Research Article

Preparation and Characterization of Cellulose Film from Velvet Tamarind Rind (*Dialium indum* L.) for Food Packaging

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Abstract

The environmental impact of plastic waste underscores the need for biodegradable films as sustainable alternatives. This study investigates velvet tamarind rind as a novel cellulose source, extracted through chemical and ultrasound treatments. The isolated cellulose exhibited good characteristics, with crystallinity indices of 66% and 85.4% for chemical and ultrasound treatments, respectively. Three types of cellulose films were prepared: Cell film (without ultrasound treatment), CellS film (with ultrasound treatment), and CellSP film (with ultrasound treatment and glycerol as a plasticizer). The CellS film exhibited a higher crystallinity index (85.4%) than the Cell and CellSP films (62.7% and 51.8% respectively). The addition of glycerol in the CellSP film resulted in the highest tensile strength of 17.2 MPa and a smoother surface compared to the other films. Notably, the organoleptic profile of grapes wrapped with the CellSP films showed comparable results to those grapes wrapped using polyvinyl chloride (PVC) wrap. These findings highlight the potential of velvet tamarind rind cellulose for eco-friendly food packaging, with properties that rival and, in some cases, surpass those of earlier studied wraps. Future work could explore scaling up production and enhancing performance through additional fillers or treatments.

Keywords: Biodegradable film, Chemical isolation, Glycerol, Ultrasonication, Velvet tamarind cellulose

1 Introduction

The use of conventional plastics produced from synthetic polymers derived from petroleum derivatives has significant environmental drawbacks, as they do not degrade naturally [1], [2]. Traditional plastics take hundreds of years to break down in the environment [3]. This issue has prompted researchers to develop an alternative [4]. Biodegradable films, which decompose quickly and effectively in the environment, offer a promising alternative to conventional plastics [5], [6]. The development of biodegradable polymers has become even more critical during and after the COVID-19 pandemic due to the increased burden of medical waste made from synthetic polymers [7]. Biopolymers or natural polymers can be utilized to create these biodegradable films [8].

The most used biopolymer in the preparation of biodegradable films is cellulose [9]. Many types of biomass have been reported by many researchers to extract cellulose such as sugarcane bagasse [10], [11], durian rind [12], vegetable waste [13], pineapple leaf [14], grass [15], bacterium [16], ginger [17], coconut husk [9], coconut dreg [18], [19], and so on. Previous studies have demonstrated the potential of plant rinds as a sustainable source of cellulose for film productions. For instance, durian rind cellulose has developed as a transparent film [12]. Another study reported the production of film from litchi rind cellulose [20]. Previous studies also reported that cellulose derived from jackfruit peel was utilized for the development of film [21]. The reasons of cellulose are widely used in the production of biodegradable films due to its affordability, abundance, renewability, environmentally friendly properties, and the most abundant natural polymer on Earth, making it a sustainable resource. Its biodegradability ensures that products made from cellulose can decompose naturally, reducing environmental pollution and offering a viable alternative to conventional plastics. Furthermore, the versatility of cellulose allows for its modification and enhancement to meet specific functional requirements, such as improved mechanical strength, barrier properties, and compatibility with other biodegradable materials. This makes cellulose an ideal candidate for developing innovative, eco-friendly packaging solutions that address the growing concerns over plastic waste and environmental sustainability [5], [17], [22].

Velvet tamarind (*Dialium indum* L.) is a native fruit of Southeast Asia, found in countries such as Malaysia, Thailand, Indonesia, and a few African nations. Known as tropical fruits, the demand for tropical fruits is reported to continue increasing, with developing countries contributing up to 98% of total global import-trade [23]. Velvet tamarind in the Aceh Besar District is widely consumed, and the rind is often simply discarded despite its high carbohydrate content [24], [25]. Incineration of this waste generates emissions that pollute the air. These challenges highlight the need to convert this underutilized waste into valuable resources. A cellulose biorefinery converts plant-based biomass into sustainable products like materials, offering eco-friendly alternatives to petroleum-based products and supporting resource efficiency within a circular economy [26], [27]. This study aligns with the principle of circular economy and supports the sustainable development goals (SDGs), particularly SDG 12 (responsible consumption and production) and SDG 15 (life on land) [28], [29]. This biomass waste typically consists of cellulose, lignin, hemicellulose, and other components. Given its complex structure and composition, efficient methods are essential for extracting cellulose from this source [30]. Cellulose, a natural fiber in plants, consists of monomers connected by β-(1,4)-glycosidic linkages [31], [32]. The commonly used methods for cellulose extraction include chemical treatment (using strong alkali followed by strong acid hydrolysis), thermal treatment, biological treatment, and mechanical methods such as ultrasonication [11], [17], [33], [34].

Ultrasound has been viewed as a potential and environmentally benign alternative for cellulose extraction processes. It works by mechanically transferring energy in the form of sound waves into the extraction system [35], [36]. Ultrasonication is one of the most commonly reported techniques used to reduce the size of cellulose [37], [38]. The ultrasound treatment improves the quality of cellulose by reducing its size and increasing its crystallinity [39], [40]. The smaller particle size of the cellulose results in greater efficiency due to a larger surface area. This larger surface area enhances the interactions between cellulose particles, making their application as a film more effective. However, despite its advantages, the application of ultrasonic treatment for biomass like velvet tamarind rind remains unexplored.

In addition to particle size, the addition of plasticizers can improve the quality of films [41]. Plasticizers such as glycerol enhance the elasticity of the film [42]. This study aims to prepare and characterize cellulose-based film derived from velvet tamarind rind waste, a locally abundant but underutilized biomass in Aceh Besar District, Aceh Province, Indonesia. Although the production of cellulose films from biomass is well-documented, the use of velvet tamarind rind as raw material has not been previously reported. This research explores the potential of this agricultural waste to produce biodegradable films, contributing to sustainable waste management and the development of eco-friendly packaging alternatives.

2 Materials and Methods

2.1 *Materials*

The Velvet Tamarind rind was obtained from Aceh Besar District, Aceh Province, Indonesia. Chemicals used in this study include sodium hydroxide (NaOH), glacial acetic acid (CH_3COOH), toluene (C_7H_8) 99%, hydrochloric acid (HCl), and sulfuric acid (H_2SO_4) 97%, glycerol ($C_3H_8O_3$). All materials were analytical grade and purchased from Merck, Co, Ltd (Selangor, Malaysia). Sodium hypochlorite (NaClO) was procured from Ajax Fine Chem, Pty, Ltd (Seven Hills, Australia).

2.2 *Cellulose isolation and film preparation*

The Velvet tamarind rind was separated from the mesocarp and endocarp, carefully washed, and crushed into a fine powder. The powder was then oven-dried at 50 °C for 20 h before being treated according to the following procedures adapted from [18] with several modifications:

The dried velvet tamarind rind powder was boiled for three hours at 80 °C in a 250 mL Erlenmeyer flask and subsequently air-dried, to remove polar residues such as water-soluble impurities, and other polar compounds. The samples were immersed in a mixture of toluene and ethanol (2:1) for 24 h, then soaked at 500 rpm and 50 °C for 48 hours using a hotplate stirrer. The soaked samples were washed with distilled water until the pH was neutral and then oven-dried. The dried samples were soaked in a 5% NaOH solution and agitated at 500 rpm and 50 °C for 4 h. After treatment, the samples were rinsed with distilled water until the pH was neutral and then oven-dried.

The dried sample from the previous step was hydrolyzed with 5M HCl at 50 °C, 250 rpm for 12 h, and then rinsed until the pH was neutral. The hydrolyzed sample was bleached by soaking it in a solution containing a mixture of NaClO and CH_3COOH (4:1) and stirred at 500 rpm and 60 °C for 2 h. The sample was then rinsed with distilled water until the pH was neutral. 50 mL suspension was poured into a Teflon plate to be dried in a conventional oven at 40 °C for 20 h (Cell film).

A total of 50 mL of treated cellulose suspension was then sonicated using a Sonics-Vibra Cell™ (Sonics & Materials, Newtown, CT, USA) ultrasonic processor. The sonication procedure was carried out for 4 h at 60 °C, pulse rate of 2 s on and 2 s off, 60% amplitude, and a frequency of 20 kHz. The solid loading ratio used for the 50 mL volume cellulose suspension was 10 g of cellulose per 50 mL suspension. The suspension was poured into a Teflon plate to be dried in a conventional oven at 40 °C for 20 h (CellS film). To prepare the CellSP film, 5% (v/v) of glycerol was added to 50 mL of sonicated cellulose suspension. The mixture was stirred using a magnetic stirrer at 50 rpm for 10 minutes. The suspension was then poured into a Teflon plate and dried in a conventional oven at 40 °C for 20 h to obtain the CellSP film [18].

2.3 *Characterization*

To determine the chemical composition of the raw material and isolated cellulose, composition analysis (residues, hemicellulose, lignin, and cellulose) was performed following previously reported methods [10]. The tensile strength of the films was evaluated using the ASTM D638-03 method at a tensile speed of 20 mm/min. To identify the functional groups of the sample, Fourier Transform Infrared Spectroscopy (FTIR) (PerkinElmer Frontier IR/FIR, USA) was used to scan the sample over a frequency range of 4000–400 cm^{-1}. Material characterization was performed with X-ray diffraction (XRD) using the PANalytical Xpert PRO instrument, scanning from $2\theta = 0°$ to 60°. The crystallinity index (ICr) percentage was calculated with Origin software. The thermal properties of the film were analyzed using Thermogravimetric Analysis/Differential Scanning Calorimetry (TGA/DSC) from Mettler Toledo. Additionally, the film's morphology was examined using FEI NOVA Nano Scanning Electron Microscopy (SEM) at 20 kV and 8 mA with 100x and 60x magnification [19].

2.4 *Organoleptic tests*

Using a hedonic (rating) scale, the obtained biodegradable films were evaluated through organoleptic testing. The organoleptic tests assessed the quality of grapes wrapped with Cell, CellS, CellSP, and conventional plastic (as control) over a 15-day period. Five respondents were asked to assess changes in the texture and color of the grapes. On the first, third, sixth, ninth, twelfth, and fifteenth days, respondents rated the grapes' color and texture on a numerical scale from 1 to 5, where 5 indicated 'very good', 4 indicated 'good', 3 indicated 'moderately good', 2 indicated 'bad', and 1 indicated 'very bad'.

2.5 *Swelling tests*

The film mass was weighed and then submerged in water for three hours in a Petri dish. The film was then removed with tweezers, and cleaned with tissue. The weight of each film was recorded. The swelling (%) of each film is calculated by the following Equation (1) [43]:

$$\%\ Swelling = \frac{Wss - Wds}{Wds}\ 100 \qquad (1)$$

W_{ds}: weight dried sample; W_{ss}: weight swollen sample

2.6 *Biodegradation tests*

This procedure involves burying the films (2×2 cm^2) with a depth of 5 cm in a container filled with compost soil. Water is then sprayed onto the soil to moisten the soil surface. Each sample was weighed before being buried. Observations were made by washing the film with distilled water, drying it in an oven, and calculating the percent weight loss from each film using Equation (2) on 1, 7, 14, 21, 28, and 35-day period.

$$\%\ Weight\ loss = \frac{Wo - W1}{Wo}\ 100 \qquad (2)$$

Where, W_o represents the initial weight and W_1 is the final weight after burial. This protocol followed the suggestion from a previous study [12].

3 Results and Discussion

3.1 *Characterization of cellulose and film*

Chemical treatment was successful in degrading lignin from lignocellulosic biomass. Results of the study revealed that the lignin structure was attacked and damaged by the NaOH solution, indicated by the change in the color mixture from yellowish to reddish-brown producing a strong stench and known as black liquor [44] as shown in Figure 1. To identify the differences in functional groups in the samples before and after chemical treatment, FTIR characterization was performed. The FTIR spectra of raw material and isolated cellulose is presented in Figure 2. NaOH acts as a delignifying agent by breaking down the ester and ether bonds in lignin, thus separating it from cellulose. This pretreatment increases the accessibility of cellulose for further processing, enhancing its purity and crystallinity [45]. The advantages of using NaOH include its effectiveness in lignin removal and its ability to operate under mild conditions. However, its disadvantages involve the generation of significant amounts of black liquor, which requires proper disposal to avoid environmental pollution and the potential degradation of cellulose if not carefully controlled [46].

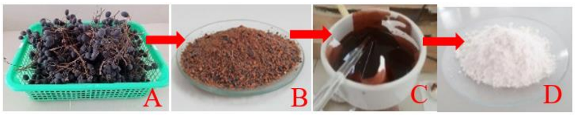


Figure 1: (A) Velvet tamarind fruit; (B) raw material from Velvet Tamarind rind; (C) black liquor during the delignification process; (D) dried isolated cellulose powder after chemical treatment.

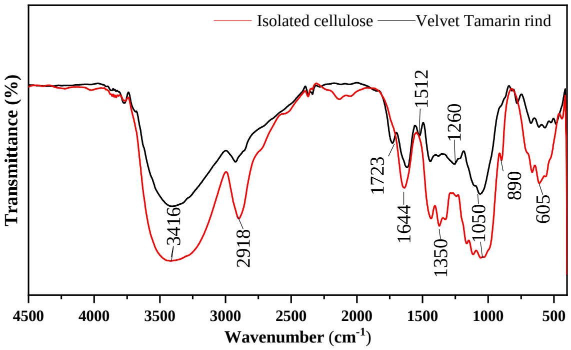


Figure 2: FTIR spectra of raw material from velvet tamarind rind and isolated cellulose.

The FTIR spectrum (Figure 2) of velvet tamarind shows an absorption band at wavenumber 1723 cm^{-1}, which is assigned to the stretching vibration of C=O from the acetyl and ester functional groups of hemicellulose and -coumarin acid from lignin and/or hemicellulose. The C-C stretching vibration of the aromatic ring in lignin was observed at wave number 1512 cm^{-1} [47]. Additionally, the absorption band at wave number 1260 cm^{-1} denotes the vibration of the aromatic ring in lignin [14]. This finding indicates that raw material contains hemicellulose and lignin. These absorption bands disappeared in the FTIR spectrum of isolated cellulose, indicating that hemicellulose and lignin were successfully removed from the sample through chemical treatment [17], [48]. Furthermore, the C-OH bond of cellulose was identified at wavenumber 605 cm^{-1} [49]. The finding demonstrates that cellulose was successfully extracted from velvet tamarind rind, highlighting its potential as a novel source of cellulose.

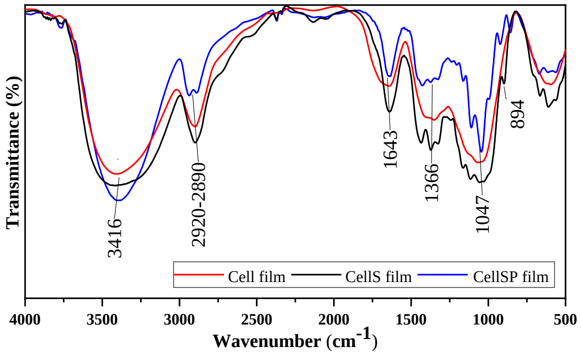


Figure 2: FTIR spectrum characterization of three film specimens.

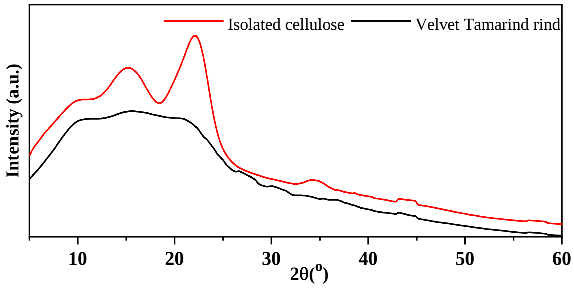


Figure 3: Diffractogram of raw material from the rind of velvet tamarind and isolated cellulose.

Figure 3 shows the results of the FTIR characterization of the three films obtained. The films exhibited absorption peaks at wavenumbers starting at 3400 cm$^{–1}$, corresponding to the hydroxyl stretching vibrations (-OH) of hydrogen bonds in cellulose. The intensity of this peak varied depending on whether glycerol was added; in the presence of glycerol, the OH stretching vibration's intensity increased. This is due to the chemical interaction between the OH functional groups of glycerol and cellulose. However, the overall intensity of the film decreased with the addition of the glycerol plasticizer. Other observed vibrations included asymmetric C-H stretching vibrations at wavenumbers 2900 and 2890 cm$^{–1}$, and symmetric CH_2 stretching vibrations from aromatic and aliphatic rings in cellulose at wavenumbers around 1300 cm$^{–1}$. The C=O bending vibration of cellulose, detected in all three films, showed an absorption peak at a wavenumber of 1643.401 cm$^{–1}$. Furthermore, the removal of pectin, hemicellulose (xylan), and lignin from cellulose resulted in a more intense stretching vibration of the C-O-C ether from glycosidic linkages at a wavenumber of approximately 898 cm$^{–1}$ compared to the raw material, indicating the formation of glycosidic linkages connecting the cellulose monomers [50].

The XRD analysis of the velvet tamarind rind and isolated cellulose was carried out, as shown in Figure 4. Figure 4 demonstrates that both raw material and isolated cellulose exhibit two prominent peaks at 2θ = 15.7° and 22°, which are typical for cellulose in lignocellulosic biomass [51]. In addition to cellulose, the material also contains hemicellulose, lignin, and other residues, which may cause differences in peak height or crystallinity index. The crystallinity index of raw material and isolated cellulose in this study were 0.009162% and 66%, respectively. After chemical treatment, the amorphous regions of cellulose are diminished and the crystalline regions are enhanced, indicating that cellulose has been successfully isolated [52], [53]. In addition, Table 1 provides the biomass composition before and after chemical treatment supporting these findings.

Table 1: Chemical composition of velvet tamarind rind before and after pretreatment.

Parameter	Raw Material (%)	Isolated Cellulose (%)
Residue	5.94	0.9
Hemicellulose	14.30	3.6
Lignin	57.63	1.4
Cellulose	22.13	94.1

Table 1 shows the critical information for assessing the efficacy of the chemical treatment in removing lignin and other non-cellulosic components. It highlights the compositional changes that occur during the process, such as the reduction in lignin and hemicellulose content and the corresponding increase in cellulose purity.

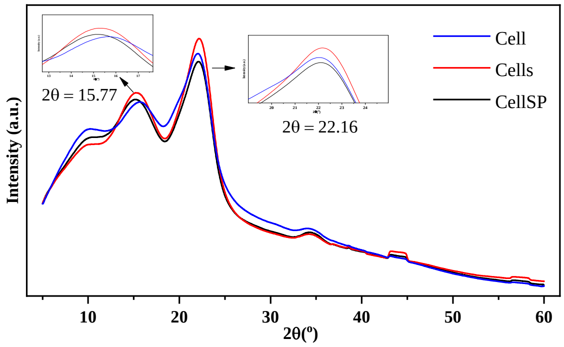
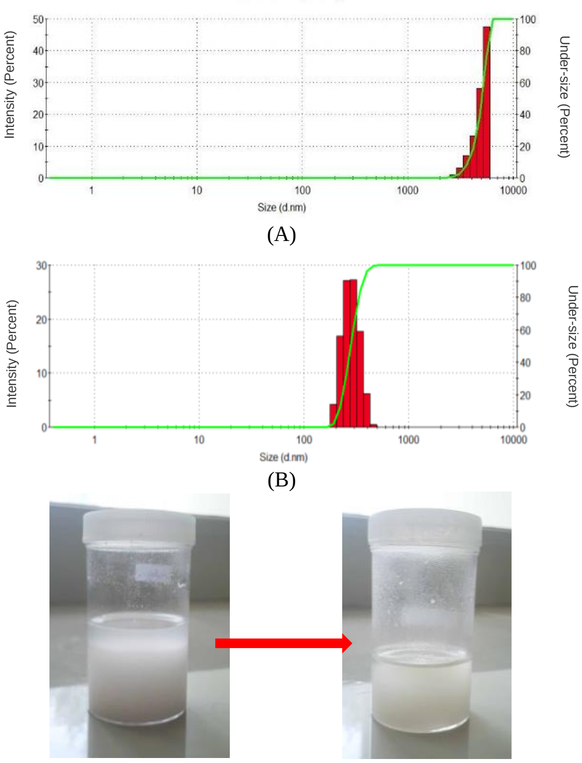


Figure 4: Diffractograms of Cell, CellS and CellSP films obtained.

The diffractogram of the three variants of the film has different peaks (Figure 5). Cell, CellS, and CellSP films have index crystallinity of 62.7, 85.4, and 51.8%, respectively. This finding is aligned with previous studies reported [43], [54], [55]. The ultrasonication treatment may enhance the crystalline structure of cellulose due to the breaking of the amorphous part of cellulose, causing the crystallinity index of CellS film to increase (from 62.7% to 85.4%) as shown in Figure 5. The findings imply that ultrasonication can selectively target the amorphous regions of cellulose while preserving or enhancing the crystalline regions under specific conditions. These-selective effects may not have been prominent in earlier studies due to differences in sample preparation or ultrasonic parameters, which might have led to complete disruption of the crystalline structure. A previous study reported that the crystallinity index of cellulose decreases after ultrasound treatment due to the formation of nano-sized particles of cellulose [17], [39], [56]. The ultrasonic waves disrupt the cellulose crystalline structure, decreasing the particle size and breaking it into nanoparticles [57]. After chemical treatment, the particle size of the isolated cellulose was approximately 4900 nm (Figure 6(A)). Following ultrasound treatment, the particle size decreased. However, in this study, the obtained cellulose did not reach the nano-sized range and instead remained in the microfiber scale. This was confirmed by particle size analysis (PSA), as shown in Figure 6(B), which indicates that cellulose with a size of approximately 200 nm, or microfiber cellulose, was obtained. The crystallinity index of the CellSP film then decreased as a result of glycerol's ability to alter the cellulose molecular chain [14], [36].

Each film was observed through DSC analysis, revealing the thermal properties of the film (endothermic and exothermic peaks) as shown in Figure 7. The Cell film and CellS film share similar thermal characteristics, with endothermic peaks at 109.8 °C and 100.6 °C, appearing at 71.99 °C and 63.92 °C, respectively. At these conditions, both films began to release their water content and start to absorb heat at rates of 1.89 and 1.13 Joules, respectively [58], [59]. Depolymerization of the molecules in the film occurs at subsequent transitions at 145.66 °C and 138.25 °C. The films start to disintegrate during the second transition, marked by the exothermic peaks at 551.7 °C and 549.3 °C, respectively.



(A)

(B)

Before and after ultrasound treatment

(C)

Figure 5: PSA result of cellulose after (A) chemical; (B) ultrasound treatment; and (C) cellulose suspension before (left) and after (right) ultrasound treatment.

Furthermore, the endothermic peak transition at 130.1 °C begins around 115.7 °C in the thermal characteristic observations of the CellSP films (Figure 7). Under these conditions, the film absorbs 0.65 joules of heat, releasing water and volatile compounds, aligning with previous studies [59], [60]. Depolymerization begins at 151.1 °C, and at the endothermic peak of 289.73 °C, the film releases glycerol, consistent with glycerol's boiling point of 290 °C. The CellSP film shows thermal degradation at around 553.8 °C, indicating stronger molecular interactions between cellulose and glycerol, which enhance its thermal resistance compared to the other films.

The obtained films exhibited varying appearances, with the CellS and CellSP films showing improved visual qualities compared to the Cell film, as depicted in Figure 8(A). Both CellS and CellSP films displayed a nearly transparent appearance, unlike the Cell film. This improvement can be attributed to significantly reduced cellulose particle size achieved through ultrasound treatment, as shown in Figure 6(A) and (B). The reduced particle size likely enhanced the uniformity of the cellulose dispersion in the matrix, minimizing light scattering and contributing to the transparency of the films. In comparison, the larger particle size of pure cellulose in the Cell film caused a less homogeneous structure leading to its opaque appearance.

To further analyze the changes in the films resulting from ultrasonication treatment and the addition of glycerol, SEM characterization was conducted, as presented in Figure 8. The cellulose particles in the Cell film remain large, rough, uneven, and less homogeneous on the surface, indicating weak interactions between the cellulose particles (Figure 8(B)) [61]. This weak interaction contributes to the lower mechanical properties, such as tensile strength, compared to the other films. This finding is supported by the SEM cross-section of the Cell film shown in Figure 8C, which reveals significant porosity and the structural arrangement of the cellulose particles. The observed porosity and lack of compactness in the structure may indirectly suggest weak physical interactions between cellulose particles.

The morphology analysis of the CellS film displayed in Figure 8(D) and (E), shows an improvement in the film's surface after ultrasound treatment. This finding is consistent with a previous study, where the ultrasound treatment improves the morphology of film [62]. Figure 8(E) indicates overlapping cellulose, making the structure denser and tighter. This is corroborated by the findings in Figure 6(B) and (C), which show that ultrasonication reduced the size and increased the homogeneity of the cellulose suspension [63]. These observations are consistent with the tensile strength analysis in Figure 9, where the CellS film exhibits higher tensile strength compared to the Cell films.

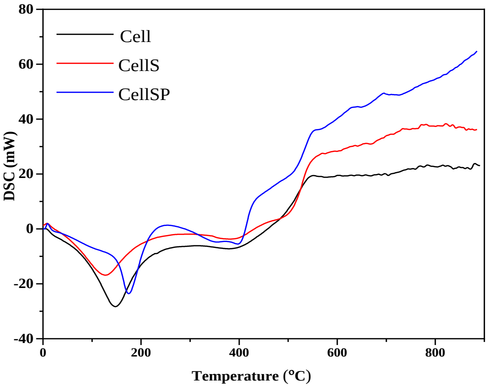


Figure 6: DSC thermograms of Cell, CellS and CellSP films.

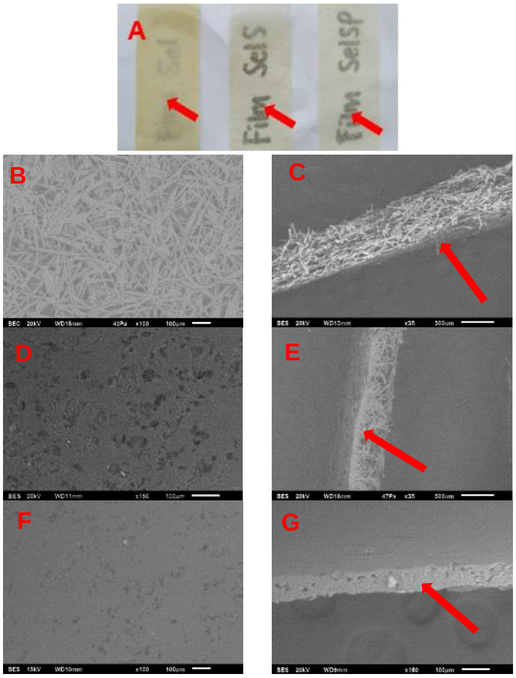


Figure 7: Visual of three films obtained (A); observation of surface morphology (left) and cross-section (right) of Cell (B, C); CellS (D, E); and CellSP (F, G) films.

SEM observations of the CellSP film (Figure 8(F) and (G)) show a flat and smooth surface as well as a dense cross-section. Ultrasonication and the addition of glycerol as a plasticizer, functioning as a cross-linking agent between cellulose structures, result in overlapping and denser cellulose. This aligns with the tensile strength test results (Figure 9), which show that CellSP films have higher tensile strength than Cell and CellS films, with values of 10.297, 16.377, and 17.162 MPa, respectively.

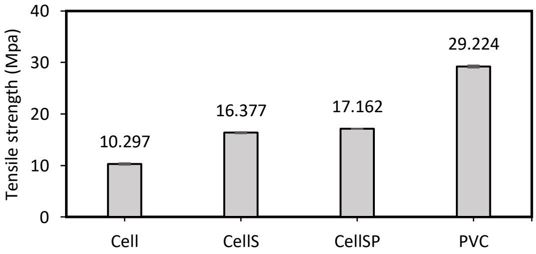


Figure 8: Tensile strength of Cell, CellS, CellSP films, and PVC wrap (control).

To compare our results with previously published data, tensile strength was used as a comparative parameter as presented in Table 2. The tensile strength values obtained in this study are comparable to and even exceed those reported in earlier research.

Table 2: Comparison of tensile strength between this present work and previously published studies.

Sample	Tensile Strength (MPa)	Ref.
Cellulose/Glycerol	5.01	[64]
Cellulose/ 50% Glycerol	~18	[65]
Chitosan/MCC-Glycerol	~11–17	[66]
Cellulose/1% Feijoa peel flour	12.00	[67]
BC/6% Glycerol	5.78	[68]
Velvet Tamarind rind-derived cellulose/Glycerol	17.16	This work

MCC – microcrystalline cellulose; BC – bacterial cellulose

3.2 *Evaluation of the films*

Organoleptic testing was conducted to assess the suitability of the films for packaging applications by comparing them with standard polyvinyl chloride (PVC) wrap. Notable differences were observed in the texture and color changes of grapes wrapped in the various films compared to PVC wrap, as shown in Figure 10. Grapes wrapped with CellSP demonstrated the best appearance among the three films, comparable to that of the PVC wrap. The results of this study show that the films did not significantly extend the shelf life of the packaged grapes, which differs from previous findings reporting that nanocellulose films were able to maintain grape quality up to the 15th day (6th day of this study). This discrepancy is likely due to differences in the size of the cellulose particles used. This study utilized cellulose microfibers, whereas previous studies employed cellulose nanofibers [18].

Figures 11 and 12 show that five panelists provided varied scores for the color and texture changes of grapes packaged with the three film types and PVC wrap. Over time, the texture and color of the grapes declined, but those wrapped in CellSP films retained better quality compared to the other films. Panelists noted that CellSP films effectively preserved grape freshness during storage, due to their fine structure and dense phase interactions, which offer superior protection against air exposure. The evaluations also indicate that CellSP films are as effective as commercial PVC wrap in preserving grapes.

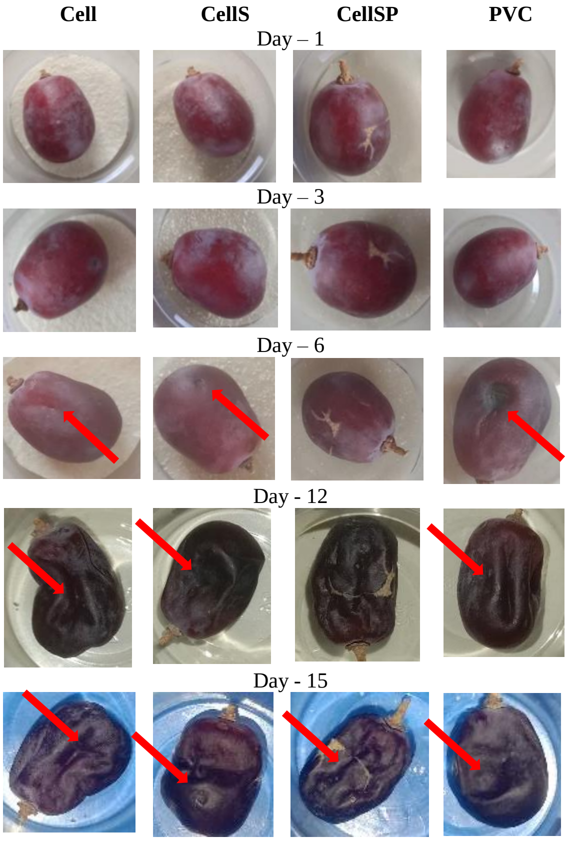


Figure 10: Visual appearance of grapes wrapped with different film variations and PVC wrap from day 1, 3, 6, 12, and 15 of storage.

In contrast, the Cell film received the lowest rating, followed by the CellS film. This lower rating is attributed to the coarse cellulose particles in the Cell film, which created porosity and allowed air infiltration, thereby inadequately protecting the grapes. The absence of a plasticizer also contributed to the Cell film breaking during the test. Although the CellS film also cracked, it demonstrated better mechanical properties and was less prone to breaking.

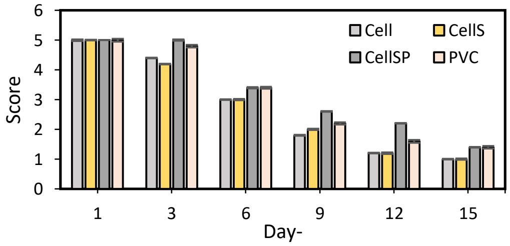


Figure 11: Organoleptic score of grapes wrapped with films, and PVC wrap (color).

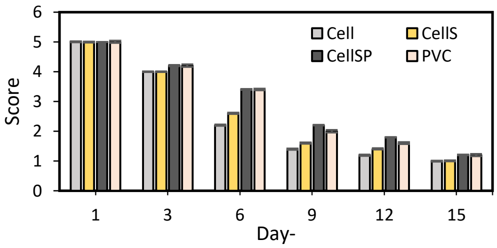


Figure 12: Organoleptic score of grapes wrapped with films, and PVC wrap (texture).

A swelling test was conducted to assess the suitability of the produced films for packaging applications. Figure 13 demonstrates that the films are hydrophilic and sensitive to high-humidity environments, while PVC wrap is completely hydrophobic and does not absorb water. Among the films, the Cell film is the most hydrophilic, with a swelling percentage of 228.23%, indicating the highest water absorption compared to the other films, which have swelling percentages of 226.32% for CellS and 173.63% for CellSP, respectively. This swelling is due to the interaction between the hydrogen bonds in cellulose and the OH groups in water.

The CellSP film shows a lower swelling rate compared to the Cell and CellS films, attributed to the effect of glycerol. Glycerol reduces the volume of cavities in the film, thereby limiting water absorption. In contrast, the Cell and CellS films feature hollow pores that facilitate water penetration into the cellulose. These observations are supported by SEM characterization shown in Figure 8(B). The findings are consistent with the higher tensile strength of the CellSP film compared to the other films and highlight differences in their biodegradability. While PVC wrap is non-biodegradable, all three film variants are completely biodegradable.

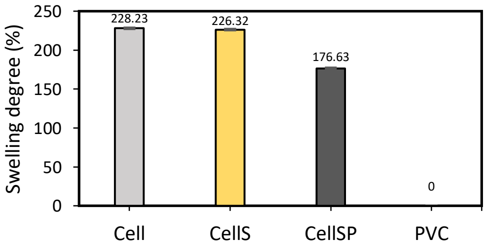


Figure 13: Swelling degree profile of the prepared films and PVC wrap.

While both cellulose and starch are polysaccharides composed of glucose monomers, cellulose has stronger β-glycosidic linkages between its monomers, making it more resistant to degradation than starch. Nonetheless, soil-based bacteria are still effective at degrading cellulose. To evaluate whether the three films disintegrate effectively or resemble PVC wraps, which are known for their resistance to decomposition in soil, we compared the biodegradation of the films with that of commercial PVC wrap.

Figure 14 shows that PVC wrap did not disintegrate at all after 5 weeks of burial due to microorganisms' inability to break down synthetic PVC. In contrast, Figure 14 demonstrates that the three film varieties decompose effectively in soil. This is due to the activity of over 90 types of microorganisms, including aerobes, anaerobes, photosynthetic bacteria, archaebacteria, and lower eukaryotes, which can degrade bioplastics [69].

The films showed degradation from the first to the fifth week, with the Cell film degrading most rapidly due to its larger cellulose particle size, which facilitates microbial attack. In contrast, the CellS and CellSP films, which were treated with ultrasonication and glycerol, exhibit different structural properties. These treatments enhance the phase interactions within the films, making them more resistant to microbial degradation [63], [70].

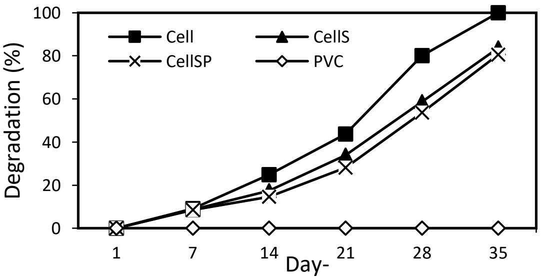


Figure 14: Biodegradation profile of the prepared films as compared with control (PVC wrap).

4 Conclusions

Cellulose was successfully extracted from velvet tamarind rind, resulting in the production of high-quality cellulose microfibers. This study led to the development of three types of films: Cell films, CellS films, and CellSP films, each exhibiting unique properties. Among these, the CellSP films demonstrated superior characteristics, such as high tensile strength, and overall performance compared to Cell and CellS films. Notably, the properties of CellSP film were comparable to commercially available PVC wrap. This study highlights the potential of utilizing agricultural waste for eco-friendly food packaging materials. Further research could optimize formulations and scale up the production process to enhance the practical application of these films.

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Author Contributions

A.A.K: formal analysis, investigation, writing – original draft preparations, reviewing and editing; R.R.: conceptualization, methodology, writing—reviewing and editing, validation, supervision, funding acquisition; J.J.: writing—reviewing and editing, supervision; H.F.; M.R.; and M.I.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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