Extraction, characterization, and fabrication of cellulose biopolymer sheets from *Pistia stratiotes* as a biodegradative coating material: an unique strategy for the conversion of invasive weeds into value-added products

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Abstract

This study explores the possibility of using Water lettuce (*Pistia stratiotes*) as a cost-effective substrate for the commercial extraction of cellulose biopolymer using a wide variety of physicochemical treatment methods to compare their efficiency in cellulose extraction. The extraction of cellulose from water lettuce, although promising due to their high cellulose content, was less explored as per the available literature. In this study, functional properties like bulk density-packed density, hydrated density, water retention capacity, oil retention capacity, emulsifying activity and setting volume of the extracted cellulose were studied. The cellulose content from water lettuce was found to be 38.94 ± 0.10% by anthrone method. Preliminary confirmation of cellulose biopolymer was done using the study of functional groups using Fourier Transform Infrared (FT-IR) analysis. Further characterization studies like Scanning Electron Microscopy (SEM), X- Ray Diffraction (XRD), Differential Scanning Calorimetry (DSC) and thermogravimetric analysis (TGA) were conducted to understand the molecular architecture and purity of the cellulose extracted. Fabrication of cellulose sheets was carried out using starch as the plasticizer. Biodegradation studies were conducted in garden soil for four weeks and a high degradation rate of 78.22 ± 0.71% was observed in the fourth week of soil burial.

Keywords Alkali treatment · Biodegradation · Biopolymer coating · Cellulose · Water lettuce

Introduction

Aquatic plants are essential in maintaining the ecosystem balance in the environment. The threats from aquatic plants arise when their growth in the water system becomes too dense. The exotic varieties tend to overgrow and invade areas, which are the breeding waters of many fishes. These plants also interfere with many recreational activities such as swimming and fishing. The overgrowth of these plants can be a result of high levels of nutrient influx contributed...
by the runoff of agricultural wastes and sewage-disposal drainage, which significantly escalates the growth [1]. When non-native plants are introduced into water bodies, they perish due to the absence of their native natural predators. The aquatic exotic plants, which are causing the main problems in water bodies are water hyacinth, water lettuce and water moss [2]. These non-native plants, which intrude into the ecosystem and often pose severe threats to the indigenous fauna and flora. Multiple strategies were developed for aquatic weed management; especially composting and using them for biogas production through anaerobic generation. These weeds are important sources of polymeric substances like cellulose that have a high demand in the global market due to their widespread application in various sectors. Utilization of water weeds for biopolymer production is in its dawn and requires more focus in the years ahead.

Cellulose is one of the primary components, which is primarily present in the cell walls of plants, photosynthetic organisms, and various microorganisms. It is a crystalline polysaccharide that constitutes a linear chain of repetitive units of glucose interconnected through β (1→4) linkages [3]. However, various pretreatment processes viz., physical, chemical, biological, or integrated processes, can significantly reduce crystallinity, which enhance the production of monomer, glucose [4].

Owing to the attractive physical and chemical properties of biopolymers have innumerable applications in different industries such as food, paper, pharmaceuticals, etc. [Umesh, Mridul, Sabarathinam Shanmugam, Timo Kikas, Nguyen Thuy Lan Chi, and Arivalagan Pugazhendhi. "Progress in bio-based biodegradable polymer as the effective replacement for the engineering applicators." Journal of Cleaner Production (2022): 132267]. Other than these applications, cellulose biomass is also used as a potential feedstock for ethanol production globally [5]. The extraction procedure of cellulose from the plant biomass proceeds through drying and powdering to maximize the surface area for better chemical reaction [6]. In the next step, the cementing molecules (lignin and hemicellulose) should be removed, as the presence of these molecules can interfere with the crystallinity of the cellulose fibers [7]. Hemicellulose and lignin tend to reduce the crystallinity ratio, thermal stability and other mechanical properties [8]. The purification techniques remove the hemicellulose and lignin, as well as prevent moisture absorption and improve the surface properties of the extracted fiber [9]. The alkali bleaching treatment is the most preferred purification method, among the different methods. This method is popular because of the easy availability of KOH/NaOH, sodium chloride and acetic acid. Alkali treatment and bleaching remove lignin and hemicellulose, and even divides the fibers into smaller parts, with almost similar dimensions and even microfibrils [10]. The removal of the hemicellulose and other non-cellulosic materials, including pigments will create void within the fiber, which results in swelling fine structure, which changes the physical structures, morphology, dimensions and mechanical properties [11]. After the bleaching step, the obtained cellulose will be almost pure, often it is followed by acid hydrolysis, for obtaining high purity cellulose [12].

In the past few decades, cellulose extraction from aquatic weeds like water hyacinth (Eichhornia crassipes) has received significant attention majorly due to its fast growth rate and accelerated biomass accumulation compared with most edible and non-edible crop plants [13]. But the cellulose extraction from other aquatic weeds is less explored in the literature and research about this is still in infancy. Pistia stratiotes, commonly known as water lettuce, are aquatic macrophytes with a wide range of pH and temperature tolerance, making them a major class of invasive aquatic weeds capable of accelerating the eutrophication process [14]. The rapid mat forming growth pattern in water bodies increases the excessive loss of water through transpiration process. These invasive macrophytes block the penetration of sunlight necessary for photosynthesis and thereby hindering primary productivity in the aquatic ecosystem.

This research work explores the possibility of integrating weed management and biopolymer production following chemical extraction methods by using a less explored invasive aquatic macrophyte water lettuce as the raw material. Cellulose extraction from water lettuce has not been widely discussed in the available literature up to our knowledge. In this study, an attempt was made to compare the effectiveness of an eco-friendly method employing soap nut powder as an alternative to chemical bleaching agent in cellulose extraction. The work further reports a simple method for developing biodegradable cellulose sheets followed by evaluation of their biodegradation rate using a standard soil burial method.

Materials and methods

Chemicals and substrate collection

The water lettuce plants used in this study were collected from Meenachil river, Kottayam, Kerala, India. The collected plants (except the roots) were sun dried for 3 days (Fig. 1). It was then dried at 60 °C in a hot air oven for 3 days to remove the water content completely and to achieve a uniform texture. The dried plants were powdered and stored for further extraction works. All the chemicals used in this study were procured from HiMedia Laboratories Pvt Ltd (Mumbai, India) and solvents (analytical grade) were purchased from Merck.
Process optimization for extraction of cellulose from *Pistia stratiotes*

**Method 1**

Powdered water lettuce was subjected to alkali treatment using 10% NaOH as suggested by Bhattacharya, Germi-nario [15] with minor modification. 10 g of water lettuce powder was treated with 150 mL of 10% NaOH at 70 °C for 2 h. The alkali treatment was repeated three times, after which the sample was filtered and subsequently washed with tap water sequentially and then with distilled water till the pH reached neutrality. The alkali-treated substrate was then bleached with 200 mL of 2% (w/v) sodium chlorite and 2% (v/v) glacial acetic acid at 80 °C for 2 h. This step was repeated 2 times. After the bleaching procedure, pH was neutralized using distilled water and the bleached fibers were maintained at 60 °C till the fibers were completely dry [16].

**Method 2**

In this method 10 g of water lettuce powder was initially treated using 150 mL of 4% NaOH for 4 h at 80 °C, this step was repeated thrice. The mixture obtained after alkali treatment was excessively washed using distilled water till the pH turned neutral. The obtained powder was then bleached using 50 mL of 4% sodium hypochlorite at 30 °C for 3 h. This step was repeated twice. After bleaching pH was neutralized using distilled water and the bleached fibers were retained at 60 °C in a hot-air oven till the fibers were completely dry [17].

**Method 3**

The alkali treatment was performed on the water lettuce powder (10 g) using 150 mL of 4% NaOH for 2 h at 60 °C; alkali treatment was done thrice and the residue obtained after filtration was washed with distilled water till the pH turned neutral. Bleaching was performed by treating the alkali-treated sample with 200 mL solution of 4% hydrogen peroxide in 4%NaOH for 2 h at 60 °C. After bleaching, the sample was washed with distilled water till the pH reached 7 [18] and incubated at 60 °C (hot air oven) till the fibers are completely dry.

**Method 4**

For the eco-friendly bleaching method, 15 g of powdered water lettuce was steam exploded for effective bleaching using 400 mL of soap-nut solution (4%) and pretreated at 121°C at 20 lbs for 1 h. After bleaching, the bleached fibers were washed to remove all the soapnut residues. The bleached fibers were then heated with 90 mL of acetic acid (80%) and 10 mL of nitric acid (45%) and incubated for 45 min at 100 °C [19]. After which the fibers were cleaned to remove acid residues with distilled water. These fibers were then treated with 100 mL of 20% acetic acid, 5 mL sulfuric acid and 2 g NaCl solution at 80–90 °C for 30 min. Again, this treated residue is washed with distilled water until the pH turns neutral, then kept at 60 °C in a hot air oven till the fibers are completely dry [20].

Based on the yield of cellulose obtained from each method, the method that gave the highest cellulose yield was fixed for further characterization studies.

Fig. 1 Collection of water lettuce (substrate) (a): Fresh water lettuce collected from the river (b) Water lettuce leaves after drying
Quantitative analysis of cellulose

The qualitative analysis of cellulose was analyzed using the anthrone test. The test was carried out after the cellulose was treated with a solution of 15 mL of acetic acid [80% (v/v)] and 1.5 mL of nitric acid for the removal of impurities. The purified cellulose was then dissolved in 80% sulphuric acid and then diluted for the anthrone assay [21].

Analysis of functional properties of the extracted cellulose

The functional property of the extracted cellulose was tested by determining the bulk density, packed density, hydrated density, water retention capacity, oil retention capacity, emulsifying activity and settling volume [22].

Bulk density

The extracted cellulose after complete drying (0.24 g) was taken in a 10 mL measuring cylinder and shook slightly, then the volume of the sample was recorded [22]. The bulk density was determined as stated below

\[
\text{Bulk density (g/mL)} = \frac{\text{amount of sample (g)}}{\text{volume of sample (mL)}} \tag{1}
\]

Packed density

In a 5 mL graduated syringe 0.24 g of dried cellulose was taken and the piston was pushed to apply pressure on the cellulose. The piston was pressed till the cellulose sample would not reduce further in volume [22]. The packed density was calculated as follows:

\[
\text{Packed density (g/mL)} = \frac{\text{amount of sample (g)}}{\text{least volume of sample (mL)}} \tag{2}
\]

Hydrated density

In a 10 mL measuring cylinder, mL-distilled water was added and then to this cylinder, 0.241 g of dry cellulose was also added. The volume of water displaced after adding cellulose was measured [23]. The hydrated density is found out by the equation:

\[
\text{Hydrated density (g/mL)} = \frac{\text{sample (g)}}{\text{mL of water displaced}} \tag{3}
\]

Water Retention Capacity (WRC) and

In a 50 mL centrifuge tube 2 g of the extracted cellulose was taken and mixed well with 30 mL of distilled water. The resulting slurry was left undisturbed for 10 min, then was centrifuged at 2000 rpm for 15 min. After centrifugation the pellet was collected by draining out the supernatant and was weighed as the wet sample weight [24]. The WRC was calculated by the formula:

\[
\text{Water Retention Capacity (g/g)} = \frac{\text{weight of water (g)}}{\text{weight of dry sample (g)}} \tag{4}
\]

Oil Retention Capacity (ORC)

The ORC was also calculated by following a procedure similar to WRC, except that palm oil was used instead of water. The ORC was calculated by the formula:

\[
\text{Oil Retention Capacity (g/g)} = \frac{\text{weight of oil (g)}}{\text{weight of dry sample (g)}} \tag{5}
\]

Emulsifying activity (EA)

To calculate EA, 7 g of the extracted cellulose was added to 100-mL soybean was added. This mixture was homogenized at 1000 rpm for 1 min. The emulsion obtained was centrifuged at 1300 rpm for 5 min [22]. The EA was calculated by the following equation:

\[
\text{Emulsifying Activity} = \left( \frac{\text{Height of emulsifier level (cm)}}{\text{Height of whole layer (cm)}} \right) \times 100 \tag{6}
\]

Settling volume (SV)

SV was measured by mixing 1 g of the extracted cellulose in 70 mL of distilled water, in a 100 mL screw cap bottle. To saturate the cellulose sample and to remove the excess gas trapped in the mixture, the bottle was subjected to 30 min of ultrasonic treatment. For degassing, the mixture was vacuum sucked for 30 min, after which it was kept in a cold room for 24 h. This will allow water to penetrate to the interstices of the cellulose sample. The mixture was then transferred into 100 mL volumetric flasks and were quantitatively measured and made up 100 mL by adding distilled water. The settling volume is the value given by the sample residue layer when the mixture was left undisturbed at room temperature for 24 h [24].
Characterization of extracted cellulose

The functional and structural characterization of cellulose biopolymers extracted from water lettuce using different analytical techniques. The functional groups of the biopolymer were examined between the IR range frequency of 4000–400 cm\(^{-1}\) using an FTIR spectrophotometer (Shimadzu IR Spirit-L) with a resolution of 4 cm\(^{-1}\). The morphology of the extracted cellulose was determined via a scanning electron microscope (SEM, Jeol JSM 6390). The purity and crystal phase of the cellulose from water lettuce was elucidated by X-ray diffractometer analysis (Shimadzu XRD 6000) at diffraction angular (2\(\theta\)) range of 5–90\(^{\circ}\). Differential scanning calorimetry (DSC) analysis of cellulose samples was exposed to a temperature range of – 50 °C to 400 °C at a rate of 10 °C/min using a DSC instrument (Netzsch DSC 204 F1). Thermogravimetric analysis (TGA) of cellulose was done using a Perkin Elmer STA 6000 from room temperature (25 °C) to 600 °C as the heating range.

Fabrication of cellulose sheets

The cellulose sheet was prepared using distilled water and plasticizer. Approximately 2.5 g of extracted cellulose was added to 100 mL distilled water and stirred for 6 h. This was then homogenized at 7400 rpm for 20 min and was kept in a cold room at 4 °C overnight. The sample was then homogenized again under the same conditions and incubated at 60 °C in an aluminum tray [19]. Plasticizers are added during the second homogenization step; the plasticizer used was 1% starch and casting was performed [20].

Biodegradation study of cellulose sheets

Pre-weighed cellulose sheets (CS) prepared from water lettuce were embedded inside a grid case (non-corroding) and buried in a plastic cartridge containing 100 g of soil sample (garden soil). Pre-weighed cellulose acetate filter paper sheets (FP) and cellophane tapes (CT) prepared in the same way were buried in garden soil to serve as a comparative standard. The moisture content of the soil was maintained at 60% by addition of water regularly. All the containers were incubated at room temperature (30 ± 5 °C) for 28 days. The weight of the CS was monitored at regular intervals (7 days) by washing the residue with distilled water and drying at 60 °C before weighing. The percentage degradation as a function of the weight loss in relation to the number of days was determined as per the equation suggested by Kim et al. (2000).

\[
\text{% Degradation} = \left(\frac{CS_{\text{Initial weight}} - CS_{\text{Final weight}}}{CS_{\text{Initial weight}}}\right) \times 100 \tag{7}
\]

Statistical analysis

Each experiment was performed in triplicate and the results were expressed as mean ± standard deviation. The standard error values are displayed as Y error bars in the graphs. The significance of the results was analysed by performing analysis of variance (ANOVA) using the Minitab 17.1.10 version \((p<0.05)\).

Results and discussions

Extraction of cellulose

Four different methods for cellulose extraction were done and compared for cellulose yield (Table 1). Method 1 gave the highest yield of 38.92 ± 0.38% (Fig. 2) and was selected for further studies.

In method 1, alkali treatment was performed using NaOH, which removes all the hemicellulose contents. The components left behind are the lignocellulosic contents and other impurities. Bleaching with sodium chlorite under acidic conditions will cause delignification [6]. Sodium chlorite is broken down into ClO\(_2\) in an acidic environment. ClO\(_2\) liberates chlorine gas during the bleaching process by oxidizing the aromatic rings of lignocellulosic materials. This reaction releases the lignin into the liquid, leaving non-soluble cellulose fibers [25]. Thus, the cellulose extracted from \(P.\ stratiotes\) using alkali and bleaching pretreatment yielded 38.94 ± 0.1%. An important modification happening during the alkali treatment is the dissociation of OH bonds in the structure of the fiber. The reaction occurs by ionizing the hydroxyl groups to become alkoxides (Fibre-OH+NaOH→Fibre-O\(^{\ominus}\)Na\(^{+}\) (alkoxide)+H\(_2\)O) [11], hence separating the inter-fibrillar regions from the cellulose fibers. Alkali treatment will remove all the main
hemicellulosic impurities, but leaves behind some lignin materials. These lignocellulosic contents are the hardest to be separated from the crude cellulose [26]. Bleaching is performed to remove these lignin components, bleaching of cellulose is also called delignification [27]. Most common of the bleaching treatment is boiling the alkali-treated fibers with sodium chlorite under acidic conditions [6]. The acidic condition is created by the acetate buffer, which contains glacial acetic acid. In the acidic condition sodium chlorite gets broken down into chlorine dioxide (ClO₂), which liberates chlorine gas during the bleaching. ClO₂ can oxidize the aromatic rings in lignin molecules and thereby release the lignin components from the fiber into the liquid [28]. The chlorine dioxide will also oxidize any hemicellulose, pectin which were not removed by the alkali treatment. Other common bleaching agents are hydrogen peroxide and sodium hypochlorite. Melikoğlu, Bilek [29] reported the extraction of cellulose from apple pomace by the optimized alkali pretreatment process (10.23% NaOH, 69.82 °C, and 161.54 min) was found to be 27.96 ± 0.78%. The enhanced extraction of cellulose can also be attributed to the presence of higher content of cellulose (40.63%) in the water lettuce biomass [30]. However, the eco-friendly method followed did not provide the expected result as the bleaching of the water lettuce powder was not proper. This may be due to different chemical constituents present in water lettuce, which can reduce the mild bleaching activities of soapnut powder, which is routinely used as a natural bleaching agent. The use of soapnut powder as an eco-friendly bleaching agent for extracting cellulose from jack fruit peel was reported by Reshmy, Philip [20]. In their study, the bleaching action of the soapnut powder was attributed to the saponin content present in the soapnut powder.

### Analysis of functional properties

The functional properties of cellulose extracted from water lettuce were compared with commercial cellulose standards (Table 2). The values of bulk density packed density and hydrated density of the cellulose isolated from water lettuce were comparatively significant over commercial cellulose (CC) reported in the literature [24]. This may be due to the smaller particle size of commercial cellulose [23]. In a study dealing with the extraction of cellulose from pineapple cores, the bulk density-packed density and hydrated density were observed to be 0.171 ± 0.003, 0.385 ± 0.013, and 1.47 ± 0.36 (g/mL) respectively [23]. In another study dealing with the extraction of cellulose from banana peels using NaOH and hydrogen peroxide, the bulk density (0.646 ± 0.27 g/mL), packed density (0.923 ± 0.07 g/mL), and hydrated density (2.50 ± 0.48 g/mL) reported were in close agreement with this study [24]. The WRC of the cellulose obtained from water lettuce was observed to be higher than that of CC probably due to its larger particle size of fibers that accelerate the interaction between water.

### Table 2 Functional properties of extracted cellulose

| Functional property                      | Extracted Cellulose | Commercial cellulose (Singamusong et al., 2014) |
|-----------------------------------------|---------------------|-----------------------------------------------|
| Bulked Density (g/mL)                   | 0.40 ± 0.01         | 0.192 ± 0.01                                  |
| Packed Density (g/mL)                   | 0.81 ± 0.02         | 0.265 ± 0.07                                  |
| Hydrated Density (g/mL)                 | 2.42 ± 0.01         | 1.67 ± 0.36                                   |
| Water Retention Capacity (WRC) (g/g)    | 2.62 ± 0.12         | 1.93 ± 0.82                                   |
| Oil Retention Capacity (ORC) (g/g)      | 3.81 ± 0.12         | 3.17 ± 0.15                                   |
| Emulsifying activity (EA)               | 59.11 ± 0.07        | 56.05 ± 0.06                                  |
| Setting volume ([cm/cm] %)              | 15.3 ± 0.11         | 14.0 ± 0.16                                   |
methoxyl, and methylene groups in the side chains of lignin are referred to as the presence of C-H deformation and C=O ring stretching at 1457.93 cm\(^{-1}\) in the spectra \([35]\). The peaks were not prominent as the extraction removed much of the lignin. The band at 1420.80 cm\(^{-1}\) correlates to the CH\(_2\) bending of cellulose \([36]\). Further, the presence of cellulose is indicated by skeletal vibrations of C-C and C-O at 1316.56 cm\(^{-1}\). In addition, these peaks at 896.75 cm\(^{-1}\) represent the \(\beta\)-glycosidic linkages between glucose molecules \([37]\). FTIR confirms the effective removal of hemicellulose and lignin contents by alkali treatment and bleaching of water lettuce.

3.3.2. SEM analysis of extracted cellulose

The morphological characterization of extracted cellulose using the SEM analysis is shown in Fig. 4, where the fibers appeared glossy fiber-shaped texture with a smooth surface \([38]\). The morphological analysis confirms that the impurities are removed to an extent after bleaching. The surface found to be 2.91 g water/g dried sample and 9.92 ± 0.1 g water/g dried sample of fiber, respectively. The WRC of the cellulose extracted can be reduced by reducing the particle size of the extracted cellulose for further application studies. In contrast, cellulose with a higher WRC is preferred for improving its texture, especially for packaging applications. The ORC of cellulose varies with the raw material employed for extraction. In this study, the ORC of cellulose from water lettuce was significantly higher than the commercial cellulose and in agreement with the ORC of cellulose extracted from pineapple core fiber \([23]\). The higher emulsifying activity of the extracted cellulose compared to the CC can be clearly related to its higher ORC. The settling volume and EA data obtained in this study were in agreement with those of cellulose extracted from the pineapple core \([23]\). Detailed assessment of the functional properties of the extracted cellulose will help in design applications from the extracted polymer.

Characterization of extracted cellulose

FTIR spectrum of extracted cellulose

The FT-IR spectroscopy gives information about the functional group and its properties. The FTIR spectra of cellulose extracted from water lettuce sp. (Fig. 3) showed a broad peak at 3331.39 cm\(^{-1}\), broad peak around 3500–3200 cm\(^{-1}\) represents free O-H stretching of the OH group present in cellulose \([31]\). The peak at 2853.03 cm\(^{-1}\) in the spectrum represents the characteristic C-H stretching vibration of cellulose \([32]\). The hemicellulose impurities from the extracted cellulose depict carbonyl aldehyde and ester (acylated) groups, which are significantly determined by the C=O stretching vibration at 1744.95 cm\(^{-1}\) \([33]\). The peak observed at 1609.29 cm\(^{-1}\) corresponds to the water absorption \([34]\). The occurrence of aromatic functional groups viz., methoxyl, and methylene groups in the side chains of lignin are referred to as the presence of C-H deformation and C=O ring stretching at 1457.93 cm\(^{-1}\) in the spectra \([35]\).
morphology also indicates the presence of non-cellulosic impurities, which are mainly lignin, hemicellulose, pectin wax, and other impurities [39], these are the natural binders of cellulose. It is also observed that the cellulose bundles are broken into small irregularly shaped fragments which happened during the delignification reactions.

**XRD spectrum of extracted cellulose**

The peak in the XRD data of extracted cellulose (Fig. 5), observed at 2θ (22.455°), is a characteristic peak observed in all cellulose XRD analyses [40]. The high-intensity peak at 11.3756°, 19.0336°, and 33.6920° correlated to the structure of cellulose I, and are commonly found in plants [41, 42]. The crystalline index was found to be 87.79%. The effective removal of recalcitrant lignin, hemicellulose, and other non-cellulosic impurities by the mercerization and bleaching of water lettuce biomass aid in the generation of highly crystalline cellulose [38].

**TGA of extracted cellulose**

As per the TGA curve (Fig. 6), the initial weight loss of 8.820% occurred at 30 °C. This reduction in weight can be attributed to the loss of water content. Subsequent reduction by 60.53% was found to be highest, between the temperature range of 202.73–400.6 °C. The greater reduction in weight occurred due to fast pyrolysis as a consequence of dehydration and degradation of cellulose. Further reduction by 10.36% at 400.6–789 °C occurred due to slow pyrolysis. The remaining residue of about 20.32% was due to the presence of lignin impurities [43, 44].

![Fig. 5 XRD spectrum of extracted cellulose from water lettuce](image)
DSC spectrum of cellulose

When the cellulose sample extracted from water lettuce was subjected to high temperature (Fig. 7) the highest peak was obtained at 110.4 °C which is lying in the glass transition range (100 to 180 °C) of cellulose [45]. Other peaks are obtained at 65.4 °C, 83.3 °C, and 157.9 °C. The peak at 65.4 °C may be due to the loss of water [46]. The other two peaks can be due to the pectin, hemicellulose, and lignin impurities.

Biodegradation of cellulose sheets

Cellulose sheets were fabricated with the incorporation of starch and dried (Fig. 8a). Further biodegradation study was carried out by packing the prepared CS in an inert matrix
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CT sheets due to their high molecular weight polypropylene composition. The high biodegradation rate of CS as compared to commercial FP as evident from (Fig. 9), may be attributed to the usage of starch as a plasticizer as compared to glycerol in commercial FP. The results obtained from this study were promising to be extended as a packaging material due to their high degree of biodegradability. The results obtained in this study were correlated with the biodegradation studies of cellulose films prepared from durian rind, where 100% biodegradation was observed within 4 weeks of soil burial [49]. In another study with nano cellulose films extracted from jackfruit peels, the cellulose films without any plasticizers incorporated reported a high degree of biodegradation with 35 days of soil burial. Further, their study reported that the moisture adsorption capacity of the plasticizers could be a key ingredient in determining the degradation rate of biopolymers [19]. A similar pattern of biodegradation was reported with cellulose films prepared from the banana pseudostem when subjected to weight loss analysis after the soil burial method for a period of 4 weeks [50]. Cellulose biodegradation was reported to produce harmless end products like methane, CO₂, and water. The methane produced can be harnessed and integrated for bioenergy generation using modern technologies [Varanasi, Jhansi L., Sinu Kumari, and Debabrata Das. “Improvement of energy recovery from water hyacinth by using integrated system.” international journal of hydrogen energy 43, no. 3 (2018): 1303-1318.].

Data represents mean±SD of various functional properties of the extracted cellulose performed in triplicate which is significant at $p < 0.05$

Degradation of polymeric sheets by enzymes produced by soil microorganisms is basically a surface phenomenon as these enzymes cannot penetrate into the interiors of the polymeric sheets [47]. Thus, weight loss can be successfully used as a measure to assess the enzymatic cleavage of polymers. Microbial degradation of biopolymers usually proceeds through four phases. In the first phase fragmentation of polymers due to enzyme activity and the effect of abiotic factors takes place and is combinedly called as biodeterioration phase. In the second depolymerization phase, a gradual reduction in the molecular weight of polymers occurs. The third phase of degradation involves the assimilation of degradation products into the metabolism of microorganisms for structural and functional responsibilities. In the final mineralization stage of degradation complete oxidation of degradation products takes place [48]. The degradation (%) of CS drastically increased from week 1 (11.13 ± 0.83) to week 4 (78.22 ± 0.71). The degradation rate of CS was consistently higher than that of FP and CT sheets used for the comparative study. Assessment of CT degradation rate of CT sheets was difficult as compared to FP and CS as the weight loss values were not showing much significant variation probably due to the inability of microbial enzymes to degrade the

(Fig. 8b) and burying it in garden soil followed by evaluation of degradation rate as a product of weight loss of the CS for a period of 4 weeks (28 days) by measuring weight loss every 7 days for further application and processing (Fig. 9).
**Conclusions**

This work explores the possibility of a cost-effective cellulose extraction strategy using water lettuce as the substrate. The study confirmed the efficiency of alkali-based extraction for maximum cellulose extraction from the substrate. The eco-friendly method for bleaching using soapnut powder was not effective in cellulose recovery from water lettuce. Further, a very simple method for the fabrication of cellulose biopolymer sheets, which can be used as coatings and packaging films, followed by its biodegradability test using soil burial was attempted in this work. The results of biodegradation studies revealed a promising degradation rate of cellulose biopolymer sheets compared to the synthetic counterparts. Further studies in the future on the mechanical properties and blending with other natural polymers can improve the functional properties of the cellulose sheet and widen its application perspectives, especially as biopolymer coatings and packaging material.

[Data represents mean ± SD of biodegradation of polymers (%) performed in triplicate for a period of 4 weeks. Means with different superscript letters (within each polymer type compared for 4 weeks) are statistically significant at P < 0.05.](This text part needs to be placed below Fig.9)

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