effective reinforcing filler.	Lee <i>et al.</i> (2018)
<i>Gelidium elegans</i>	CNF	Alkalization, bleaching treatment and Acid hydrolysis	The nanocellulose was isolated with a higher crystallinity (73%), an aspect ratio of 25, and exceptional thermal stability, making it an ideal material for nanocomposite construction.	Chen <i>et al.</i> (2016)
<i>Cladophora glomerata</i>	CNF	Micro-fluidization and Enzymatic treatment	Algal CNFs, generated using identical techniques, exhibited superior crystallinity, smaller diameters, and greater thermal stability compared to CNFs from bleached eucalyptus pulp (BEP), suggesting the potential novelty and promise of algal CNFs as nano-materials.	Xiang <i>et al.</i> (2016)

<i>Laminaria japonica</i>	CNC	Acid hydrolysis	Achieving an optimal CNC yield of 52.3% was possible. The aqueous dispersions of kelp CNC exhibited characteristic optical and gel effects.	Liu <i>et al.</i> (2017)
<i>Gelidiella acerosa</i>	CNC	Microwave-assisted alkali treatment, Bleaching, and Acid hydrolysis	It was possible to separate rod-shaped CNC with a 32 nm average diameter that can be applied to polymer composite applications.	Singh <i>et al.</i> (2017)
<i>Cladophora glomerata</i>	CNC	Acid hydrolysis	SEM and TEM images revealed a mesh-like nanocrystal network with an average diameter of 30.6 (± 0.85) nm. The XRD analysis revealed that <i>Cladophora</i> -derived nanocellulose exhibited a high crystallinity index of 94.0%.	Suciyati <i>et al.</i> (2022)
Sargassum	CNF	Acid hydrolysis and Basic hydrolysis	Nanofibers obtained <i>via</i> basic hydrolysis exhibited slightly larger dimensions while remaining within the nanometric scale. The crystallinity index difference between the two hydrolysis methods was minimal, at 1.04%. These findings suggest that basic hydrolysis is a viable method for nanofiber production with promising potential for cost reduction.	Rodríguez <i>et al.</i> (2024)
<i>Cladophora glomerata</i>	CNC	Chemical treatment and acid hydrolysis	Cellulose nanocrystals (CNCs) were derived from algal cellulose <i>via</i> sulfuric acid (H_2SO_4) hydrolysis, exploring diverse reaction parameters such as temperature, acid concentration, and reaction duration. The study revealed that the yield was significantly influenced by acid concentration, while variations in temperature and reaction time had negligible effects.	Mihhels <i>et al.</i> (2023)
<i>Cladophora sp.</i>	CNC	Acid hydrolysis	Nanocrystalline cellulose (NCC) was synthesized from <i>Cladophora</i> algae cellulose <i>via</i> sulfuric acid hydrolysis under elevated temperatures. Hydrolysis conditions included 2 M and 3 M sulfuric acid for 15 hours, as well as 5 M sulfuric acid for 5, 10, and 15 hours, effectively categorizing the resultant material as NCC.	Steven <i>et al.</i> (2021)
<i>Sargassum</i> spp.	Cellulose nanoplatelets	Cast evaporation	A one-pot process utilizing <i>Sargassum</i> spp. for the isolation of highly amorphous cellulose nanoplatelets demonstrates significant potential due to its procedural simplicity, compatibility with diverse raw materials, and versatile applications, including the use as a high-transmittance material in food additives and packaging.	Chávez <i>et al.</i> (2022)

4. APPLICATIONS OF NANOCELLULOSE

In the development of biocomposites, and particularly for applications involving sophisticated functional materials, nanocellulose might be viewed as the renewable reinforcing agent of the next generation (Panchal *et al.* 2018). The environmental impact of many sectors can be reduced by substituting natural materials for synthetic or petrochemical ones. The industrial production of cellulose nanoparticles is rising quickly, with some businesses already manufacturing tonnes per

day, driving the search for suitable products in a variety of industries (Dufresne, 2019).

4.1 Applications of Algal Nanocellulose

Emerging as a novel resource, algal nanocellulose boasts elevated cellulose content and enhanced thermal stability, offering substantial potential across various applications. These encompass its utilization as a reinforcing agent in nanocomposite manufacturing and as a nanofiller for polymer matrices

(Ilyas and Atikah, 2021). The bioplastics made from cellulose extracted from algal biomass could significantly reduce environmental impact and strain on food resources, particularly in contrast to older-generation feedstocks, especially those related to lignocellulosic materials (Zanchetta *et al.* 2021). Through innovative green chemistry techniques,

nanocelluloses sourced from macro- and micro-algae can be skillfully manipulated and processed to create valuable, sustainable nanomaterials. These materials find utility in diverse applications such as wind turbines, solar cells, and wound dressing, among various others (Patel *et al.* 2022). Table 3 presents the applications of nanocellulose derived from algae.

Table 3. Applications of algal nanocellulose

Algae	Application	Conclusion	References
<i>Gelidium sesquipedale</i>	Aerogels	The seaweed <i>Gelidium sesquipedale</i> can be utilized for the creation of bioactive aerogels with a focus on food packaging applications.	Oliveira <i>et al.</i> (2019)
Unpurified algae waste	Nano-reinforcing fillers	For the production of nanocomposites, the produced CNCs were employed as fillers for nano-reinforcing. The tensile characteristics of the PVA-CNC nanocomposites were improved.	Achaby <i>et al.</i> (2018)
Brown algae waste	Milk thickeners	The casein micelles in the milk were absorbed by the brown algae cellulose through hydrogen bonds to produce a flimsy gel-like structure, resulting in a significant thickening effect when the Brown Algae Cellulose Nano Fibers (BACNF) were added.	Gao <i>et al.</i> (2018)
<i>Cladophora sp.</i>	Treating chronic wounds	The inflammatory reaction brought on by lipopolysaccharides (LPS) can be suppressed by the chemically altered <i>Cladophora</i> Nanocellulose (CC) films.	Hua <i>et al.</i> (2015)
<i>Ulva Lactuca</i>	Antimicrobial agent	<i>Ulva</i> /Ag/cellulose nanocomposites derived from algae were evaluated for their antibacterial properties against various bacterial species associated with dental caries. They exhibit promise as cost-effective and safe antibacterial products, offering potential applications against decay-causing bacteria.	Hamouda <i>et al.</i> (2023)
<i>Ulva Lactuca</i>	Adsorbent	CNC/graphene oxide nanocomposite film has proven to be a practical, cost-effective, and environmentally friendly adsorbent suitable for eliminating Fe (II) and Fe (III) from polluted water.	Badaani <i>et al.</i> (2023)
<i>Ulva Lactuca</i>	Antimicrobial agent	The CNC derived from <i>Ulva Lactuca</i> biomass demonstrated significant antimicrobial potential, effectively overcoming considerable challenges posed by various bacterial species.	Sheekh <i>et al.</i> (2023)
<i>Chara corallina</i>	Adsorbent	Nanocellulose-based membranes from macroalgae were designed to adsorb heavy metal ions from water. These membranes efficiently remove multiple contaminants, offering a sustainable solution for global drinking water purification.	Yousif <i>et al.</i> (2024)

5. CONCLUSION

Algae-derived nanocellulose represents a sustainable and high-quality alternative to conventional lignocellulosic sources, offering distinct advantages such as high purity, ease of processing, and reduced environmental impact. Its exceptional structural and mechanical properties, coupled with its renewable and biodegradable nature, position it as a valuable resource for the development of advanced materials. Extraction

methodologies optimized for algal biomass not only enhance yield and quality but also open pathways for tailoring surface functionality, thereby expanding its applicability in sectors ranging from biomedicine and packaging to electronics and environmental remediation. Despite these promising attributes, large-scale utilization remains limited, highlighting the need for further research in process optimization, cost reduction, and integration into existing industrial frameworks. Continued advancements in algal nanocellulose production and

application are expected to accelerate its adoption, reinforcing its role as a key contributor to sustainable material innovation.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).



REFERENCES

- Abitbol, T., Rivkin, A., Cao, Y., Nevo, Y., Abraham, E., Shalom, -B. T., Lapidot, S. and Shoseyov, O., Nanocellulose, a tiny fiber with huge applications, *Curr. Opin. Biotechnol.*, 39, 76–88 (2016). <https://doi.org/10.1016/j.copbio.2016.01.002>
- Achaby, E. M., Kassab, Z., Aboulkas, A., Gaillard, C. and Barakat, A., Reuse of red algae waste for the production of cellulose nanocrystals and its application in polymer nanocomposites, *Int. J. Biol. Macromol.*, 106, 681–691 (2018). <https://doi.org/10.1016/j.ijbiomac.2017.08.067>
- Ahankari, S. S., Subhedar, A. R., Bhadauria, S. S. and Dufresne, A., Nanocellulose in food packaging: A review, *Carbohydr. Polym.*, 255, 117479 (2021). <https://doi.org/10.1016/j.carbpol.2020.117479>
- Arad, S. M. and Ontman, -L. O., Red microalgal cell-wall polysaccharides: biotechnological aspects, *Curr. Opin. Biotechnol.*, 21(3), 358–364 (2010). <https://doi.org/10.1016/j.copbio.2010.02.008>
- Badaani, A. A. A., Hifney, A. F., Adam, M. S. and Gomaa, M., Low-cost biosorption of Fe(II) and Fe(III) from single and binary solutions using *Ulva Lactuca*-derived cellulose nanocrystals–graphene oxide composite film, *Sci. Rep.*, 13(1), 6422 (2023). <https://doi.org/10.1038/s41598-023-33386-7>
- Baghel, R. S., Reddy, C. R. K. and Singh, R. P., Seaweed-based cellulose: Applications and future perspectives, *Carbohydr. Polym.*, 267, 118241 (2021). <https://doi.org/10.1016/j.carbpol.2021.118241>
- Baghel, R. S., Reddy, C. R. K., Jha, B., Characterization of agarophytic seaweeds from the biorefinery context. *Bioresour. Technol.*, 159, 280-285. (2014). <https://doi.org/10.1016/j.biortech.2014.02.083>
- Beaumont, M., Tran, R., Vera, G., Niedrist, D., Rousset, A., Pierre, R., Forget, A., Hydrogel-forming algae polysaccharides: From seaweed to biomedical applications, *Biomacromolecules*, 22(3), 1027-1052 (2021). <https://doi.org/10.1021/acs.biomac.0c01406>
- Bras, L. D., Strømme, M., Mihranyan, A. Characterization of dielectric properties of nanocellulose from wood and algae for electrical insulator applications. *J. Phys. Chem. B.*, 119(18), 5911-5917 (2015). <https://doi.org/10.1021/acs.jpcc.5b00715>
- Bogolitsyn, K., Parshina, A., Aleshina, L., Prusskii, A., Tokko, O., Polomarchuk, D., Bogdanovich, N. and Savrasova, Y., Nanocrystalline cellulose from Arctic brown algae *Laminaria digitata* and *Saccharina latissima*, *Bioact. Carbohydr. Diet. Fiber*, 31, 100416 (2024). <https://doi.org/10.1016/j.bcdf.2024.100416>
- Chanda, M. J., Merghoub, N. and Arroussi, E. H., Microalgae polysaccharides: the new sustainable bioactive products for the development of plant biostimulants?, *World J. Microbiol. Biotechnol.*, 35, 1–10 (2019). <https://doi.org/10.1007/s11274-019-2745-3>
- Chandana, A., Mallick, S. P., Dikshit, P. K., Singh, B. N. and Sahi, A. K., Recent developments in bacterial nanocellulose production and its biomedical applications, *J. Polym. Environ.*, 30(10), 4040–4067 (2022). <https://doi.org/10.1007/s10924-022-02507-0>
- Charreau, H., Cavallo, E. and Foresti, M. L., Patents involving nanocellulose: Analysis of their evolution since 2010, *Carbohydr. Polym.*, 237(x), 116039 (2020). <https://doi.org/10.1016/j.carbpol.2020.116039>
- Chávez, G. L., Terán, -T. A. and Camacho, -P. O., One-pot isolation of nanocellulose using pelagic *Sargassum* spp. from the Caribbean coastline, *J. Appl. Phycol.*, 34(1), 637-645 (2022). <https://doi.org/10.1007/s10811-021-02643-5>
- Chen, Y. W., Lee, H. V., Juan, J. C. and Phang, S. M., Production of new cellulose nanomaterial from red algae marine biomass *Gelidium elegans*, *Carbohydr. Polym.*, 151, 1210–1219 (2016). <https://doi.org/10.1016/j.carbpol.2016.06.083>
- Čolić, M., Tomić, S. and Bekić, M., Immunological aspects of nanocellulose, *Immunol. Lett.*, 222, 80–89 (2020). <https://doi.org/10.1016/j.imlet.2020.04.004>
- Colusse, G. A., Carneiro, J., Duarte, M. E. R., Carvalho, J. C. D. and Nosedá, M. D., Advances in microalgal cell wall polysaccharides: a review focused on structure, production, and biological application, *Crit. Rev. Biotechnol.*, 42(4), 562–577 (2022). <https://doi.org/10.1080/07388551.2021.1941750>
- Domozych, D. S., Ciancia, M., Fangel, J. U., Mikkelsen, M. D., Ulvskov, P. and Willats, W. G. T., The cell walls of green algae: a journey through evolution and diversity, *Front. Plant Sci.*, 3, 1-7 (2012). <https://doi.org/10.3389/fpls.2012.00082>

- Du, X., Zhang, Z., Liu, W. and Deng, Y., Nanocellulose-based conductive materials and their emerging applications in energy devices – A review, *Nano Energy*, 35, 299–320 (2017). <https://doi.org/10.1016/j.nanoen.2017.04.001>
- Dufresne, A., Nanocellulose processing properties and potential applications, *Curr. For. Rep.*, 5(2), 76–89 (2019). <https://doi.org/10.1007/s40725-019-00088-1>
- Gao, H., Duan, B., Lu, A., Deng, H., Du, Y., Shi, X. and Zhang, L., Fabrication of cellulose nanofibers from waste brown algae and their potential application as milk thickeners, *Food Hydrocoll.*, 79, 473–481 (2018). <https://doi.org/10.1016/j.foodhyd.2018.01.023>
- Ghilan, A., Nicu, R., Ciolacu, D. E. and Ciolacu, F., Insight into the latest medical applications of nanocellulose, *Materials*, 16(12), 4447 (2023). <https://doi.org/10.3390/ma16124447>
- Gómez, C. H., Serpa, A., Velásquez, -C. J., Gañán, P., Castro, C., Vélez, L. and Zuluaga, R., Vegetable nanocellulose in food science: A review, *Food Hydrocoll.*, 57, 178–186 (2016). <https://doi.org/10.1016/j.foodhyd.2016.01.023>
- Hafid, H. S., Omar, F. N., Zhu, J. and Wakisaka, M., Enhanced crystallinity and thermal properties of cellulose from rice husk using acid hydrolysis treatment, *Carbohydr. Polym.*, 260(x), 117789 (2021). <https://doi.org/10.1016/j.carbpol.2021.117789>
- Hakim, A. A. and Mourad, R., Nanocellulose and its polymer composites: preparation, characterization, and applications, *Russ. Chem. Rev.*, 92(4), 1-30 (2023). <https://doi.org/10.57634/RCR5076>
- Hamouda, R. A., Qarabai, F. A. K., Shahabuddin, F. S., Shaikh, A. T. M. and Makharita, R. R., Antibacterial activity of Ulva/nanocellulose and Ulva/Ag/cellulose nanocomposites and both blended with fluoride against bacteria causing dental decay, *Polym.*, 15(4), 1047 (2023). <https://doi.org/10.3390/polym15041047>
- Hoeng, F., Denneulin, A. and Bras, J., Use of nanocellulose in printed electronics: a review, *Nanoscale*, 8(27), 13131–13154 (2016). <https://doi.org/10.1039/C6NR03054H>
- Hua, K., Carlsson, D. O., Ålander, E., Lindström, T., Strømme, M., Mihranyan, A., Ferraz, N., Translational study between structure and biological response of nanocellulose from wood and green algae, *RSC Adv.*, 4(6), 2892-2903 (2014). <https://doi.org/10.1039/C3RA45553J>
- Hua, K., Strømme, M., Mihranyan, A. and Ferraz, N., Nanocellulose from green algae modulates the in vitro inflammatory response of monocytes/macrophages, *Cellul.*, 22(6), 3673–3688 (2015). <https://doi.org/10.1007/s10570-015-0772-2>
- Huang, J., Ma, X., Yang, G. and Alain, D., Introduction to nanocellulose, *Nanocellulose: From Fundamentals to Advanced Materials*, Wiley, 1–20 (2019). <https://doi.org/10.1002/9783527807437.ch1>
- Huber, T., Müssig, J., Curnow, O., Pang, S., Bickerton, S. and Staiger, M. P., A critical review of all-cellulose composites, *J. Mater. Sci.*, 47(3), 1171–1186 (2012). <https://doi.org/10.1007/s10853-011-5774-3>
- Ilyas, R. A. and Atikah, M. S. N., Production of nanocellulose from sustainable algae marine biomass, *Seminar on Advanced Bio-and Mineral based Natural Fibre Composites* 1-9 (2021).
- Jacob, S., Reshmy, R., Antony, S., Madhavan, A., Sindhu, R., Awasthi, M. K., Kuddus, M., Pillai, S., Varjani, S., Pandey, A. and Binod, P., Nanocellulose in tissue engineering and bioremediation: mechanism of action, *Bioeng.*, 13(5), 12823–12833 (2022). <https://doi.org/10.1080/21655979.2022.2074739>
- Jeong, T. S., Choi, C. H., Lee, J. Y. and Oh, K. K., Behaviors of glucose decomposition during acid-catalyzed hydrothermal hydrolysis of pretreated Gelidium amansii, *Bioresour. Technol.*, 116, 435–440 (2012). <https://doi.org/10.1016/j.biortech.2012.03.104>
- John, M. J. and Thomas, S., Biofibers and biocomposites, *Carbohydr. Polym.*, 71(3), 343–364 (2008). <https://doi.org/10.1016/j.carbpol.2007.05.040>
- Jorfi, M. and Foster, E. J., Recent advances in nanocellulose for biomedical applications, *J. Appl. Polym. Sci.*, 132(14), 41719 (2015). <https://doi.org/10.1002/app.41719>
- Kaur, P., Sharma, N., Munagala, M., Rajkhowa, R., Aallardyce, B., Shastri, Y. and Agrawal, R., Nanocellulose: resources, physio-chemical properties, current uses and future applications, *Front. Nanotechnol.*, 3, 747329 (2021). <https://doi.org/10.3389/fnano.2021.747329>
- Kedzior, S. A., Gabriel, V. A., Dubé, M. A. and Cranston, E. D., Nanocellulose in emulsions and heterogeneous water-based polymer systems: A review, *Adv. Mater.*, 33(28), 2002404 (2021). <https://doi.org/10.1002/adma.202002404>
- Khalid, M. Y., Rashid, A. A., Arif, Z. U., Ahmed, W. and Arshad, H., Recent advances in nanocellulose-based different biomaterials: types, properties, and emerging applications, *J. Mater. Res. Technol.*, 14, 2601–2623 (2021). <https://doi.org/10.1016/j.jmrt.2021.07.128>
- Khalil, H. P. S. A., Davoudpour, Y., Islam, M. N., Mustapha, A., Sudesh, K., Dungani, R. and Jawaid, M., Production and modification of nanofibrillated cellulose using various mechanical processes: a review, *Carbohydr. Polym.*, 99, 649–665 (2014). <https://doi.org/10.1016/j.carbpol.2013.08.069>
- Klemm, D., Cranston, E. D., Fischer, D., Gama, M., Kedzior, S. A., Kralisch, D., Kramer, F., Kondo, T., Lindstrom, T., Nietzsche, S., Welcke, -P. K. and Rauchfuß, F., Nanocellulose as a natural source for groundbreaking applications in materials science: Today's state, *Mater. Today*, 21(7), 720–748 (2018). <https://doi.org/10.1016/j.mattod.2018.02.001>

- Kraan, S., Pigments and minor compounds in algae, *Funct. Ingredients from Algae for Foods and Nutraceuticals*, 205–251 (2013). <https://doi.org/10.1533/9780857098689.1.205>
- Le, C. T., Unamunzaga, C., Mantecon, L. and Helbert, W., New structural insights into the cell-wall polysaccharide of the diatom *Phaeodactylum tricornutum*, *Algal Res.*, 26, 172–179 (2017). <https://doi.org/10.1016/j.algal.2017.07.021>
- Lee, H. R., Kim, K., Mun, S. C., Chang, Y. K. and Choi, S. Q., A new method to produce cellulose nanofibrils from microalgae and the measurement of their mechanical strength, *Carbohydr. Polym.*, 180, 276–285 (2018). <https://doi.org/10.1016/j.carbpol.2017.09.104>
- Liu, Y., Liu, H. and Shen, Z., Nanocellulose-based filtration membrane in industrial wastewater treatment: A review, *Mater.*, 14(18), 5398 (2021). <https://doi.org/10.3390/ma14185398>
- Liu, Z., Li, X., Xie, W. and Deng, H., Extraction, isolation and characterization of nanocrystalline cellulose from industrial kelp (*Laminaria japonica*) waste, *Carbohydr. Polym.*, 173, 353–359 (2017). <https://doi.org/10.1016/j.carbpol.2017.05.079>
- Mihhels, K., Yousefi, N., Blomster, J., Solala, I., Solhi, L. and Kontturi, E., Assessment of the alga *Cladophora glomerata* as a source for cellulose nanocrystals, *Biomacromol.*, 24(11), 4672–4679 (2023). <https://doi.org/10.1021/acs.biomac.3c00380>
- Mihryan, A., Cellulose from cladophorales green algae: From environmental problem to high-tech composite materials, *J. Appl. Polym. Sci.*, 119(4), 2449–2460 (2011). <https://doi.org/10.1002/app.32959>
- Mishra, R. K., Sabu, A. and Tiwari, S. K., Materials chemistry and the futurist eco-friendly applications of nanocellulose: Status and prospect, *J. Saudi Chem. Soc.*, 22(8), 949–978 (2018). <https://doi.org/10.1016/j.jscs.2018.02.005>
- Mondal, S., Review on nanocellulose polymer nanocomposites, *Polym.-Plast. Technol. Eng.*, 57(13), 1377–1391 (2018). <https://doi.org/10.1080/03602559.2017.1381253>
- Nasir, M., Hashim, R., Sulaiman, O. and Asim, M., Nanocellulose: Preparation methods and applications, *Cellul.-Reinf. Nanofiber Compos.*, 261–276, (2017). <https://doi.org/10.1016/B978-0-08-100957-4.00011-5>
- Nishiyama, Y., Structure and properties of the cellulose microfibril, *J. Wood Sci.*, 55(4), 241–249 (2009). <https://doi.org/10.1007/s10086-009-1029-1>
- Niyazbekova, Z. T., Nagmetova, G. Z. and Kurmanbayev, A. A., An overview of bacterial cellulose applications, *Eurasian J. Appl. Biotechnol.*, 2, 1–17 (2018). <https://doi.org/10.11134/btp.2.2018.3>
- Norizan, M. N., Shazleen, S. S., Alias, A. H., Sabaruddin, F. A., Asyraf, M. R. M., Zainudin, E. S., Abdullah, N., Samsudin, M. S., Kamarudin, S. H. and Norrahim, M. N. F., Nanocellulose-based nanocomposites for sustainable applications: A review, *Nanomater.*, 12(19), 3483 (2022). <https://doi.org/10.3390/nano12193483>
- O’Sullivan, A. C., Cellulose: the structure slowly unravels, *Cellul.*, 4(3), 173–207 (1997). <https://doi.org/10.1023/A:1018431705579>
- Oliveira, D. J. P., Bruni, G. P., Fabra, M. J., Zavareze, R. D. E., López, -R. A. and Martínez, -S. M., Development of food packaging bioactive aerogels through the valorization of *Gelidium sesquipedale* seaweed, *Food Hydrocoll.*, 89, 337–350 (2019). <https://doi.org/10.1016/j.foodhyd.2018.10.047>
- Ong, X. R., Chen, A. X., Li, N., Yang, Y. Y. and Luo, H. K., Nanocellulose: Recent advances toward biomedical applications, *Small Sci.*, 3(2), 2200076 (2023). <https://doi.org/10.1002/smssc.202200076>
- Panchal, P., Ogunsona, E. and Mekonnen, T., Trends in advanced functional material applications of nanocellulose, *Processes*, 7(1), 10 (2018). <https://doi.org/10.3390/pr7010010>
- Park, S., Baker, J. O., Himmel, M. E., Parilla, P. A. and Johnson, D. K., Cellulose crystallinity index: measurement techniques and their impact on interpreting cellulase performance, *Biotechnol. Biofuels*, 3(1), 10 (2010). <https://doi.org/10.1186/1754-6834-3-10>
- Patel, A. K., Vadrle, A. P., Singhania, R. R., Michaud, P., Pandey, A., Chen, S. J., Chen, W. C. and Dong, C. D., Algal polysaccharides: current status and future prospects, *Phytochem. Rev.*, 22(4), 1167–1196 (2022). <https://doi.org/10.1007/s11101-021-09799-5>
- Raju, V., Revathiswaran, R., Subramanian, K. S., Parthiban, K. T., Chandrakumar, K., Anoop, E. V. and Chirayil, C. J., Isolation and characterization of nanocellulose from selected hardwoods, viz., *Eucalyptus tereticornis* Sm. and *Casuarina equisetifolia* L., by steam explosion method, *Sci. Rep.*, 13(1), 1199 (2023). <https://doi.org/10.1038/s41598-022-26600-5>
- Ram, F., Yadav, P. and Shanmuganathan, K., Nanocellulose/melanin-based composites for energy, environment, and biological applications, *J. Mater. Sci.*, 57(30), 14188–14216 (2022). <https://doi.org/10.1007/s10853-022-07512-1>
- Ramamurthy, M., Vasanthkumar, N. P., Perumal, G. and Senthilkumar, N., Formulation and Features of Chitosan and Natural Fiber Blended Bio-composite towards Environmental Sustainability, *J. Environ. Nanotechnol.*, 14(1), 104–112 (2025). <https://doi.org/10.13074/jent.2025.03.243932>
- Reshmy, R., Philip, E., Paul, S. A., Madhavan, A., Sindhu, R., Binod, P., Ashok, P. and Sirohi, R., Nanocellulose-based products for sustainable applications – recent trends and possibilities, *Rev. Environ. Sci. Bio/Technol.*, 19(4), 779–806 (2020). <https://doi.org/10.1007/s11157-020-09551-z>
- Reshmy, R., Thomas, D., Philip, E., Paul, S. A., Madhavan, A., Sindhu, R., Binod, P., Puhazhendhi, A., Sirohi, R., Tarafdar, A. and Pandey, A., Potential of nanocellulose for wastewater treatment, *Chemosphere*, 281, 130738 (2021). <https://doi.org/10.1016/j.chemosphere.2021.130738>

- Ribeiro, R. S. A., Pohlmann, B. C., Calado, V., Bojorge, N. and Pereira, J. N., Production of nanocellulose by enzymatic hydrolysis: Trends and challenges, *Eng. Life Sci.*, 19(4), 279–291 (2019). <https://doi.org/10.1002/elsc.201800158>
- Rodríguez, -Q. J., Rodríguez, M. K., Samaniego, -B. C. A., García, -J. E. G. and Alvarado, -R. C., Development of nanocellulose hydrogels from Sargassum seaweed as controlled nutrient release systems and their application in germination, *Ecol. Eng. Environ. Technol. (EET)*, 25(11), 308–320 (2024). <http://doi.org/10.12912/27197050/192775>
- Ross, I. L., Shah, S., Hankamer, B. and Amiralian, N., Microalgal nanocellulose – opportunities for a circular bioeconomy, *Trends Plant Sci.*, 26(9), 924–939 (2021). <https://doi.org/10.1016/j.tplants.2021.05.004>
- Salas, C., Nypelö, T., Rodriguez, -A. C., Carrillo, C. and Rojas, O. J., Nanocellulose properties and applications in colloids and interfaces, *Curr. Opin. Colloid Interface Sci.*, 19(5), 383–396 (2014). <https://doi.org/10.1016/j.cocis.2014.10.003>
- Salem, D. M., Ismail, M. M. Characterization of cellulose and cellulose nanofibers isolated from various seaweed species. *Egypt. J. Aquat. Res.*, 48(4), 307–313. (2022). <https://doi.org/10.1016/j.ejar.2021.11.001>
- Saud, A., Saleem, H. and Zaidi, S. J., Progress and prospects of nanocellulose-based membranes for desalination and water treatment, *Membranes*, 12(5), 462 (2022). <https://doi.org/10.3390/membranes12050462>
- Sheekh, -E. M. M., Yousuf, W. E., Kenawy, E. R. and Mohamed, T. M., Biosynthesis of cellulose from *Ulva Lactuca*, manufacture of nanocellulose and its application as antimicrobial polymer, *Sci. Rep.*, 13(1), 10188 (2023). <https://doi.org/10.1038/s41598-023-37287-7>
- Siddhanta, A. K., Kumar, S., Mehta, G. K., Chhatbar, M. U., Oza, M. D., Sanandiya, N. D., Kondaveeti, S., Cellulose contents of some abundant Indian seaweed species, *Nat Commun.*, 8(4), 1934578X1300800423 (2013). <https://doi.org/10.1177/1934578X1300800423>
- Singh, S., Gaikwad, K. K., Park, S. I. and Lee, Y. S., Microwave-assisted step-reduced extraction of seaweed (*Gelidiella acerosa*) cellulose nanocrystals, *Int. J. Biol. Macromol.*, 99, 506–510 (2017). <https://doi.org/10.1016/j.ijbiomac.2017.03.004>
- Sterner, M., Edlund, U. Multicomponent fractionation of *Saccharina latissima* brown algae using chelating salt solutions. *J Appl Physiol*, 28(4), 2561–2574. (2016). <https://doi.org/10.1007/s10811-015-0785-0>
- Steven, S., Mardiyati, Y., Shoimah, S. M., Rizkiansyah, R. R., Suratman, R. and Santosa, S. P., Preparation and characterization of nanocrystalline cellulose from *Cladophora* sp. algae, *Int. J. Adv. Sci. Eng. Inf. Technol.*, 11(3), 1035–1041 (2021). <https://doi.org/10.18517/ijaseit.11.3.10278>
- Stiger-Pouvreau, V., Bourgougnon, N., Deslandes, E. Carbohydrates from seaweeds, *Seaweed in health and disease prevention*, Academic Press, 223–274 (2016). <https://doi.org/10.1016/B978-0-12-802772-1.00008-7>
- Suciayati, S. W., Manurung, P., Junaidi, J., Sembiring, S. and Situmeang, R., Synthesis and characterization of nanocellulose from *Cladophora* sp., *Ecol. Environ. Conserv.*, 28(2), 521–527 (2022). <http://doi.org/10.53550/EEC.2022.v28i02s.004>
- Tafete, G. A., Abera, M. K. and Thothadri, G., Review on nanocellulose-based materials for supercapacitors applications, *J. Energy Storage*, 48, 103938 (2022). <https://doi.org/10.1016/j.est.2021.103938>
- Thomas, P., Duolikun, T., Rumjit, N. P., Moosavi, S., Lai, C. W., Johan, M. R. B. and Fen, L. B., Comprehensive review on nanocellulose: Recent developments, challenges and future prospects, *J. Mech. Behav. Biomed. Mater.*, 110, 103884 (2020). <https://doi.org/10.1016/j.jmbbm.2020.103884>
- Trache, D., Hussin, M. H., Haafiz, M. K. M. and Thakur, V. K., Recent progress in cellulose nanocrystals: sources and production, *Nanoscale*, 9(5), 1763–1786 (2017). <https://doi.org/10.1039/C6NR09494E>
- Trache, D., Tarchoun, A. F., Derradji, M., Hamidon, T. S., Masruchin, N., Brosse, N. and Hussin, M. H., Nanocellulose: from fundamentals to advanced applications, *Front. Chem.*, 8, 392 (2020). <https://doi.org/10.3389/fchem.2020.00392>
- Van-Hai, L., Son, H. N. and Seo, Y. B. Physical and bio-composite properties of nanocrystalline cellulose from wood, cotton linters, cattail, and red algae, *Cellulose*, 2(3), 1789–1798 (2015). <https://doi.org/10.1007/s10570-015-0633-z>
- Wei, H., Rodriguez, K., Renneckar, S. and Vikesland, P. J., Environmental science and engineering applications of nanocellulose-based nanocomposites, *Environ. Sci. Nano*, 1(4), 302–316 (2014). <https://doi.org/10.1039/C4EN00059E>
- Xiang, Z., Gao, W., Chen, L., Lan, W., Zhu, J. Y. and Runge, T., A comparison of cellulose nanofibrils produced from *Cladophora* glomerata algae and bleached eucalyptus pulp, *Cellul.*, 23(1), 493–503 (2016). <https://doi.org/10.1007/s10570-015-0840-7>
- Xu, S. Y., Huang, X. and Cheong, K. L., Recent advances in marine algae polysaccharides: Isolation, structure, and activities, *Mar. Drugs*, 15(12), 388 (2017). <https://doi.org/10.3390/md15120388>
- Yahya, E. B., Elarbash, S. S., Bairwan, R. D., Mohamed, M. M. I., Khan, N. B., Harlina, P. W. and Abdul Khalil, A. H. P. S., The role of microorganisms in the isolation of nanocellulose from plant biomass, *Forests*, 14(7), 1457 (2023). <https://doi.org/10.3390/f14071457>
- Yousif, Y. M., Hassan, O. M. and Ibraheem, I. J., Removal of heavy metal ions from water using nanocellulose-based membranes derived from macroalgae *Chara corallina*, *J. Degrad. Min. Lands Manage.*, 11(3), 5793–5803(2024). <https://doi.org/10.15243/jdmlm.2024.113.5793>

- Zainuddin, Z., Zaini, H. H. M. and Mohammad-Noor, N., Preliminary study on nanocellulose production in local seaweeds, *Int. STEM J.*, 2(1), 36–42 (2021).
- Zaki, M., Abdul, K. H. P. S., Sabaruddin, F. A., Bairwan, R. D., Oyekanmi, A. A., Alfatah, T., Danish, M., Mistar, E. M. and Abdullah, C. K., Microbial treatment for nanocellulose extraction from marine algae and its applications as sustainable functional material, *Bioresour. Technol. Rep.*, 16, 100811 (2021). <https://doi.org/10.1016/J.BITEB.2021.100811>
- Zanchetta, E., Damergi, E., Patel, B., Borgmeyer, T., Pick, H., Pulgarin, A. and Ludwig, C., Algal cellulose, production and potential use in plastics: Challenges and opportunities, *Algal Res.*, 56, 102288 (2021). <https://doi.org/10.1016/j.algal.2021.102288>
- Zhang, Q., Zhang, L., Wu, W. and Xiao, H., Methods and applications of nanocellulose loaded with inorganic nanomaterials: A review, *Carbohydr. Polym.*, 229, 115454 (2020). <https://doi.org/10.1016/j.carbpol.2019.115454>
- Zhao, Y., Moser, C., Lindström, M. E., Henriksson, G. and Li, J., Cellulose nanofibers from softwood, hardwood, and tunicate: preparation–structure–film performance interrelation, *ACS Appl. Mater. Interfaces*, 9(15), 13508–13519 (2017). <https://doi.org/10.1021/acsami.7b01738>