ALGAL NANOCELLULOSE: A POTENTIAL RESOURCE FOR ADVANCED BIOMATERIALS

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Nanocellulose, a nanosized form of cellulose, has emerged as a transformative material with unique properties, such as biodegradability, mechanical strength, and large surface area, making it highly valuable for untapped applications such as biomedicine, bioplastics, environmental remediation, and energy storage. Although lignocellulosic biomass remains the primary source of cellulose, its high energy requirements contribute to deforestation and environmental degradation. Consequently, algae have emerged as sustainable alternatives owing to their high cellulose purity, rapid growth and minimal requirements of resources. Nano-sized cellulose, such as nanocrystalline cellulose (NCC), bacterial nanocellulose (BNC), and cellulose nanofibrils (CNFs), is gaining attention due to its unique properties, such as large surface-to-volume ratio, mechanical strength, tunable surface chemistry, biocompatibility *etc*. This review focuses on the production, characterisation and application of algal nanocellulose, covering extraction techniques (chemical, enzymatic, and green solvent-based methods) and recent advancements in genetic engineering for higher cellulose yield and commercial challenges. A life cycle assessment (LCA) comparison of algal and plant-derived nanocellulose is discussed. Key areas, such as the integration of biorefinery approaches and emerging biomedicine applications, are explored to tackle scalability as well as sustainability issues. Finally, regulatory guidelines (ISO, FDA, EFSA) and future research directions are explored to provide comprehensive solutions for scaling up algal nanocellulose into emerging applications.

Keywords: algae, nanocellulose, sustainability, valorisation

INTRODUCTION

Importance and applications of cellulose and nanocellulose

Cellulose, the most abundant polysaccharide on earth, with approximately 700 billion tons of cellulose being produced each year at an annual biomass production estimated to be between 10^{11} and 10^{12} tons.[1] However, more recent data are required to obtain a more precise estimate. Traditionally, cellulosic biomass is utilized as animal feed, in paper-making, mushroom cultivation, and for heating. However, in recent years, the focus has shifted towards advanced applications in material sciences, biomedical sciences (drug delivery, tissue engineering), food and other commercial applications. For instance, nanocellulose is used for the development of drug delivery systems for the controlled release of medication. Cellulose-based composites exhibit high strength, light weight, transparency, and biocompatibility, making them ideal for various commercial products.

Nanocellulose, a nano-sized form of cellulose, offers a greater potential due to its nanoscale, which results in a large surface area, high mechanical strength and other unique properties. These properties make it a valuable reinforcing agent in cellulose composites. To improve its interfacial capabilities, nanocellulose's intrinsic surface chemistry frequently needs to be altered, especially when it comes to applications in the biomedical domains, including drug delivery systems, tissue repair, and wound healing. Beyond healthcare, nanocellulose is being explored for environmental remediation.[2-4] Biomedical applications encompass wound dressings, tissue repair, medical implants, and drug delivery systems.[5] Existing commercial products cater to wound healing and periodontal tissue recovery. Due to such applications, along with its renewable nature and cost-effectiveness, the demand for nanocellulose is permanently increasing. The global market potential for nanocellulose is estimated at 35 million metric tons annually, and the demand is expected to keep increasing.[6] Figure 1 shows the growing nanocellulose market and predictions till 2030.

Traditionally, cellulose can be extracted from wood pulp, cotton, grasses, and agricultural residues, but new sources and methods are constantly being explored for high-quality and high-quantity cellulose.[7] It is estimated that lignocellulosic plants and straw species contain 23-53% and 35-45% cellulose, respectively.[8-9]

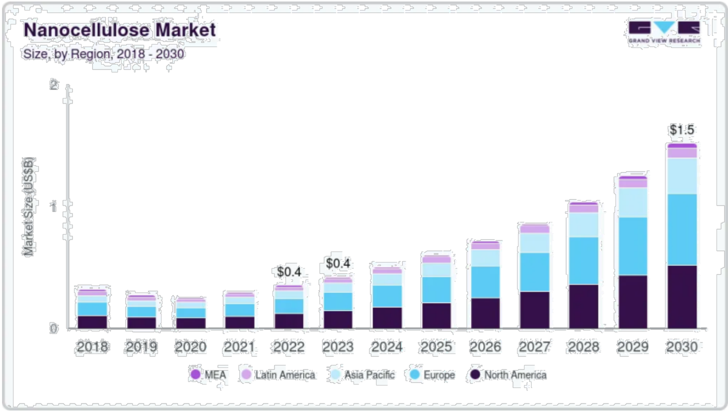

Figure 1: Global nanocellulose market (source: https://www.grandviewresearch.com/industry-analysis/nanocellulose-market)

Challenges and limitations of traditional sources

Traditional sources of cellulose, like wood pulp and cotton, often involve significant challenges, such as high energy consumption during the extraction process, exerting a high environmental impact.[10,11] Cellulose extraction from wood is an energy and resource-intensive process. Many pretreatment processes require harsh chemicals like NaOH and H_2SO_4, which can harm the environment and human health.[12,13] Effluents from the paper and pulp industries are known to pose the risks of water pollution. Moreover, wood-based cellulose is a significant cause of deforestation, accounting for 14% of global deforestation.[14]

The other major source of cellulose, cotton, requires large amounts of water for its growth, which also negatively affects the environment. Studies showed that 10,000 litres of water are consumed to produce 1 kilogram of cotton.[15,16] Energy consumption for cotton cultivation varies from region to region. For instance, 19,558 MJ/ha and 52,507.8 MJ/ha of energy are consumed during cotton cultivation in Turkey and Iran, respectively.[16]

On the other hand, algal cellulose has been reported to have better mechanical properties than wood cellulose.[17] In addition, algal cellulose has better crystallinity, lower moisture absorption, and better processability when compared with wood cellulose.[17] While traditional cellulose sources like wood and cotton are widely utilised, the exploration of more sustainable alternatives is necessary.

Algae as a promising alternative source

The algae, comprising both macroalgae (seaweeds) and microalgae, offer a suitable and sustainable alternative to traditional cellulose sources. Their rapid growth, physiological adaptability to various aquatic environments, and minimal resource requirements make algae a superior alternative. The cellulose extracted from algae possesses outstanding properties that make it increasingly utilized in biomedicine, bioplastics, and renewable composites applications.

Recent studies have highlighted the possibility of algal cellulose in high-value applications. Celluloses produced by red, green, and brown algae can be sulfonated or acetylated into carboxymethyl cellulose (CMC), which can be used for tissue engineering applications because of its biocompatibility and functional versatility. Nanocellulose derived from microalgae has shown promising characteristics in reinforcing polymers, providing good mechanical characteristics, thermal stability and compostability.[16] Consequently, these developments pave the way for novel applications.

Extracting algal cellulose was studied through milder methods, such as enzymatic hydrolysis and acid treatments. These processes resulted in cellulose with high crystallinity indices, which are suitable for use in bioethanol production and industrial bio-composites.[17] However, there have been challenges for scaling up the production and strain selection, both of them intended to increase yields. Integrated bioprocessing and advanced bioengineering are important to focus on to explore their impact and further realise algae's potential as a cellulose source.[18]

Cellulose obtained from algae has huge potential for the bioeconomy, enabling ways of achieving a sustainable industry and conservation of the environment. Research and innovation will continue in the direction of algal biotechnology, which is expected to further engrain the raw material as a renewable material for manufacturing in several sectors.

ALGAL SOURCES FOR CELLULOSE AND NANOCELLULOSE PRODUCTION

Overview of different algal species

Microalgae and macroalgae (seaweeds) have displayed unique advantages, including fast growth, cultivation on non-arable land, and the ability to grow in diverse conditions. The cellulose content in algae is between 0.7-45%, varying with species, growth conditions, and extraction methods.[19,20] While plant sources generally contain higher cellulose content, algal cellulose has very high crystallinity and requires relatively simple extraction methods, making it suitable for very specialized applications.[21]

Among macroalgae, *Laminaria digitata* and *Laminaria saccharina* have been subjected to treatment to extract NCC using eco-friendly approaches, the products obtained showcased high thermal stability and crystallinity.[22] Also, red algae, *Gelidium elegans*, possess properties of high crystallinity and thermal stability, which are critical for producing nanocomposites.[23] Freshwater green algae, such as *Chara corallina*, have shown some promise in the manufacture of CNC membranes for the purification of water.[24] Some invasive species, such as *Sargassum*, are now being tapped into to produce nutrient-loaded nanocellulose hydrogels for agricultural applications, for example, to help seed germination.[25] *Cladophora* provide long nanocellulose fibres with better structural properties, especially *Cladophora glomerata*, which has a very low moisture uptake as well as greater crystallinity, thus making it a feasible candidate for application in the areas of functional materials and biomedicine.[26,27] Extraction methods including enzymatic hydrolysis coupled with mechanical disintegration have worked towards giving improvements in extraction efficiency and material properties. Thus, algae-derived nanocelluloses has potential in securing a place in environmentally friendly technologies to confront sustainability issues, while having extensive applications in bioplastics, biomedicine and environmental remediation.[18]

Advantages and disadvantages of different algal species

Cellulose from algae can be considered as a potential alternative to plant cellulose to be explored. Microalgae, such as *Chlorella* and *Spirulina*, are high-storage, efficient biomass producers and good cellulose sources. These algal species are also sustainable alternatives since they use relatively less fresh water and arable land.[39] *Ulva lactuca* is a cellulose-rich macroalgae utilized for bioethanol production using enzymatic hydrolysis.[40] Furthermore, species such as *Nannochloropsis* co-produce lipids and polysaccharides, increasing their economic value.[41]

However, several challenges are associated with algal cellulose production. Harvesting, cellulose extraction, and scalability issues in macroalgae increase the overall processing costs. Besides, the problem of the scalable output is also due to the variation in cellulose content in different algal species and high energy requirements for biomass harvesting and cellulose extraction.[42] For example, advances like hydroxyl radical-aided thermal pretreatment improved cellulose recovery and enzymatic digestibility and decreased energy consumption. Co-production of pigments, bioethanol, and biochar enhances the economic feasibility of algal cellulose production and biorefineries.[43]

Future research sould be focused on genetic manipulations for high cellulose yield, energy-efficient harvesting, and the setting up of integrated biorefineries to solve the major challenges. Process optimization is a key factor in economic and sustainable cellulose production.

EXTRACTION OF CELLULOSE FROM ALGAE

Pretreatment methods

Pretreatment methods are known to disrupt algal cell walls, thereby improving cellulose and nanocellulose extraction. Pretreatment methods are mainly categorized into chemical, biological, and physical techniques, each having different mechanisms and applications.

Table 1
Cellulose content of microalgae and macroalgae and potential applications

Category	Algal genus/ species	Cellulose content (% dry weight)	Potential applications	Refs.
Microalgae	*Chlorella vulgaris*	10–47.5	Bioplastics, bioethanol, biomaterials	28,29
	Chlorella pyrenoidosa	15.4	Nutraceuticals, biofuels	18
	Scenedesmus quadricauda	15.4–31	Bioremediation, biofuels	18
	Staurastrum sp.	72	High-strength materials, nanocellulose	30
	Nannochloropsis gaditana	25–75	Bio-packaging, pharmaceuticals	31
	Chlorella sorokiniana	17.69	Biofuels, bioplastics	32
	Haematococcus pluvialis	16.55	Bio-packaging, pharmaceuticals	32
	Chlamydomonas hedleyi	18.67	Bioplastics, biomaterials	32
Macroalgae	*Ulva lactuca*	12.4–19	Bio-composites, biofuels	18
	Ulva prolifera	19.4	Bioplastics, sustainable packaging	32,33
	Ulva pertusa	6.7	Fertilizers, bioactive compounds	34
	Ulva spp.	40.7	High-strength biocomposites	18
	Cladophora glomerata	21.6–45	Nanocellulose for high-tech applications	35
	Cladophora rupestris	28.5	Industrial nanocellulose applications	18
	Valonia ventricosa	75	Bioplastics, eco-friendly materials	18
	Enteromorpha sp.	21	Bio-packaging, textiles	18
	Fucus vesiculosus	8–13.5	Pharmaceutical gels, bio-coatings	36
	Fucus serratus	13.5	Industrial applications, healthcare products	18
	Laminaria digitata	1.1–20	Nanocellulose, bio-packaging	36
	Laminaria saccharina	18	Sustainable textiles, bio-packaging	18
	Halidrys siliquosa	14	Eco-friendly materials	18
	Himanthalia lorea	8	Biodegradable materials	18
	Ptilota plumosa	24	Biomedical scaffolds, bio-packaging	18
	Rhodymenia palmata	7	Food additives, nutraceuticals	18
	Gelidium elegans	17.2-90.8	Bioplastics, nanocellulose, biofuels	23
	Sargassum sp.	20.35	Biofuels, bioplastics	37
	Porphyra umbilicalis	9.84	Food additives, bio-packaging	33
	Macrocystis pyrifera	5.90	Bioenergy, bio-composites	32
	Gelidium amansii	9-51.3	Food, cosmetics and biomedicine	33,38

Chemical pretreatment

Most chemical approaches, for example, alkaline and acid hydrolysis, focus on sodium hydroxide and sulfuric acid to break open algal cells and cell wall matrix, facilitating cellulose release.[44] However, these methods often end up in environmental issues because of harsh chemicals and toxic byproducts.[45]

Non-conventional methods, including ozonation, hydrogen peroxide oxidation, and ionic liquids, are gaining attention. Ozonation facilitates effective delignification with minimal chemical residues, and it can be a good, sustainable method for algal biomass processing. Similarly, pretreatment using hydrogen peroxide enhances cellulose accessibility by having minimal toxic residues and offering an environmentally sustainable method.

With recent advancements, deep eutectic solvents (DES) and ionic liquids (ILs) have been found as environmentally green alternatives for selective lignin and hemicellulose dissolution, without harming the cellulose structure. One of the types of deep eutectic solvents based on choline chloride-oxalic acid has been proven for the direct production of nanocellulose with no need for prior pulping processes. Similarly, ionic liquids (ILs) are salts that are liquid at or near room temperature, having tunable properties for selective biomass fractionation. Deep eutectic solvents (DES) and ionic liquids (ILs) show a promising alternative, but their cost is limiting large-scale applications. Further efficient recovery and recycling is another challenge. Further research is needed to optimize deep eutectic solvents (DES) and ionic liquids (ILs) composition for specific algal species and to develop cost-effective recovery methods.[46]

Biological pretreatment

Biological pretreatment involves enzymatic hydrolysis, in which enzymes break down cell wall components, thereby enhancing production efficiency. Enzyme-based pretreatments are considered cost-effective methods. Recent research in genetic engineering has shown potential in producing microbial strains with high-yielding enzymes.[47]

Recent advancements in genetic engineering aim to produce microbial strains with high yields of specific enzymes. For instance, cellulases, hemicellulases, and pectinases are used to selectively degrade cell wall polysaccharides, improving cellulose accessibility. More advancements involve the use of enzyme cocktails for different algal biomass to develop cost-effective enzyme production.[48]

In addition to enzymatic hydrolysis, microbial and fungal pretreatments offer promising alternatives. Microbial fermentation using genetically modified bacteria has shown potential in the selective degradation of the cell wall, thereby improving nanocellulose yield. Also, fungal species, such as *Trichoderma reesei*, have been explored for their cellulolytic enzyme for improved breakdown of complex biopolymers into accessible cellulose. While these approaches are environmentally friendly solutions, further research is needed to optimize microbial and fungal strain selection for algal cellulose processing.

Physical pretreatment

Physical techniques, such as steam explosion, ultrasonic-assisted extraction, and microwave-assisted treatments have gained popularity for their scalability and energy efficiency. Steam explosion involves high-pressure steam, followed by destroying biomass using rapid depressurization, as a result, cellulose becomes much more accessible to chemicals.[49,50] Ultrasonic cavitation breaks down cell walls, allowing cellulose to be extracted.[51] Physical methods are energy efficient, but may lead to the degradation of cellulose, if not controlled properly. Further research is needed to optimize process parameters, such as temperature, pressure and time, to maximize cellulose extraction, while minimizing degradation.

Beyond conventional physical methods, high-pressure homogenization and ball milling are also alternatives for processing biomass. The high-pressure homogenization provides uniform nanocellulose dispersion, but is an energy and cost-intensive process with a need for optimization of parameters for scalability.[52] Ball milling is also used for size reduction, making it accessible for enzymatic degradation. However, excessive ball milling may lead to cellulose degradation if not controlled properly. If this pretreatment method is combined with biological or chemical pretreatment, then the final cellulose recovery can be improved.

The synergistic effect of microwave-alkali pretreatments is also effective in the removal of lignin and maintaining the integrity of the cellulose.[45] Using a combination of chemical and physical pretreatments, such as acid-ultrasound, has improved overall effects, enhancing both yield and quality. Hydrogen peroxide as oxidative pretreatment offers an efficient and greener option by reducing environmental impact and maintaining cellulose recovery.[45,48,53] The optimization and integration of pretreatment methods in biorefinery models requires a holistic approach that would cover techno-economic and environmental aspects. Life cycle assessment (LCA) and techno-economic analysis (TEA) should be used to evaluate the sustainability and economic viability of pretreatment methods.[54,55]

Extraction techniques

Extracting cellulose and nanocellulose from algae is a key factor for creating sustainable, eco-friendly materials with diverse applications. Traditional extraction methods, such as chemical and mechanical, have unique contributions, efficiency, and product purity. It is found that sodium hydroxide (NaOH) treatment is effective in removing hemicelluloses and lignin-like impurities from algal cell walls and increasing the overall purity of cellulose.[56,57] The best method for isolating nanocellulose is acid hydrolysis using sulfuric acid. The acid concentration and temperature during the reaction have a huge impact on yield as well as structural properties.[58]

Deep eutectic solvents (DES) and ionic liquids (IL) have been proven to produce less toxic wastes, besides, they can be recycled again and again, which overall reduces their environmental impact.[59] Enzyme-based methods are also efficient, providing lower exposure to harmful chemicals, while yielding high-quality nanocellulose.[60] On the other hand, mechanical methods like high-pressure homogenization and ultrasonication carry out effective fragmentation of cellulosic fibres, thereby allowing large scale production. There are other methods, such as TEMPO-mediated oxidation, which improves surface charge and helps with working with hydrophilic materials.[61,62] The synergistic effect of chemical and mechanical treatment has shown its feasibility with high-quality nanocellulose production along with reduced cost. Another advancement with microwave-assisted extraction has also proved to be effective with low time and energy consumption.[63]

Marine microalgae are recognized as a sustainable biomass source due its renewability and high cellulosic content. Advancements in extraction efficiency have been made through process optimization studies. These studies focused on algal type, maturity, and environmental conditions. Future research could be directed towards bio-inspired extraction methods that mimic the natural degradation process, thereby promoting environmentally sustainable cellulose-based materials for advanced applications in remediation, biomedicine packaging and other areas.[64,65]

Purification and characterization of extracted cellulose

The extraction and characterization of cellulose from algae is a promising area of research, given the potential of this biopolymer. Species, such as *Cladophora*, demonstrate unique properties, including high crystallinity (over 95%), mesoporosity, and an extensive specific surface area, which differs from other cellulose-producing algal species.[66] The purification process typically consists of alkali treatment to remove non-cellulosic material, followed by bleaching to improve purity. Acid hydrolysis yields nanocellulose with better crystallinity and suitability for specific applications.

The oxidative hydrolysis and enzyme treatments contribute to the efficiency of nanocellulose production. The resulting nanocellulose is of uniform morphology with fibrillar or spherical forms, without subsequent surface modification.[67] Further research is needed to develop sustainable purification methods, such as enzymatic or membrane-based techniques. The impact of different purification methods on the properties of algal cellulose and nanocellulose needs to be studied.

Characterization techniques, such as FTIR, XRD, SEM, and TEM, have already been fine-tuned for analysis of the structural, morphological, and functional properties of algae cellulose and nanocellulose.[68-71] Conventional characterization methods require advanced microscopy techniques, such as atomic force microscopy (AFM) and transmission electron microscopy (TEM), which provide higher-resolution images of nanocellulose structures. Before deciding on the applicability of the obtained materials, such techniques help assess the efficiency of the extraction techniques used, as well as the suitability of algal cellulose for the proposed uses.

PRODUCTION OF NANOCELLULOSE FROM ALGAL CELLULOSE

Overview of nanocellulose types

Nanocellulose is categorized into three distinct groups: cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs), and bacterial nanocellulose (BNC). CNCs are rod-like structures with high crystallinity, generally obtained from acid hydrolysis. CNCs are rigid and optically transparent, making them ideal reinforcement agents in advanced materials.[72] CNCs produced by mechanical treatment, such as high shear blending, show fibrillar morphology, along with a combination of amorphous and crystalline regions. They have good mechanical strength and barrier properties, which underlines their importance in biocomposites and coatings.[73] The acid hydrolysis process used to produce CNCs can be energy-intensive and can generate harmful by-products.

CNFs are generally produced by mechanical treatment, such as high shear homogenization. It shows fibrillar morphology, with a combination of amorphous and crystalline regions. They have good mechanical strength. Mechanical treatment is an energy-intensive process and advancements are required to optimize it, usually, this method is supplemented by enzymatic or chemical treatments.

Bacterial nanocellulose is synthesized by microbial fermentation, and is characterized by high purity, entangled three-dimensional network and excellent tensile strength. These attributes make it very useful in biomedical applications, such as wound dressings and tissue scaffolds. BNC is comparatively more expensive than CNCs and CNFs, as it requires sterile fermentation conditions and specialized equipment. Research advancements are needed for the optimization of fermentation conditions or for using low-cost substrates.[74] Nanocellulose has intrinsic properties of biodegradability, biocompatibility and tunable surface chemistry, which can be improved by techniques, such as TEMPO-mediated oxidation. This makes nanocellulose a safe alternative drug delivery, filtration, and sustainable packaging. Some studies suggested that nanocellulose will provide sustainable solutions to industries as well as environmental problems.[75,76,77]

Issues in scaling up production processes, without compromising quality, and considering environmental and toxicological effects of using chemically modified cellulose are key areas to focus on. Research on processing technology and the applicability in nanomedicine and environmental remediation will continue to be relevant.

Top-down approaches

Nanocellulose produced from algal cellulose has gained a lot of attention in green applications. Top-down approaches involve mechanical, chemical, and enzymatic methods for effective extraction of cellulose nanofibers (CNFs) and cellulose nanocrystals (CNCs).

Mechanical methods, such as high shear homogenization, ball milling or ultrasonication, apply intense shear forces for the disintegration of cellulose fiber into nanocellulose. One of the major challenges in mechanical treatment is high energy consumption, which limits its sustainability.[78]

The chemical approach, involving acid treatment, specifically sulfuric acid hydrolysis, has become very popular due to its efficiency in the production process. However, there is always a risk of over-hydrolysis that can be overcome by enzymatic treatments.

The enzymatic process utilises enzymes, such as endoglucanases and xylanases, to carry out selective degradation of amorphous cellulose under mild conditions, with the least impact on the environment.

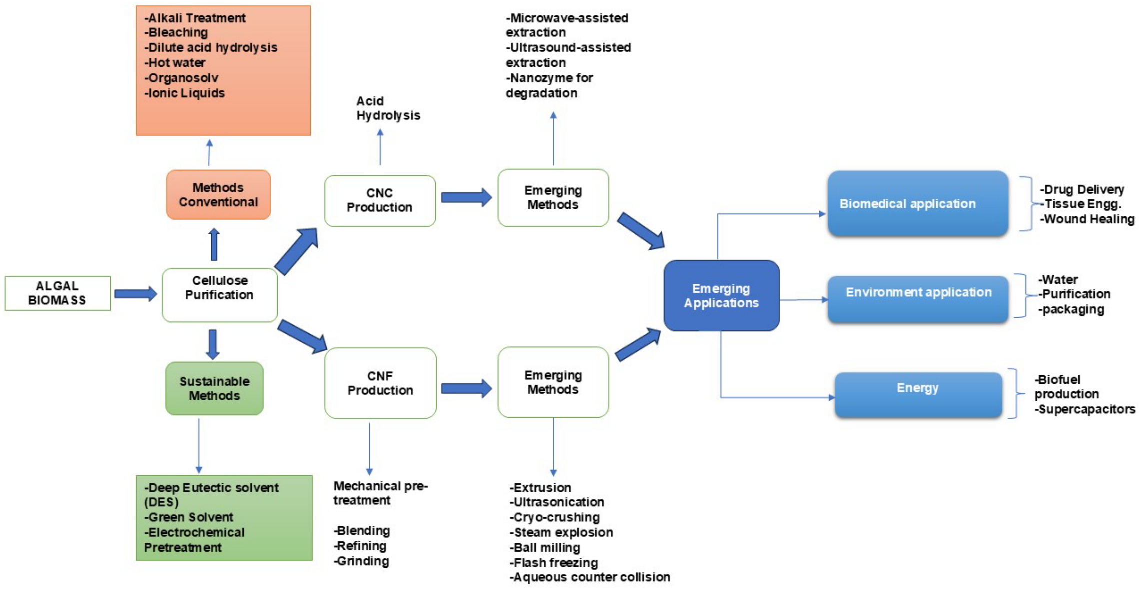

Figure 2: Overview of nanocellulose production using conventional and emerging methods, along with its potential applications

The hybrid approach combines mechanical, chemical and enzymatic processes to maximize the total yield of nanocellulose, while minimizing the eco-footprint. These advancements in extraction methods have become critical to scaling up the production of algal nanocellulose in adherence to green chemistry principles and industrial needs.[79]

Bottom-up approach (biosynthesis and self-assembly)

The bottom-up approach involves biosynthetic and self-assembly systems created within cellular architecture and metabolic pathways. In biosynthesis, algal species like *Cladophora* and *Chaetomorpha*, polymerize glucose units enzymatically into cellulose. Also, the produced cellulose has a high surface area and crystallinity.[80]

Recent advances in synthetic biology have made it possible to genetically engineer algal strains so that they produce more cellulose and allow for precise control over nano-structural features. Phosphorylase-catalysed synthesis is coupled with polymerization of material to design the material for specific functionalities towards biomedical and environmental applications.[81,82,83]

The spontaneous self-assembly of algal cellulose into complex nanostructures, like hydrogels, aerogels, and biofilms, is facilitated by molecular interactions that include hydrogen bonds, van der Waals forces, and electrostatic attractions.[84,85,86] To enhance the properties of nanoparticles and impart multifunctionality, scientists are exploring cross-linking, thus finding applications in water purification and drug delivery systems.[87] Innovations in recent times indicated algal cellulose as a renewable nano-material. These involve enzymatic hydrolysis and green chemical approaches that allow eco-friendly processing without compromising the quality of nanocellulose. Additionally, genetically engineered algae are capable of producing cellulose with desired characteristics, exploring new pathways towards scalable routes towards advanced bio-composites.[88]

Despite the advancements, challenges in production scale-up and economic production continue to exist. Future research should be focused on identifying algal strains with improved cellulose productivity and incorporating *in situ* functionalization approaches along with biosynthesis and self-assembly. These efforts would lead to the sustainable development of nanocellulose for biomedical, environmental, and industrial applications.

Table 2
Summary of cellulose surface modification techniques

Modification type	Method	Effect on nanocellulose	Key applications	Refs.
Ionic modification	Phosphorylation	Increases charge, flame retardancy	Biomedical, flame-resistant materials	93
	Carboxymethylation	Enhances dispersion, reactivity	Food, pharmaceutical, and paper industry	93,94
	TEMPO-mediated oxidation	Improves hydrophilicity	Biomedical, composites	93,95
	Sulfonation	Provides stability	Energy storage, catalysis	93
Hydrophobic modifications	Acetylation	Improves hydrophobicity	Water-resistant coatings, composites	96-98
	Etherification	Improves solubility	Biomedical implants, flexible electronics	93,95
	Sialylation	Increases hydrophobicity	Nanocomposites, water repellent coating	95,99
	Amidation	Enhances biocompatibility, stability	Drug carriers, tissue scaffolds	93,95,100
Polymer grafting	Grafting-from	High polymer density	Advanced biomaterials, membranes	100,102
	Grafting-to	Functionalized polymer networks	Hydrogels, conductive films	95,101
	Grafting-through	Polymerizable nanocellulose	Flexible electronics	103-105

Properties of algal nanocellulose

Algal nanocellulose is a promising biomaterial with a high aspect ratio, considerable surface area, and high mechanical strength. This makes it suitable for applications in composites, biomedicine, and energy storage. The high aspect ratio of nanocellulose extracted from *Laminaria hyperborea* facilitates stress transfer, significantly improving the mechanical performance of composites.[89] Such characteristics help maintain strong percolation networks for improved load transfer and mechanical performance, which are crucial in reinforcing polymer matrices.

Algal nanocellulose has a very large surface area, which is an ideal material in adsorption, catalysis, and polymer reinforcement applications. Nanocellulose extracted from *Ulva lactuca* shows polydisperse and spherical shape with particle size ranging from 10-15 nm, which is explored for enhancing the catalytic activity of nanoparticles. Similarly, cellulose nanocrystals isolated from *Cladophora glomerata* have long, rod-like morphology lengths exceeding 4 nm and are used in composites.[90] The major contributor to the mechanical properties of algal nanocellulose is its crystalline fibre, a network of hydrogen bonds, that provides high tensile strength and stiffness. These materials provide the possibility of surface functionalization, which is suitable for the hydrophobic-hydrophilic balance and also for interfacial adhesion within composites.[91]

Algal nanocellulose has potential in energy harvesting applications due to its piezoelectric properties for sustainable energy devices.[92] With the unique set of properties of algal nanocellulose, it is emerging as a versatile, high-performance material for critical applications in a circular bioeconomy.

RECENT ADVANCES AND DEVELOPMENTS

Genetic engineering and metabolic engineering of algae for enhanced cellulose production

The convergence of genetic and metabolic engineering holds immense potential in cellulose and nanocellulose production processes, aligning with sustainability goals. Genetic manipulations focus on cellulose synthesis by overexpressing cellulose synthase genes. These genes, such as CesA (cellulose synthase A), are important for cellulose biosynthesis. With recent advancements in technologies, such as CRISPR/Cas9, the goal is to get a precise modification and redirect carbon flux toward cellulose biosynthesis more efficiently.[106]

Integrating genetic engineering, metabolic engineering holds immense potential for creating sustainable cellulose and nanocellulose processes, which are in demand due to their renewable nature and exceptional properties across various industries and biomedical applications. Omics technologies, such as transcriptomics, proteomics, and metabolomics, shine a light on the regulatory networks leading the cellulose biosynthetic pathway, offering targets for metabolic flux optimization and enhanced production. This engineering approach primarily targets increasing cellulose yields and strategies that enable the direct secretion of cellulose into the growth medium, simplifying the downstream processing of algae as a platform for nanocellulose production. Furthermore, engineered strains can produce nanocellulose with superior mechanical properties. Genome-scale models help in identifying novel pathways and targets, driving further improvements in yield and cost reduction, thereby improving the economic viability of these approaches.[107]

Despite these advancements, a major challenge lies in scaling up and improving the metabolic burden associated with high cellulose yields. Integrating systems biology with synthetic biology offers promising solutions, paving the way for the development of robust algal strains and thereby increasing productivity. These advancements can establish algae as an environmentally friendly alternative source for biofuel and bioproducts, reducing the burden on plants and mitigating deforestation, thereby accelerating the transition to a circular bioeconomy.

Integration of extraction and nanocellulose production processes

The idea of integrating separation processes with nanocellulose production is rapidly growing as an important approach to improve efficiency, sustainability and scaling up in producing biomaterials. Advances in pretreatment and processing technologies, with the synergy of chemical, mechanical, enzymatic, and biological processes to further enhance yield and minimize environmental impact. Steam explosion and chemical hydrolysis were found to disrupt the lignocellulosic biomass and further efficient extraction of cellulose. For example, TEMPO-mediated oxidation along with mechanical disintegration produces high-purity cellulose nanofibrils with consistent dimensions and surface functionalities.[108] Enzymatic hydrolysis involves a mixture of different cellulases and has resulted in selective depolymerization of amorphous cellulose, while increasing crystalline cellulose, which is important in nanocellulose applications.[109] Technologies using deep eutectic solvents, ultrasound-assisted extraction, and ionic liquids offer advantages like reduced energy consumption, cleaner processing, and scalability. Ultrasound-assisted extraction reduces dependence on hazardous chemicals, while improving the yield and quality of nanocellulose.

Ionic liquids are recyclable and reusable, with tunable extraction mechanisms.[110]

To further improve the economic and environmental viability of nanocellulose production, integrated approaches in the biorefinery framework will be supported by integrating nanocellulose extraction with biofuel production and lignin valorisation. Enzymatic processes are optimized for the simultaneous production of sugars for biofuels as well as nanocellulose. Innovations in $Cr(NO_3)_3$ catalysed hydrolysis led to high crystallinity and yield under optimized conditions.[111] Supercritical fluid extraction and anaerobic microbial hydrolysis also hold promise as low-energy, scalable applications in biomedicine and nanocomposites.[112]

Collectively, these methods integrated into the framework of green chemistry, allowing for the sustainable production of nanocellulose. Advances will require addressing energy efficiency problems, process optimization and scaling up for large-scale applications as critical areas with enormous potential of nanocellulose for many industries, including biomedicine, energy, and advanced materials.

Valorisation of algal biomass residues and co-products

The valorisation of algal biomass and byproducts is considered an important aspect of the biorefinery process towards sustainability. Residual algal biomass is left after lipid or protein extraction, retaining some part of the initially present material consisting of proteins, carbohydrates, and bioactive molecules, which can be transformed into high-value applications in different industries. Protein can be used as an animal feed or a nutraceutical, while carbohydrates become a substrate for bioethanol, bioplastics, and fermentative bioprocesses.[113] Furthermore, other products like pigments, antioxidants, and polysaccharides from algae can be used in pharmaceuticals, cosmetics, and functional foods.[114] The advancements in the biorefinery process mostly focus on integrating circular economy principles to optimize the utilization of resources and reduce waste. The defatted algal biomass was used in biofuels, short-chain carboxylic acids, and biohydrogen, thereby heightening the resource circularity.[115]

Hydrothermal and catalytic treatment methods have shown promising possibilities of turning residual algal biomass into valuable products like sugars, organic acids, and methane through optimized co-digestion approaches.[116,117] Similarly, brown algal residues have promising adsorbing capacities towards hazardous metals and can be used in environmental remedial applications.[118] Dual-purpose strategies can integrate the benefits of environmental remediation as well as profit-making industry. For instance, integrating wastewater treatment into algal cultivation will lead to enriched biomass and clean water, thereby supporting the idea of a circular bioeconomy.[119] These advancements are promising, but challenges are still there concerning scaling up technologies and developing cost-prohibitive aspects, such as pretreatment and extraction. These innovations involve enzymatic hydrolysis processes, fermentation technologies, and techno-economic assessments, which can help to address these issues[120] Integration of these valorization pathways with LCA and market dynamics will be crucial in uncovering their full potential towards the sustainable development of algal bioindustries.

Emerging applications of algal cellulose and nanocellulose

Algal cellulose and nanocellulose have gained a lot of attention for their renewable nature, mechanical properties, and environmental sustainability. Algae-derived nanocellulose membranes from *Chara corallina* have demonstrated effectiveness in water purification systems with the removal of up to 99% of bacteria, addressing important environmental challenges. Additionally, there is promising potential for nanocellulose in the field of biomedical engineering.[121] Additionally, there is promising potential for nanocellulose in the field of biomedical engineering, where algal nanocellulose can be used as scaffolds for tissue engineering, wound healing, and drug delivery systems. It also has tunable surface chemistry as well as antibacterial effects against *Staphylococcus aureus* and *Escherichia coli*, which emphasizes its versatility for producing advanced antimicrobial materials.[122]

Nanocellulose from *Cladophora* is being explored for use in energy storage and green electronics applications. Also, it can be used in paper-based energy devices, battery separators and organic solar cells. These possibilities are due to its high porosity and low moisture adsorption. Nanocellulose incorporated within nanocomposite materials improves thermal stability and crystallinity, which is important in high-performance materials in biomedicine and electronics. It has shown interesting applications in advanced air and water purification systems in line with the principles of circular bioeconomy. For instance, using the cellulase enzyme for enzymatic hydrolysis to extract algal nanocellulose is environmentally sustainable and cost-effective. Algal nanocellulose allows innovation in high-value applications, such as bioplastics, catalysis, and environmental remediation with green extraction and biomass production. It shows the multifunctionality of nanocellulose and is expected to play a major role in sustainable technologies and innovations in the future.

CHALLENGES AND FUTURE PERSPECTIVES

Several factors impact the potential on an economic scale and scalability for algal cellulose and nanocellulose production. Some of the factors are processing efficacy, feedstock, and cost dynamics. Although traditional acid hydrolysis methods for nanocellulose production are efficient, they come with high acid concentration requirements, effluent disposal, and high energy demand related challenges. Mechanical and enzymatic processes are less harmful to the environment, but generally require sophisticated equipment and are energy-intensive.[123] Combining enzymatic hydrolysis with certain biorefineries or using supercritical CO_2 are some of the new tools used to reduce costs and improve scalability.[124]

To explore the complete potential of pretreatment methods, it will be necessary to integrate pretreatment methods, such as chemical, biological, and physical methods. Hybrid methods such as acid-ultrasound-assisted processing and microwave-alkali treatment have demonstrated improved extraction, while also maintaining structural integrity. Future research must focus on process optimization through life cycle assessment (LCA) and techno-economic analysis (TEA) to check the long-term feasibility of these methods in algal nanocellulose production.

Life cycle assessment has revealed that enzymatic methods have a lesser impact on the environment than chemical approaches, though it remains important to perform optimization to obtain further improvements in energy efficiency.[125] This will also lower production costs substantially and reduce the environmental footprint. Feedstocks such as agricultural residues have a lot of versatility due to their varied end-use potential.[126] This presents high cellulose productivity along with unique structural properties and makes it a good option as a raw material for the nanocellulose market. However, the production processes need to be scaled up to meet the commercial use demand. A recent study conducted on energy demands and global warming potential of nanocellulose production shows 87 to 19,000 MJ of energy, and 0.79 to 800 kg CO_2 eq./kg CNF depending on different feedstocks and production methods.[127]

The techno-economic analysis further explains production cost levels, plant capacity, and the integration of value-added co-products as the determining factor of economic viability. For instance, it has also been seen that the inclusion of residual biomass as fuel or profitable co-products into the production process improves profitability.[126] Geospatial mapping technologies are also helpful to optimize production locations, which would reduce transportation costs, while making better use of resources.

Despite all these advances, there are several challenges to solve. The high-energy consumption of pretreatment processes and uncertainties in downstream processing limit the scale-up process. In addition to that, current conversion efficiencies of solar energy to algal biomass are far from optimal. Hence, the conversion efficiency of solar energy into algal biomass needs to improve before the optimum yield and economic value are achieved. Addressing these technical and economic difficulties, along with standardizing production methods, will be essential for the widespread adoption of algal cellulose and nanocellulose.

Production of algal cellulose and nanocellulose is exciting, as it can be considered an environmentally sustainable option, compared to cellulose obtained from conventional sources, thereby contributing to the global goal of reducing environmental degradation. Algae are a renewable and fast-growing resource that can thrive in areas where crops cannot grow normally. Algae require little land and freshwater for production, which leads to a reduction in environment-related issues caused by producing cellulose from wood-based sources. Also, cultivation and processing methods, such as enzymatic hydrolysis, do not require the use of harsh chemicals and consume less energy, making the extraction of algal cellulose a good alternative.[128]

The algal nanocellulose is a sustainable alternative due to its biodegradable nature, non-toxicity and high mechanical strength. This versatility allows applications, such as biodegradable packaging, biomedical devices, and water treatment. These contribute to closing bioeconomy loops, helping to reduce greenhouse gas emissions and waste, thereby contributing to the bioeconomy. Life assessment focuses on energy efficiency and lower environmental impact. It is found that enzymatic processes are more favourable than traditional techniques, especially when renewable sources are considered as feedstock.[129] Newer pretreatment and functionalization strategies can manage different levels of hydrophilicity and hydrophobicity for various applications, while reducing environmental impact over the product's life cycle. As production processes and applications improve, algal cellulose and nanocellulose can play a key role in sustainable manufacturing without harming the environment.

Algal nanocellulose can be considered a sustainable alternative to conventional materials, with unique characteristics that would be helpful in biomedicine, environmental remediation, and energy storage. Thus, in the context of commercial potential, the regulatory aspects appear complex. Institutional frameworks can provide a working methodology, however specific guidelines regarding algae-derived cellulose are lacking. Regulatory bodies, including ISO, FDA, and EFSA, have mandates that cover aspects of nanocellulose. ISO standards, such as ISO/TS 20477:2017, provide the necessary vocabulary and classification for nanocellulose, while the ISO 10993 main standards for biocompatibility assessment concern biomedical use. Furthermore, FDA provisions require that algal nanocellulose, when it comes in contact with food, it must pass rigorous and stringent safety standards to attain the status of GRAS (Generally Recognized as Safe). EFSA guidelines focus on pre-market authorization under the Novel Foods Regulation (EU 2015/2283).

Despite these provisions and guidelines, challenges are still there in algal-derived nanocellulose. The lack of guidelines further complicates compliance and testing. Global standards for purity, crystallinity, and biocompatibility are still to be established. So far, ISO and ISTM documents have mainly provided general guidelines on the properties of algal nanocellulose. Addressing this gap would improve the understanding and utilization of algal cellulose in various applications.[130] Future research should be focused on bridging these gaps with the creation of proper protocols to assess safety and performance. Regulatory bodies should create the required guidelines needed, synchronising international standards will enhance global trade. On a more convenient note, the combination of algal nanocellulose production integrated into the biorefinery framework can be a bargaining element concerning the economic viability of the future sustainable project. Therefore, the process whereby algal nanocellulose can be standardized and brought under regulation will go a long way towards ensuring that safety, efficacy, and environmental impact issues might be addressed regarding the biomedical, food, and pharmaceutical applications. Such collaboration should enable data concerning algal nanocellulose availability for regulatory approval in fulfilling its global demand for sustainable and high-performance materials.

Ensuring safety and efficacy in biomedical applications involves the active reduction of impurities. For the food industry, the demand is for toxicological assessments to comply with regulations. Occupational health and environmental impact concerns highlight the importance of long-term studies. Strong collaborative policies are needed for emerging regulatory developments and technological advances. Critical care biodegradability and sustainable practice will help us develop algal nanocellulose at scale, while ensuring societal and ecological priorities.[131-134]

Future research should focus on optimizing algae cultivation systems to improve biomass yield and then developing green-chemistry-based extraction methods for reduced environmental impacts, while maintaining high product quality.[135] Table 3 shows the cellulose yield from algae, reported in the literature.

Next-generation mechanochemical and enzymatic processes may also overcome challenges related to scalability, thus unlocking their market opportunities for industrial applications.[136] In addition, other promising areas involve genetic engineering to enhance algal cellulose biosynthesis and hybrid composite development for high-value applications, such as renewable energy devices and drug delivery systems.[137] Integration into advanced composites, aerogels, and membranes will therefore add novel functionality to nanocellulose. Last but not the least, academic-industry collaborations that focus on life cycle assessment, as well as the environmental benefits of nanocellulose products, will be important drivers in many industrial areas, thus reinforcing their transformative role in sustainable innovation.

Table 3
Cellulose yield from different species of algae

Algal species (Class)	Extraction method	Cellulose yield (% dry weight)	Refs.
Caulerpa taxifolia (green algae)	Multi-step, chemical (acid/alkali)	11.0	138
Ulva lactuca (green algae)	Optimization with ethanol/salts	20.94	139
Ulva ohnoi (green algae)	Sequential extraction	3.8	140
Nannochloropsis gaditana (microalgae)	Chemical (toluene/ethanol, NaOH, $NaClO_2$)	25	141
Gracilaria edulis (red algae)	Repeated acid-base treatment	4.88–5.3	142
Kappaphycus alvarezii (red algae)	Multi-step, chemical	2	143
Sargassum wightii (brown algae)	Multi-step, chemical	10.2	144

CONCLUSION

Algal nanocellulose is a transformative material offering a sustainable alternative to conventional cellulose sources, focused on its biodegradability, exceptional mechanical strength, and high surface area, to explore applications in biomedicine, bioplastics, environmental remediation, and energy storage. Although lignocellulosic biomass remains a primary source of cellulose, but also contributes to significant deforestation and environmental damage due to energy-intensive processes, both macroalgae and microalgae offer convincing solutions due to their sustainable cultivation, high cellulose purity, rapid growth, and minimal resource requirements. Algal nanocellulose also has advantages such as enhanced crystallinity, lower moisture absorption, and improved processability compared to wood cellulose. Since most algae lack lignin, the nanocellulose extracted from them exhibits superior purity. Nano-sized celluloses, including cellulose nanocrystals and nanofibrils, are gaining attention due to their high surface-to-volume ratio, robust mechanical strength, tunable surface chemistry, and inherent biocompatibility. However, scaling up cellulose production remains a challenge primarily due to varying cellulose content across various algal species and energy requirements associated with biomass harvesting and cellulose extraction.

Current research advancements in pretreatment methods – chemical (*e.g.*, alkaline and acid hydrolysis, deep eutectic solvents, ionic liquids), biological (enzymatic hydrolysis), and physical (*e.g.*, steam explosion, ultrasound-assisted extraction, microwave-assisted treatments) – are aimed to efficiently disrupt algal cell walls and improve cellulose recovery. Each method offers unique advantages and disadvantages in terms of efficiency, environmental impact and cost-effectiveness. Integrated multiple approaches, such as microwave-alkali and acid-ultrasonication pretreatments, improve cellulose extraction. Advancements in green solvents, such as DES and ILs, hold potential, but require optimization and cost reduction for scaling up. Algal nanocellulose shows potential in biomedical applications (*e.g.*, drug delivery, tissue engineering, wound healing), environmental remediation (*e.g.*, water purification), energy storage (*e.g.*, green electronics, battery separators), and bioplastics. Furthermore, its integration of algal nanocellulose production into the biorefinery framework can help in valorising algal biomass residues and co-products, thereby supporting a circular bioeconomy.

Future research should focus on prioritizing genetic manipulations for high cellulose yield, the development of energy-efficient harvesting methods and the establishment of an integrated biorefinery to maximize algal cellulose. The development of regulatory guidelines addressing safety, efficacy, and environmental impact is also crucial for biomedical applications, food and pharmaceutical applications. Ultimately, industry–academia collaboration will be vital for innovations and realising the full potential of algal nanocellulose as a key sustainable biomaterial contributing to material science, sustainability goals and economic opportunities in the green economy.

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