Optimization of Sodium Hydroxide Concentration for the Extraction and Characterization of Cellulose Fibers from *Ulva lactuca*

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ABSTRACT

As demand for sustainable biopolymers is growing, *Ulva lactuca* has emerged as a promising macroalgal source of cellulose. Alkaline hydrolysis using sodium hydroxide (NaOH) is widely applied in cellulose extraction to remove lignin; however, the influence of sodium hydroxide (NaOH) concentration during delignification process of *U. lactuca* remains insufficiently understood. Hence, this study aimed to identify the optimal NaOH concentration for cellulose extraction from *U. lactuca* and to characterize the resulting fibers. Alkaline treatments were performed using NaOH concentrations of 10%, 20%, 30%, and 40%. The extracted cellulose was evaluated for yield, functional groups, thermal stability, crystallinity index (CrI), and morphology using Fourier Transform Infrared (FTIR) Spectroscopy, X-ray diffraction (XRD), simultaneous thermal analysis, and Field emission-scanning electron microscopy (FE-SEM). Results showed that cellulose yields ranged from 4.38% to 5.44%, with no significant differences among treatments. In contrast, NaOH concentration significantly affected cellulose morphology, with enhanced delignification and fibrillar refinement observed at higher alkali levels. FTIR spectra confirmed cellulose purity through characteristic O–H and C–H stretching vibrations, β-glycosidic linkages, and the absence of hemicellulose-related peaks. XRD analysis showed that 30% NaOH treatment produced the highest CrI (84.09%), while higher concentrations induced structural degradation. Thermal analysis revealed a two-stage degradation process, consisting of moisture loss at 120–150 °C followed by major cellulose decomposition at 250–300 °C. Overall, 30% NaOH was identified as the optimal concentration for extracting α-cellulose from *U. lactuca*. These findings provide important insights for optimizing alkaline extraction processes and support the potential utilization of *U. lactuca* as a sustainable raw material for cellulose-based bioproducts.

Keywords: green seaweed, *Ulva lactuca* cellulose fiber, SDGs

Introduction

Cellulose is a polysaccharide composed of glucose units linked by β-1,4-glycosidic bonds, with the chemical formula $(C_6H_{10}O_5)_n$, where n denotes the degree of polymerization (Wang et al., 2020). Cellulose is predominantly derived from plants, which are the primary contributors to its production. It is a key component of plant cell walls, where it exists as a mixture of homologous polymers, often found in combination with other polysaccharides and lignin in varying proportions. Due to its renewability and biodegradability, cellulose has a wide range of industrial applications, including use as a raw material in the production of paper, textiles, and bioplastics.

Ulva lactuca, a green macroalga classified within the Chlorophyceae group, is a significant source of cellulose (Tirpan et al., 2020). This species contains 30.89 ± 1.87% ash, 2.24 ± 0.37% fat, 2.85 ± 0.79% protein, 7.54 ± 0.19% crude fiber, and 20.86 ± 2.29% carbohydrates (by difference) (Santi et al., 2012). This seaweed is widely distributed along coastlines, making it an abundant and cost-effective biomass resource. *U. lactuca* cellulose content has been shown to vary with maturity and environmental conditions. Biomass age is a significant determinant of overall cellulose concentration and extraction yield, with younger individuals tending to yield lower cellulose fractions (Schiener et al., 2015; Wahlström et al., 2020), *U. lactuca* offers potential as a renewable source of cellulose. Baghel et al. (2021) reported a higher cellulose content in Ulva spp., ranging from 3.5% to 16.3%, highlighting variations depending on factors, such as species-specific cell wall structure, growth stage, environmental conditions, and biomass processing or extraction methodology. In *Ulva* spp., cellulose coexists with ulvan, minor hemicelluloses,

proteins, lipids, pigments, and minerals; sequential removal of these components concentrates cellulose in residual biomass, enabling efficient lignin-free extraction . The relatively low and variable cellulose content in Ulva spp., together with the presence of a complex non-cellulosic matrix dominated by ulvan and minor hemicelluloses (Lahaye & Robic, 2007; Domozych et al., 2012), necessitates selective extraction strategies for effective cellulose isolation. Alkaline treatment using sodium hydroxide (NaOH) has been widely adopted due to its ability to efficiently solubilize ulvan, proteins, pigments, and minerals while preserving the crystalline framework of cellulose (Wahlström et al., 2020; Baghel et al., 2021). This methodological compatibility between biomass composition and extraction chemistry underpins the extensive use of NaOH for cellulose recovery from biomass of Ulva species.

The success of cellulose extraction depends heavily on the extraction methodology, particularly alkaline hydrolysis conditions. The NaOH effectively removes lignin and enhances cellulose content by facilitating delignification and purification of the cellulosic fraction (Tirpan et al., 2020). Similarly, optimizing NaOH concentration, temperature, and extraction time for *U. lactuca* yielded 4.82% cellulose with a crystallinity index of 72.58% under 5% NaOH at 100 °C for 2 h, highlighting the importance of its concentration on both yield and physicochemical properties of extracted cellulose (Gomaa et al., 2021). Furthermore, NaOH treatments in other biomass sources have been shown to significantly influence cellulose crystallinity by removing amorphous components, suggesting that careful adjustment of alkali conditions is critical to maximize cellulose quality and integrity during extraction (e.g., alkaline extraction studies) (Ardila et al, 2024).

These findings indicate the necessity of further investigation to determine the most effective NaOH concentration for cellulose extraction from *U. lactuca*. Although previous studies have demonstrated the feasibility of extracting cellulose from Ulva species, systematic evaluation of NaOH concentration and its influence on the physicochemical characteristics of the resulting cellulose—such as crystallinity, morphology, and thermal stability—remains limited. Addressing this knowledge gap is important for improving extraction efficiency and ensuring the production of cellulose with properties suitable for industrial applications. Establishing an optimized extraction protocol is therefore a fundamental prerequisite for transforming this abundant marine biomass into a high-value, sustainable industrial resource that can potentially replace petroleum-based materials.

From a sustainability perspective, advancing the efficient utilization of marine biomass also supports broader global efforts toward sustainable material production. By enabling the conversion of widely available macroalgal biomass into renewable cellulose-based materials, this research contributes to SDG (Sustainable Development Goals) 12 (Responsible Consumption and Production) by promoting the use of biodegradable, renewable materials. In addition, the development of efficient cellulose extraction methods contributes to SDG 9 (Industry, Innovation, and Infrastructure) by fostering innovation in the production of bioplastics and other eco-friendly materials. By optimizing the use of *U. lactuca* for cellulose extraction, we also contribute to SDG 14 (Life Below Water), ensuring that seaweed-based biomass is sustainably sourced without harming marine ecosystems (Mogany et al., 2024).

Therefore, the present study aims to determine the optimal NaOH concentration for cellulose extraction from *U. lactuca* and to comprehensively characterize the extracted cellulose in terms of yield, functional groups, crystallinity, thermal stability, and microstructure. The novelty of this work lies in the systematic investigation of a wide range of NaOH concentrations combined with integrated structural and physicochemical characterization, providing new insights into how alkaline conditions influence cellulose quality and enabling the identification of optimal extraction conditions for sustainable macroalgal cellulose utilization.

Materials and Methods

Materials

The focal species, *U. lactuca*, was obtained from Lombok, West Nusa Tenggara, Indonesia. Hydrogen peroxide (H_2O_2) and NaOH were purchased from CV Anugrah Chemical, Jakarta, Indonesia, while acetic acid (CH_3COOH) was supplied by Glatt Chemical, Bandung, Indonesia. All chemicals used in this study were of technical grade.

Preparation of *U. lactuca* powder

The studied species, *U. lactuca*, was washed with running water until clean. The preparation of *U. lactuca* powder began with soaking the seaweed in freshwater for 24 hours to remove dirt and mineral salts. The soaked seaweed was then washed under running water, followed by size reduction using a laboratory blender. Subsequently, it was dried using an oven at 60 °C until constant weight was achieved (typically 24-48 h) (de Faria et al., 2013). The dried seaweed was ground into powder using a porcelain mortar and pestle set. The ground seaweed was sieved using a 400-mesh flour sieve and then stored in a plastic container.

Extraction of cellulose fibers

The cellulose extraction from *U. lactuca* was based on the method by Nurhayati & Kusumawati (2014). For the extraction process, 20 grams of *U. lactuca* powder were placed into a 500 mL beaker. The first step involved the removal of hemicellulose using a 0.5 M CH_3COOH solvent with heating at 80 °C for 2 hours and followed by delignification using various concentrations of NaOH solvents (10%, 20%, 30%, and 40%) with heating at 80 °C for 2 hours. Further, the bleaching process was carried out using a 2% H_2O_2 solution and heated at 80 °C for 2 hours. The solution obtained from the extraction process was allowed to stand at ambient temperature. Consequently, the seaweed residue was filtered using a 400-mesh sieve and washed with distilled water until a neutral pH was achieved. The resulting pulp product was stored at room temperature and dried in an oven at 60 °C to obtain cellulose fibers in dry form.

Yield Determination

The cellulose yield was calculated as the ratio of the dry weight of extracted cellulose to dry weight of the initial seaweed and expressed as a percentage (%):

$$\text{Celllulose yield (\%)} = \frac{\text{Dry weight of extracted cellulose}}{\text{Dry weight of seaweed}} \times 100$$

Statistical analysis was performed using one-way analysis of variance (ANOVA) using IBM Statistics V21 (IBM, USA). Differences were considered statistically significant at $p<0.05$.

Functional Group Analysis

Functional groups of the extracted cellulose were identified using an ATR-IR spectrometer (Bruker Optics, Germany). Spectra were recorded in the wavenumber range of 4000-500 cm^{-1} using the ATR mode. The resulting data are presented as spectral peaks exhibiting specific transmittance values.

Thermal Stability Analysis

Thermal stability of cellulose fibers was evaluated using Simultaneous Thermal Analysis (PerkinElmer STA 6000, USA), which combines Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC). About 10 mg of dried sample was heated from 25-500^{o}C under nitrogen flow rate of 20 mL/min, with a heating rate of 10^{o}C/min. Changes in sample mass during the analysis were evaluated using Origin 2019 software.

Crystallinity Analysis

Crystallinity analysis was carried out using Shimadzu XRD-7000 MaximaX (Japan). Measurements were performed at room temperature using CuKα radiation (λ = 1.54 Å) at 40 kV, 30 mA over a 2θ range of 10-50 ^{o}. The crystallinity index (CrI) of each sample was calculated using Segal method (Segal et al., 1959):

$$\%CrI = \frac{I_{002}}{I_{002}+I_{am}} \times 100$$

Where I_{002} is the maximum diffraction intensity of the (002) crystalline peak and Iam is the intensity of the amorphous region.

Morphological Analysis

The morphology of fiber was examined using field emission scanning electron microscope (FE-SEM, Thermo Scientific, Italy) operated at 5 kV. Samples were freeze-dried, mounted on sample holders using carbon tape, and sputter-coated with a thin conductive layer prior to imaging.

Results and Discussion

Yield of cellulose

To evaluate the effectiveness of the cellulose extraction process from *U. lactuca*, this study involved varying the concentration of NaOH for delignification, ranging from 10% to 40%. The cellulose yield from this process ranged from 4.38 ± 0.77% to 5.44 ± 0.27% (Figure 1). The statistical analysis indicated no significant effect of NaOH concentration on cellulose yield ($p > 0.05$). The properties and yield of extracted cellulose depend on factors such as NaOH concentration and the raw material (Bouredja et al., 2015). Notably, the concentrations exceeding 17% have been shown to reduce cellulose yield, likely due to overextraction or degradation of the cellulose fibers.

A critical step in cellulose extraction from biomass is the effectiveness of the delignification process. In the context of *U. lactuca*, the term “delignification” refers to the removal of non-cellulosic cell wall components, primarily ulvan and hemicellulose-like polysaccharides, rather than true lignin as found in terrestrial lignocellulosic biomass. These matrix polysaccharides form a complex network with cellulose microfibrils through hydrogen bonding and ionic interactions, and disruption of this network is essential for effective cellulose release (Wahlström et al., 2020; Baghel et al., 2021). The decrease in yield with increasing NaOH concentration may result from incomplete delignification at low concentrations and excessive dissolution of non-cellulosic components at high concentrations. While higher NaOH concentrations enhance lignin removal and promote the disruption and solubilization of hemicellulosic structures, excessively strong alkaline conditions may reduce overall process efficiency by dissolving valuable biomass components

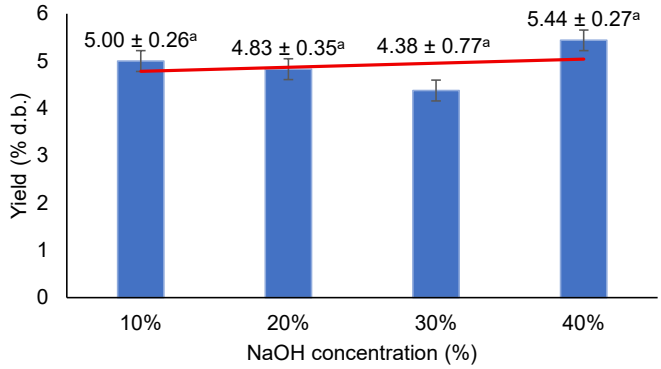

Figure 1. Yield of cellulose fibers extracted from *U. lactuca* using different NaOH concentrations (the mean values with the same lowercase letter are insignificantly different ($p<0.05$).

However, increased Na+ ion penetration at higher concentrations can also improve cellulose release, potentially increasing yield under optimal conditions (Prasetia et al., 2018).

The highest cellulose yield observed in this study was lower than that reported in studies using lower concentrations of NaOH or alternative pretreatment methods. Specifically, Patrichi et al. (2023) achieved a 20.944% yield of *U. lactuca* cellulose using a substrate-to-liquor ratio of 1/20, a 90% ethanol concentration, and a 4 g/L salt concentration. Differences in yield between studies can be attributed to the pretreatment methods, extraction conditions, and particularly the source material. Plants with higher fiber content generally yield more cellulose (Nurnasari & Nurindah, 2018). Further, the cellulose content in banana pseudostems varies across studies, with reported values ranging from approximately 45% to 56.4%. In addition, one study indicates that banana pseudostems contain about 49–45% cellulose (Li et al., 2015), while another reports a cellulose content of 56.4% (Diarsa & Gupte, 2021).

Moreover, the chemical properties of the raw material, such as lignin and hemicellulose content, also significantly influence the yield. In alkaline treatments, Na+ ions can penetrate the porous structure of cellulose, altering its crystallinity and facilitating delignification. Strong bases like NaOH can also convert monosaccharides and terminal groups in polysaccharides into carboxylic acids, potentially affecting the chemical structure of the cellulose and reducing its yield (Knill & Kennedy, 2003; Kim et al., 2016;).

Visual Description of Cellulose Fiber

The progressive morphological changes in cellulose fibers were revealed following delignification with varying NaOH concentrations (Figure 2). At the initial observation, cellulose fibers appear in their natural state, both in wet and dry conditions. The wet cellulose fibers appear clumped together, indicating that the bonds between the fibers are still strong. After drying, the fibers are more separated but remain relatively coarse in form. A more significant change is observed when the cellulose fibers are extracted with NaOH solution. The higher the NaOH concentration used, the finer and more uniform the resulting cellulose powder becomes. This suggests that NaOH may play a crucial role in breaking the bonds that hold the cellulose fibers together, resulting in smaller particles (Cai et al., 2015; Permata et al., 2021).

At a NaOH concentration of 10%, cellulose fibers begin to exhibit alkaline-induced structural degradation, primarily associated with fiber swelling and partial disruption of hydrogen-bonded networks, while the cellulose backbone remains largely intact. As the concentration increases to 20% and 30%, alkaline hydrolytic effects intensify, leading to progressive weakening of inter-fiber associations and enhanced fibrillation, which results in finer cellulose particles. This investigation is consistent with previous studies demonstrating a direct relationship between NaOH concentration and the extent of alkaline-induced fiber disintegration (Sayakulu & Soloi, 2022). At 40% NaOH, the cellulose undergoes severe alkaline swelling and

Figure 2. Cellulose fiber in wet state (a), Cellulose fiber in dry state (b), Cellulose fibers extracted from *U. lactuca* using 10% (c), 20% (d), 30% (e), and 40% (f) NaOH.

partial depolymerization, accompanied by extensive disruption of crystalline domains and possible cellulose I–to–cellulose II transformation, producing a highly uniform and fine cellulose powder. These effects reflect the breakdown of inter- and intra-fiber bonding under strong alkaline conditions (Budtova & Navard, 2016; Martin-Bertelsen et al., 2020).

These findings further support the notion that higher NaOH concentrations improve the delignification process and enhance the physical properties of cellulose fibers by breaking down their structural components more efficiently (Bouredja et al., 2015; Utoro et al., 2023).

Fourier Transform Infra-Red (FTIR)

In the FTIR spectrum of *U. lactuca* cellulose fibers, measured across the wavenumber range of 4000–500 cm^{-1} (Figure 3), the presence of several distinct peaks confirms the structural integrity of cellulose and the presence of its characteristic functional groups. The O-H stretching vibration peak observed at 3335 cm^{-1} is particularly important because it signals the hydroxyl (–OH) group, which is essential for the cellulose structure and its ability to form hydrogen bonds. Meenakshi et al. (2002) and Zhao et al. (2019) point out that sharp peaks in the 3700–3000 cm^{-1} range are indicative of the intramolecular hydrogen bonding that stabilizes the cellulose polymer. This region reflects the distinctive hydrogen-bonding pattern found in cellulose, which contributes to its crystalline nature and its high degree of hydrophilicity, both important properties in cellulose-based materials.

Additionally, the peak at 2914 cm^{-1} corresponds to the C-H stretching vibration, further affirming the presence of cellulose. This absorption is often observed in cellulose structures due to the aliphatic nature of the cellulose backbone (Chen et al., 2018). The presence of such a peak is critical for confirming the carbohydrate-based nature of the material and distinguishing cellulose from other potential contaminants or fibers, such as hemicellulose or lignin.

A significant feature in FTIR analysis is the absence of a peak at around 1730 cm^{-1}, a characteristic absorption for acetyl and uronate ester groups that are commonly found in hemicellulose. This absence is a positive indicator of cellulose purity, suggesting that the treatment process, likely involving alkali or other treatments, successfully removed the hemicellulose content. The absence of this peak aligns with findings by Leite et al. (2017), who note that the absence or reduction of peaks typically linked to hemicellulose and lignin signals a more refined cellulose structure. This purification is critical for various cellulose applications, as the removal of non-cellulosic components enhances the material's mechanical and

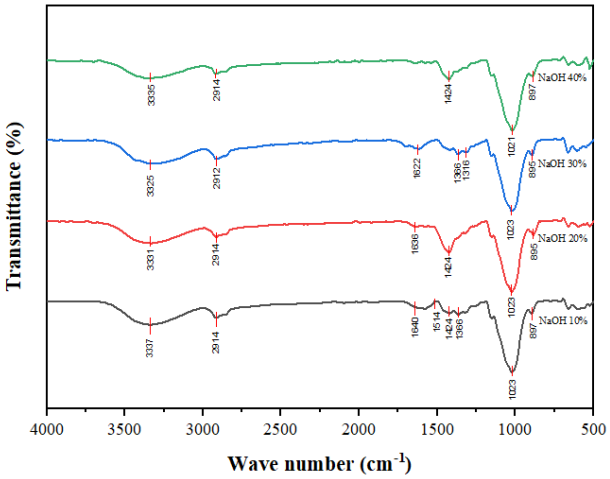

Figure 3. FTIR Spectrum of cellulose fiber extracted from *U. lactuca*

Tabel 1. FTIR spectrum and functional group content of cellulose fiber extracted from *U. lactuca*

Wavenumber (cm^{-1})	Functional Groups	Interpretation	Reference
3400 - 3300	O-H	Cellulose	Cai et al. (2015).
1514	C-H	Hemicellulose and pectin	Cai et al. (2015).
1640	OH-Bond	Water molecules adsorbed onto cellulose	Karimi et al. (2014).
2921 - 2923	C-H	Cellulose	Salem et al. (2022).
669-900	$-(CH_2)_n$	Cellulose	Karimi et al. (2014).
897	C-H	Cellulose	Johar et al. (2012).

chemical properties.

Furthermore, the minor peak observed at 1640 cm^{-1} (Table 1), attributed to water adsorption, indicates that despite the cellulose being dried prior to FTIR analysis, residual moisture remains within the fiber matrix. This is consistent with the characteristic bending vibration of the O-H group of water molecules adsorbed onto the cellulose surface. Abidi et al. (2014) explain that water-induced peaks typically appear around 1640 cm^{-1}, as well as in the 3100–3600 cm^{-1} region, reflecting the moisture content within the material. Water plays a crucial role in cellulose properties, influencing its interaction with other materials and its behavior in various environmental conditions.

Additionally, the absorption band at 897 cm^{-1}, linked to the C-H vibrations of the β-glycosidic linkage, is another hallmark feature of cellulose. This peak confirms the β-D-glucopyranose units that form the primary structure of cellulose (Ding et al., 2020). The β-glycosidic bond is responsible for the rigidity and structural integrity of cellulose, which is crucial for its role as a strong, stable polymer (Etale et al., 2023). This characteristic peak serves as a clear indication of the cellulose's molecular structure and its ability to form crystalline structures, which directly impacts its mechanical properties and its suitability for various applications in materials science and engineering (Rongpipi et al., 2019).

Treatment with NaOH has been shown to significantly alter the FTIR spectrum, reflecting the dissolution of non-cellulosic components such as lignin and hemicellulose. Alkali treatments are effective at breaking down the ester bonds between cellulose, hemicellulose, and lignin, leading to a more purified cellulose structure. This change in the FTIR spectrum post-treatment signifies the successful removal of these components, further enhancing the quality and utility of the cellulose for various applications (Rongpipi et al., 2019).

X-ray diffraction (XRD)

The XRD spectrum of *U. lactuca* cellulose fibers reveals a prominent peak at 2θ = 21.48°, which is indicative of the α-cellulose crystalline structure (Figure 4). Doh et al. (2020) points out that a peak in the range of 2θ = 20° to 24° is a characteristic feature of cellulose derived from marine organisms, including seaweed. The XRD spectrum of cellulose typically shows two distinct peaks, especially one corresponding to the crystalline portion of the cellulose (I_{002}), and another representing the amorphous region (Iam). The crystalline peak (I_{002}) appears at around 21°, while the amorphous peak (Iam) is usually observed at approximately 12°. In this study, the presence of the 21° peak with high intensity suggests that the sample primarily consists of α-cellulose, with a crystallinity index of 84.09%.

Crystallinity of cellulose fibers were affected by the concentration of NaOH used in the extraction process as shown in this study. Cellulose fibers treated with 10% NaOH exhibited the lowest crystallinity (75.34%), whereas fibers treated with 30% NaOH showed the highest crystallinity (84.09%). This findings indicates that the alkaline treatment helps to increase the crystalline portion of the cellulose fibers by removing or disrupting the amorphous regions, such as hemicellulose and lignin (Machmudah et al., 2025). A 30% NaOH solution effectively reduces the lignin content, leading to a more ordered cellulose structure. This increase in crystallinity was corroborated by infrared spectroscopy data, which also showed the highest cellulose content in the 30% NaOH-treated fibers.

However, a higher concentration of NaOH (40%) resulted in a noticeable decrease in crystallinity (74.29%), as observed in the XRD analysis. This decrease is

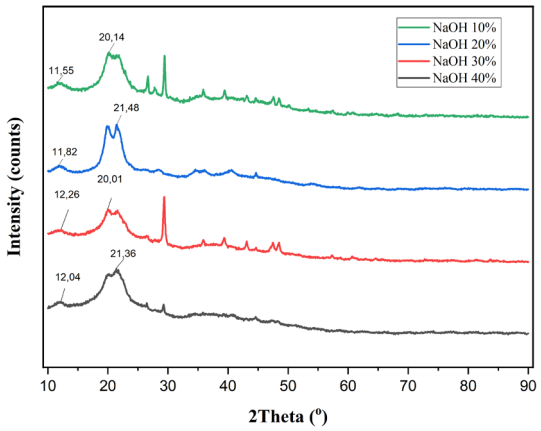

Figure 4. The XRD diffractogram of cellulose fibers extracted from *U. lactuca*

attributed to alkali-induced disruption of the crystalline cellulose structure rather than direct cleavage of the β-1,4-glycosidic backbone. At high alkali concentrations, Na^+ and OH^- ions penetrate the crystalline regions, weaken and disrupt the extensive intra- and intermolecular hydrogen-bonding network, and induce pronounced alkali swelling. This process facilitates chain separation and partial rearrangement of cellulose chains, often accompanied by a transformation from cellulose I to the less ordered cellulose II polymorph, thereby increasing the amorphous fraction and reducing overall crystallinity (Sandy et al., 2010; Mittal et al., 2011; Ji et al., 2018; Machmudah et al., 2025).

Simultaneous Thermal Analysis (STA)

Four cellulose fiber samples were tested, each exhibiting distinct thermal behavior. The cellulose fibers begin to decompose at around 120 °C, with two distinct peaks observed in the thermogravimetric curve (Figure 5). The first peak, between 120-150 °C, represents the evaporation of water from the fibers, while the second peak, between 250-300 °C, is linked to the thermal degradation of the cellulose itself. Johar et al. (2012) elucidate that this early-stage weight loss is due to the high moisture content in the cellulose fibers. As the temperature increases, the water evaporates completely, causing a sharp decrease in the curve, which indicates the high moisture content of the fibers. This moisture loss absorbs heat, which is reflected as fluctuations in the DSC curve within the temperature range of evaporation, visible across all cellulose samples.

The variation in NaOH concentration during the delignification process significantly influences these thermal behaviors by modifying cellulose purity, crystallinity, and molecular organization (Sun et al., 2004; Mittal et al., 2011). Moderate NaOH concentrations enhance thermal stability by removing thermally labile non-cellulosic components such as hemicellulose and matrix polysaccharides, which typically decompose at lower temperatures, thereby shifting the main cellulose degradation peak toward higher temperatures (Yang et al., 2007; Poletto et al., 2014). In contrast, excessively high NaOH concentrations may reduce thermal stability due to alkali-induced swelling, partial depolymerization, and disruption of crystalline domains, leading to an earlier onset of cellulose thermal degradation (Budtova & Navard, 2016; Ji et al., 2018).

These findings align with Aulia et al. (2013), who studied cellulose derived from Empty Fruit Bunches (EFB) of oil palm. In their research, they observed a similar weight loss pattern, with cellulose nanocrystals beginning to decompose at around 160 °C. The temperature-dependent weight loss in both studies underscores the importance of temperature in cellulose degradation. Such differences in thermal degradation profiles reported across studies can therefore be attributed, at least in part, to variations in alkaline treatment severity, which directly affect cellulose chain integrity, crystallite size, and thermal resistance (Poletto et al., 2014; Arnata et al., 2022).

The TGA analysis of the cellulose fibers aims to establish a relationship between the loss of mass and temperature. In the current study, the cellulose fibers were heated from room temperature up to 500 °C. The resulting TGA curve reveals that from 100 °C to 250 °C, the cellulose fibers experience significant weight loss, indicating the evaporation of water (Figure 5). After surpassing 350 °C, the mass continues to decrease gradually, leaving only a small residue at 500 °C. This final mass is notably smaller than the initial sample, highlighting the extent of thermal decomposition (Hideno, 2016). The amount of residual char and the rate of mass loss at elevated temperatures further confirm that NaOH concentration during pretreatment plays a critical role in determining the thermal degradation pathway and stability of the extracted cellulose (Yang et al., 2007; Mittal et al., 2011).

Morphology of cellulose

The morphological characteristics of the cellulose fibers were analyzed using FE-SEM at magnifications

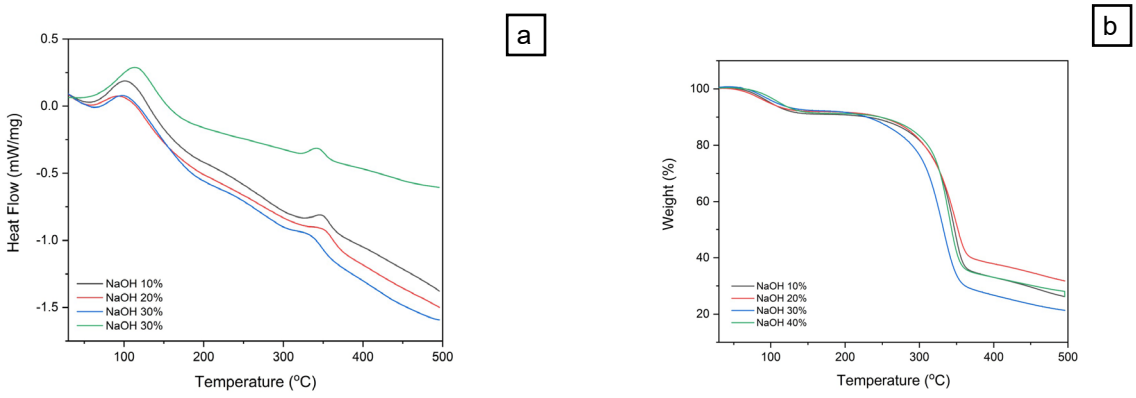

Figure 5: DSC (a) and TGA (b) curves of cellulose fiber extracted from *U. lactuca*

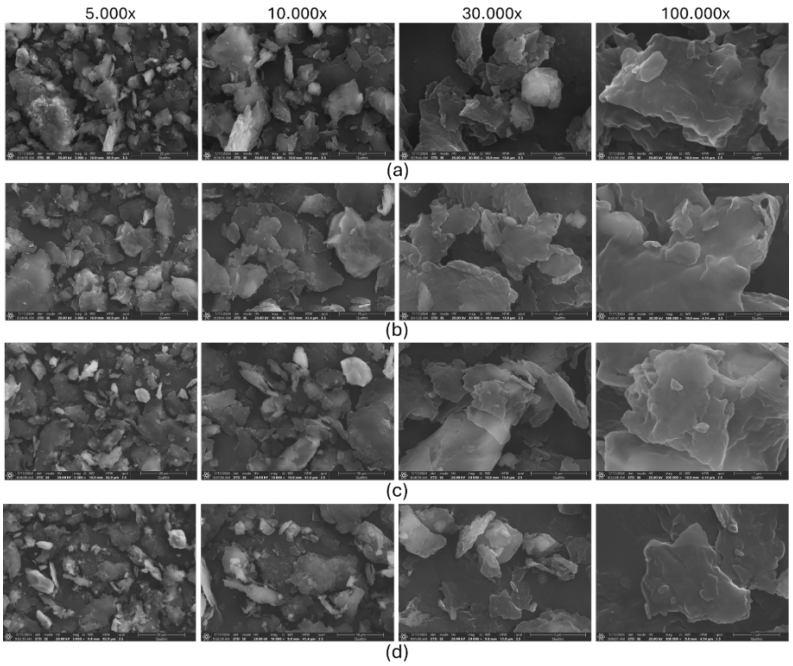

Figure 6. Cellulose fibers extracted from *U. lactuca* using NaOH solutions: 10% (a), 20% (b), 30% (c), and 40% (d).

ranging from 5,000× to 100,000×, highlighting the morphological differences among the four samples (Figure 6). Notably, the use of a 40% NaOH solution (Figure 6d) shows cellulose fibers with a denser and smoother sheet-like morphology compared to the 10%, 20%, and 30% NaOH treatments; the surface morphology of the other three samples appears fibrous, indicating the presence of cellulose (Uranchimeg et al., 2022). NaOH can degrade the lignin structure that surrounds cellulose and hemicellulose in lignocellulosic materials (Ciftci et al., 2018).

At the lowest concentration of NaOH (10%), the cellulose fibers appear less organized. Many of the fibers are still grouped together in aggregates, and they have not been fully separated into individual fibers. Additionally, the surface of the fibers looks less clean, which suggests the presence of residual non-cellulosic materials that were not completely dissolved during the extraction process. When the NaOH concentration was increased to 20%, there is a marked improvement in the organization of the fibers. Individual fibers become more distinct and separate from one another, indicating a more defined fibrous structure compared to the 10% NaOH treatment. Nevertheless, the fibers are still somewhat agglomerated, and the surface, though cleaner, is not as polished as it could be.

At a concentration of 30% NaOH, the cellulose fibers appear to be well-organized and separated. The individual fibers are clearly distinguishable, with their surfaces looking much cleaner. The pores on the fiber surface are more noticeable, which suggests that this concentration has effectively removed a significant amount of the non-cellulosic components, resulting in a purer form of cellulose. Finally, at the highest NaOH concentration of 40%, the cellulose fibers are the most organized and separated. The surface is the cleanest, with the pores of the fibers clearly visible. This suggests that a higher concentration of NaOH is highly effective in removing impurities such as lignin, hemicellulose, and other non-cellulosic components from the cell walls of *U. lactuca*. As a result, the fibers are purer and their structure is more defined.

These differences in the morphology of the cellulose fibers are likely the result of the varying abilities of NaOH to dissolve components that make up the cell wall of *U. lactuca*, including lignin, hemicellulose, and pectin. Higher NaOH concentrations (30-40%) enhance the removal of these materials, yielding purer, more porous, and better-structured fibers. These improvements are important for enhancing the quality of cellulose extracted from seaweed, making it more suitable for a wide range of applications, such as biocomposites, biofuels, and other industrial uses.

In summary, this study demonstrates that while the yield of cellulose from *U. lactuca* remains statistically stable across varying alkaline concentrations, the structural and thermal properties are highly dependent on the intensity of the NaOH treatment. The optimal concentration of 30% NaOH was found to be the threshold for achieving maximum crystallinity (84.09%) and high

purity, as evidenced by the removal of ulvan-related functional groups in FTIR and the appearance of well-separated, porous microstructures in FE-SEM. However, exceeding this concentration to 40% NaOH leads to a decline in structural integrity due to severe alkaline swelling and crystalline disruption. These findings highlight the potential of *U. lactuca* as a high-quality biopolymer source, yet also reveal challenges regarding relatively low extraction yields compared to terrestrial biomass. Future research should focus on intensifying the pre-treatment phase, such as utilizing microwave-assisted or enzymatic extraction, to improve yield without compromising the high crystallinity achieved. Furthermore, exploring the conversion of the extracted cellulose into nanocellulose (CNC/CNF) would provide deeper insights into its potential for high-end applications in biodegradable packaging and biomedical engineering.

Conclusions

The properties of cellulose extracted from *U. lactuca* are significantly influenced by NaOH concentration, with 30% NaOH optimally applied to produce well-defined fibers with high crystallinity. Structural degradation resulted from excessive alkali treatment, but the cellulose yield was not notably affected. These findings emphasize the importance of controlling alkali concentration for potential biocomposite and biodegradable packaging applications.

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