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MICROWAVE-ASSISTED EXTRACTION OF CELLULOSE FROM *LAMINARIA DIGITATA* BIOMASS

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Abstract

Cellulose was isolated from the brown seaweed Laminaria digitata using both conventional alkaline extraction and microwave-assisted extraction to assess the efficiency of microwave treatment in enhancing extraction while preserving cellulose integrity. Microwave-assisted extraction using 4% (m/v) sodium hydroxide at 336 W for 30 min yielded 5.6 ± 0.53% cellulose, comparable to 5.7 ± 0.79% obtained via conventional extraction over 24 h. Microwave-assisted extraction offered a significant advantage by reducing the extraction time nearly 48-fold without compromising the yield. FTIR analysis confirmed characteristic cellulose bands, indicating preserved functional groups. Structural indices (TCI 1.48 ± 0.12; LOI 1.23 ± 0.06; HBI 0.68 ± 0.01) suggested moderate crystallinity, good lateral order, and relatively weak hydrogen bonding. SEM analysis revealed a rough and porous surface, while EDS analysis confirmed high purity with carbon and oxygen as the main elements (56.30 wt% and 41.50 wt%, respectively) and only trace calcium. These results indicate effective removal of non-cellulosic and mineral components, exposing crystalline cellulose domains. Overall, MAE is a rapid, efficient, and eco-friendly method for isolating cellulose from L. digitata, producing a structurally intact, chemically pure biopolymer suitable for applications in biocomposites, nanocellulose, and other bio-based materials.

Keywords: *Cellulose, Seaweed, Microwave-Assisted Extraction, Structural Characterization, Hydration Properties.*

INTRODUCTION

Cellulose is the most abundant natural polymer, composed of *β*-1,4-linked *D*-glucose units (Kabir *et al.*, 2022). This renewable biopolymer can be extracted from various natural sources, including plants, agricultural residues, and microbial biomass (Sundarraj & Thottiam, 2018). Marine biomass, particularly seaweed, has gained increasing attention as a promising alternative source of cellulose. The cultivation of seaweeds offers numerous advantages compared to terrestrial agriculture. Their production requires no arable land, fertilizers, or fresh water, and they demonstrate impressively fast growth rates and high productivity despite minimal external constraints (Machado *et al*., 2024). These traits not only make seaweeds a sustainable raw material but also reduce the overall environmental footprint associated with biomass sourcing.

The cellulose concentration in seaweed is highly variable, typically ranging from 1% to 15%. This variability is contingent on several factors, including the specific species, its maturity, and prevailing environmental conditions, such as light and nutrient availability (Salem & Ismail, 2022). Brown seaweeds (Phaeophyceae) were identified as a viable biomass source for cellulose extraction due to their relatively high carbohydrate content and wide distribution in marine ecosystems. Cellulose derived from marine biomass exhibits several favorable physicochemical properties, including biodegradability, renewability, and excellent biocompatibility (Machado *et al*., 2024). These characteristics make it highly attractive for application across diverse industrial sectors, including packaging, pharmaceuticals, cosmetics, textiles, and bioengineering (Machado *et al*., 2024; Rise *et al*., 2024). Its hydrophilic nature and high water-holding capacity (WHC) enable its use in specialized applications, such as bioscaffolding, hydrogel formation, and as a carrier matrix for microbial immobilization in biotechnological processes (Yuliani, Pratiwi, Ratnaningsih, 2024).

Despite growing interest in alternative sources and applications of cellulose, extracting and purifying cellulose from marine biomass remains challenging. Traditional cellulose isolation methods generally involve a combination of mechanical disruption, chemical treatments (bleaching and alkaline extraction), and, sometimes, enzymatic hydrolysis to remove non-cellulosic components (Femina & Asokan, 2024). Among these, chemical methods remain the most widely adopted due to their relatively high yield and operational simplicity in industrial settings. The conventional chemical isolation of cellulose typically comprises three main stages: (1) a defatting process to remove lipids and pigments, (2) bleaching to eliminate colored compounds and oxidizing materials, and (3) alkaline extraction (most commonly using sodium hydroxide) to remove hemicelluloses and residual proteins (He *et al*., 2021). Of these processes, alkaline extraction is considered the critical step for achieving high-purity cellulose; however, it also represents a major bottleneck. This stage is often associated with prolonged reaction times, ranging from several hours to 24 h, as well as significant energy input, which collectively hinder the scalability and sustainability of the process (Salem & Ismail, 2022).

According to these limitations, there is an increasing demand for the development of more efficient, cost-effective, and eco-friendly extraction procedures. Advanced extraction techniques, microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE), offer promising alternatives to the conventional extraction procedure (Shrivastav *et al*., 2025). These technologies facilitate cell wall disruption and enhance chemical penetration by reducing processing time and energy consumption while preserving the structural integrity of cellulose (Femina & Asokan, 2024).

The primary objective of this study was to improve the efficiency of cellulose isolation from brown seaweed biomass by developing an advanced MAE procedure. The performance of this method was assessed through yield analysis and detailed structural characterization of the resulting cellulose, including morphological and hydration properties. Special emphasis was given to examining the WHC of the isolated cellulose at room temperature, given its relevance to industrial and biotechnological applications. The findings contribute to a growing body of research that supports the feasibility of integrating green extraction technologies into cellulose production, particularly when utilizing non-conventional biomass (seaweed). The successful optimization of these processes is anticipated to greatly enhance the commercial potential of seaweed-derived cellulose, consistent with the broader objectives of sustainable resource utilization and a circular bioeconomy.

MATERIALS AND METHODS

Chemicals and Reagents

Ethanol (96%*v/v*), sodium hydroxide (NaOH), and sodium hypochlorite (NaClO) were supplied from Zorka Pharma (Šabac, Serbia), while the sodium acetate buffer solution was obtained from Sigma-Aldrich(St. Louis, Missouri, USA). All other chemicals used were of analytical grade and products of Sigma-Aldrich(St. Louis, Missouri, USA).

Plant material

Brown seaweed (*Laminaria digitata* Huds., Laminariaceae) biomass was obtained from Ozonway (Belgrade, Serbia). The seaweed biomass was dried at room temperature in the dark for a week. The sample was ground in an electric mill (Braun Aromatic KSM2, Kronberg im Taunus, Germany), and a fraction of 0.5 mm particle size was used for further analysis. The moisture content of 10.6% (*m/m*) was determined by drying the brown seaweed biomass sample at 105 °C in a laboratory oven until a constant weight was achieved.

Isolation of cellulose from brown seaweed biomass

After defatting with 96% (*v/v*) ethanol, 50 g of brown seaweed biomass was added to 500 mL of 1.4% NaClO solution with stirring. The pH value was adjusted to 3 using an acetate buffer. The bleaching of plant material was carried out at 70°C for 5 h, after which the solid fraction was repeatedly washed with distilled water until the pH reached neutral. The bleached sample was further subjected to alkaline extraction using 500 mL of a 4% (*m/v*) NaOH solution to remove non-cellulosic carbohydrates. This phase was carried out using two different procedures: the conventional procedure and MAE. In the conventional procedure, the extraction was performed at 60°C overnight (Siddhanta *et al*., 2009). In the modified conventional procedure, an open-vessel MAE system (Vivax MWO-2070 BL) was operated at a microwave power of 336 W for 30 min. After cooling to room temperature, both alkaline samples were filtered using Whatman No. 1 filter paper. The resulting solid fraction was washed with distilled water until the pH became neutral, and then dried to obtain cellulose. The percentage yield of raw cellulose was calculated relative to dry biomass.

Structural characterization of isolated cellulose

Fourier Transform Infrared (FTIR) Spectroscopy was employed to characterize the isolated cellulose structurally. Before analysis, KBr pellets were prepared by thoroughly mixing the cellulose sample with spectroscopic-grade potassium bromide. The FTIR spectra were recorded over the wavenumber range of 4000–400 cm^{-1} with a resolution of 2 cm^{-1} using a Bohm Hartmann & Braun MB-series spectrophotometer (Quebec, Canada). Data acquisition and spectral processing were carried out using *Win-Bomem Easy* software (Galactic Industries, Salem, New Hampshire, USA).

To gain deeper insight into the crystalline structure of the isolated cellulose, specific crystallinity indices were calculated from the FTIR spectra: **Total Crystallinity Index (TCI), Lateral Order Index (LOI)**, and **Hydrogen Bond Intensity (HBI) (Stanciu, Tanasă, Teacă, 2025)**. These indices are widely used to evaluate the relative crystallinity, molecular ordering, and hydrogen bonding interactions within cellulose samples. The intensity ratios of characteristic absorption bands were used for these calculations (Table 1).

Table 1: FTIR absorption bands and formulas used for crystallinity index calculations (Source: Stanciu, Tanasă, Teacă, 2025)

Index	Formula	Band 1 (cm^{-1})	Band 2 (cm^{-1})	Interpretation
TCI (Total Crystallinity Index)	A_{1371}/A_{2931}	1371 (C-H bending in crystalline cellulose)	2931 (C-H stretching)	Indicates the overall degree of crystallinity
LOI (Lateral Order Index)	A_{1430}/A_{887}	1430 (CH_2 symmetric bending in crystalline cellulose)	887 (C-O-C stretching of amorphous cellulose)	Reflects the lateral order or molecular alignment
HBI (Hydrogen Bond Intensity)	A_{3353}/A_{1336}	3353 (O-H stretching, hydrogen bonding)	1336 (C-H bending)	Estimates the hydrogen bonding strength and water affinity

The morphology of the native cellulose powder surface was examined using Scanning Electron Microscopy (SEM) analysis on a FEI Inspect S50 scanning electron microscope (Hillsboro, OR, USA). A small amount of powder was spread onto an aluminum specimen stub and secured with double-sided adhesive tape. Images were recorded at magnifications of 180× and 700×, employing an accelerating voltage of 30 kV under a vacuum of 10^{-6} mbar. The elemental composition of the sample was determined using energy-dispersive spectroscopy (EDS) integrated into the SEM system.

Determination of the water-holding capacity of native cellulose

The WHC of cellulose was determined using the standard centrifugation method (Song et al., 2024). This method is based on measuring the amount of water absorbed and retained by a dry sample after centrifugation.

The WHC was calculated according to Eq. 1:

$$\mathrm{WHC}\left(\frac{g}{g}\right) = \frac{m_2 - m_1}{m_1} \quad (1)$$

where m_1 is the mass of the dry sample and m_2 is the mass of the sample after immersion in water and centrifugation at 6,000 rpm for 10 min.

Determination of the swelling capacity of native cellulose

The swelling capacity (SC), representing the water-binding ability of the isolated cellulose, was determined using a gravimetric method (Song et al., 2024). Dry cellulose samples extracted from brown seaweed biomass (0.5 g) were immersed in 20 mL of distilled water at room temperature. After 24 h, the volume of the swollen powder was measured. The SC are presented as the ratio of the initial volume of dry cellulose to its volume after absorbing water over a specified time, as defined in Equation (2):

$$\mathrm{SC}\left(\frac{mL}{g}\right) = \frac{V_1 - V_0}{m_1} \quad (2)$$

where V_1 is the volume of swollen powder (mL), V_0 is the volume of dry cellulose powder (mL), and m_1 is the mass of dry cellulose powder (g).

Statistical analysis

All experiments were performed in triplicate, and the results are expressed as mean values ± standard deviation to ensure statistical reliability and reproducibility. Statistical analyses were performed using IBM SPSS Statistics version 27 (IBM Corp., Armonk, NY, USA). This software was used to process the data, assess variability, and support the interpretation of experimental outcomes.

RESULTS AND DISCUSSION

Yield of isolated cellulose from brown seaweed biomass

In this study, cellulose was isolated from the brown seaweed *L. digitata* using both a conventional extraction procedure and MAE during alkaline treatment. The aim was to evaluate the effectiveness of microwave in enhancing the extraction efficiency while maintaining cellulose integrity. The application of MAE resulted in a cellulose yield of 5.6 ± 0.53%, whereas the conventional extraction procedure yielded 5.7 ± 0.79%. Despite the nearly identical yields, the main advantage of MAE is the approximately 48-fold reduction in extraction time, achieved without any loss in the amount of isolated cellulose.

A microwave power of 336 W and an extraction time of 30 min were selected as the optimal parameters based on preliminary optimization trials (data not shown). Additionally, the literature reports that moderate power levels and controlled extraction times are effective in preserving cellulose integrity while enhancing extraction efficiency (Raissa *et al*., 2025). The choice of 336 W was guided by the need to achieve sufficient energy input to disrupt the cell wall matrix without causing thermal degradation of cellulose. Excessive microwave power can lead to localized overheating, potentially resulting in depolymerization or discoloration of the final product (Joardder & Karim, 2023). Conversely, lower power levels tend to be insufficient

for effective penetration into the dense seaweed matrix. The selected 30-minute duration represents a compromise between maximizing yield and minimizing thermal damage, and it was found to be sufficient for the effective breakdown of the seaweed cell wall and release of cellulose into the solution.

Microwave radiation enhances extraction primarily through its volumetric heating mechanism, in which polar molecules (water and hydroxide ions) rapidly absorb microwave energy, resulting in localized heating and internal pressure buildup (Mishra et al., 2024). This leads to more effective rupture of the seaweed cell wall, facilitating the release of cellulose from deeper layers (Plianwong & Sirirak, 2024). In the case of *L. digitata*, whose cell walls contain tightly bound polysaccharides such as alginate and fucoidan (Deniaud-Bouët*et al*., 2014), this internal heating mechanism plays a crucial role in reducing extraction time and improving process efficiency. The cellulose yield obtained in this study aligns with values reported in the literature for brown seaweeds, which typically range between 1% and 10%, depending on species, seasonal and environmental factors, and the specific extraction conditions applied (Machado *et al*., 2024). Plianwong&Sirirak (2024) successfully extracted cellulose nanocrystals from the seaweed *Cladophora glomerata* using a bleaching method involving 30% (*v/v*) H_2O_2 and MAE for 30 min. Their method yielded high-purity CNCs and significantly reduced the total extraction time from 74 h to just 60 min, demonstrating the capacity of microwave radiation to drastically accelerate complex extraction processes. Raissa *et al*. (2025) investigated the recovery of cellulose from *Triplochiton scleroxylon* (Ayous) sawdust using MAE. The optimal conditions — microwave power of 466 W, extraction time of 39 min, and 33% (*m/v*) NaOH — yielded a remarkably high cellulose recovery of 88%. Despite the differences in the starting materials (wood-based sawdust and seaweed), the fundamental extraction challenges remain similar, involving the disruption of complex cell wall architectures and the separation of cellulose from associated biopolymers. In both cases, MAE leverages rapid volumetric heating and localized pressure buildup to enhance solvent penetration and accelerate chemical reactions. The much higher recovery observed in the *Triplochiton scleroxylon system can be attributed to the higher microwave power and alkali concentration used, as well as to the inherent structural differences between lignocellulosic and seaweed materials*. Although wood biomass generally contains well-organized and tightly packed fibers surrounded by lignin, brown seaweed cell walls are rich in polysaccharides, such as alginate and fucoidan. They can form more hydrated, chemically resistant matrices that hinder reagent access to cellulose microfibrils.

Additionally, MAE supports the principles of green chemistry by offering lower energy consumption, reduced use of chemicals, and shorter processing times, making it a promising method for sustainable processing (Shrivastav *et al*., 2025). The scalability and industrial relevance of microwave-based processes are further enhanced by their reproducibility and ease of integration into continuous-flow systems.

FTIR analysis of isolated cellulose

The FTIR spectrum of native cellulose isolated from brown seaweed biomass is presented in Fig. 1. The broad peak with maximum intensity at 3353 cm^{-1} indicated the valence vibration of the O–H bonds. The valence and deformation vibrations of the C–H bond caused the appearance of peaks at 2931 cm^{-1} and 1371 cm^{-1}, respectively. Notably, characteristic peaks for cellulose were identified in the wavelength range of 1660 – 900 cm^{-1}. The peak at 1650 cm^{-1} corresponded to the vibrations of water molecules that are absorbed in cellulose (He *et al*., 2021).

The peaks around 1164 cm^{-1} and 1126 cm^{-1} arose from the valence vibrations of the C–O–C bond.

Additionally, the deformation vibrations of the $–CH_2$ group and the C–H bond were observed at 1430 cm^{-1} and 1371 cm^{-1}, respectively, and are associated with the crystalline structure of cellulose. The peak at 1054 cm^{-1} was attributed to the deformation vibrations of the –C–O–C bond within the pyranose ring. The peak at 887 cm^{-1} was due to the β-glycosidic bond between glucose units and is attributed to the C–O–C valence vibration, specifically the stretching vibration of this bond. This peak is commonly used to identify cellulose in various biological and synthetic materials and is also considered responsible for the amorphous regions within cellulose.

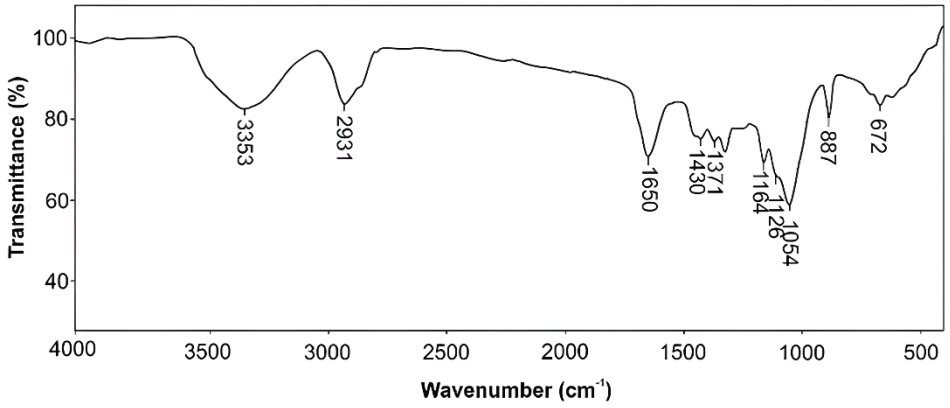


Figure 1: Infrared spectrum of native cellulose isolated from brown seaweed biomass (Source: Authors' analysis)

The spectrum of isolated cellulose closely resembled that of commercial cellulose (Zhang *et al*., 2017), showing no new bands but exhibiting slight variations in both intensity and position. This similarity suggests that the primary functional groups in cellulose were not altered, indicating that no chemical reactions occurred during the isolation process. Notable changes were observed in the position of the bands, particularly for the valence vibration of the O-H group. In the spectrum of isolated cellulose, this peak shifted to lower wavenumbers than that observed for commercial cellulose (from approximately 3500 cm^{-1} to 3380 cm^{-1}). This shift is likely attributed to the formation of intramolecular or intermolecular hydrogen bonds, conformational changes, and interchain interactions within the cellulose molecules. This peak indicated the presence of a larger amorphous region within the isolated cellulose structure. Consequently, the isolated cellulose demonstrated a satisfactory level of purity and quality, consistent with the findings of He *et al*. (2021).

Significant insights into the internal organization of cellulose can be obtained from the TCI, LOI, and HBI indices. These indices provide semi-quantitative information on the structural characteristics of cellulose, including the degree of crystallinity, molecular chain ordering and hydrogen-bonding intensity. Together, these parameters enable a comprehensive understanding of the structural integrity and performance of the isolated cellulose. They are essential for evaluating extraction quality and for defining its potential applications in biotechnological, pharmaceutical, and industrial processes. Higher TCI and LOI values indicate greater crystallinity and molecular order, whereas higher HBI values indicate stronger hydrogen bonding

and potentially enhanced WHC. The obtained index values were TCI = 1.48 ± 0.12, LOI = 1.23 ± 0.06, and HBI = 0.68 ± 0.01, reflecting the specific structural characteristics of this biopolymeric component. The TCI value (1.48) indicated that the isolated cellulose possesses a moderate degree of crystallinity, consistent with the expected characteristics of cellulose derived from seaweed (He *et al*., 2018). Compared to typical values for highly crystalline cellulose from wood sources (TCI > 1.8) (Lamo et al., 2024), the slightly lower TCI observed here suggests the presence of a greater proportion of amorphous regions, which may result from the inherent heterogeneity of seaweed cell walls. The relatively high LOI value (1.23 ± 0.06) indicates good lateral ordering of the cellulose chains, likely due to the efficient removal of amorphous components during the extraction process and the partial reorganization of molecular chains into more stable structures. Such ordering enhances mechanical stability and material resilience. In contrast, the lower HBI value (0.68 ± 0.01) reflects weaker hydrogen bonding between cellulose chains. This may be associated with a reduced number of available hydroxyl groups or their partial involvement in interactions with residual components of the seaweed matrix. Weaker hydrogen bonding can result in lower WHC but may simultaneously confer greater flexibility and chemical reactivity to the isolated cellulose, which is advantageous for its modification and further functionalization. Overall, the obtained TCI, LOI, and HBI values indicate that cellulose isolated from brown seaweed possesses a well-preserved crystalline structure with moderate ordering and relatively weaker intermolecular interactions, consistent with the structural characteristics of seaweed-derived cellulose. This structural profile enables native, isolated cellulose to be suitable for applications in the development of biodegradable films, hydrogels, and biocomposites, as well as for biosorption materials for the removal of heavy metals and organic pollutants from aqueous systems.

Morphology and Elemental Profile of the Surface of Isolated Native Cellulose

The morphology and elemental composition of isolated native cellulose were examined using SEM and EDS analysis. At lower magnification (180×), SEM micrographs revealed that the cellulose exhibited an irregular and porous surface structure (Fig. 2a). Such rough surface morphology suggests an increase in specific surface area, a feature commonly reported for cellulose fibers obtained from marine biomass following alkaline and bleaching treatments (Varma et al., 2025). The observed porosity is likely the result of degradation and solubilization of matrix polysaccharides such as alginate and fucoidan, which naturally surround cellulose microfibrils in brown seaweed cell walls. At higher magnification (700×), the microfibrous nature of the cellulose became more distinct (Figure 2b). The pronounced fibrillar morphology of the isolated material suggests that the applied extraction and purification procedures effectively disrupted the amorphous regions and exposed the underlying crystalline cellulose domains.

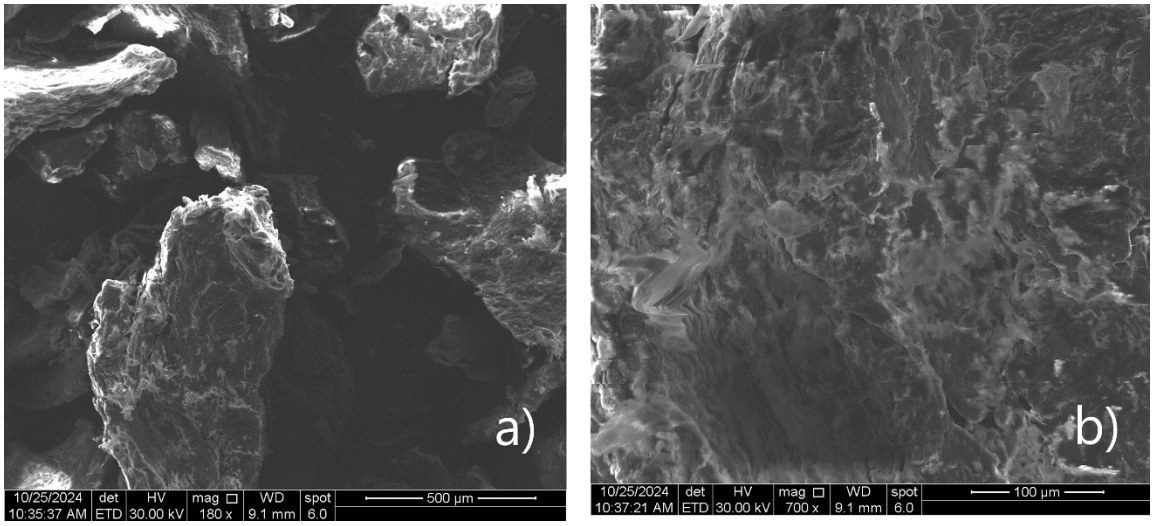
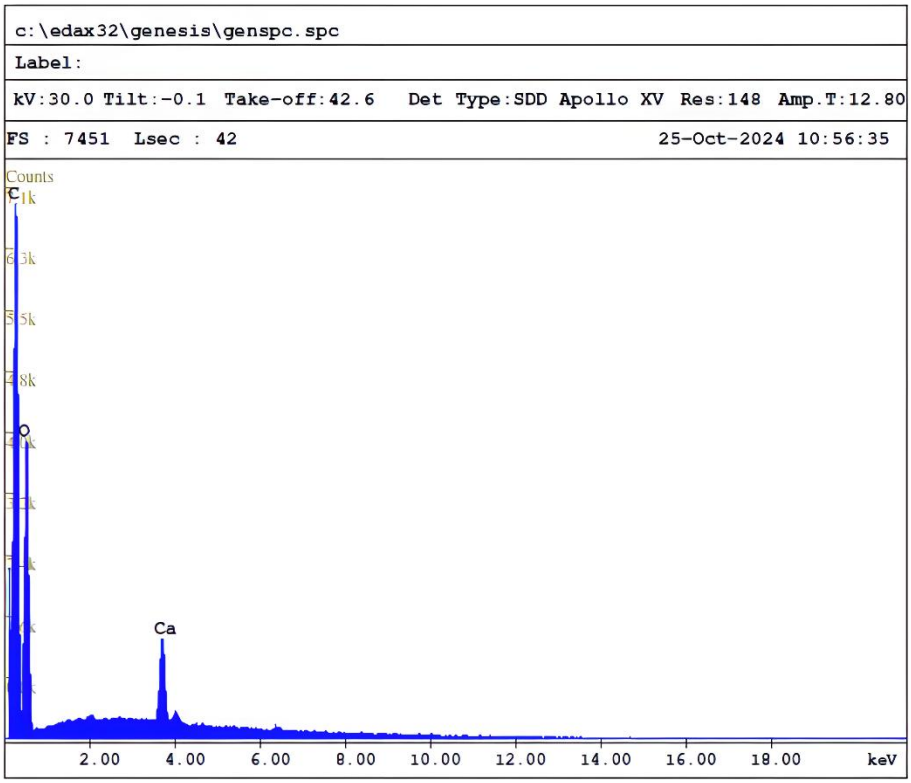


Figure 2: Scanning electron microscope images of isolated native cellulose from brown seaweed (*L. digitata*) biomass at magnification of 180× (a) and 700× (b) (Source: Authors' depiction)

The elemental composition obtained using EDS analysis further corroborates these observations. As illustrated in the EDS spectrum (Fig. 3), carbon (C) and oxygen (O) were identified as the predominant elements, forming the fundamental structural framework of cellulose. Quantitatively, carbon accounted for 56.30 wt% (63.89 at%), while oxygen represented 41.50 wt% (35.36 at%). These values are in close agreement with the theoretical stoichiometry of cellulose, confirming that the extracted material is polysaccharide-based and largely free from non-cellulosic impurities.



Element	Wt %	At %
C K	56.30	63.89
O K	41.50	35.36
CaK	2.19	0.75
Total	100.00	100.00

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
C K	1290.95	7.83	0.43	164.85
O K	703.54	14.77	0.59	47.63
CaK	281.22	66.19	1.11	4.25

Figure 3: Surface elemental analysis of isolated native cellulose using EDS analysis (Source: Authors' analysis)

For the isolated cellulose, the O/C molar ratio was determined to be 0.737, which is slightly lower than the theoretical value (0.83). Minor deviations from the theoretical ratio can be attributed to residual moisture or to the partial presence of hydroxyl and carbonyl surface groups introduced during chemical treatment. The O/C ratio observed in this study is consistent with previously reported EDS data for microcrystalline cellulose derived from *Valoniopsis pachynema* green macroalgae (Sunesh et al., 2024). The authors reported that further chemical treatment increased the O/C ratio, reflecting a higher oxygen content resulting from delignification.In addition to these major elements, traces of calcium (Ca) were detected (2.19 wt% and 0.75 at%). Similar calcium residues have been reported in other studies on seaweed-derived cellulose, where they were attributed to incomplete demineralization or to the strong binding affinity between Ca^{2+} ions and carboxyl groups within the seaweed matrix (Sunesh et al., 2024). However, the low Ca signal intensity observed in this study confirmed that the applied

purification process efficiently removed mineral impurities and preserved the structural and chemical integrity of the cellulose.

Overall, the combination of morphological and elemental analyses demonstrated that the applied isolation procedure successfully yielded cellulose with high purity. The rough, porous surface morphology, coupled with an O/C ratio consistent with the theoretical cellulose composition, confirms the removal of non-cellulosic materials and the exposure of crystalline cellulose domains. These features not only validate the efficiency of the extraction process but also enhance the material's potential for further modification and application in nanocellulose production, biocomposites, and bio-based films, where high surface reactivity and purity are essential.

Hydration properties of isolated cellulose

The WHC of the cellulose isolated from brown seaweed was determined to be 3.88 ± 0.013 g/g (387.6%), indicating a moderate ability of the material to retain water. Although that value demonstrated a considerable capacity for water binding, it is lower than the value reported by He et al. (2021) for cellulose extracted from *Lophatherum gracile* Brongn. (8.56 g/g). This discrepancy can be attributed to differences in the structural organization and morphology of the two cellulose samples. Low HBI limits the number of accessible hydroxyl groups available for interaction with water molecules, thereby diminishing WHC. Moreover, the presence of residual amorphous regions may further hinder the diffusion and binding of water within the cellulose matrix. By contrast, the cellulose from *Lophatherum gracile* Brongn. was treated with a higher concentration of NaOH (18%*m/v*), which induced a polymorphic transformation from cellulose I to cellulose II. This structural modification results in increased reactivity and higher sorption capacity, owing to the disruption of the ordered crystalline regions and the exposure of a greater number of hydrophilic sites. Additionally, the smaller particle size of cellulose II increases its specific surface area, facilitating greater contact between the hydroxyl groups and water molecules (Chen et al., 2013). These structural differences explain the observed variability in the WHC between the two cellulose sources.

The SC of the cellulose isolated from brown seaweed biomass was measured at 0.83 ± 0.09 mL/g. At room temperature, the cellulose swelled to approximately 25% of its original volume, which falls within the typical range of 20–40% reported for native cellulose structures (Ottesen & Syverud, 2021). However, this value is considerably lower than the 4 mL/g reported for cellulose from *Lophatherum gracile* Brongn. (He et al., 2021). A lower swelling degree can also be associated with higher crystallinity and a lower HBI value in seaweed-derived cellulose, which limits the penetration of water molecules into the tightly packed crystalline regions. Furthermore, cellulose I, the predominant polymorph identified in the isolated sample, exhibits a more ordered, compact structure than cellulose II, leading to reduced water uptake and swelling.

Accordingly, the hydration behavior of cellulose extracted from brown seaweed is strongly influenced by its semi-crystalline structure, low hydrogen bonding intensity, and the predominance of cellulose I polymorph. These features collectively contribute to moderate water-holding and swelling capacities, consistent with the material's partially ordered morphology. Although these values are lower than those of cellulose II-rich samples, they reflect a more stable, less reactive structure, which can be advantageous in applications requiring dimensional stability and moisture resistance.

CONCLUSION

In this study, pure cellulose was successfully isolated from the brown seaweed *L. digitata* using MAE operated at 336 W for 30 min. The extraction procedure significantly improved process efficiency, yielding cellulose amounts comparable to those obtained via conventional extraction, yet substantially reducing the required processing time. These results demonstrate that MAE is an effective, rapid, and environmentally favorable alternative for the isolation of cellulose from marine biomass. FTIR, SEM, and EDS analysis confirmed that the isolated cellulose retained characteristic functional groups, exhibited high purity, and displayed a rough, porous morphology. Structural indices indicated moderate crystallinity, good molecular order, and favorable hydration properties. The findings highlight the potential of brown seaweed-derived cellulose as a sustainable alternative to conventional cellulose sources, with broad applications in eco-friendly materials, biocomposites, nanocellulose, and advanced bioengineering products.

CRediT AUTHOR STATEMENT

Ivana M. Savić Gajić: Conceptualization, Methodology, Investigation, Writing – original draft**.**
Ivan M. Savić: Supervision, Investigation, Methodology, Reviewing and Editing.

All authors have read and agreed to the published version of the article.

COMPLIANCE WITH ETHICAL STANDARDS

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