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Physical and Chemical Properties of Bacterial Cellulose-Based Bioplastic Innovation from Sago Liquid Waste for Eco-Friendly Secondary Food Packaging

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bacterial cellulose;
bioplastics;
food packaging;
sago liquid waste.

ABSTRACT. The increasing demand for plastic food packaging has raised concerns over the environmental impact of plastic waste. Previous research has used sago liquid waste as a primary food packaging material, namely, edible coatings on tomatoes and edible films on sausages. However, research on secondary food packaging has not been conducted. The method used in this research involves a series of stages, from synthesizing bacterial cellulose to make bioplastics. The bioplastics were made with bacterial cellulose fermented from sago liquid waste and mixed with varying compositions of carboxymethyl cellulose (CMC), zinc oxide (ZnO), polyvinyl alcohol (PVA), and glycerol. Chemical characteristics, as determined by functional group analysis, showed that bioplastics still exhibited the typical functional groups of bacterial cellulose, as well as additional groups from glycerol, CMC, PVA, and ZnO, indicating the success of chemical structure modification in bioplastics. The crystallinity level of bioplastics also increased with the concentration of the mixture, with the highest crystallinity value of 37.084% in bioplastic sample A4. The physical characteristics of bioplastics, such as transparency, thickness, moisture content, water solubility, water uptake, and water vapor transmission rate, increased with increasing bioplastic mixture.

INTRODUCTION

Plastic is one of the most widely used polymers today. It is used worldwide because of its advantages, especially as a container or for food packaging (Pangestu *et al*., 2019). Increased production and consumption of packaged food have encouraged innovation in food packaging plastics. Based on their layers, food packaging plastics are divided into three categories: primary, secondary, and tertiary packaging. About 99% of plastics worldwide are still based on fossil fuels, while only 1% come from natural materials such as starch (Regnier, 2019). To reduce environmental impact, more environmentally friendly plastic innovations are needed, such as replacing synthetic plastics with naturally degradable ones.

Bioplastics are plastics derived from biological compounds that can be naturally degraded by microorganisms (Pangestu *et al*., 2019). Bioplastics for food packaging have been widely developed for primary packaging, such as edible films and coatings for several food products (Azerado *et al*., 2022; Yanti *et al*., 2021a; Yanti *et al*., 2023). The use of bioplastics for secondary food packaging remains minimal because they require more potent properties. Secondary packaging can be reused many times, reducing the need for plastic. Polylactic acid (PLA), polyhydroxyalkanoate (PHA), cellulose, and starch are common biopolymers as raw materials for bioplastics (Narancic *et al*., 2020). Among them, cellulose is the most abundant polymer, which can be obtained from plants or synthesized by bacteria (Musa *et al*., 2016). Bacterial cellulose is a biopolymer produced by bacterial fermentation and is biodegradable and non-toxic (Yanti *et al*., 2017). Manufacturing bacterial cellulose requires materials containing carbohydrates and nitrogen, such as sago liquid waste (Harianingsih and Suwardiyono, 2017). Sago liquid waste is produced year-round during sago starch processing (Yanti *et al*., 2018) and has been shown

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to yield bacterial cellulose known as "nata de sago" (Narancic *et al*., 2020), making it a potential biopolymer for bioplastic raw materials.

Previous research has developed bacterial cellulose from sago liquid waste as primary packaging, such as edible film (Yanti *et al*., 2021a), but not yet for secondary food packaging. However, its application and characterization for secondary food packaging, which requires superior mechanical strength and durability, remain unexplored.

This study focuses on the development and comprehensive characterization of a bacterial cellulose-based bioplastic derived from sago liquid waste, engineered specifically for secondary food packaging. This research aims to develop a renewable biopolymer from sago effluent with high mechanical strength yet still easily degradable. The results are expected to accelerate the production of environmentally friendly plastics with properties similar to those of synthetic plastics and to reduce the negative environmental impact of sago effluent. Therefore, this study aims to characterize the physicochemical properties of bioplastics from sago liquid waste bacterial cellulose developed for environmentally friendly secondary food packaging.

RESEARCH METHODS

Sample Preparation

Sago liquid waste was taken from one of the sago producers in Tondonggeu Village, Nambo District, Kendari, Indonesia. Sago liquid waste was collected from the sago reservoir, placed in jerry cans until full, and tightly capped. The sago liquid waste was then filtered to remove impurities before use. The filtered sago liquid waste was stored at room temperature for 2 days before use.

Equipment Sterilization

Before fermenting sago liquid waste, the tools used in the fermentation process were first sterilized using a vertical autoclave at 121 °C for 20 minutes.

Bacterial Cellulose Synthesis

Bacterial cellulose was produced by using sago liquid waste as a substrate. In the production of bacterial cellulose, sago liquid waste was filtered and boiled for 5 minutes. Subsequently, 10% sugar and 1.5% zwavelzure ammoniak (ZA-PT. Timur Raya Tunggal) were added while stirring until dissolved. The mixture was boiled for 5 minutes and cooled to room temperature. After cooling, 1% glacial acetic acid (DIXI) and a 25% 7-day-old *Acetobacter xylinum* LKN6 inoculum were added aseptically. The mixture was homogenized and transferred to a fermentation container, which was then covered with sterile newsprint. Fermentation was carried out for approximately 14 days at room temperature (about 20 – 25 °C). The resulting bacterial cellulose pellicle was harvested, washed with fresh water, and soaked in 1% sodium hydroxide (NaOH-Himedia) solution for 24 hours. Finally, the cellulose was rinsed with running water and drained (Yanti *et al*., 2021b).

Preparation of Cellulose Slurry

Slurry was prepared by mixing purified bacterial cellulose with water at a 25% concentration. The bacterial cellulose was cut into approximately 1 × 1 cm pieces to facilitate blending. Water was then added in a 1:4 (w/v) ratio, and the mixture was pureed using a blender. The resulting slurry was allowed to stand at room temperature for 24 hours before use.

Making Bioplastics

Bioplastics were produced by mixing 50 mL of the slurry with 0.01 g zinc oxide (ZnO-MERCK) and varying concentrations of carboxymethyl cellulose (CMC-Chongliong) and polyvinyl alcohol (PVA-MERCK), as detailed in Table 1. The mixture was stirred until homogeneous, after which glycerol (EMSURE ACS Reag MERCK**)** was added at 0.25% of the total solution. The solution was then heated at 85 °C on a hot plate. Once a homogeneous solution was obtained, it was poured into a 15 × 15 cm mold and dried in an oven at 50 °C for 1 – 2 days. The dried films were subsequently peeled off for characterization.

Table 1. Bioplastic material mixture formulation sample A1 – A4.

Bioplastics Sample	Bacterial cellulose (mL)	ZnO (g)	Glycerol (%)	CMC (g)	PVA (g)
A1	50	0.01	0.25	0.6	0.6
A2	50	0.01	0.25	0.9	0.9
A3	50	0.01	0.25	1.2	1.2
A4	50	0.01	0.25	1.5	1.5

Chemical Characterization

Chemical characteristics carried out include analysis of functional groups using Fourier Transform Infrared (Shimadzu IRPrestige-21) and crystallinity using X-ray diffraction (Malvern Panalytical Aeris Instrument Suite version 1.7b (136)). The crystallinity value was calculated using the Herman method, as described by Sangian *et al.* (2021). To determine the crystallinity value (*Cr*), Equation 1 was used.

$$Cr = \frac{I_{crystal}}{I_{amorphous}+I_{crystal}} \times 100\ \% \tag{1}$$

Description:

$I_{crystal}$ = crystal intensity

$I_{amorphous}$ = amorph intensity

Physical Characterization Test

Physical characteristic tests carried out include thickness, moisture content, water solubility, water uptake, and water vapor transmission rate analysis to corroborate information on the physical strength of bioplastics.

Bioplastics thickness

The thickness value was measured at 5 different positions and averaged. The film thickness was determined using a manual micrometer (Mitutoyo, Japan) with an accuracy of 0.001 mm (Nafchi *et al.*, 2018).

Moisture content (Wc) test

The moisture content of the bioplastics was measured according to the method described by Enwere *et al.* (2024). The bioplastic samples were weighed and then dried in an oven at 105 °C for 24 hours. The dried samples were weighed, and the percentage of moisture content was calculated using Equation 2.

$$\mathrm{Wc}\ (\%) = \frac{W_1 - W_2}{W_1} \times 100 \tag{2}$$

Description:

W1 = initial weight before baking

W2 = final weight after baking

Water solubility (Ws) test

The water solubility of the bioplastics was measured according to the method described by Steven *et al.* (2022). The bioplastics were analyzed by immersing the samples in water. Samples measuring 2 × 2 cm were weighed on an analytical balance to determine their initial weight. The weighed samples were placed in a beaker filled with 50 mL of deionized water and left at room temperature for 1 hour. The insoluble samples were then removed and dried in an oven at 60 °C for 24 hours. The final samples were weighed on digital scales to determine their final weight. The percentage of sample solubility in water was calculated using Equation 3.

$$\mathrm{Ws} = \frac{W_1 - W_2}{W_1} \times 100\% \tag{3}$$

Description:

W1 = initial weight of edible film

W2 = weight remaining after soaking

Water uptake (Wu) test

The water uptake of the bioplastics was measured according to the method described by Oluwasina *et al.* (2019). Water uptake testing was conducted by cutting a 2 × 2 cm sample of bioplastic and weighing it. The sample was placed in a container containing 50 mL of distilled water. After 1 hour at room temperature, the sample was removed and cleaned with gauze before weighing. This test was calculated using Equation 4.

$$\mathrm{Wu}\ (\%) = \frac{W_2 - W_1}{W_1} \times 100 \tag{4}$$

Description:
W1 = weight of the sample before soaking in water
W2 = weight of the sample after soaking in water

Water vapor transmission rate (WVTR) analysis

The WVTR of the bioplastics was measured according to the method described by Bahtiar *et al.* (2018). Bioplastic samples were cut into 2 × 2 cm and stored in tightly sealed containers filled with silica. All samples were then placed in a desiccator filled with distilled water. Water vapor transmission testing of bioplastics was conducted for 24 hours. The relative humidity used in this test was approximately 80%. The water vapor transmission rate analysis was calculated using the following Equation 5.

$$\text{WVTR} = \frac{\Delta m}{A \times t} \tag{5}$$

Description:
Δm = sample mass probe
A = sample area
t = time

RESULTS AND DISCUSSION

Products of Bacterial Cellulose-Based Bioplastic from Sago Liquid Waste Fermentation

Bioplastics produced with varying material mixtures exhibit morphological differences, with sample A1 being more transparent than sample A2. Samples A3 and A4 are also more transparent than sample A2 (Figure 1). Variations in the concentration of mixed materials can also affect the physical characteristics of bioplastics, including thickness, moisture content, water solubility, water uptake, and water vapor transmission rate.

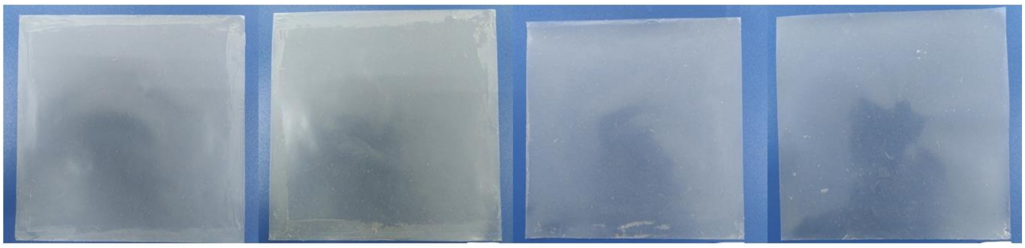
(a) (b) (c) (d)

Figure 1. Bioplastic samples with different PVA-CMC compositions (a) Sample A1 containing 0.6 g of PVA-CMC mixture, (b) Sample A2 containing 0.9 g of PVA-CMC mixture, (c) Sample A3 containing 1.2 g of PVA-CMC mixture, and (d) Sample A4 containing 1.5 g of PVA-CMC mixture.

Physical Properties of Bioplastics

The thickness of the bioplastic was measured at five different points using a micrometer, and the average was calculated. The thicknesses of the bioplastics are shown in Figure 2a, and the results indicate that the four bioplastic samples have different thicknesses. The four bioplastics had thicknesses ranging from 0.076 to 0.146 mm. The highest bioplastic thickness was obtained from bioplastic A4 with a mixture concentration of 1.5 g, namely 0.146 mm, and the lowest was obtained from bioplastic A1 with a mixture concentration of 0.6 g, namely 0.076 mm. According to the Japanese Industrial Standard (JIS) (JIS Z1707:2019), the maximum bioplastic thickness is 0.25 mm, so the thicknesses of the four bioplastics are still within the established standard. The differences in thickness values observed across the four bioplastic samples were due to variations in the concentrations of the materials used in this study, namely CMC and PVA. Karimah *et al.* (2025) in their study on the effect of chitosan and CMC concentrations found that the higher the concentration of the materials used, the thicker the bioplastic obtained.

The moisture content in bioplastics can affect shelf life and quality deterioration during storage and use. The highest moisture content of bioplastics, as shown in Figure 2b, is 30.609% in sample A1, and the lowest is 12.151% in sample A4. The maximum moisture content for bioplastic packaging, according to JIS Z1707:2019, is <13%. The results of this study show that only one sample, A4, complies with the standard, while the other three do not meet the JIS quality standards.

Water solubility in bioplastics can affect their degradation rates in both aquatic and soil environments. Data shown in Figure 2c, the highest solubility of bioplastics in water was 76.352% in sample A1, and the lowest was 37.773% in sample A4. Lower solubility values are an important requirement, especially for use as food packaging.

However, high solubility is closely related to degradability, as the higher the solubility of bioplastics, the faster and easier they degrade (Moga *et al*., 2019). The water uptake capacity of bioplastics can affect their suitability for food packaging; the lower the water uptake capacity, the more ideal the packaging. Data presented in Figure 2d show that the highest water uptake was 375.73% in sample A1, and the lowest was 142.909% in sample A4. The decrease in water uptake was caused by an increase in the concentration of CMC and PVA, which can form more internal hydrogen bonds. ZnO, as a filler, also enhances the hydrophobic properties of bioplastics, thereby improving their water retention (Buntinx *et al*., 2024).

The water vapor transmission rate is a key factor in determining the quality of bioplastic moisture barriers. The water vapor transmission rate is the amount of water that can penetrate a specific area of bioplastic film per unit of time. Data presented in Figure 2e show that the bioplastic with the highest water vapor transmission rate is sample A1 with a value of 1.1424 (g/m^2 day), and the bioplastic with the lowest water vapor transmission rate is sample A4 with a value of 0.876 (g/m^2 day). This indicates that the bioplastic with better moisture-retention capabilities is sample A4, because the lower the number, the better the moisture barrier (Barron and Sparks, 2020).

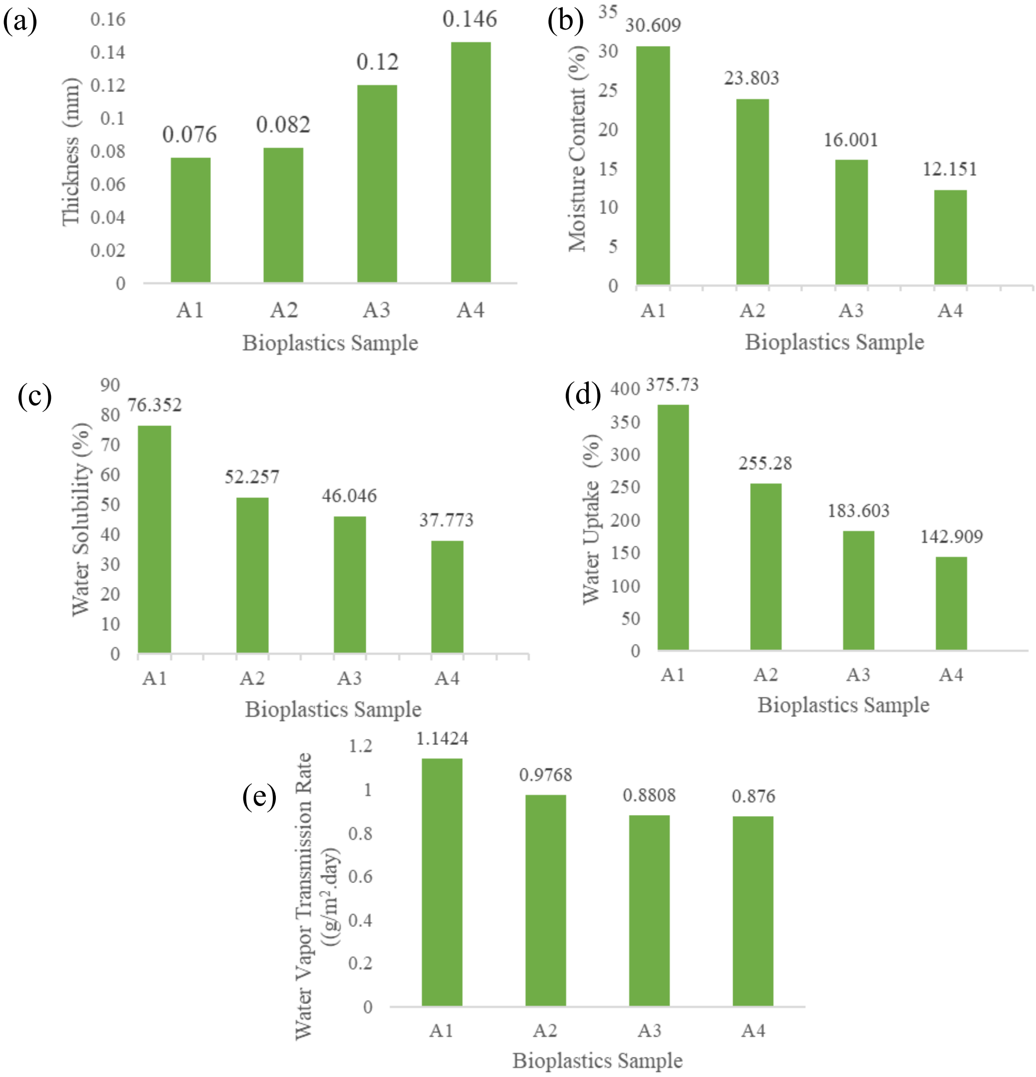

Figure 2. Physical properties of bioplastics (a) bioplastics thickness, (b) moisture content, (c) water solubility, (d) water uptake, and (e) water vapor transmission rate.

Functional Group Bioplastics

The analysis of bioplastic functional groups was performed using Fourier Transform Infrared (FTIR). This analysis was based on wave number data from the sample. The analysis results for bioplastic and bacterial cellulose samples in Figure 3 show the characteristic absorption bands of the main functional groups that comprise cellulose and bioplastics. A comparison of the peak positions provides information about the presence of cellulose functional groups and other components in bioplastics. Wave number values between 3700 – 3200 cm^{-1} indicate the presence of O–H stretching, wave numbers between 3000 – 2850 cm^{-1} indicate the presence of C–H stretching, wave numbers between 1300 – 1000 cm^{-1} indicate the presence of C–O–C stretching (Yanti *et al.*, 2021b), wave numbers between 1000 – 927 cm^{-1} indicate the presence of C–O–C deformation of the carboxymethyl group in CMC (Casaburi *et al.*, 2018), and wave numbers between 1150 – 1000 cm^{-1} indicate the presence of C–O stretching. The presence of peaks at 550 and 490 cm^{-1} indicates wave values for ZnO (Murthy *et al.*, 2021). These wave values were observed in cellulose and bioplastic samples, namely, peaks at 3331 cm^{-1}, 2867 cm^{-1}, 1208 cm^{-1}, and 1050 cm^{-1}, indicating the presence of O–H, C–H, C–O–C, and C–O groups. This indicates that bioplastics are still cellulose-based.

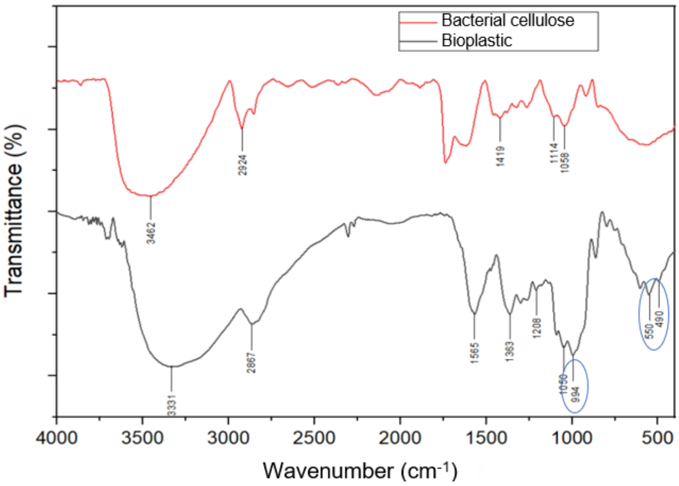

Figure 3. FTIR spectra (a) bacterial cellulose and (b) bioplastics.

Crystallinity

The XRD was employed to investigate the crystalline structures of the samples (Sangian *et al.*, 2021). Figure 4 shows the XRD spectrum of bioplastics produced from bacterial cellulose mixed with ZnO, CMC, and PVA at varying concentrations. The XRD patterns are characteristic of the specific bioplastics' structures and show varying degrees of crystallinity among the various samples, depending on their composition (Sangian *et al.*, 2021). The clear peak in bioplastic sample A1 is at 22.62°, shifting to 22.75° for bioplastic A2, then the peak of bioplastic A3 is at 22.77°, and sample A4 is at 22.61°. After calculating the crystallinity level of the four bioplastic samples, it was found that sample A1 had a crystallinity level of 32.977%, sample A2 had a crystallinity level of 33.215%, sample A3 had a crystallinity level of 35.788%, and sample A4 had the highest crystallinity level of 37.084%. The higher the crystallinity of bioplastics, the greater their mechanical strength. However, very high crystallinity can cause increased cracking in bioplastics (Afshar *et al.*, 2024).

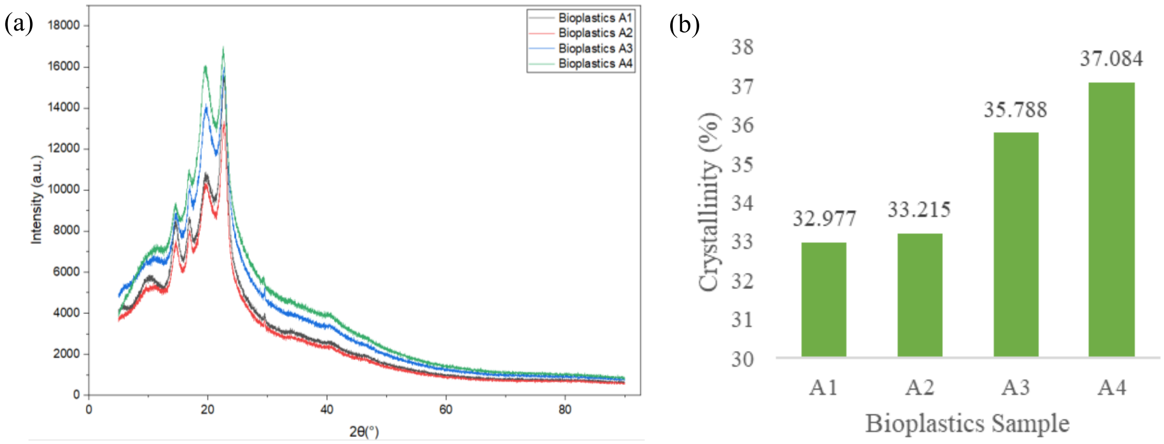

Figure 4. Crystallinity of bioplastic samples (a) XRD spectra of bioplastic samples (b) crystallinity value of bioplastic samples.

CONCLUSION

Bioplastics made from bacterial cellulose produced by fermenting sago liquid waste, with mixed ingredients including ZnO, CMC, and PVA, exhibited characteristics that varied with the composition of the mixture. Based on the analysis results, chemical characteristics, as determined by functional group analysis, showed that bioplastics still exhibited the typical functional groups of bacterial cellulose, as well as additional groups of glycerol, CMC, PVA, and ZnO, indicating the success of chemical structure modification. The crystallinity level of bioplastics also increased with the concentration of the mixture, with the highest crystallinity value of 37.084% in bioplastic sample A4. The physical characteristics of bioplastics, such as transparency, thickness, moisture content, water solubility, water uptake, and water vapor transmission rate, increased with increasing bioplastic mixture. This shows that based on the physical and chemical characteristics of bioplastics made from cellulose bacteria fermented from sago liquid waste and then formulated with mixed ingredients such as ZnO, PVA, and CMC, they can be used as environmentally friendly secondary food packaging.

CONFLICT OF INTEREST

There is no conflict of interest in this article.

AUTHOR CONTRIBUTION

AM: Methodology, Formal Analysis, Investigation, Manuscript Drafting, Visualization, Data Curation, Writing Original Draft, Review and Editing: NAY: Conceptualization, Validation, Supervision, Project Administration, Funding Acquisition; LOANR: Methodology, Validation, Supervision; RK: Methodology, Formal Analysis, Investigation, Visualization.

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DECLARATION OF GENERATIVE AI

While writing this article, the author used Grammarly to correct spelling and suggest alternative words. After using this tool/service, the author reviewed and edited the content as needed and assumes full responsibility for the content of the published article.

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