

Assessment of Electrothermal Pretreatment of Rambutan (*Nephelium lappaceum* L.) Peels for Producing Cellulose Fibers

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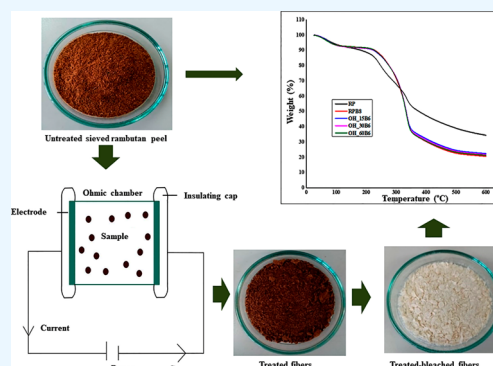


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Supporting Information

ABSTRACT: Agroindustrial wastes are renewable sources and the most promising sustainable alternative to lignocellulosic biomass for cellulose production. This study assessed the electrothermal pretreatment of rambutan peel (RP) for producing cellulose fibers. The pretreatment was carried out by Ohmic heating at a solid-to-liquid ratio of 1:10 (w/v) in a water/ethanol (1:1, v/v) mixture as the electrical transmission medium at 60 ± 1 °C for different holding times (15, 30, and 60 min). Ohmic heating did not significantly influence the total fiber yield for the various holding times. However, the compositions of the samples in terms of extractives, lignin, hemicellulose, and α -cellulose content were significantly influenced. In addition, the electrothermal pretreatment method reduced the bleaching time of RP by 25%. The pretreated fibers were thermally stable up to 240 °C. Ohmic heating pretreatment times of 15 and 30 min were found most promising, reducing the required bleaching chemicals and increasing the α -cellulose yield. The pretreated bleached cellulose fibers had similar properties to nontreated bleached fibers and could be efficiently processed into stable gels of strong shear-thinning behavior with potential application as rheology modifiers in food products. Our results demonstrate that rambutan peel could serve as a promising sustainable alternative to woody biomass for cellulose production. Ohmic heating meets the requirements for industrial applications as it is eco-friendly, improves the efficiency and energy consumption in fiber processing, and could as well be included in the processing of similar food wastes.



1. INTRODUCTION

Rambutan (*Nephelium lappaceum* L.) is an exotic tropical fruit belonging to the *Sapindaceae* family, indigenous to Southeast Asia. The fruit is currently cultivated globally in different tropical areas,^{1,2} with a global production of around 1.3 million tonnes.³ Thailand is considered the second-largest producer of this fruit, with an annual production of around 270 000 tons.⁴ Rambutan can be eaten fresh, mostly in dessert or fruit salad, or processed into jam, jellies, and juice.¹ Out of the total weight of the fruit, the peel contributes about 45.9–64.7%, accounting for about 123 930–174 690 tons per annum.⁴ The processing companies normally leave the peel as waste, which local farmers often use as manure. The global processing of crops, such as cereals, starchy roots, fruits, and vegetables, accounts for 250 million tons of agroindustrial wastes annually,⁵ to which rambutan peels contribute. These peels are a rich agroindustrial resource with polyphenolic, mineral, and cellulosic components that could potentially be used for producing value-added products in biorefinery scenarios.

Different pretreatment approaches have been adopted to disrupt lignocellulosic structures to enhance the accessibility of cellulose. These include physical, chemical, biological, and combined treatments.^{6–12} The physical and chemical pretreat-

ments reduce biomass recalcitrance and change the specific surface area, particle size, and degree of polymerization.¹³ However, they are limited by either long processing time, high energy demand, high cost, exposure to toxic chemicals, or environmental problems associated with chemical waste.^{14,15} Biological pretreatments (such as enzymatic and whole-cell processes) are reported to increase both accessibility and purity of cellulose.^{9,12} It remains the most eco-friendly method for cellulose extraction with regard to the principles of green chemistry. However, enzymatic pretreatments are limited by several factors, such as costs associated with enzyme production, enzyme inhibition by components, resistance to enzymatic digestibility, and the physical barrier property of hemicellulose limiting enzyme accessibility, and adsorption of enzymes by lignin, which deactivates hydrolyzing actions.^{16,17}

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Ohmic heating (OH) is an electrothermal technique associated with the passage of an alternating electric current through a substrate that acts as an electrical resistor.^{18–21} OH represents a milder form of heat treatment in which electrical energy is converted into thermal energy under rapid and uniform heating of liquids.^{20,22} Rapid, precise, and uniform dissipation of heat in the process limits losses and side reactions and enables the utilization of OH also on thermosensitive compounds.^{23,24} It has therefore become one of the most modern and eco-friendly technologies in food processing with multifaceted applications.²⁵ It was earlier established that OH could promote the release of extractive (noncellulosic) compounds from plant tissues due to the ability of the electric current to destruct the cell membrane and make it permeable.²¹

The emerging biorefinery industries with high demands for cellulose-based materials increasingly explore also agroindustrial biomasses in combination with eco-friendly techniques for their sustainable conversion.²⁶ Previous studies on rambutan peel only focused on the extractives leaving the fibers. A preliminary study on Ohmic heating extraction of phenolic compounds from rambutan peel revealed that the process loosens the coherent structure of the peel.²¹ This study addresses Ohmic heating as a sustainable pretreatment technique to produce highly crystalline cellulose fibers from rambutan peel. The physiochemical characteristics of the fibers were investigated and their gel-forming capability was evaluated using a simple and inexpensive method. Thus, we want to communicate an electrothermal technique that allows for the eco-friendly and efficient processing of rambutan peel into valuable intermediates.

2. MATERIALS AND METHODS

2.1. Materials. Rambutan (*N. lappaceum* L.) is harvested between May and July every year. Peels were obtained from Malee Sampran Public Co., Ltd., Nakhon Pathom Province (Central Province of Thailand), in May 2019. All reagents were of analytical grade and used without any further purification.

2.2. Pretreatment of Rambutan Peel Fibers Using the Ohmic Heating Technique. Ohmic heating pretreatment was carried out following our previously reported method, with some minor modifications.²¹ The peel was washed and dried at 55 °C for 24 h to an average moisture content of $8.07 \pm 0.18\%$, ground into smaller particles, and sieved with a 35 mesh sieve. OH extraction was performed at a sample-to-liquid ratio of 1:10 (w/v) using a water/ethanol (1:1, v/v) mixture as the electrical transmission medium. The Ohmic heating system was made up of a 5 kW voltage-variable transformer (model TDGC2-5K, Silicon, Xiamen, China), a digital multimeter (Gwinstek GDM-8261A, Good Will Instrument Co., Ltd., New Taipei, Taiwan), and a T-cell Ohmic heating chamber with a diameter of 0.228 m. The chamber was connected to the transformer with two titanium electrodes, applying a maximum current of 20 A and a voltage of 450 V at a constant frequency of 50 Hz. The electrode diameter was 0.084 m, and the gap between the two electrodes was 0.205 m. A K-type thermocouple (FLIR Commercial Systems, Inc., NH) was used to continuously record the temperature of the sample. The current was measured using a Pearson current monitor (model 411, Pearson Electronics Inc., CA). A digital volt-ohm-milliammeter (VOM) (Gwinstek, Model GDM-8261A, Jiangsu Sheng, China) was used to record the temperature, voltage, and current. The sample was placed in the Ohmic heating chamber whose temperature was maintained at 60 ± 1 °C. Voltage was maintained at 450 ± 3 V throughout

heating at different holding times of 15, 30, and 60 min, with continuous stirring at 900 rpm using a magnetic stirrer bar.

2.3. Determination of Fiber Yield. The samples after OH treatment were passed through cotton stacked in clean cloth using the mechanical press to separate extract solution from the fibers. The fibers were then dried in an oven at 55 °C until constant moisture content equivalent to the initial moisture content of untreated fibers was obtained. The yield of OH-treated fibers was calculated using eq 1.

$$\text{yield (\%)} = \frac{\text{weight of fiber after extraction}}{\text{total weight of fiber before extraction}} \times 100 \quad (1)$$

2.4. Chemical Composition. The chemical composition of the fiber was analyzed according to the standard TAPPI methods. Lignin content was determined according to the T222 om-98 by reaction with 72% (w/v) sulfuric acid. Holocellulose content, which comprises α -cellulose and hemicellulose, was determined according to TAPPI T202 om-88, with the acid chlorite method. The α -cellulose content was estimated after treating the holocellulose fibers with sodium hydroxide solution (17.5%). Hemicellulose content was calculated by subtracting the α -cellulose content from the holocellulose content.²⁷

2.5. Bleaching of Pretreated Fibers. The Ohmic heating pretreated fibers were bleached at a fiber-to-liquid ratio of 1:20. Briefly, 10 g of fibers was treated with 1.4 wt % sodium chlorite (NaClO₂) solution at a pH of 4.0, which was adjusted with 0.5 mL of glacial acetic acid at 70 °C. Sodium chlorite and acetic acid were added at the same loading ratio every hour until white, decolorized fibers were obtained.²⁸ The samples were washed with distilled water until neutral and dried at 55 °C for 24 h. The fibers were labeled as follows: unbleached rambutan peel (RP), bleached rambutan peel (RP_B), 15 min Ohmic heating bleached fibers (OH_15B), 30 min Ohmic heating bleached fibers (OH_30B), and 60 min Ohmic heating bleached fibers (OH_60B).

2.6. Whiteness Index. The color measurement of the dried fibers was done using a colorimeter (Miniscan XE, Hunter Associates Laboratory, Reston VA), according to the method reported earlier.²⁸ In brief, the instrument was calibrated with a white standard plate with color values as follows; “ $L = 100$, $a = 0$ and $b = 0$, L^* (lightness) values ranging from 0 (black) to 100 (white); a^* (red and green) values ranging from -80 (greenness) to 100 (redness); and b^* (blue and yellow) values range from -80 (blueness) to 70 (yellowness)”. The whiteness index (WI) was calculated according to eq 2

$$\text{WI} = 100 - [(100 - L)^2 + a^2 + b^2]^{0.5} \quad (2)$$

where L , a , and b refer to coordinates in Hunter's L , a , and b color difference equation.²⁹

2.7. Scanning Electron Microscopy (SEM). The morphology of the sample was studied using a scanning electron microscope (QUANTA 450, Thermo Fisher Scientific, MA). The samples were sputtered with gold (5–10 nm thickness) and measured at an acceleration voltage of 10–15 kV.

2.8. XRD Analysis. An X-ray diffractometer (Bruker D8 Advance, Berlin, Germany) using Cu K α radiation ($\lambda = 1.54$ Å) at 40 kV was used to measure the crystallinity of fibers. The samples were scanned at 2θ angles from 5 to 50° with a scanning rate of 5°/min. The pattern was deconvoluted, and the crystallinity index (CrI) was calculated by dividing the total

Table 1. Chemical Composition and Fiber Yield after Ohmic Heating Pretreatment of Rambutan Peel^a

sample	extractives (%)	lignin (%)	hemicellulose (%)	α -cellulose (%)	yield after ohmic extraction (%)
RP	13.2 \pm 0.6 ^b	35.3 \pm 0.4 ^b	15.7 \pm 0.5 ^a	24.4 \pm 0.1 ^a	
OH-15	6.2 \pm 0.7 ^a	33.1 \pm 0.1 ^{ab}	17.4 \pm 0.4 ^b	26.4 \pm 0.4 ^c	60.9 \pm 0.3 ^a
OH-30	5.4 \pm 0.9 ^a	29.5 \pm 0.1 ^a	17.3 \pm 0.2 ^b	26.9 \pm 0.2 ^d	61.0 \pm 0.3 ^a
OH-60	5.9 \pm 0.8 ^a	32.4 \pm 0.2 ^{ab}	17.6 \pm 0.2 ^b	25.7 \pm 0.2 ^b	61.1 \pm 0.8 ^a

^aValues are presented as mean \pm standard deviation. The values with different superscript letters in a column are significantly different ($p < 0.05$).

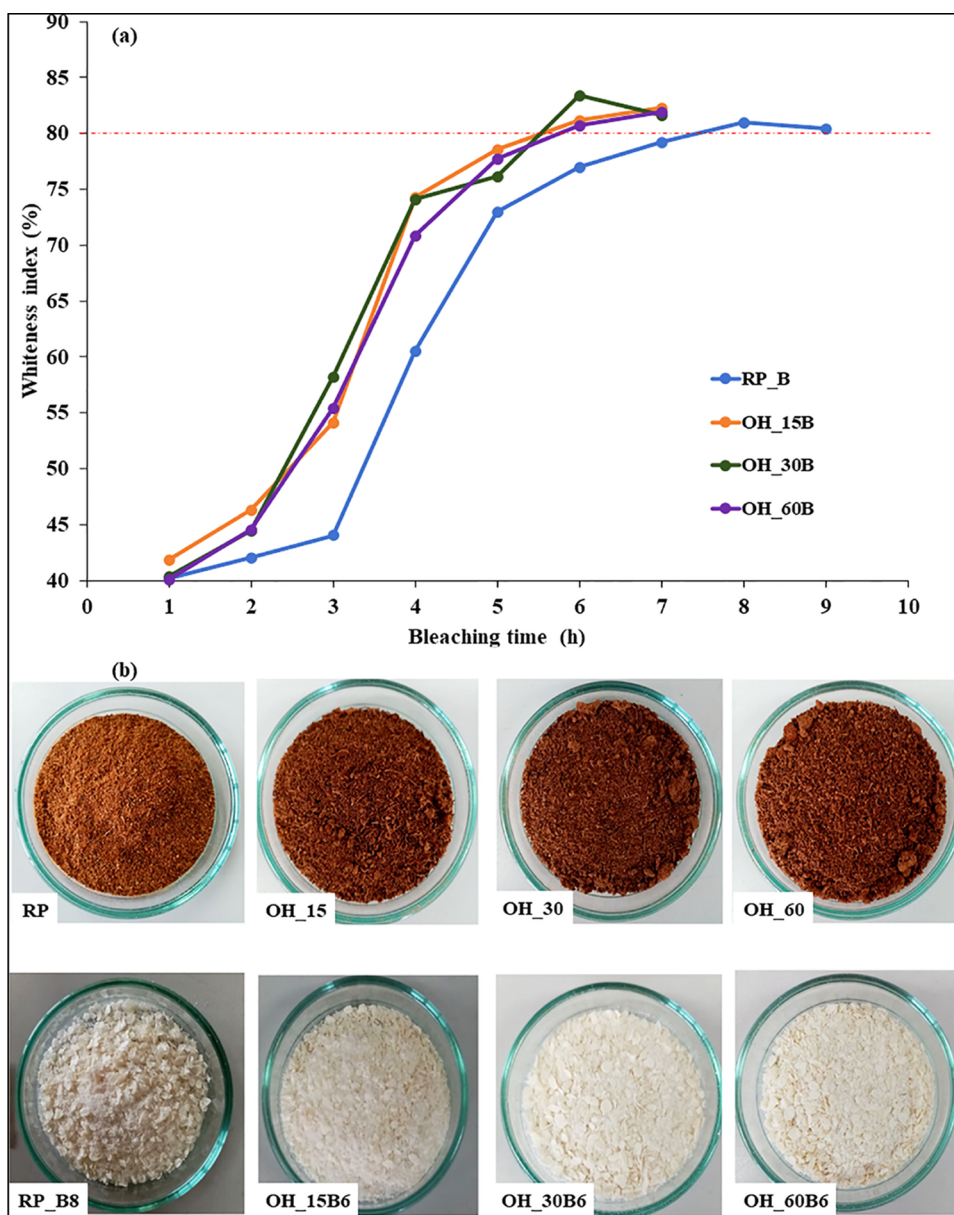


Figure 1. Relationship between whiteness index and bleaching time: (a) bleached rambutan peel (RP_B) and 15/30/60 min Ohmic heating bleached fibers (OH_15B)/(OH_30B), (OH_60B), and (b) photographs of unbleached RP, eight times bleached RP (RPB8), and six times Ohmic heating bleached fibers (OH_15B6, OH_30B6, and OH_60B6).

area of main peaks of crystalline cellulose by the area of the total peaks (all crystalline plus amorphous peaks) according to eq 3.³⁰

$$\text{crystallinity index (CrI)} = \frac{\text{integrated area of all the crystalline peaks}}{\text{integrated area of all the crystalline and amorphous peaks}} \times 100 \quad (3)$$

2.9. Fourier Transform Infrared (FTIR) Spectroscopy.

The chemical compositions and functional groups of the fibers were analyzed using infrared spectroscopy in the attenuated total reflection (ATR) mode using a PerkinElmer Frontier IR single-range spectrometer (PerkinElmer Inc., MA).³¹ The spectra were recorded in the range from 500 to 4000 cm^{-1} in the absorbance mode at a resolution of 4 cm^{-1} .

2.10. Thermogravimetric Analysis (TGA). A thermal gravimetric analyzer (Mettler Toledo, Model TGA2, Zurich, Switzerland) was used to carry out thermogravimetric analysis (TGA) and derivative thermogravimetric analysis (DTG) of the fibers. The samples were pyrolyzed under a nitrogen atmosphere at a heating rate of 10 °C/min and a flow rate of 20 mL/min from 50 to 600 °C.

2.11. Preparation of an Aqueous Cellulose Gel from Bleached Fibers. Dried fibers were soaked in (0.5% w/v) deionized water for 30 min and blended (Philips blender, HR2115-600W, Jakarta, Indonesia) for 5 min. The resulting gel was sonicated for 15 min and kept for further analysis. For morphological analysis, 15 g of gel was weighed into a Petri dish and dried in an oven at 60 °C for 24 h. The surface topography and roughness of the product were characterized by atomic force microscopy (AFM). One milliliter of each gel was prepared on a glass slide and dried in an oven at 55 °C overnight. The sample was measured in tapping mode using an Asylum model MFP-3D AFM (Bio, CA) at ambient temperature. The 3-dimensional image of the sample was generated with Gwyddion software.³² The SEM of the dried gel was performed as described in Section 2.7.

2.12. Viscosity of the Cellulose Gel. The apparent viscosity of the cellulose gels was measured at room temperature using a digital concentric cylinder rheometer (Brookfield Engineering Laboratories Inc., MA, model DV-III). 9 mL of each sample was measured using a viscometer equipped with a small sample adapter, consisting of a cylindrical sample chamber and spindle.

2.13. Statistical Analysis. All experiments were performed at least in triplicate. One-way analysis of variance (ANOVA) was used for comparing mean values at a statistical significance of $p < 0.05$. Bonferroni's test was used for comparing group means.

3. RESULTS AND DISCUSSION

3.1. Chemical Composition of Fibers. The chemical compositions of the fibers upon Ohmic heating treatment were compared for different holding times. Table 1 shows the chemical composition, which revealed no significant difference in the total fiber yield at various holding times of Ohmic heating pretreatments at a constant temperature of 60 °C. Perhaps, there was no decomposition of the fibers at 60 °C, even at a longer pretreatment time. However, there was a significant difference between untreated and OH pretreated fibers with regard to extractive release. This difference may be attributed to the electrothermal effect of Ohmic heating, which causes the opening of the cell walls and subsequent better release of extractives. Ohmic heating pretreatment for 30 min showed the lowest lignin content of $29.5 \pm 0.1\%$ in the remainder, according to TAPPI method T222 om-98. The polysaccharide components showed a significant difference between OH-treated and untreated samples in terms of hemicellulose and α -cellulose contents. OH-30 had the highest α -cellulose content of $26.9 \pm 0.2\%$ in the remainder based on TAPPI method T202 om-88, demonstrating that the OH pretreatment technique is well suited to enrich the cellulosic phase in the remainder by solubilizing noncellulosic components of the rambutan peel.

3.2. Influence of the Treatment on Fiber Bleaching. Bleaching of cellulose fibers is a well-known treatment method in fiber processing. In this process, the cellulose purity and whiteness of the fibers are increased by removing noncellulosic polymers, mostly lignin.³³ The extent of bleaching can be evaluated, among others, by the whiteness index (WI). WI was

determined after bleaching treatment to establish the amount of chemical and time required to get white cellulose fibers from rambutan peel at a target value above 80%.³⁴ Figure 1a shows the whiteness index of the fibers at each bleaching stage, and Figure 1b shows the photographic images of the fibers before and after bleaching. The pretreated fibers achieved WI values above 80 after bleaching with six portions of sodium chlorite. However, it took eight portions to obtain the target WI value in the case of the untreated fibers (no Ohmic heating). This result confirmed that OH pretreatment might be economically beneficial as it allows producing cellulose fibers from RP at a reduced chemical input of 25%. OH is an electrothermal process with rapid and uniform heating, which triggers softening and increases permeability of plant cell wall tissue, generating openings through which the solvent can enter to solubilize substrates. This mechanism results in rapid breakdown of the cell walls and disruption of their integrity, which in turn causes better accessibility for the bleaching agent, more rapid oxidation of the lignin, cleavage of lignin–carbohydrate linkages, destruction of chromophores, and faster removal of the oxidation products.³⁵ There was a reduction in WI of the fibers for a longer bleaching time, which may be attributed to thermal degradation of cellulose, generation of oxidized groups (carbonyl carboxyl) along the cellulose chains,^{36,37} and generation of the particular chemical behavior of cellulose-derived key chromophores.^{38,39}

The chemical composition of the different bleached fibers was determined by infrared spectroscopy (Figure 2). All spectra

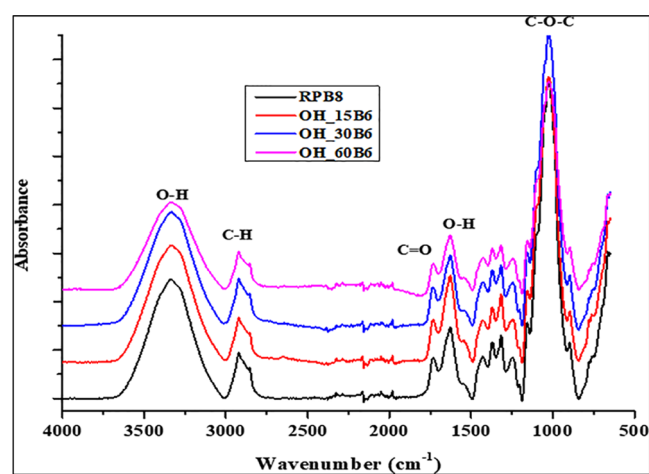


Figure 2. FTIR spectra of ohmic heating pretreated cellulose fibers from rambutan peel.

showed the expected bands, which can be attributed to cellulose and similar polysaccharides. The bands at around 2900 cm^{-1} and ~ 1050 to 1150 cm^{-1} correspond to the C–H and C–O–C symmetric stretching of the glucopyranosidic units, respectively.^{40–42} The absorption band at $\sim 1730 \text{ cm}^{-1}$ can be attributed to the C=O stretching of acetyl groups in hemicellulose⁴³ and carboxyl groups in minor pectin residues,⁴⁴ and those at around 1649 cm^{-1} can be attributed to the O–H bending of the adsorbed water. In general, bleached samples RPB8, OH_15B6, OH_30B6, and OH_60B6 feature comparable spectra, which indicates that they have also comparable chemical compositions. In general, the intensity of the indicated bands of the bleached samples is significantly higher than that of

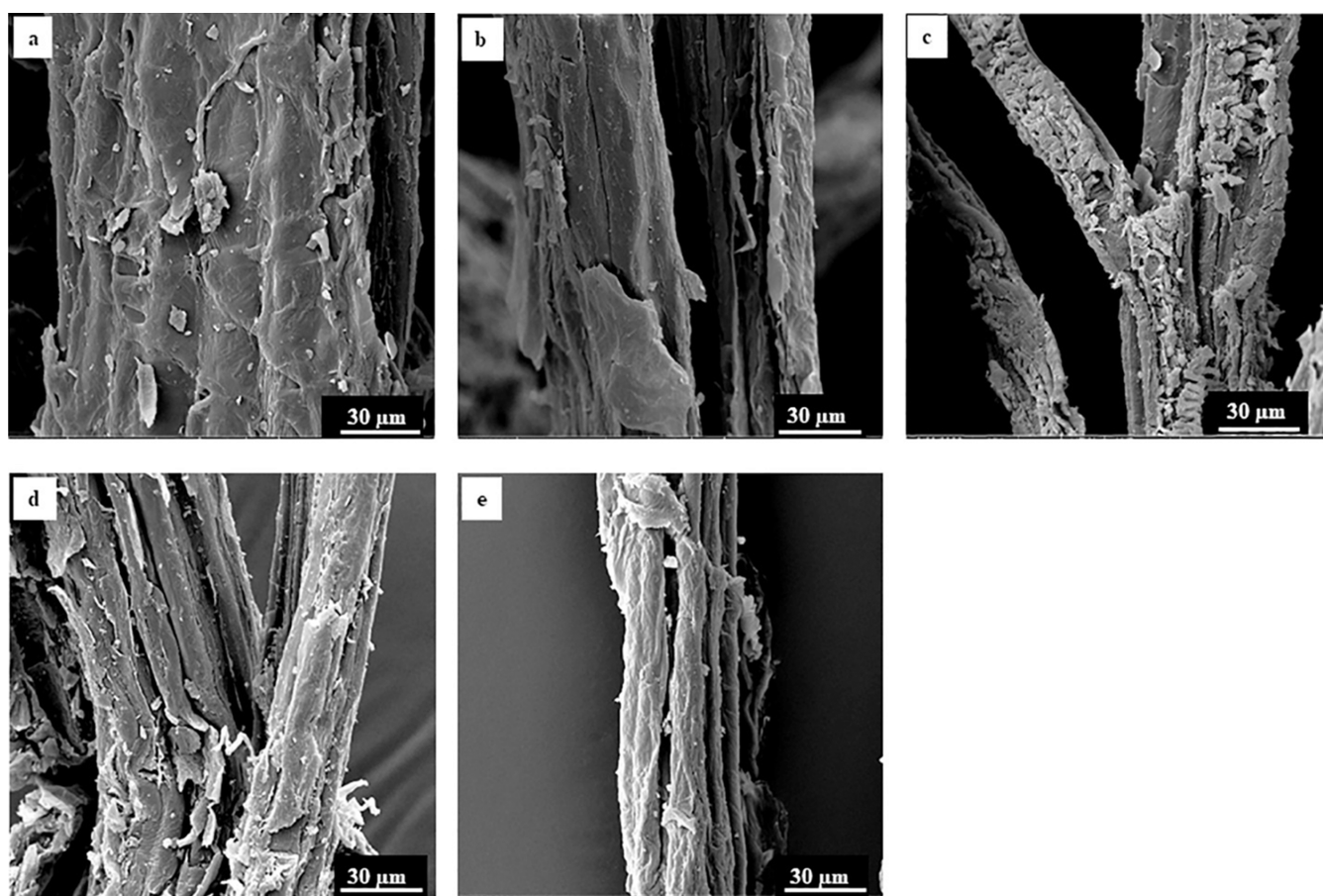


Figure 3. SEM images of (a) ramblutan peel (RP); (b) untreated bleached ramblutan peel (RPB8); and Ohmic heating pretreated bleached fibers (c) OH_15B6 (15 min), (d) OH_30B6 (30 min), and (e) OH_60B6 (60 min).

the nonbleached reference (RP). This is due to the high amount of lignin and extractives in the nonbleached samples.

3.3. Morphology and Physical Properties of Bleached Fibers. Figure 3 shows the surface morphology of the bleached fibers with and without Ohmic heating pretreatment. The bleaching process removes noncellulosic substances (mostly lignin) from the middle lamella, which holds the fiber together. In comparison to the nonbleached fiber (Figure 3a), the bleached nontreated RP is slightly fibrillated. The surface structure of the pretreated fibers shows individual fibril bundles and hence stronger fibrillation (Figure 3b–e). This can be attributed to the electrothermal effect of the Ohmic heating process that disrupts the cell wall structure.

Cellulose, in nature, is composed of crystalline and amorphous areas. X-ray diffraction analysis of the Ohmic heating treated fibers (Figure 4a–e) showed the crystalline domains with characteristic peaks at $2\theta = 15.7, 22.6, 29.8,$ and 34.19° , corresponding to the 110, 200, 211, and 004 lattice planes, respectively. The unbleached fibers in Figure 4a show broader peaks. The crystallinity index (CI) of the fibers was calculated from eq 3. OH-30B6 had the highest CI of 64.21% compared with RP (38.27%), and eight times bleached fiber (RPB8) had a CI of 62.19%, being nearly high (Figure 4f). The broad halo in the RP is an indication of amorphous components that are removed by ohmic heating and bleaching. The CI decrease in OH-60B6 is due to the prolonged pretreatment of fibers causing thermal degradation of the cellulose crystals and reduction of the crystallite sizes.⁴⁵ This is in full agreement with the results from the whiteness experiments discussed above. In

general, RPB8, OH_15B6, and OH_30B6 had similar crystallinity indices, which confirms that Ohmic treatment reduces the bleaching time and amount of chemicals, without diminishing the fiber properties. The crystalline values obtained in this study make ramblutan peel a viable agroindustrial material for the production of cellulosic materials with moderate-to-high crystallinity.

Typical TGA and derivative thermogravimetry (DTG) curves of the cellulose fibers are presented in Figure 5a,b, showing weight loss to occur in distinct two steps in the treated fibers and in three stages for the untreated one. The first loss was seen at a temperature below 100°C for both untreated and treated fibers, which can be attributed to the evaporation of water and volatile matters in the fibers.^{46,47} The second weight loss/decomposition stage of the treated fibers occurred at a temperature above 240°C , which is the starting point of the cellulose materials' thermal degradation. However, the second weight loss in untreated fiber occurred between 200 and 250°C , which represents the thermal degradation of lignin and extractives⁴⁸ and is largely absent for the treated fibers, while the third stage starts at a temperature above 250°C . The T_{onset} was 208.5°C for RP, which has increased to about 240°C in the treated fibers (Table 2). The maximum mass loss was observed within temperatures ranging from 322 and 328°C , which can be attributed to the thermal decomposition of the remaining carbonaceous matter. Complete decomposition of cellulosic components occurred at around 602°C , leaving only a carbon/ash/mineral residue (34.28, 20.56, 22.37, 21.80, and 21.23% for RP, RPB8, OH-15B6, OH-30B6, and OH-60B6, respectively). A

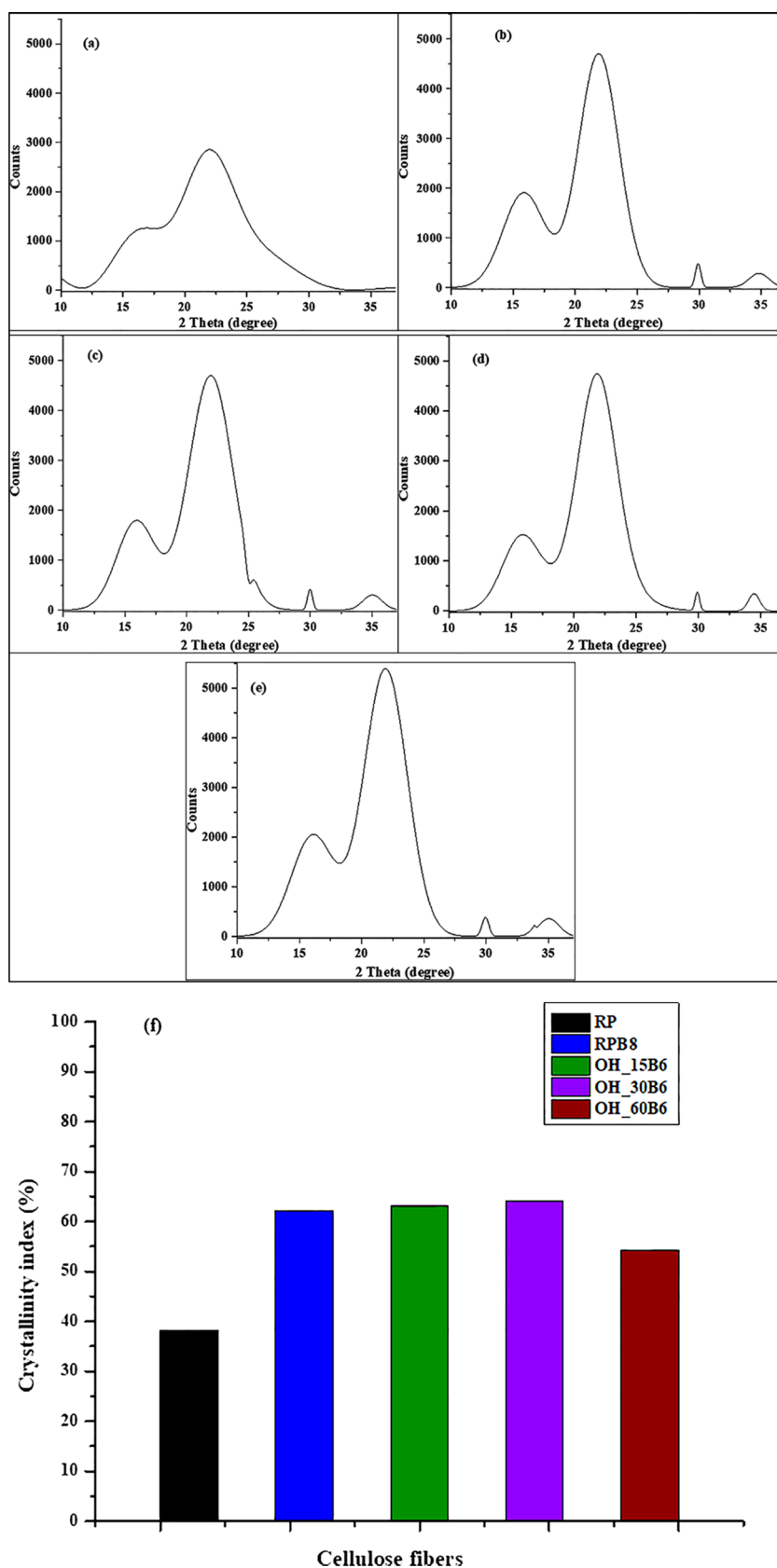


Figure 4. XRD patterns of (a) rambutan peel (RP); (b) untreated bleached rambutan peel (RPB8); and Ohmic heating pretreated bleached fibers (c) OH_15B6 (15 min), (d) OH_30B6 (30 min), and (e) OH_60B6 (60 min). (f) Crystallinity indices of the fibers.

high mineral residue in RP is generally laudable; previous studies have reported the presence of mineral elements in rambutan

peel.^{49,50} It can be concluded that OH pretreatment had no negative effect whatsoever on the thermal properties of the

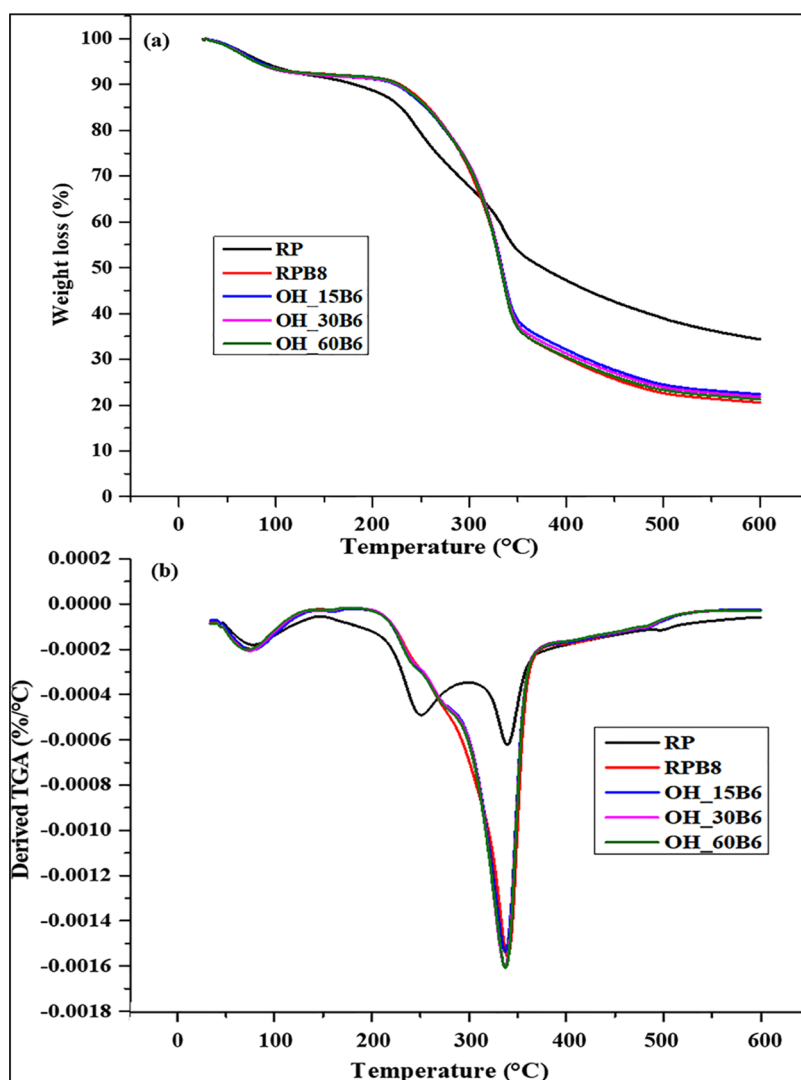


Figure 5. Weight loss curves (a) and derivative thermogravimetry (DTG) (b) of untreated and treated cellulose fibers from rambutan peel.

Table 2. Summary of Thermal Degradation Values of Untreated and Treated Rambutan Peel Fibers

sample	initial weight loss temperature (°C)	T_{onset} (°C)	T_{max} (°C)	residue (%)
RP	76.23	208.5	322.73	34.38
RPB8	72.80	242.1	328.11	20.56
OH-15B6	74.19	238.5	327.82	22.37
OH-30B6	71.41	240.3	327.87	21.80
OH-60B6	70.74	240.5	327.44	21.23

cellulose fibers, as the values are within those reported for cellulose fibers extracted by other approaches.

3.4. Preparation of Cellulose Gels from the Bleached Rambutan Fibers. Figure 6 shows the appearance of the prepared cellulose gels. All bleached samples could be efficiently fibrillated using a standard commercial blender. This stays in contrast to the unbleached rambutan peel (RP), which formed an unstable suspension with a dark-colored precipitate (indicated by the red cycle in Figure 6a). This behavior is due to the presence of lignin, which tethers together the cellulose fibril bundles and makes the RP surface hydrophobic, thereby inhibiting the interaction of water molecules and fibrillation. The removal of lignin and other noncellulosic components by

Ohmic heating/bleaching enhanced the hydrophilicity of the fibers and their interaction with water.⁵¹ Figure 6b displays the suspensions in Petri dishes, showing that all bleached fibers had a similar appearance and translucency. As demonstrated by the straightforward gel formation using a simple blender, the bleached samples have a high fibrillation tendency, which might be beneficial in the production of nanocelluloses.

The apparent viscosity of the cellulose gels (at 0.5 wt % solid content), presented in Figure 7, decreases sharply as the shear rate is increased; the samples are hence thixotropic and have strong shear-thinning properties (Figure 7). The RPB8 gel exhibited slightly higher viscosity than the OH pretreated gels; the latter ones feature a very similar rheological behavior. The observed shear-thinning effect is based on shear-induced particle alignment along flow streamlines, causing a decrease in viscosity.⁵² Figure 7 demonstrates that OH pretreated gels exhibited stronger shear-thinning behavior than RPB8, indicating that the OH pretreated samples feature a smaller particle size and less heterogeneous particle size distribution. Moreover, films were produced from cellulose gels and their morphologies were studied by SEM and AFM (Figures S1 and S2). All films from the bleached samples had similar roughness and contained non-fibrillated cellulose fibers. Fibrillation will be further

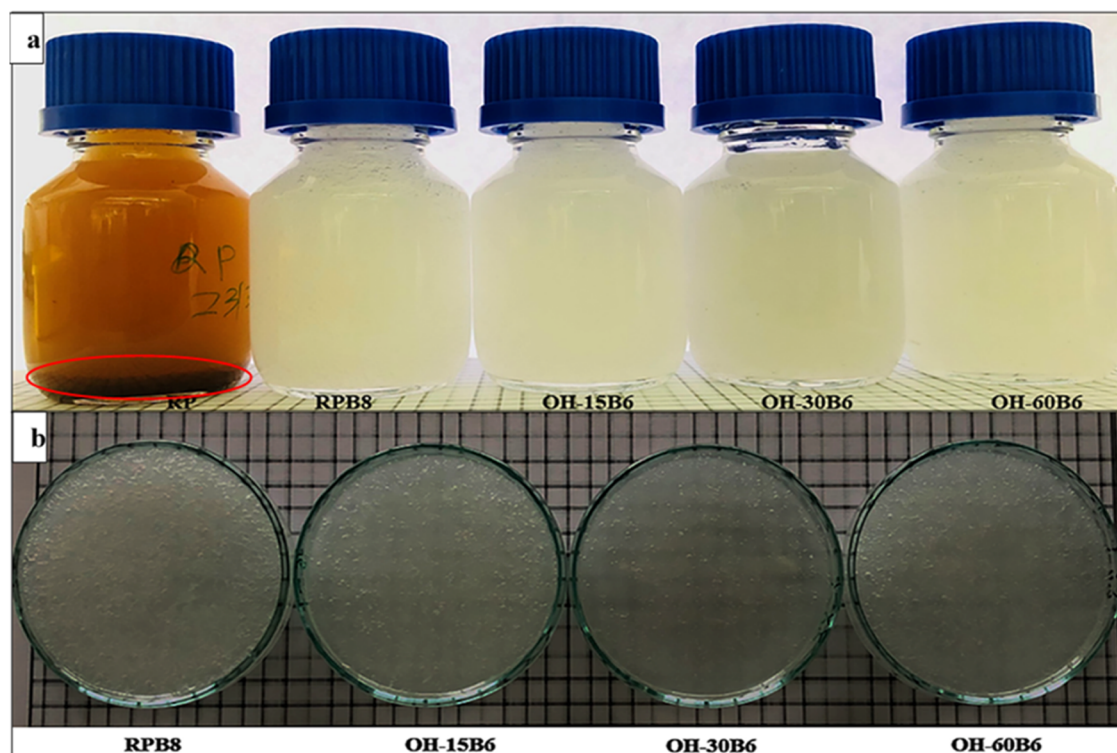


Figure 6. (a) Optical appearance of rambutan peel (RP), untreated bleached rambutan peel (RPB8), and Ohmic heating pretreated bleached fibers (OH_15B6, OH_30B6, and OH_60B6) gel. (b) Transparency of the resulting cellulose gels.

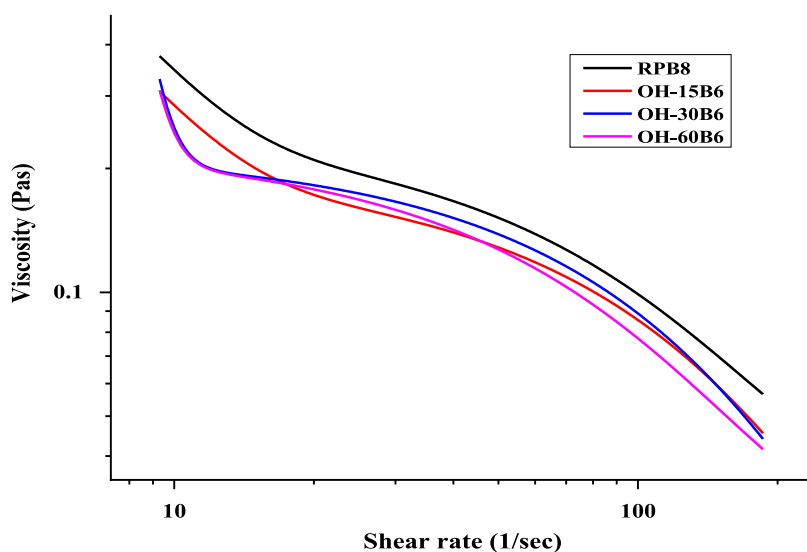


Figure 7. Viscosity of gels from untreated bleached rambutan peel (RPB8) and 15 min (OH_15B6), 30 min (OH_30B6), and 60 min (OH_60B6) Ohmic heating pretreated bleached fibers.

optimized in follow-up studies of more homogeneously fibrillated celluloses with a narrow size distribution.

4. CONCLUSIONS

This study has established Ohmic heating as a pretreatment method of rambutan peels, a bulk agroindustrial residue, to produce cellulosic fibers with moderate-to-high crystallinity. The electrothermal pretreatment reduced the time and amount of bleaching chemicals involved in cellulose fiber production by 25% and can be hence considered an efficient and cost-effective pretreatment method. In addition, Ohmic heating can be

considered particularly eco-friendly, meeting essential requirements for industrial applications in food waste processing. The treated and bleached rambutan peel could serve as a promising sustainable alternative to wood-based biomass for the production of cellulosic materials because of its good fibrillation tendency. The as-prepared gels are thixotropic and have potential applications in pulp and paper, food processing, tissue engineering, and cosmetics. Further work will concentrate on the optimization of the procedure, in particular with regard to optimizing the bleaching chemicals toward greener, oxygen-based compounds and on the utilization of the extracted,

noncellulosic components to further optimize the sustainability of the overall process.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsomega.2c04551>.

SEM images of films from the cellulose gels and AFM micrographs (PDF)

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Notes

The authors declare no competing financial interest.

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