

Optimization of extraction and characterization of cellulose from edamame pod waste for active biofilm applications

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Abstract. Edamame pod waste, a by-product of soybean processing, represents a promising lignocellulosic biomass source for biopolymer development. This study aimed to optimize cellulose extraction from edamame pod waste using Response Surface Methodology (RSM) with a Box–Behnken Design (BBD) and to characterize the extracted cellulose for potential biofilm applications. Four independent factors—particle size (40–80 mesh), extraction temperature (60–90 °C), extraction time (1–3 h), and NaOH concentration (5–10%, w/v)—were investigated, with cellulose yield (%) and whiteness index (WI) as responses. The optimized conditions (80 mesh, 75°C, 1 h, 7.5% NaOH) produced cellulose with a yield of 54.5% and a WI of 70%. Subsequent alkaline hydrogen peroxide (AHP) washing enhanced cellulose purity, increasing cellulose content from 41.25% to 65.14% and reducing hemicellulose and lignin to 19.07% and 9.21%, respectively. FTIR analysis confirmed successful delignification through the disappearance of lignin-associated peaks (1508–1512 cm⁻¹) and the presence of characteristic β-1,4-glycosidic linkages. Thermal characterization using Thermogravimetric Analysis (TGA) and Derivative Thermogravimetry (DTG) showed a single-step degradation pattern with *Tonset* ≈ 275 °C, *Tmax* ≈ 350 °C, and ~13% residue at 600 °C, indicating high thermal stability and purity comparable to commercial cellulose. These findings demonstrate that edamame pod waste can be efficiently converted into high-purity, thermally stable cellulose through an eco-friendly alkaline extraction process, providing a sustainable raw material for the development of biodegradable biopolymers and active biofilms as alternatives to synthetic plastics.

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1 Introduction

Plastic pollution has emerged as a critical global concern due to the accumulation of non-biodegradable synthetic polymers in the environment, which disrupts ecosystems and contributes to the growing microplastic crisis [1]. More than 400 million tons of synthetic plastics are produced annually, primarily derived from petroleum-based resources that are resistant to degradation and difficult to recycle [2,3]. These materials pose long-term environmental risks and contribute to carbon emissions during production and disposal [4]. These challenges highlight the urgent need to explore renewable, low-cost, and abundant resources for sustainable packaging materials [5-7].

Biopolymers derived from renewable biomass have gained increasing attention as potential substitutes for petroleum-based plastics due to their biodegradability, biocompatibility, and lower environmental impact [8]. Among them, cellulose, polylactic acid (PLA), and polyhydroxyalkanoates (PHA) have shown promising potential for packaging and biomedical applications [9]. Cellulose, the most abundant biopolymer on earth, is particularly attractive because of its renewable nature, mechanical strength, film-forming ability, and chemical versatility [10]. However, commercial cellulose production largely depends on wood and cotton sources, which require high energy input and compete with food-related land use. To overcome this limitation, attention has shifted toward utilizing agricultural residues as sustainable feedstocks for cellulose extraction [11,12].

Agricultural by-products such as rice straw, sugarcane bagasse, corn stalks, pea pods, and soybean hulls contain significant amounts of cellulose and represent low-cost, renewable raw materials [13,14]. Valorizing these lignocellulosic wastes not only reduces environmental burden but also supports the development of circular bioeconomy systems through resource efficiency and waste minimization [15,16]. Soybean by-products, including okara, hulls, and pods, have been identified as potential cellulose sources due to their rich fibre and lignin content [17]. In particular, edamame pod waste—generated during the processing of immature soybeans—is abundant but remains underutilized despite its high cellulose fraction and potential as a renewable polymer source [18]. Recent studies reported that edamame pods exhibit considerable variability in lignocellulosic composition depending on genotype and growing environment, with neutral detergent fiber (NDF) contents reaching up to 9% across selected cultivars [19]. Environmental stress also influences cellulose biosynthesis, where combined drought and heat stress reduce ROS-quenching ability and subsequently suppress cellulose synthesis during pod-filling in susceptible edamame varieties [20]. Although direct cellulose extraction from edamame pods is still limited, related legume studies—such as pea and broad bean pods yielding cellulose microfibers with crystallinity values of 79% and 70%—support the potential of edamame pod waste as a promising cellulose source [21].

Cellulose extraction from lignocellulosic biomass generally involves alkaline delignification, bleaching, and purification processes to remove hemicellulose and lignin [22,23]. The efficiency of these treatments depends on several parameters, including alkali concentration, temperature, extraction time, and particle size, which influence yield and purity. Optimization of these variables is essential to ensure efficient extraction and reduce chemical and energy consumption. Response Surface Methodology (RSM) has been widely applied for such optimization, enabling statistical modelling of factor interactions and determination of optimal process conditions [24].

Despite extensive studies on cellulose extraction from other agricultural residues, investigations focusing on edamame pod waste remain limited. Furthermore, integrating alkaline extraction with hydrogen peroxide pretreatment (AHP) offers enhanced delignification efficiency, but this approach has not been widely applied to this material. Therefore, this study aims to optimize cellulose extraction from edamame hull waste using RSM with Box–Behnken design and characterize the resulting cellulose through FTIR

analysis, lignocellulose composition, thermogravimetric analysis (TGA), and derivative thermogravimetry (DTG). These findings are expected to contribute to the utilization of edamame processing waste as a sustainable raw material for the development of environmentally friendly active biofilms.

2 Materials and Methods

2.1 Sample preparation and cellulose extraction

Edamame pod waste was collected from PT Mitra Tani 27, Jember, East Java. The pods were washed with distilled water to remove adhering dirt and impurities, then dehydrated at 60°C until constant weight. The dried pods were ground using a disk mill and sieved to obtain powder. Prior to extraction, the powdered sample was subjected to an alkaline hydrogen peroxide (AHP) washing step to remove surface impurities, residual pigments, and part of the non-cellulosic fractions. All reagents, including sodium hydroxide (NaOH), acetic acid, and hydrogen peroxide (H₂O₂), were of analytical grade and used without further purification.

2.2 Alkaline Hydrogen Peroxide (AHP) washing

Cellulose extraction was carried out following an alkaline treatment and optimized using Response Surface Methodology (RSM) with a Box–Behnken design (BBD). Four independent factors were considered: particle size (40, 60, 80 mesh), extraction temperature (60, 75, 90°C), extraction time (1, 2, 3 h), and NaOH concentration (5, 7.5, 10% w/v). The measured responses were cellulose yield (%) and whiteness index (WI).

2.3 Determination of responses

The cellulose yield (%) was calculated as the weight of extracted cellulose relative to the initial dry weight of edamame pod powder. Whiteness index (WI) was measured using a colorimeter following standard procedures.

2.4 Characterization of extracted cellulose

The cellulose obtained under optimal extraction conditions was further characterized to assess structural integrity and purity. Fourier-transform infrared spectroscopy (Shimadzu, Japan) was employed to identify functional groups within the range of 4000–400 cm⁻¹. To ensure methodological completeness, FTIR analysis followed standard cellulose characterization procedures reported in previous studies [24,25], including baseline correction and interpretation of characteristic cellulose absorption bands (O–H stretching, C–H stretching, and β-(1→4)-glycosidic linkage).

Lignocellulosic composition, including cellulose, hemicellulose, and lignin contents, was determined using the Chesson–Datta method to evaluate the effectiveness of the extraction process.

The thermal stability of the extracted cellulose was analysed using a thermogravimetric analyser (TGA/DSC3+ HT, Mettler Toledo, Greifensee, Switzerland) at the Centre for Development of Advanced Science and Technology, University of Jember. The testing procedure was carried out according to the method described by [10], with slight modifications. Approximately 5 mg of dry cellulose sample was placed in a platinum crucible and heated in a nitrogen (N₂) gas atmosphere to prevent oxidative degradation. Heating was

carried out from 25°C to 600°C at a constant heating rate of 20°C/minute, with a nitrogen gas flow rate of 60 mL/minute to maintain inert conditions during the analysis process. A Thermogravimetric Analysis (TGA) curve was recorded to determine the weight loss profile and char residue percentage at 600°C. Meanwhile, a Derivative Thermogravimetry (DTG) curve was used to identify the onset temperature (Tonset) and maximum degradation temperature (Tmax), which indicate the main points of thermal damage to cellulose. This analytical approach follows commonly applied procedures for evaluating cellulose thermal behavior as reported in previous studies [24,25], ensuring consistent comparison with established characterization methods. These parameters were used to evaluate the thermal stability and purity of cellulose extracted from edamame skin waste.

3 Results and Discussion

3.1 Sample preparation and cellulose extraction

Cellulose extraction from edamame pod waste was successfully optimized using Response Surface Methodology (RSM) with a Box–Behnken Design (BBD). The effects of particle size, extraction temperature, extraction time, and NaOH concentration on cellulose yield and whiteness index (WI) were evaluated. The experimental design and results are presented in Table 1, where yield and WI ranged from 43% to 54.5% and 60% to 70%, respectively, depending on the extraction conditions.

Table 1. Box–Behnken design matrix for cellulose extraction from edamame pod waste, showing the effects of particle size (A), extraction temperature (B), extraction time (C), and NaOH concentration (D) on yield (%) and whiteness index (WI).

Std	Run	Factor 1 A (mesh)	Factor 2 B (°C)	Factor 3 C (hour)	Factor 4 D (%)	Response 1 Yield (%)	Response 2 WI (%)
10	1	80	75	2	5	45.5	63.8
19	2	40	75	3	7.5	44.5	62.2
24	3	60	90	2	10	43	61.3
15	4	60	60	3	7.5	46	65.5
23	5	60	60	2	10	45.6	64.4
5	6	60	75	1	5	52	68.3
22	7	60	90	2	5	45.2	63
21	8	60	60	2	5	48.6	65.2
12	9	80	75	2	10	49.5	69.2
7	10	60	75	1	10	47	65.1
1	11	40	60	2	7.5	43.5	61.5
14	12	60	90	1	7.5	45.2	63.5
8	13	60	75	3	10	43.3	62.4
6	14	60	75	3	5	45.5	62
9	15	40	75	2	5	44	63
3	16	40	90	2	7.5	45	63.5
18	17	80	75	1	7.5	54.5	70
17	18	40	75	1	7.5	43.5	65
13	19	60	60	1	7.5	45.5	65.8
16	20	60	90	3	7.5	46	62.3
11	21	40	75	2	10	43	60
20	22	80	75	3	7.5	53.4	69.7
2	23	80	60	2	7.5	52.5	68
4	24	80	90	2	7.5	49.7	67

Notes: four independent variables were evaluated: particle size (A), extraction temperature (B), extraction time (C), and NaOH concentration (D). The responses measured were cellulose yield (%) and whiteness index (WI).

Analysis of variance (ANOVA) showed that temperature and NaOH concentration had significant ($p < 0.05$) effects on both yield and WI, while particle size and extraction time exhibited moderate interaction effects. The fitted quadratic model demonstrated high accuracy with R^2 values of 0.981 for yield and 0.969 for WI, indicating that the model adequately represented the data.

These findings agree with previous studies reporting that increasing temperature and alkali concentration promotes lignin solubilization and hemicellulose removal, thereby enhancing cellulose recovery and fibre brightness [12,14,25]. However, overly high NaOH levels may cause cellulose degradation and reduced yield [18,26].

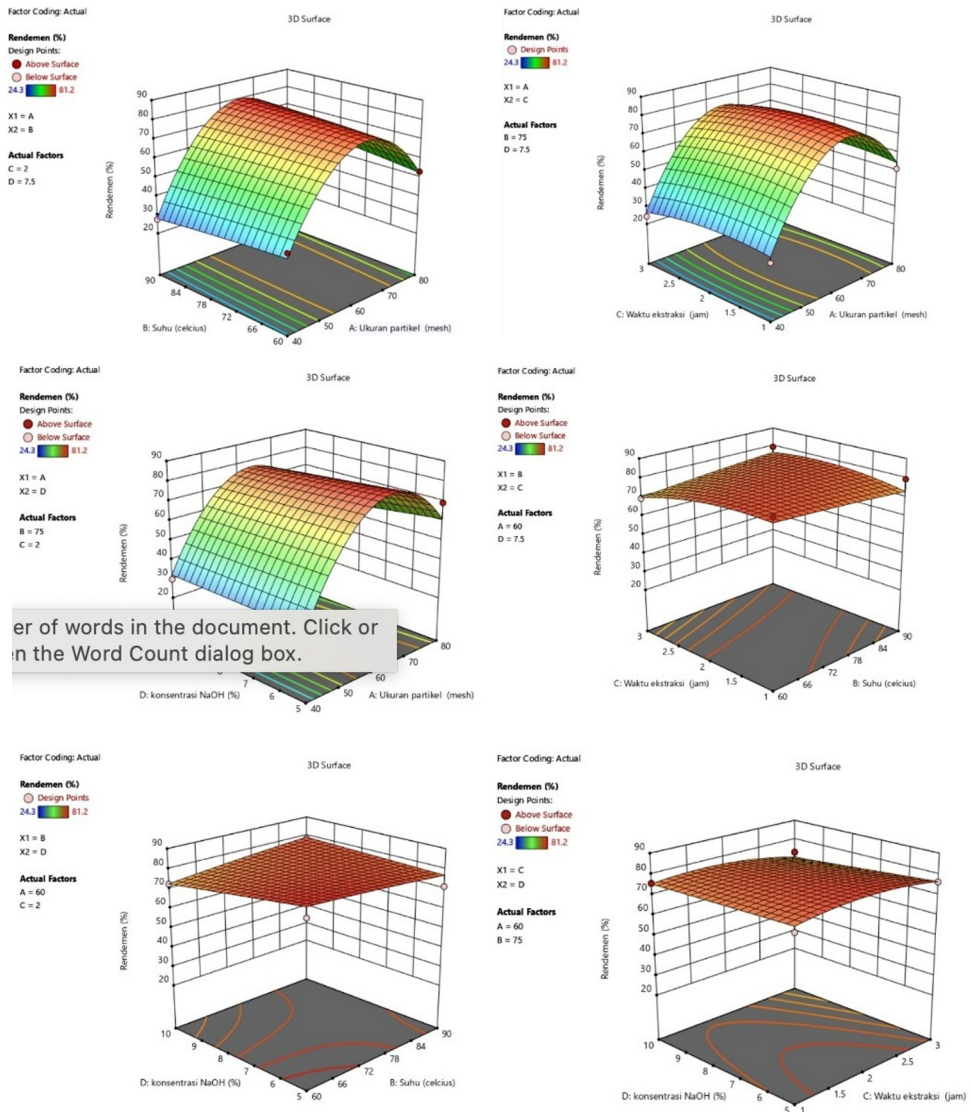


Fig. 1. 3D response surface: Particle size vs NaOH vs Yield

Three-dimensional response surfaces further illustrated the influence of variables. Figure 1 shows that cellulose yield increased with NaOH concentration and temperature up to an

optimal point, beyond which degradation occurred. Similarly, Figure 2 demonstrates that WI improved with NaOH concentration, reflecting enhanced delignification efficiency, but excessive alkali treatment caused slight darkening due to oxidative discoloration of residual lignin [11,18,25].

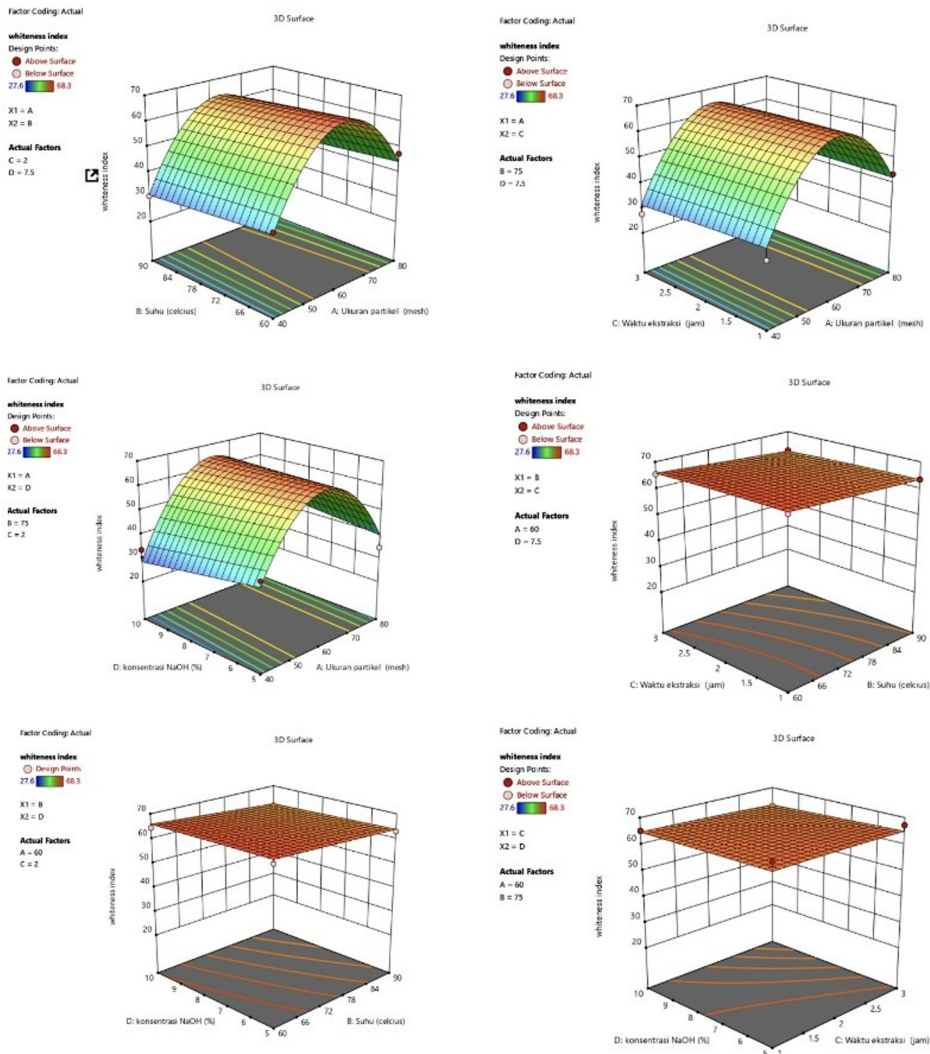


Fig. 2. 3D response surface: Particle size vs NaOH vs Whiteness Index

The optimized conditions—75 °C, 1 h, 7.5% NaOH, and 80 mesh particle size—resulted in maximum cellulose yield 54.5% and whiteness index 70%. These results are comparable to cellulose extracted from soybean hulls and sugarcane bagasse, which achieved yields between 60–70% under similar alkaline conditions [12,14,25].

3.2 Lignocellulosic Composition

The lignocellulosic composition of the edamame pod waste after AHP washing is shown in Table 2. Duplicate analyses (samples A and B) yielded cellulose contents of 56.63% and 63.29%, with an average of 59.96%. The hemicellulose contents were 9.52% and 8.82%

(average 9.17%), while lignin contents were 1.50% and 2.29% (average 1.89%). The resulting lignocellulosic fraction reflects a predominance of cellulose as the main structural carbohydrate, with minor contributions from hemicellulose and lignin.

Table 2. Lignocellulosic composition of edamame pod waste.

Sample	Hemicellulose (%)	Cellulose (%)	Lignin (%)	Lignocellulose (%)
115.1.9.25-A	9.52	56.63	1.50	71.025
115.1.9.25-B	8.82	63.29	2.29	
Average ± SD	9.17 ± 0.50	59.96 ± 4.71	1.89 ± 0.56	

The substantial cellulose proportion confirms the effectiveness of the AHP post-treatment in removing non-cellulosic components such as lignin and hemicellulose. This delignification and purification step is crucial for improving cellulose whiteness and reactivity, ensuring compatibility for subsequent biopolymer or biofilm formation [11,27]. The observed composition is consistent with previous findings on soybean hulls and other agro-residues that typically contain 55–65% cellulose after alkaline or oxidative pretreatment [11,24].

3.3 FTIR characterization

The FTIR spectrum of cellulose extracted from edamame pod waste is presented in Fig. 3. The spectrum displays characteristic absorption peaks typical of cellulose, confirming the successful removal of non-cellulosic constituents such as lignin and hemicellulose.

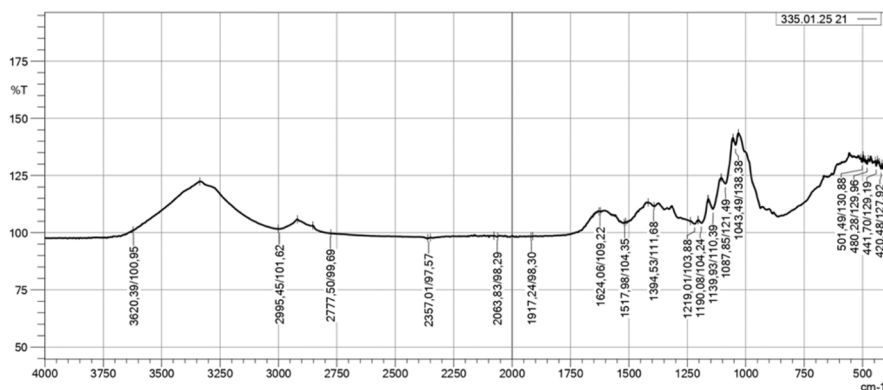


Fig. 3. FTIR spectra of cellulose from edamame pod waste.

A broad absorption band observed around 3335 cm^{-1} corresponds to the stretching vibration of hydroxyl groups ($-\text{OH}$) involved in intra- and intermolecular hydrogen bonding within the cellulose structure [10]. The band at 2896 cm^{-1} is attributed to the $\text{C}-\text{H}$ stretching vibration of aliphatic groups present in the glucose units [14]. A weak absorption near 1634 cm^{-1} is associated with $\text{O}-\text{H}$ bending of absorbed water molecules, indicating the hygroscopic nature of cellulose [14].

The peaks in the region of $1420\text{--}1365\text{ cm}^{-1}$ correspond to CH_2 bending and symmetric deformation vibrations, while the peak near 1314 cm^{-1} is assigned to $\text{C}-\text{O}-\text{H}$ in-plane bending, both of which are characteristic of cellulose I structure. The bands observed at 1160 cm^{-1} and 1054 cm^{-1} are associated with $\text{C}-\text{O}-\text{C}$ asymmetric stretching and $\text{C}-\text{O}$ stretching of the β -1,4-glycosidic linkage, respectively [14,28]. The absorption peak around 897 cm^{-1} represents β -glycosidic linkage ($\text{C}-\text{H}$ deformation) between the anhydro glucose units, further confirming the cellulose backbone [14].

The absence of peaks near 1730 cm^{-1} and 1510 cm^{-1} , which correspond to carbonyl (C=O) stretching in hemicellulose and aromatic skeletal vibrations in lignin, respectively, indicates that these components were effectively removed after alkaline extraction and AHP washing [10,28]. This spectral pattern confirms the formation of high-purity cellulose comparable to that obtained from other agricultural residues such as soybean hulls, sugarcane bagasse, and pineapple leaves [14,25].

3.4 Thermogravimetric Analysis (TGA) and Derivative Thermogravimetry (DTG)

Thermal stability analysis was conducted to evaluate the structural resistance of cellulose to heat exposure, which serves as a critical parameter in determining its potential applications in high-temperature processing, such as in the fabrication of bio-composites and biopolymers [29]. The thermal degradation behavior of cellulose extracted from edamame pod waste was examined using Thermogravimetric Analysis (TGA) and Derivative Thermogravimetry (DTG), as illustrated in Figure 4.

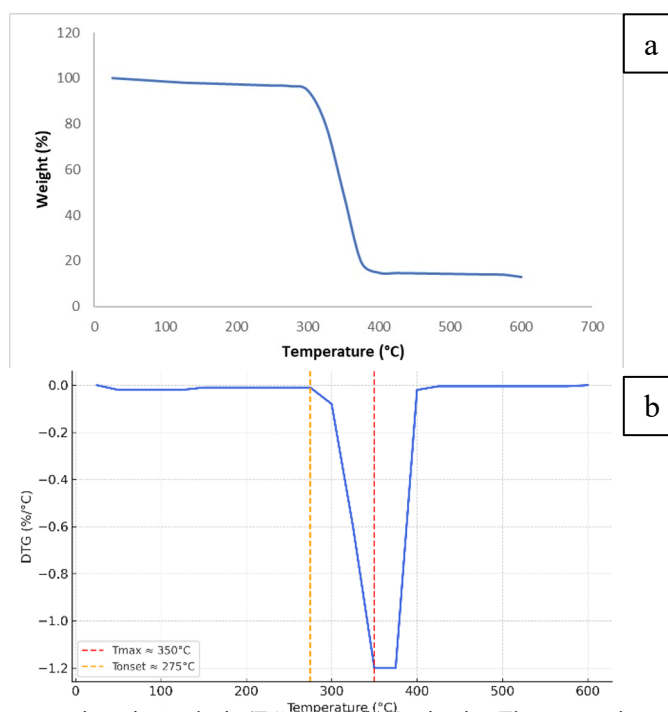


Figure 4. (a) Thermogravimetric Analysis (TGA) and (b) Derivative Thermogravimetry (DTG) curves of cellulose extracted from edamame pod waste using the optimized alkaline extraction process.

The TGA curve exhibited two major stages of mass loss. The initial weight reduction of approximately 5–8% occurred below 120°C , corresponding to the evaporation of moisture and the release of low-molecular-weight volatile compounds adsorbed on the cellulose surface. The main degradation stage appeared in the temperature range of $275\text{--}375^{\circ}\text{C}$, which can be attributed to the depolymerization process and cleavage of glycosidic bonds within the cellulose backbone [30].

The DTG curve displayed a single sharp peak with a maximum decomposition temperature (T_{max}) of around 350°C , indicating that the sample predominantly consists of a single thermally active component, namely cellulose [31]. The onset decomposition temperature (T_{onset}) was observed at approximately 275°C , demonstrating that the extracted cellulose possesses high thermal stability.

At 600°C , the remaining mass (char residue) was about 13%, suggesting a high level of purity with minimal lignin and hemicellulose content. The absence of multiple degradation peaks in the DTG curve further confirms that the alkaline extraction and bleaching treatments effectively removed most non-cellulosic components.

Overall, the high degradation temperature and low char residue indicate that the cellulose extracted through the optimized alkaline treatment exhibits high purity and strong structural integrity. These characteristics highlight the potential of cellulose derived from edamame pod waste as a thermally stable raw material for bio-composite applications, consistent with previous findings on cellulose isolates from agricultural residues.

4 Conclusion

This study confirmed that edamame pod waste can serve as a sustainable raw material for cellulose extraction using an alkaline treatment optimized through Response Surface Methodology (RSM). The optimal extraction conditions (80°C , 2.5 h, 8.5% NaOH, 60 mesh) produced cellulose with high yield, brightness, and purity, further improved by AHP washing. FTIR analysis verified the successful isolation of cellulose through the presence of β -1,4-glycosidic linkages and the absence of lignin and hemicellulose peaks. Thermal analysis (TGA–DTG) revealed a single-step degradation pattern with $T_{onset} \approx 275^{\circ}\text{C}$, $T_{max} \approx 350^{\circ}\text{C}$, and $\sim 13\%$ residue at 600°C , confirming high thermal stability and structural integrity. These results demonstrate an efficient and eco-friendly process for valorizing agricultural waste into high-purity cellulose suitable for advanced biopolymer, biofilm, and biocomposite applications, supporting circular bioeconomy initiatives in soybean-based industries.

5 References

- [1] R. Kaur, L. Pathak, and P. Vyas, “Biobased polymers of plant and microbial origin and their applications - a review,” *Biotechnology for Sustainable Materials*, vol. 1, no. 1, p. 13, Oct. 2024, doi: 10.1186/s44316-024-00014-x.
- [2] S. Huang, Q. Dong, S. Che, R. Li, and K. H. D. Tang, “Bioplastics and biodegradable plastics: A review of recent advances, feasibility and cleaner production,” *Science of The Total Environment*, vol. 969, p. 178911, Mar. 2025, doi: 10.1016/j.scitotenv.2025.178911.
- [3] S. N. Idris *et al.*, “The degradation of single-use plastics and commercially viable bioplastics in the environment: A review,” *Environ Res*, vol. 231, p. 115988, Aug. 2023, doi: 10.1016/j.envres.2023.115988.
- [4] P. Fan, H. Yu, B. Xi, and W. Tan, “A review on the occurrence and influence of biodegradable microplastics in soil ecosystems: Are biodegradable plastics substitute or threat?,” *Environ Int*, vol. 163, p. 107244, May 2022, doi: 10.1016/j.envint.2022.107244.
- [5] M. Jabeen, K. Tariq, and S. U. Hussain, “Bioplastic an alternative to plastic in modern world: A systemized review,” *Environmental Research and Technology*, vol. 7, no. 4, pp. 614–625, Dec. 2024, doi: 10.35208/ert.1467590.

- [6] N. S. K. Gowthaman, H. N. Lim, T. R. Sreeraj, A. Amalraj, and S. Gopi, “Advantages of biopolymers over synthetic polymers,” in *Biopolymers and their Industrial Applications*, Elsevier, 2021, pp. 351–372. doi: 10.1016/B978-0-12-819240-5.00015-8.
- [7] R. S. Riseh, M. G. Vazvani, M. Hassanisaadi, and V. K. Thakur, “Agricultural wastes: A practical and potential source for the isolation and preparation of cellulose and application in agriculture and different industries,” *Ind Crops Prod*, vol. 208, p. 117904, Feb. 2024, doi: 10.1016/j.indcrop.2023.117904.
- [8] M. Sharma *et al.*, “A review of valorization of agricultural waste for the synthesis of cellulose membranes: Separation of organic, inorganic, and microbial pollutants,” *Int J Biol Macromol*, vol. 277, p. 134170, Oct. 2024, doi: 10.1016/j.ijbiomac.2024.134170.
- [9] A. Mtibe, M. J. John, J. E. Andrew, and T. C. Mokhena, “Sequential extraction of carbohydrates and lignin from agricultural waste and their structural characterization,” *Biomaterials and Polymers Horizon*, vol. 1, no. 2, Aug. 2022, doi: 10.37819/bph.001.02.0216.
- [10] O. Romruen, T. Karbowski, W. Tongdeesontorn, K. A. Shiekh, and S. Rawdkuen, “Extraction and Characterization of Cellulose from Agricultural By-Products of Chiang Rai Province, Thailand,” *Polymers (Basel)*, vol. 14, no. 9, p. 1830, Apr. 2022, doi: 10.3390/polym14091830.
- [11] T. Wang and Y. Zhao, “Optimization of bleaching process for cellulose extraction from apple and kale pomace and evaluation of their potentials as film forming materials,” *Carbohydr Polym*, vol. 253, p. 117225, Feb. 2021, doi: 10.1016/j.carbpol.2020.117225.
- [12] R. Bortolatto, P. R. S. Bittencourt, and F. Yamashita, “Biodegradable starch / polyvinyl alcohol composites produced by thermoplastic injection containing cellulose extracted from soybean hulls (*Glycine max L.*),” *Ind Crops Prod*, vol. 176, p. 114383, Feb. 2022, doi: 10.1016/j.indcrop.2021.114383.
- [13] M. L. Tummino *et al.*, “Antibacterial properties of functionalized cellulose extracted from deproteinized soybean hulls,” *Cellulose*, vol. 30, no. 12, pp. 7805–7824, Aug. 2023, doi: 10.1007/s10570-023-05339-w.
- [14] A. Moramarco, E. Ricca, E. Acciaro, E. Laurenti, and P. Bracco, “Cellulose Extraction from Soybean Hulls and Hemp Waste by Alkaline and Acidic Treatments: An In-Depth Investigation on the Effects of the Chemical Treatments on Biomass,” *Polymers (Basel)*, vol. 17, no. 9, p. 1220, Apr. 2025, doi: 10.3390/polym17091220.
- [15] A. Karim, E. F. Osse, and S. Khalloufi, “Innovative strategies for valorization of byproducts from soybean industry: A review on status, challenges, and sustainable approaches towards zero-waste processing systems,” *Heliyon*, vol. 11, no. 3, p. e42118, Feb. 2025, doi: 10.1016/j.heliyon.2025.e42118.
- [16] Y. Nan, D. Gomez-Maldonado, M. C. Iglesias, D. C. Whitehead, and M. S. Peresin, “Valorized soybean hulls as TEMPO-oxidized cellulose nanofibril and polyethylenimine composite hydrogels and their potential removal of water pollutants,” *Cellulose*, vol. 30, no. 6, pp. 3639–3651, Apr. 2023, doi: 10.1007/s10570-023-05086-y.
- [17] P. Singh and K. Krishnaswamy, “Sustainable zero-waste processing system for soybeans and soy by-product valorization,” *Trends Food Sci Technol*, vol. 128, pp. 331–344, Oct. 2022, doi: 10.1016/j.tifs.2022.08.015.
- [18] P. Suanto, Saloma, A. P. Usman, A. Saggaff, M. Ismail, and N. H. A. Khalid, “The Characterization of Nanocellulose with Various Durations and NaOH Concentration,” *International Journal of Innovative Research and Scientific Studies*, vol. 5, no. 1, pp. 18–29, Feb. 2022, doi: 10.53894/ijirss.v5i1.343.

- [19] D. Yu *et al.*, “Chemical Compositions of Edamame Genotypes Grown in Different Locations in the US,” *Front Sustain Food Syst*, vol. 5, Feb. 2021, doi: 10.3389/fsufs.2021.620426.
- [20] J. M. Hlahla, M. S. Mafa, R. van der Merwe, and M. J. Moloi, “Tolerance to combined drought and heat stress in edamame is associated with enhanced antioxidative responses and cell wall modifications,” *Physiol Plant*, vol. 177, no. 2, Mar. 2025, doi: 10.1111/pp1.70187.
- [21] Z. Kassab, Y. Abdellaoui, M. H. Salim, and M. El Achaby, “Cellulosic materials from pea (*Pisum Sativum*) and broad beans (*Vicia Faba*) pods agro-industrial residues,” *Mater Lett*, vol. 280, p. 128539, Dec. 2020, doi: 10.1016/j.matlet.2020.128539.
- [22] B. Tsegaye, C. Balomajumder, and P. Roy, “Organosolv pretreatments of rice straw followed by microbial hydrolysis for efficient biofuel production,” *Renew Energy*, vol. 148, pp. 923–934, Apr. 2020, doi: 10.1016/j.renene.2019.10.176.
- [23] P. Parkhey, A. K. Ram, B. Diwan, J. S. Eswari, and P. Gupta, “Artificial neural network and response surface methodology: a comparative analysis for optimizing rice straw pretreatment and saccharification,” *Prep Biochem Biotechnol*, vol. 50, no. 8, pp. 768–780, Sep. 2020, doi: 10.1080/10826068.2020.1737816.
- [24] E. G. Bacha, “Response Surface Methodology Modeling, Experimental Validation, and Optimization of Acid Hydrolysis Process Parameters for Nanocellulose Extraction,” *S Afr J Chem Eng*, vol. 40, pp. 176–185, Apr. 2022, doi: 10.1016/j.sajce.2022.03.003.
- [25] G. T. Melesse, F. G. Hone, and M. A. Mekonnen, “Extraction of Cellulose from Sugarcane Bagasse Optimization and Characterization,” *Advances in Materials Science and Engineering*, vol. 2022, pp. 1–10, Oct. 2022, doi: 10.1155/2022/1712207.
- [26] J. Peng *et al.*, “Influence and mechanism of NaOH concentration on the dissolution of cellulose and extraction of CNF in alkaline solvents at 15 °C,” *Carbohydr Polym*, vol. 353, p. 123265, Apr. 2025, doi: 10.1016/j.carbpol.2025.123265.
- [27] A. Hernández-Guzmán, I. M. Navarro-Gutiérrez, P. A. Meléndez-Hernández, J. U. Hernández-Beltrán, and H. Hernández-Escoto, “Enhancement of alkaline-oxidative delignification of wheat straw by semi-batch operation in a stirred tank reactor,” *Bioresour Technol*, vol. 312, p. 123589, Sep. 2020, doi: 10.1016/j.biortech.2020.123589.
- [28] I. Iliyın, H. Purwaningsih, and T. T. Irawadi, “Isolation and Characterization of Cellulose from Banana Stems using Microwave Heating,” *Jurnal Kimia Valensi*, vol. 6, no. 2, pp. 169–176, Jan. 2021, doi: 10.15408/jkv.v6i2.15962.
- [29] J. Zhang *et al.*, “Effect of High-Temperature Hydrothermal Treatment on the Cellulose Derived from the Buxus Plant,” *Polymers (Basel)*, vol. 14, no. 10, p. 2053, May 2022, doi: 10.3390/polym14102053.
- [30] E. Apaydın Varol and Ü. Mutlu, “TGA-FTIR Analysis of Biomass Samples Based on the Thermal Decomposition Behavior of Hemicellulose, Cellulose, and Lignin,” *Energies (Basel)*, vol. 16, no. 9, p. 3674, Apr. 2023, doi: 10.3390/en16093674.
- [31] A. Paajanen and J. Vaari, “High-temperature decomposition of the cellulose molecule: a stochastic molecular dynamics study,” *Cellulose*, vol. 24, no. 7, pp. 2713–2725, Jul. 2017, doi: 10.1007/s10570-017-1325-7.