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Utilization of Bacterial Cellulose of Nata de Soya as an Alternative Raw Material for Honeycomb Paper Wrap

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ABSTRACT. The growing production of wood-based paper has contributed to deforestation and environmental pollution, underscoring the urgent need for alternative, sustainable raw materials. Bacterial cellulose derived from nata de soya presents a promising non-wood source for paper production. This study investigated the utilization of bacterial cellulose from nata de soya as a raw material for honeycomb paper wrap applications. Bacterial cellulose obtained from 18-day-old nata de soya was processed into paper with the addition of kaolin and tapioca as functional additives. Four formulations were evaluated: Formula 1 (100% bacterial cellulose), Formula 2 (62% bacterial cellulose and 38% kaolin), Formula 3 (76% bacterial cellulose and 24% tapioca), and Formula 4 (52% bacterial cellulose, 32% kaolin, and 16% tapioca). The resulting papers were characterized in terms of thickness, grammage, moisture content, tensile strength, and load-bearing capacity. The results demonstrated that Formula 4 exhibited the most favorable performance, with a thickness of 0.43 mm and a grammage of 191 g/m², complying with packaging paper standards (SNI 8218:2015). The moisture content was 5.66%, within the acceptable limit specified by SNI 7274:2008, and the tensile strength reached 1.659 kN/m, exceeding the minimum standard requirement. Furthermore, the honeycomb paper wrap produced using Formula 4 showed a load-bearing capacity comparable to that of commercial products. These findings indicate that bacterial cellulose paper formulated with a combination of kaolin and tapioca has strong potential as a sustainable alternative material for honeycomb paper wrap.

1. INTRODUCTION

The rapid growth of online shopping has led to a significant rise in plastic waste. It is mainly because most online purchases are packaged with protective materials like bubble wrap, which is made from plastic [1]. To address this environmental issue, the use of alternative, eco-friendly packaging materials, such as honeycomb paper wrap, has become a promising solution. This product is made from paper with a hexagonal structure similar to a honeycomb, which effectively protects products without generating plastic waste that is difficult to decompose [2].

Honeycomb paper wrap offers greater flexibility than styrofoam packaging and is more cost-effective than bubble wrap because it does not require additional materials to seal the product. Figure 1 shows the form of a honeycomb paper wrap.

Figure 1. *Bubble Wrap* and Commercial *Honeycomb Paper Wrap* [3]

The raw material for honeycomb paper wrap is wood-pulp-based paper, which is closely linked to deforestation. According to data from the Indonesian Ministry of Industry [4], the Indonesian pulp and paper industry consumes 86.6 million cubic meters of wood annually. The increasing demand for wood has made Indonesia the country with the second-highest deforestation rate globally in 2024, as shown in Table 1.

Table 1. Countries with the Highest Deforestation Rates in the World [5]

No	Country	Changes in Forest Area (mi^2)
1	Brazil	-356.287
2	Indonesia	-101.977
3	DR Congo	-94.495
4	Angola	-48.865
5	Tazmania	-44.962

Given these alarming deforestation rates, finding alternative raw materials for paper production is crucial to reducing the demand for wood and lowering deforestation in Indonesia. One promising alternative material is bacterial cellulose, which is highly productive and does not contribute to deforestation. Bacterial cellulose can be cultivated in just 18 days [6], whereas wood cellulose requires up to 6 years for cultivation [7]. Additionally, the process of turning bacterial cellulose into pulp is simpler than that of wood cellulose. Wood cellulose pulping typically involves mechanical or chemical processes, both of which are complex and can generate significant environmental waste.

In contrast, bacterial cellulose does not require delignification, a process necessary for wood pulp that generates polluting waste and is expensive to manage. Bacterial cellulose is also highly pure and can be produced from various low-cost substrates [8]. A comparison of bacterial cellulose with wood cellulose is presented in Table 2.

Table 2. Comparison of Microbial Cellulose and Wood Cellulose [9][10]

No	Aspect	Bacterial Cellulose	Wood Cellulose
1	Composition	Free of lignin and hemicellulose	Contains lignin and hemicellulose
2	Cultivation age	18 Days	4-6 Years
3	Sustainibility	Environmentally Friendly	Not Environmentally Friendly
4	Isolation Process	1. Extraction	1. Delignification 2. Hydrolysis
5	Crystallinity	80-100%	40-60%

Another advantage of bacterial cellulose is its ability to be produced from waste materials, such as tofu wastewater, which are typically of no value. Sayow [11] reported that 1 kg of soybeans can produce up to 6 liters of liquid waste. This waste can be processed using a bacterium of *Acetobacter xylinum* to produce nata de soya, which contains up to 10% cellulose [6]. Utilizing this waste not only reduces environmental pollution but also aligns with the "waste cleaning" concept, which transforms waste into valuable products while minimizing negative environmental impacts [12]. The potential for producing bacterial cellulose from tofu wastewater is further supported by its nutrient-rich composition, which is ideal for bacterial growth, as shown in Table 3.

Tofu wastewater, as shown in Table 3, can be used as a growth medium for *Acetobacter xylinum*, which synthesizes the cellulose component in nata de soya. By adding sugar as a carbon source and urea as a nitrogen source, nata production can reach 700–800 g/L in the medium within 18 days of incubation [6]. The bacterial cellulose content in nata de soya can reach 5–10%. The prepared nata de soya is then dried and pressed to produce bacterial cellulose, which can be used to make honeycomb paper wrap. Unlike paper made from wood cellulose, which requires extensive cooking and chemical additives to dissolve unwanted wood parts, resulting in more polluting waste, bacterial cellulose paper production is simpler and more environmentally friendly [15].

Previous studies have reported that paper made from bacterial cellulose exhibits high purity, good tensile strength, and environmental benefits due to its lignin- and hemicellulose-free composition. However, bacterial cellulose-based paper often suffers from limitations, including low structural rigidity, poor dimensional stability, and insufficient load-bearing capacity when used as a packaging material. These weaknesses restrict its direct application in structured packaging systems such as honeycomb paper wrap.

Table 3. Nutrient Composition of Tofu Wastewater [13] [14]

Composition	Concentration
Protein	0.42%
Fat	0.13%
Carbohydrate	0.11%
Water	98.87%
Calsium	13.60 ppm
Phosporus	1.74 ppm
Iron	4.55 ppm

The production of paper from bacterial cellulose also involves the addition of various additives, such as tapioca and kaolin, which serve different purposes like strengthening the structure, increasing volume, providing color, aiding the manufacturing process, and brightening the paper [16]. Tapioca helps to close pores in the paper, making it less water-penetrable and increasing its grammage, while kaolin serves as a filler that coats the paper surface, providing durability [17]. In addition to increasing grammage, tapioca also enhances fiber bonding, improving the paper's tensile strength [18].

Despite extensive studies on bacterial cellulose derived from nata de coco and its use in biodegradable materials, research on bacterial cellulose from nata de soya—particularly for structured packaging applications such as honeycomb paper wrap—remains limited. Most previous studies emphasize film formation, membranes, or general paper characteristics, without systematically addressing the performance of honeycomb-structured packaging. Furthermore, the combined effects of inorganic fillers and natural binders on the mechanical properties and load-bearing capacity of bacterial cellulose paper have not been sufficiently investigated. Therefore, this study addresses this research gap by evaluating the synergistic roles of kaolin and tapioca in producing bacterial cellulose-based honeycomb paper wrap.

2. MATERIALS AND METHODS

2.1 Materials

Tofu wastewater was collected from a small-scale tofu factory in Jebres, Surakarta, Indonesia. Analytical-grade caustic soda (NaOH), glacial acetic acid (CH_3COOH), yeast extract, dipotassium phosphate (K_2HPO_4), magnesium sulfate ($MgSO_4$), ammonium sulfate ($(NH_4)_2SO_4$), technical-grade ZA fertilizer, and distilled water were supplied by the Bioprocess Laboratory, Department of Chemical Engineering, Universitas Sebelas Maret. Commercial tapioca (starch-based polysaccharide) and commercial kaolin were purchased from a chemical supplier in Surakarta, Indonesia.

2.2 Equipment

The equipment used in this study included erlenmeyer flasks, an incubator shaker, fermentation trays, newspaper covers, beakers, an electric stove, a blender, and A4-sized screen-printing frames.

2.3 Methods

2.3.1 Inoculum Development

The inoculum medium was prepared by boiling 1000 milliliters of tofu wastewater for 15 minutes, then adding 2 grams of yeast extract, 4 grams of dipotassium phosphate, 0.5 grams of magnesium sulfate, 13 grams of ammonium sulfate, and 100 grams of sugar. The medium was transferred to a sterile erlenmeyer flask and heated to 121 °C for 20 minutes. The substrate was inoculated with a 10% v/v *Acetobacter xylinum* stock culture and incubated in an incubator shaker at room temperature and 75 rpm for 7 days. The inoculum was ready for use.

2.3.2 Production of Nata de soya

The bacterial cellulose production medium was prepared by boiling 1,000 mL of tofu wastewater for 15 minutes, then adding 26 g of ammonium sulfate, 100 g of sugar, and 20 mL of glacial acetic acid. The medium was transferred to a sterile Erlenmeyer flask and cooled to room temperature. 10% v/v of *Acetobacter xylinum* inoculum was added to the room-temperature medium, then homogenized in a shaker incubator for 20 minutes at 90 rpm. After homogenization, the medium inoculated with *Acetobacter xylinum* was poured into a tray, covered with a used newspaper, and incubated for 18 days before harvesting. The processing steps of nata de soya production are shown in a flowchart presented in Figure 2.

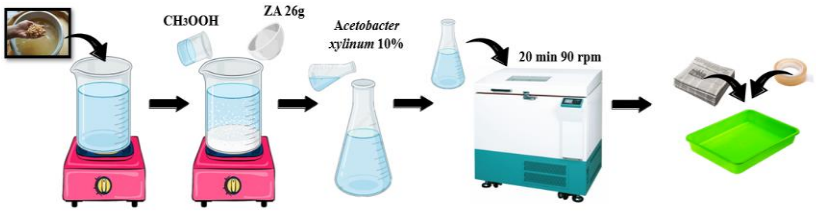

Figure 2. Nata de soya Production Equipment Setup

2.3.3 Paper and Honeycomb Paper Wrap Production

Nata was cut into small pieces and boiled in a 1% NaOH solution (w/v) for 20 minutes at 60°C. The nata was then cooled to room temperature and neutralized with a 5% acetic acid solution (v/v). The neutralized nata was mixed with additives according to the formula in Table 4 and then blended for approximately 10 minutes. The pulp was poured into an A4 screen-printing mold and dried in direct sunlight until dry, producing paper sheets as shown in Figure 3. The resulting paper was then cut according to the pattern shown in Figure 4.

Table 4. Experimental Formula

No	Formula	Composition (% w/w)		
		Bacterial Cellulose	Tapioca	Kaolin
1	Formula 1	100	-	-
2	Formula 2	62	-	38
3	Formula 3	76	24	-
4	Formula 4	52	16	32

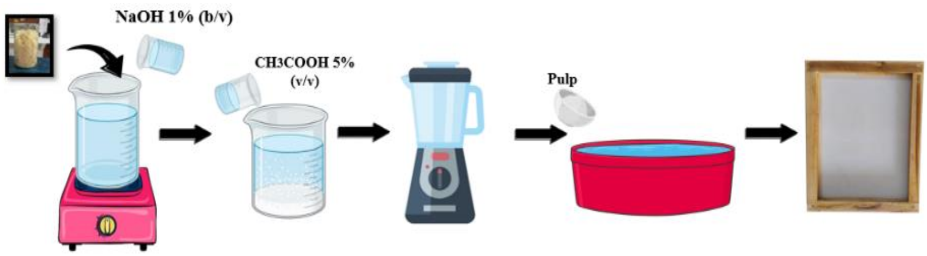

Figure 3. Honeycomb Paper Wrap Production Equipment Setup

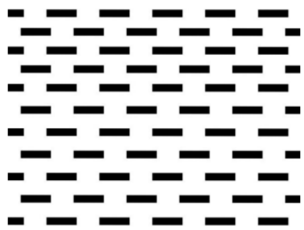

Figure 4. Pattern of *Honeycomb Paper Wrap*

2.3.5 Characterization

2.3.5.1 Grammage and Paper Thickness

Each paper variant was cut into 18 cm x 5 cm pieces. The thickness of the paper was measured using a micrometer screw gauge. Grammage is the mass of the paper sheet in grams divided by its area in square meters (g/m^2) [19]. The uniformly cut paper samples were then weighed using an analytical balance under standard conditions. Grammage was calculated using equation 2.1.

$$\text{Gramatur}\left({}^{g}/_{m^2}\right)=\frac{\text{sample weight (g)}}{\text{surface area (cm}^2)}\times\frac{10.000\ \text{cm}^2}{1\text{m}^2}$$

2.3.5.2 Moisture Content

The moisture content of the paper was tested by drying the paper chips of each variation in an oven at 105°C for 2 hours, then cooling them in a desiccator for 10 minutes. The drying process was repeated until a constant weight was obtained [19]. Moisture content was calculated using equation 2.2.

$$\text{Moisture content (\%)} = \frac{\text{(initial sample weight (g) - final sample weight (g))}}{\text{initial sample weight (g)}} \times 100\%$$

2.3.5.3 Tensile Strength

Tensile strength is the maximum ability of a pulp sheet, paper, or cardboard to withstand a tensile force applied to both ends until failure (breakage) occurs. This value is expressed as the force per unit width of the test specimen and is measured under standard conditions [19]. Each paper variation was cut to 16 cm × 2.54 cm and tested using a Universal Testing Machine (UTM) according to the TAPPI T-494 method.

2.3.5.4 Honeycomb Paper Wrap Load-Bearing Capacity

Load-bearing capacity is the maximum load the honeycomb paper wrap can withstand before structural damage occurs. Each variation was tested for weight resistance by placing 250g and 500g weights on the honeycomb paper wrap and observing changes in the hexagonal structure of the paper. Load-bearing capacity can be calculated using equation 2.3.

$$\text{Load-Bearing Capacity } \left({}^{g}/_{cm^2}\right) = \frac{\text{maximum weights (g)}}{\text{surface area of weights (cm}^2\text{)}}$$

3. RESULT AND DISCUSSION

Pulp resulting from bacterial cellulose was visually presented in Figure 5.

Figure 5. Pulp from Bacterial Cellulose

The purification of bacterial cellulose with NaOH yielded a white pulp that is significantly lighter than wood cellulose pulp. It is primarily due to the absence of lignin and other extractive substances typically found in wood pulp. The production of paper from wood cellulose often involves the use of bleaching chemicals, which can pollute the environment. In contrast, the bacterial cellulose pulp production process is more straightforward and more environmentally friendly [20]. The bacterial cellulose pulp was then cast using an A4-sized screen-printing frame and dried in direct sunlight. The dried paper sheets made from bacterial cellulose are shown in Figure 6.

Among the formulations tested, paper made with Formula 1 could not be cast successfully because it lacked the additives needed to strengthen the paper structure. Paper made with Formula 2 produced a yellowish, coarse texture, while paper made with Formula 3 resulted in a white but still coarse surface. Formula 4 produced the best paper, with a smooth, white surface. The combination of tapioca and kaolin in Formula 4 played a crucial role in enhancing the paper's quality.

The differences in paper properties among the formulations can be explained by the distinct roles of kaolin and tapioca in the paper matrix. Kaolin primarily acts as an inorganic filler, increasing paper thickness and surface smoothness by filling the voids between cellulose fibers. However, kaolin particles do not significantly contribute to inter-fiber bonding. Consequently, excessive kaolin content, as observed in Formula 2, results in reduced tensile strength and increased brittleness. In contrast, tapioca functions as a natural polymeric binder. During drying, gelatinized starch molecules penetrate the cellulose fiber network and form hydrogen bonds, thereby enhancing fiber-to-fiber adhesion. This mechanism explains the higher tensile strength observed in Formula 3 compared to Formula 2. The superior performance of Formula 4 can be attributed to the synergistic effect of tapioca and kaolin. Tapioca improves inter-fiber bonding, while kaolin increases paper density and surface uniformity. The combined effect results in a paper with balanced mechanical strength, acceptable moisture content, and adequate grammage, making it suitable for honeycomb paper wrap applications.

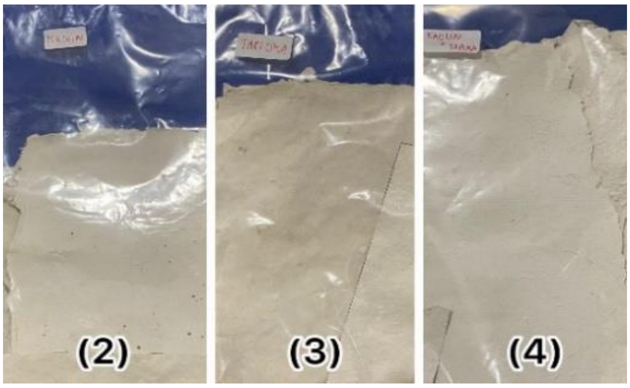

Figure 6. Photo of experimental paper result

3.1 Grammage and Paper Thickness

The grammage and thickness values of the paper are shown in Table 5.

Table 5. Paper thickness and grammage test results

Formula	Thickness (mm)	Grammage (gr/m^2)	Category (SNI 8218:2015) [21]	
			Low (26-210)	High (225-300)
Formula 1	-	-	-	-
Formula 2	0,26	91,11	✓	-
Formula 3	0,38	183,33	✓	-
Formula 4	0,43	191,00	✓	-
Commercial Kraf	0,22	80	✓	-

All the paper formulations met the low grammage category for packaging paper as per SNI 8218:2015. Formula 4 exhibited the highest thickness (0.43 mm) and grammage (191.00 g/m^2), indicating a denser, more robust structure. This improved structure can be attributed to the added tapioca and kaolin, which enhance fiber bonding and increase paper mass [18].

3.2 Moisture Content

The moisture content of the paper is shown in Table 6. Papers made using Formula 2 and Formula 3 exceeded the maximum moisture content specified by SNI 7274:2008, indicating that these papers retained more moisture, possibly due to suboptimal drying conditions and the influence of ambient humidity during storage [23]. In contrast, Formula 4 had a moisture content of 5.66%, which is within the acceptable range, making it suitable for packaging applications.

Table 6. Moisture content test results

Formula	Moisture Content (%)	Moisture Content (SNI 7274:2008) [22]
		Max 6%
Formula 1	-	-
Formula 2	8,83	✗
Formula 3	7,44	✗
Formula 4	5,66	✓
Commercial Kraft	4,62	✓

3.3 Tensile Strength

The tensile strength measurements for the paper produced using Formulas 1-4 yielded varied values. They were listed in Table 7.

Table 7. Tensile Strength Test Result

Formula	**Tensile Strength (kN/m)**	**Tensile Strength (SNI 8218:2015)** [21] Min 1,6 kN/m
Formula 1	-	-
Formula 2	1,32	×
Formula 3	2,025	✓
Formula 4	1,659	✓
Commercial Kraft	1,603	✓

The paper produced with formula 2 failed to meet the tensile strength requirement per SNI 8218:2015. It is likely because kaolin, while acting as a filler, does not provide strong inter-fiber bonding, leading to weaker paper [25]. Formula 4, however, met the tensile strength standards with a value of 1.659 kN/m, slightly higher than that of commercial kraft paper. The addition of tapioca as a sizing agent in Formula 4 strengthened fiber bonds, resulting in a more durable paper [25].

3.4 Honeycomb Paper Wrap

The resulting paper is then cut according to a pattern and subsequently stretched to form a honeycomb. The honeycomb paper wrap produced from the experimental paper is shown in Figure 7.

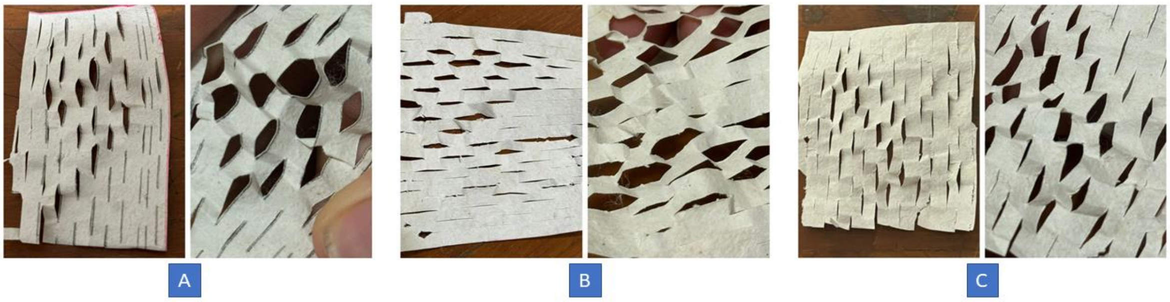

Figure 7. Photos of Honeycomb Paper Wrap: Formula 2 (A), Formula 3 (B), and Formula 4 (C)

The bacterial cellulose honeycomb paper wrap is whitey, unlike the commercial honeycomb paper wrap. In terms of volume, the bacterial cellulose paper is thicker and sturdier, while the commercial honeycomb paper wrap is thinner and lighter. Therefore, in terms of physical characteristics, bacterial cellulose paper can create a more substantial cushion for wrapping and protecting items.

3.5 Honeycomb Paper Wrap Load-Bearing Capacity

Each honeycomb paper wrap variation was subjected to a load-bearing test, and the results were compared with those of commercial honeycomb paper wrap. The load-bearing test results are shown in Table 8.The honeycomb paper wrap made from formula 2 paper has a lower load-bearing capacity than the commercial version. It can be attributed to the brittleness of kaolin, which resulted in a weaker structure. In contrast, Formula 4's honeycomb paper wrap demonstrated load-bearing capacity equivalent to that of the commercial product, showcasing its potential as an effective and sustainable packaging material. [26].

Table 8. Honeycomb Paper Wrap Load-Bearing Capacity Test Result

Formula	**Load-Bearing Capacity (gr/cm^2)**
Honeycomb paper wrap commercial	46,526
Formula 2	43,681
Formula 3	46,526
Formula 4	46,526

4. CONCLUSION

Paper produced using Formula 1 could not be formed into a stable sheet because it lacked additives. Formula 2 met the grammage requirement but failed to satisfy tensile strength and moisture content standards. Formula 3 met grammage and tensile strength requirements but exceeded the allowable moisture content. In contrast, Formula 4 satisfied all quality parameters, including grammage, tensile strength, and moisture content. When applied as a honeycomb paper wrap, paper produced with Formula 4 exhibited a load-bearing capacity comparable to that of commercial products and higher tensile strength. These results indicate that bacterial cellulose paper formulated with a combination of kaolin and tapioca has strong potential as a sustainable alternative material for honeycomb paper wrap.

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