



Cellulose-Based Advanced Materials from Algae for Aquatic Environment Sustainability: Prospects and Challenges

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Abstract

Heavy metal pollution and organic pollutants are serious threats to aquatic ecosystems and require sustainable remediation technologies. Land-based plants and bacterial cellulose have limitations such as deforestation, high processing costs, and scalability issues. Marine macroalgae (e.g. *Sargassum* sp., *Ulva* sp. and *Cladophora* sp.) are a promising alternative because of their rapid growth, high native crystallinity, no lignin content, and no land-use competition. This review emphasizes advanced cellulose materials from algal biomass, and the classifications are divided into microcrystalline cellulose, nanofibrillated cellulose, and cellulose nanocrystals. Extraction methodologies such as chemical, mechanical, and enzymatic processes, and surface functionalizations are critically evaluated with their functional performance in heavy metal adsorption, dye filtration, and membrane separation for wastewater treatment. Important technological and economic bottlenecks, including phyla-dependent structural heterogeneity, preservation of native crystallinity during extraction, and commercial biorefinery feasibility via co-product valuation, are also discussed. Prospective applications of advanced materials from algae for a sustainable environment are also discussed. This paper presents future perspectives on the increase of algal nanocellulose production for sustainable aquatic environment restoration.

Keywords: Algae; Cellulose; Advanced material; Sustainable materials; Aquatic environment.

1. Introduction

The demand for bio-based advanced materials is growing, driven by increasing pollution in aquatic ecosystems and the imperative for environmental sustainability. Among various natural biomass sources, algae have emerged as a highly promising precursor due to their abundant availability, rapid growth rate, and the fact that they do not compete with land used for food crops. A key structural component of algae that has garnered significant attention is cellulose—a natural polysaccharide composed of β -D-glucose monomers linked together by β -(1,4)-glycosidic bonds [1]. Globally, total algae biomass production (macro- and microalgae combined) was estimated at 35.82 M tonnes (fresh weight) [2].

Through processes including intracellular biodegradation, bioaccumulation, and biosorption, algae have been recognized in recent years as a sustainable and affordable resource for the detoxification of dangerous contaminants [3]. Algae can be transformed into carbon-rich compounds like hydrochar, biochar, and activated carbon in addition to directly aiding in the removal of pollutants [4]. These materials are highly effective at adsorbing organic

pollutants in wastewater treatment because of their high specific surface areas and various functional groups. High adsorption efficiency is exhibited by algae-derived adsorbents due to the synergistic effects of many interactions, such as hydrogen bonding, electrostatic forces. Because of the synergistic effects of multiple interactions, such as electrostatic forces, hydrogen bonding, π - π interactions, and pore filling effects, algae-derived adsorbents have high adsorption efficiency. These interactions rely on the engineered surface functional groups and porous structure of carbon-rich materials derived from algae [5].

In this frame, algae-based cellulose, in particular marine macroalgae, becomes a far better candidate for advanced materials. Macroalgae have advantages over cellulose from terrestrial plants due to high crystallinity and thermal stability and easier extraction process; no lignin content requires only mild extraction conditions [6]. Moreover, the structural and physicochemical properties of cellulose material differ between macroalgal genera [7]. For comparison, crystallinity of natural cellulose from terrestrial plants is commonly in the range of 40-70% [8]. Meanwhile, the cellulose extracted from the Antarctic alga *Cystosphaera jacquinottii* has a crystallinity of 70% [9], and marine algae from the genera *Cladophora* and *Valonia* have a very high crystallinity up to 95% [10]. The total absence of lignin in algae (*Cladophora*) allows cellulose to be extracted using mild treatments without undergoing aggressive delignification processes. This leaves the natural hydrogen-bonding structure between cellulose chains completely intact and free from chemical degradation, preserving its exceptionally high natural crystallinity.

Algae can produce cellulose nanofibrils within their cell walls through the self-assembly of cellulose chains, forming fibers with both amorphous and crystalline structures. The composition of this cellulose varies across different phyla: it is rich in hemicellulose and cellulose in Chlorophyta, Rhodophyta, and Charophyta; it exists as complex cellulose mixtures—such as xylofucoglucan sulfate—in Ochrophyta (Phaeophyceae); and it can even form protective plates (thecae) in dinoflagellates. In addition to cellulose, other matrix polysaccharides—such as ulvan, pectin, agar, alginate, or carrageenan—are also abundant. Extracting these polysaccharide co-products alongside cellulose has the potential to enhance the overall economic viability of algal biorefineries [11,12]. This potential is further bolstered by the abundant availability of wild algal biomass, such as *Sargassum* sp., in coastal regions (for instance, India, which is home to 844 species of seaweed) [13]. The population explosion (blooming) of algae can block sunlight, damage coral reefs, and cause fish mortality due to the deoxygenation of water (anoxia) [14]. Therefore, the utilization of algae to produce advanced cellulose-based materials not only provides added economic value but also addresses environmental issues [15]. Although cellulose nanostructures from algae are highly promising for applications in water purification technology [16, 17], there remain knowledge gaps and fundamental technical challenges. The differences in cellulose structures and the presence of complex matrix polysaccharides in different algal phyla have not allowed standardization of the methods for nanocellulose extraction and isolation. The second problem is that the conditions for the efficient “green extraction” should be optimized without losing the high crystallinity of algal cellulose, which has not been fully resolved. Third, most of the studies have been focused on the isolation of specific species without a comprehensive synthesis relating the molecular characteristics of algae, nanofabrication methods, and performance evaluation, especially when considering sustainable aquatic ecosystem restoration. The objective of this review is therefore to present a comprehensive discussion on the prospects and applications of advanced materials based on algal cellulose, as well as the technical and economic challenges involved in their development, for the sustainable maintenance of aquatic ecosystems.

2. Cellulose-Based Advanced Materials

Nanocellulose is the name given to cellulosic materials having nanometer dimensions. Its main sources are plants, animals, and bacteria. Interest in the extraction of nanocellulose from different sources of biomass for use in various fields has been increasing. As a bio-based compound, nanocellulose can be produced from plant biomass, bacteria, and algae using several methods (Fig. 1). Cellulose exhibits a natural chemical structure characterized by numerous hydroxyl groups, as well as a certain number of carboxyl and aldehyde groups. Nanocellulose has high surface area, active functional groups, mechanical strength, and crystallinity due to its nanostructure. The structural properties of nanocellulose enable it to be used in a variety of environments. Nanocellulose can be classified into two main groups: (1) nanostructured cellulose (microcrystalline and microfibrillated cellulose) and (2) nanofibers (nanofibrillated, nanocrystalline and bacterial cellulose).

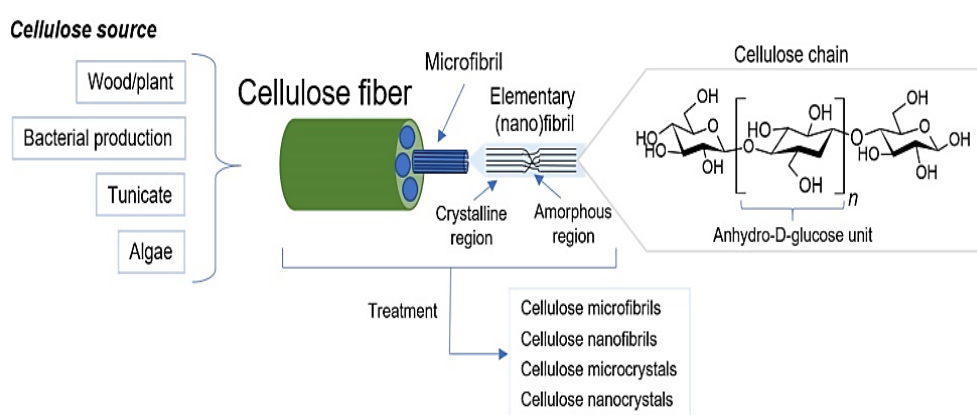


Fig. 1. Cellulose as a nanomaterials source [18]

2.1. Microcrystalline Cellulose

Microcrystalline cellulose is a natural material derived from purified and partially depolymerized cellulose, characterized by its fine particle size (Fig. 2). It is typically obtained from wood pulp. Microcrystalline cellulose is used in a wide range of fields. It is used as a filler and binder in pharmaceutical tablets, a fat substitute and stabilizer in food products, and as a plastic composite component. Crystalline cellulose fibers are roughly 5 nm in diameter and 20–30 nm long, with a crystallinity of 83% [19].



Fig. 2. Microcrystalline cellulose isolated from red algae *Gracilaria longissima*: (A) optical photograph, (B) Scanning electron microscope (SEM) image, 500x magnification [20]

At the nanoscale, cellulose I α microfibrils consist of both crystalline and paracrystalline phases. An amorphous mass of cellulose chains makes up the paracrystalline portions, while a collection of rigidly ordered microcrystals makes up the crystalline portions. Van der Waals interactions and hydrogen bonds hold cellulose chains together to produce these crystalline areas, which are known as crystalline cellulose. The diameter of the cellulose microfibrils and the diameter of the crystalline areas are comparable. In contrast, acid hydrolysis easily hydrolyzes the amorphous phase. Shorter, more highly crystalline particles are produced by this procedure. As a result, the cellulose chain's degree of polymerization drops, although the overall weight hardly changes [21].

2.2. Microfibrillated Cellulose

Cellulose chains are organized into crystalline microfibril strands surrounded by a non-cellulosic matrix. Various processes are employed to extract high-purity microfibrils from cell walls. These processes generally rely on a sequence of chemical and mechanical treatments. Bleaching—using NaOH or H₂O₂—is performed to degrade lignin, while NaOH is used to dissolve pectin and hemicellulose (Fig. 3).

Mechanical treatments, such as homogenization, are employed to produce a homogeneous suspension of microfibrils. Cellulose microfibrils can be isolated from various sources, including sugar beet and potato pulp, as well as different types of algae [22]. Microfibrillated cellulose from various plant sources can be isolated using chemical and mechanical treatments. Chemical treatments are effective for delignification and the dissolution of hemicellulose.

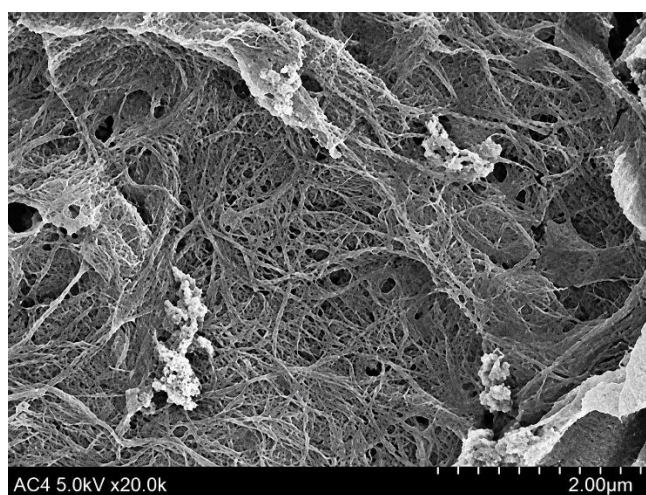


Fig. 3. Microfibrillated cellulose isolated from red algae *Gelidium amansii* [23]

2.3. Nanofibrillated Cellulose

Cellulose nanofibers—also referred to as microfibrillated cellulose, microfibrillar cellulose, or microfibrils—have become a subject of great interest to researchers due to their compelling applications in nanocomposites. To produce these structures, cellulose fibers must undergo mechanical dispersion to delaminate the fibers, thereby isolating the nanometric-scale fibers. This nanofibrillation process is energy-intensive, requiring significant power consumption to operate efficiently. In an effort to reduce energy requirements and improve process efficiency, various pre-treatments have been developed for cellulose fibers prior to nanofibrillation. Cellulose nanofibers—along with other forms such as microfibrillated cellulose, nanofibers, and microfibrils—can be processed via mechanical, chemical, or enzymatic methods. Cellulose fibers can also be subjected to strong acidic conditions to

hydrolyze the amorphous fractions of the cellulose, resulting in the formation of highly crystalline, rod-shaped cellulose nanowhiskers. These rod-like structures are variously termed nanowhiskers, nanofibers, and nanofibrils, microfibrillated or nanofibrillated cellulose (NFC) [24].

The extraction of cellulose nanofibers can be carried out using an enzymatic process. Enzymatic hydrolysis is considered environmentally friendly. Fig. 4 illustrates nanofibers obtained through both chemical and enzymatic processes. The enzymes employed are categorized into endoglucanases, exoglucanases, and cellobiohydrolases [25]. The resulting nanofibers from cellulose exhibit greater homogeneity compared to those obtained solely through mechanical treatment. While the production of nanocellulose via enzymatic hydrolysis is less advanced than processes utilizing acids or bases, it possesses specific, advantageous characteristics that warrant further development and investment. Carboxymethylation is a sequential two-step process in which hydroxyl groups of cellulose are replaced by carboxymethyl groups by a chemical reaction between cellulose and monochloroacetic acid in the presence of NaOH.

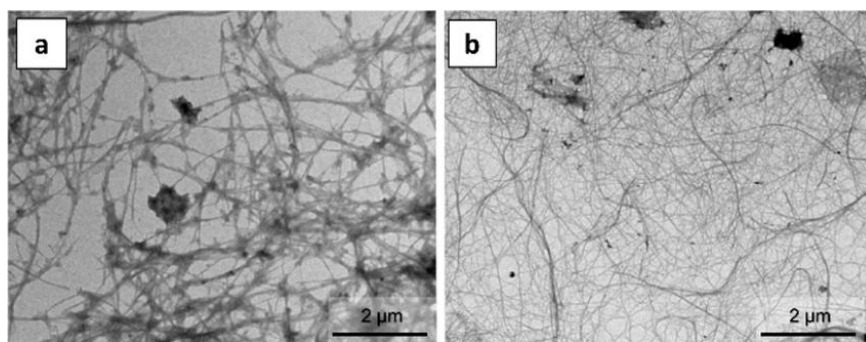


Fig. 4. Transmission electron microscope (TEM) images of cellulose nanofibers obtained from (a) chemical treatment, (b) enzymatic treatment [26]

Furthermore, this process uses TEMPO mediated catalytic oxidation where a selective oxidative catalyst is used to impart negative charge to the fiber surfaces. This causes electrostatic repulsion between the oxidized anionic carboxyl groups on the fibers. This widely used and highly effective treatment reduces energy consumption by up to an order of magnitude compared to dispersion processes based on mechanical energy and leads to highly uniform nanocellulose fibers typically of 3-4 nm width and several micrometers length. When this process is combined with sonication, cellulose is severely degraded and extensively separated. This finishes the next stage of the defibrillation process. Note that the TEMPO reagents used in the treatment of cellulose pulp lead to a decrease of the degree of polymerization [27].

2.4. Nanocrystals Cellulose

Cellulose nanocrystals are a type of nanomaterial derived from cellulose that possess many desirable properties, such as exceptional mechanical strength, biocompatibility, biodegradability, and a high specific surface area. The unique characteristics of cellulose nanocrystals make them useful as building blocks for a wide range of applications, including reinforcing agents, biomedical implants, rheology modifiers, nanocomposites, and electronic components.

Currently cellulose nanocrystals are found in wood, non-wood fibers, algae, tunicates and various residues or agro-industrial biomass. The most promising of these are agro-industrial residues or cellulosic biomass because they are inexpensive and widely available. Given the abundance, renewability, and sustainability of cellulosic raw materials, much research has focused on utilizing agricultural residues or biomass—such as rice straw, grape pomace,

pineapple leaves, sugarcane bagasse, and banana rachis—for the extraction of nanocellulose crystals. The extraction process begins with the purification of cellulose fibers through a pretreatment stage, which includes delignification and bleaching, followed by the isolation of cellulose nanocrystals via hydrolysis with 63% sulfuric acid [28].

The morphology of the cellulose nanocrystals is shown in Fig. 5. The nanocrystals have an average length of 291 ± 24 nm and a diameter of 20-50 nm. Strong hydrogen bonding between the particles allows for the formation of very stable and ordered structures of cellulose nanocrystals. To minimize particle agglomeration, cellulose nanocrystals are typically used in the form of a "never-dried" dispersion. However, the actual content of the cellulose nanocrystals is not clearly defined; consequently, the stoichiometry of the modification reaction remains questionable.

In an alternative methods, dry cellulose nanocrystals are utilized in the form of cellulose aerogels, obtained via the freeze-drying of cellulose nanocrystals. During freeze-drying, much of the original structure of the cellulose nanocrystals—as it existed in an aqueous environment—is preserved, and aggregation is largely prevented. Such nanocellulose can be redispersed in various media with the aid of sonication. Compared to the original (never-dried) cellulose nanocrystals, the freeze-dried counterparts exhibit a slightly larger average particle size and a narrower particle size distribution. This is attributed to partial aggregation and the rearrangement of the smallest cellulose nanocrystal particles into larger structures during the freeze-drying process [29].

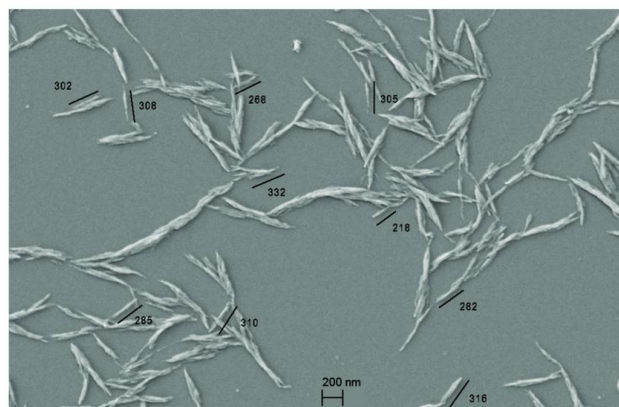


Fig. 5. SEM image of nanocrystalline cellulose [29]

2.5. Nanowhisker Cellulose

Several terms are used to define cellulose nanowhiskers, such as nanocrystalline cellulose, nanocellulose fibers, and cellulose whiskers. The distinctions between them depend on the production method employed and their lateral dimensions. Cellulose nanowhiskers (Fig. 6) are fibrous forms of cellulose produced through the acid hydrolysis of cellulose derived from plants, animals, or bacteria, with lateral dimensions ranging from 3 to 30 nm. In contrast, microcrystalline cellulose consists of microcrystalline particles produced via the acid hydrolysis of plant-based cellulose, utilizing a broader range of reaction conditions. During the 1990s, the terms "microcrystalline cellulose" and "microcrystalline" were also applied to cellulose nanowhiskers [30].

Cellulose nanowhiskers are fibers that are engineered under controlled conditions, and high purity single crystals are formed after removal of amorphous regions. This results in a highly ordered structure that not only produces very high tensile strength but also very significant changes in electrical, optical, magnetic, and dielectric properties. These whiskers have a higher tensile strength than high-volume-fraction materials available today and thus can

be used to make composites with the highest strength achievable. Cellulose nanowhiskers are obtained by pre-hydrolysis pulping, soda pulping, bleaching, and producing microcrystalline cellulose, followed by either sulfuric acid hydrolysis or swelling agent N,N-dimethylacetamide (DMAc) treatment [31]. Further defibrillation takes place during the acid hydrolysis, leading to the formation of needle-like cellulose nanowhiskers. The cellulose nanowhiskers are well dispersed with diameters of 3–9 nm and lengths of 150–450 nm [32].

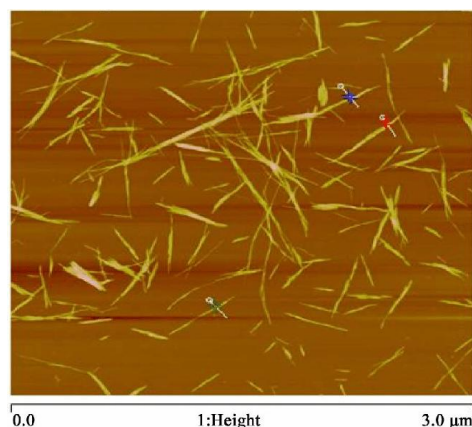


Fig. 6. TEM images of cellulose nanowhisker [32]

2.6. Bacterial Nanocellulose

Bacterial nanocellulose was first discovered by Adrien Brown in 1886. It was found to grow to a thickness of up to 25 mm and demonstrated significant strength during studies on acetic fermentation. Brown also identified the bacterial membrane—originally attributed to an organism named *Bacterium xylinum*, which was later reclassified as *A. xylinum*. Several species of bacteria and cyanobacteria have since been identified as producers of bacterial nanocellulose. Genera such as *Rhizobium*, *Gluconacetobacter*, *Acetobacter*, and *Agrobacterium* are known to be bacteria producing cellulose [33]. *G. xylinus* is recognized as a species capable of synthesizing cellulose on a commercial scale and is the most efficient producer. While bacterial cellulose and plant-derived cellulose share a similar chemical composition, they differ in their physical properties and fiber structure. Plant cellulose predominantly contains the cellulose I β crystalline structure, whereas bacterial nanocellulose is considered to possess both cellulose Ia and I β crystalline structures [34]. Bacterial nanocellulose offers unique properties such as a high degree of polymerization, tensile strength, crystalline content, and have a water-holding capacity value from 60 to 700 times its dry weight, and an ultrafine nanofiber structure with diameters of less than 100 nm [35]. Further studies indicate that the bacterial cellulose has a similar chemical structure compare to those produced by plants. To date, bacterial nanocellulose represents the purest natural cellulose [36].

Both bacterial cellulose and plant-derived cellulose consist of linear chains of β -1 $\rightarrow$ 4-D-glucopyranose of polysaccharides, which vary in terms of purity, degree of polymerization, and crystallinity [37]. The advantages of bacterial nanocellulose include ease of production and application [38], exceptionally high-purity [39] without component of hemicellulose and lignin. Pristine bacterial cellulose possesses 3.0 GPa of elastic modulus and 70 MPa of tensile strength [40]. It is composed of cellulose nanofibers characterized by an interconnected network of fibrils, which feature various bonds and aggregates, forming a three-dimensional structure [41].

3. Potential Application

Currently, stringent environmental regulations require the utilization of green materials or bio-based products, encouraging investment in greener processes, industrial ecology, and sustainability. Furthermore, there is a concerted effort to foster healthy aquatic ecosystems, given that water bodies ultimately serve as the final destination for pollutants—whether they enter directly or indirectly [42]. Managing wastewater laden with heavy metals and ensuring environmental quality constitutes a considerable technological hurdle. Bacterial nanocellulose is an attractive alternative material for wastewater purification and water reuse technologies because of its strong 3D nanofibrillar network and favorable conformation. Bacterial nanocellulose meets the needs of developing specialized materials used for environmental sustainability, ushering in a new era of sustainable materials.

Algal biomass is a very versatile and sustainable precursor for a wide range of environmental and industrial applications. Algae can be broadly divided into two groups based on their cellular structure and scale: microalgae and macroalgae. Microalgae are microscopic single-cell organisms, for example *Chlorella* sp., *Spirulina* sp. and *Nannochloropsis* sp. They are characterized by different morphologies, ranging from spherical cells to helical filaments. Conversely, macroalgae are visible multicellular biomass, classified into green (*Ulva lactuca*), brown (*Sargassum* sp.) and red algae (*Gracilaria* sp.). Algal lineages, micro- and macro-: Multi-faceted solutions for environmental sustainability. Important applications (Fig. 7) include carbon sequestration and oxygen production for climate change mitigation, bioenergy production (such as lipid-derived biodiesel, bioethanol, and biogas) [43], and wastewater bioremediation via nutrient removal and heavy metal adsorption [44]. Algal biomass is also a useful feedstock for the production of sustainable bioplastics, biocomposites and high value compounds such as nutraceuticals, aquaculture feed and functional food ingredients [45].

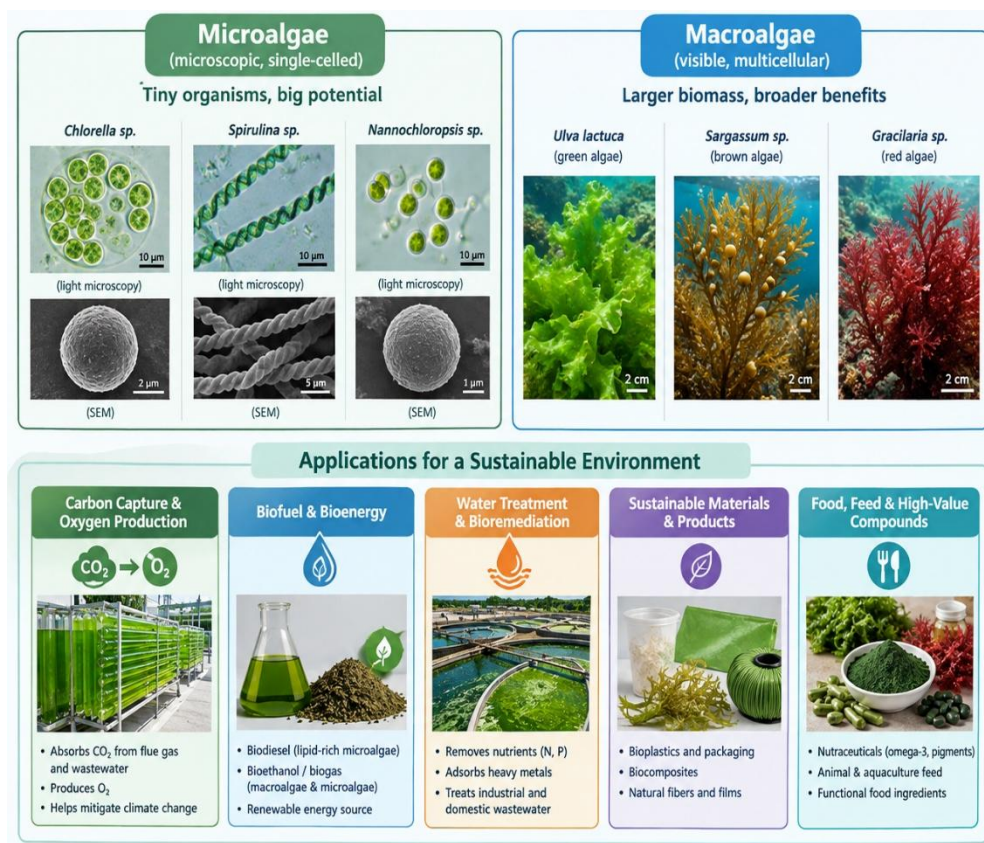


Fig. 7. Applications of algae for sustainable environment

Table 1 summarizes the possible applications of advanced materials derived from various algal species for environmental sustainability. Considerable efforts have been made to process macroalgal biomass, especially *Sargassum*, into various nanostructured forms to address water treatment problems. For example, nanocellulose from *Sargassum* can be incorporated into composite membranes for water filtration or produced in acetate membranes for dye adsorption. *Sargassum* biomass can also be processed into effective membrane structures for removing heavy metals [46]. Besides brown algae, green algae species have demonstrated great potential for sustainable packaging and biomaterials. Thin films are prepared from cellulose nanocrystals obtained from the green macroalgae *Ulva* species and *Cladophora rupestris* and are suitable for food packaging [47]. *Ulva lactuca* nanofibers are also employed as structural parts in composite biomaterials. Finally, *Posidonia oceanica* microcrystalline cellulose is a versatile reinforcing agent for a wide range of industrial and environmental applications.

Table 1. Prospective applications of advanced materials from algae for a sustainable environment

Algal Sources	Advanced Material type	Application Form	Performance	Ref.
<i>Sargassum</i>	Nanocellulose	Composite Membrane	88.9% for Methylene blue	[48,49]
<i>Sargassum</i>	Micropowder	Membrane	95.9 % of Cd ²⁺ was removed	[50,51]
<i>Ulva</i> species	Cellulose Nanocrystals	Packaging film	Increase 279% in tensile strength	[47]
<i>Cladophora rupestris</i>	Cellulose Nanocrystals	PackagingvFilm	improved its tensile strength by 78%.	[52]
<i>Ulva lactuca</i>	Nanofiber	Composite	87.5% ion metal adsorption	[53,54]
<i>Posidonia oceanica</i>	Microcrystalline cellulose	Reinforcement	Many application	[55]

4. Challenge

The promise of algal biomass-derived nanocellulose for aquatic environmental applications is exciting. However, there are key technical and economic challenges that must be solved before mass production and commercialization are possible. The high operational costs from a supply chain point of view are due to seasonal availability of biomass, high moisture content that requires drying energy, and logistical costs of harvesting and transportation. Mechanistically the major technological bottleneck is the structural heterogeneity between different algal phyla. Unlike terrestrial plants, algae do not contain lignin, but have complex cell-wall matrix polysaccharides (e.g. alginates, ulvans and sulfated galactans) [56] that interfere with cellulose isolation, preventing the standardization of extraction protocols.

Achieving industrial-scale production requires the development of efficient "green extraction" methods that isolate high-purity nanocellulose without degrading its native high crystallinity—a crucial feature for structural and filtration applications. Furthermore, because pristine algal nanocellulose exhibits high hydrophilicity [57] and bioinert properties [58], precise surface functionalization (such as TEMPO-mediated oxidation [59] or grafting with functional chelators [60]) is often necessary to enhance adsorption capacity toward specific pollutants like heavy metals or synthetic dyes. However, chemical modification techniques involve toxic reagents, high solvent consumption, and complex purification steps, creating a major trade-off between material performance, cost, and process sustainability. To solve this

trade-off, researchers need to follow green functionalization strategies. This includes the use of recyclable catalytic systems (e.g. substitution of NaClO by H₂O₂ or enzymes in oxidation), bio-based crosslinkers (e.g. citric acid or chitosan) and low-solvent mechanochemical methods such as reactive ball-milling. Furthermore, the optimization of surface-targeted functionalization maintains the native crystallinity of algal cellulose high and reduces the consumption of chemicals. Overcoming these challenges will require integrated multi-product biorefinery strategies—co-extracting valuable matrix polysaccharides alongside nanocellulose—to offset processing costs, minimize chemical waste, and establish an economically viable path toward aquatic ecosystem restoration.

5. Conclusion

Algae-based cellulose is a highly prospective, environmentally friendly platform for the development of advanced materials for sustainable aquatic environment restoration. Marine macroalgae (e.g., *Sargassum* sp.) overcome major drawbacks of land-based plants and bacterial cellulose by offering high crystallinity, superior thermal stability, and low-energy extraction pathways, as lignin is absent. Excess or invasive algal biomass is converted into nanostructured materials (cellulose nanocrystals, nanofibrils and composite membranes) which show excellent performance in heavy metal removal, organic dye adsorption and wastewater filtration. However, scale-up of algal nanocellulose from laboratory synthesis to commercial application requires tackling considerable technical and economic challenges. Major challenges are standardization of extraction procedures from different algal phyla, optimization of energy-efficient “green” isolation procedures that do not alter crystallinity, and reduction of biomass harvest and chemical costs. In an effort to make the process economically viable and to support water sustainability worldwide, it is essential to close these gaps with integrated biorefinery approaches, i.e., the co-extraction of valuable polysaccharides together with cellulose.

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Author Declaration

Data availability statement: Data will be made available on request.

CRedit authorship contribution statement: FAN: Conceptualization, Data curation, Formal analysis; MAA: Resources, Software, Supervision; RS: Writing – original draft, Writing – review and editing

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Artificial Intelligence Statement: The authors declare that generative AI tools (e.g., Grammarly, ChatGPT) were used solely to assist with language editing and grammar improvement. All scientific content, data interpretation, and conclusions were developed entirely by the authors.

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