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Research Article

Biofoam Cassava Starch and Sugarcane Bagasse Cellulose with the Addition of Polyvinyl Alcohol and Chitosan

Biofoam Pati Singkong dan Selulosa Ampas Tebu dengan Penambahan PVA dan Kitosan

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Abstract

The persistence of non-biodegradable styrofoam waste is contributing to the development of sustainable packaging materials from renewable resources, such as biofoam from natural biopolymers. Therefore, this study aimed to develop biofoam based on cassava starch and cellulose isolated from sugarcane bagasse, modified with polyvinyl alcohol (PVA) and chitosan. The biofoam was synthesized using a baking process and evaluated for physical and mechanical properties, including water absorption, density, tensile strength, and biodegradability. To examine the effect of formulation, PVA concentrations ranged from 10% to 15%, while chitosan was added at 1.5%, 2.0%, and 2.5%. The result showed that water absorption values ranged from 6.4–14.2%, with densities at 0.370–0.613 g/cm³, tensile strengths 0.030–0.613 MPa, and biodegradability levels 74.4–100% within 14 days. Although the optimal formulation was achieved with 10% PVA and 2.5% chitosan, all samples met the Indonesian National Standard (SNI) for biodegradability, showing potential to replace conventional styrofoam.

Keywords: bagasse; biofoam; cassava starch; cellulose; chitosan; PVA

Abstrak

Masalah limbah styrofoam yang sulit terurai secara alami mendorong pengembangan material kemasan alternatif yang ramah lingkungan dan berbasis sumber daya terbarukan. Salah satu pendekatan yang potensial adalah pemanfaatan biopolimer alami dalam bentuk biofoam. Penelitian ini bertujuan untuk mengembangkan biofoam berbasis pati singkong dan selulosa hasil isolasi dari ampas tebu dengan penambahan PVA dan kitosan sebagai agen modifikasi. Foam disintesis menggunakan metode baking process dan dievaluasi berdasarkan sifat fisis dan mekanis, yaitu uji penyerapan air, kerapatan, kekuatan tarik, dan laju biodegradasi. Variasi konsentrasi PVA yang digunakan adalah 10% dan 15%, sedangkan kitosan sebesar 1,5%, 2,0%, dan 2,5%. Hasil penelitian menunjukkan bahwa seluruh formulasi memiliki nilai penyerapan air 6,4–14,2%, kerapatan 0,370–0,613 g/cm³, kekuatan tarik 0,030–0,613 MPa, serta laju biodegradasi 74,4–100% dalam 14 hari. Formulasi optimum diperoleh pada kombinasi 10% PVA dan 2,5% kitosan. Seluruh sampel memenuhi standar biodegradabilitas SNI dan berpotensi sebagai pengganti styrofoam konvensional.

***Kata kunci**: ampas tebu; biofoam; kitosan; pati singkong; PVA; selulosa*

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1. Introduction

The accumulation of plastic waste is an increasingly urgent global environmental problem, particularly in developing countries like Indonesia. According to a World Bank report, Indonesia is the second-largest contributor to plastic waste after China [1]. A major cause of this problem is the use of synthetic polymer-based packaging, such as polystyrene (Styrofoam), which is commonly applied in the food industry [2].

According to the Environmental Protection Agency (EPA), polystyrene foam is classified as hazardous waste because it contains compounds that can potentially cause various diseases [3]. Despite the widespread application due to various properties such as lightweight, heat-resistant, and economically efficient properties, polystyrene is a non-biodegradable material [4]. This material contains styrene, a toxic and carcinogenic compound capable of polluting the environment, which poses a risk to human health [5].

The use of environmentally friendly alternative materials has become a key focus in efforts to reduce the environmental impact of traditional plastics [6]. One promising solution is the application of biofoam, which is typically produced from renewable biomass such as starch. This material provides benefits like plentiful availability, low production costs, and easily modified structural properties [7]. However, starch-based biofoam faces several limitations, such as the tendency to absorb significant amounts of water and weak mechanical performance due to hydrophilic nature and insufficiently stable molecular structure [8]. Therefore, material modification through the addition of reinforcing agents and binders is essential to enhance performance [9].

In line with development efforts, this study used cassava starch as the main component because of the ability to degrade biologically and availability from sustainable resources [10]. The presence of dominant amylopectin content (±91.94%) increases the maximum viscosity, accelerates gelatinization, and enables the formation of a stable gel at high temperatures. These properties make cassava a potential primary matrix for environmentally friendly foam formulations [11].

Previous studies have reported that cassava starch-based biofoam has good biodegradability, but the mechanical properties remain relatively low, even after modification with chitosan [12]. This indicates that the use of cassava starch without optimal structural reinforcement remains limited. To address the limitation, several types of natural fibers, such as pineapple fiber and bagasse, have been used in the production of biofoam [13]. Sugarcane bagasse is a waste byproduct from sugarcane processing with a cellulose content of approximately 37% [14], which can be used as a filler in biofoam. Cellulose, a linear chain glucose polymer, enhances mechanical strength and decreases water absorption [15].

In several studies, cassava starch biofoam supplemented with bagasse showed high tensile strength and decreased water absorption. However, there is limited interaction between the starch matrix and reinforcing material because bagasse has not experienced a cellulose isolation process [10]. Khanoonkon et al. [16] also reported that the addition of bagasse cellulose to cassava starch-based biofoam increased structural stability and

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mechanical properties by forming a more effective reinforcing network. The resulting biofoam still showed high hydrophilicity, showing the need for further modifications to improve the material's performance.

Firdausi et al. [17] used cassava starch with an inorganic filler in the form of eggshell powder ($CaCO_3$). Meanwhile, the inorganic filler did not play a role in forming the biodegradable polymer network, leading to physical improvement in mechanical properties.

In this study, PVA (polyvinyl alcohol) was added to increase elasticity and reduce water absorption, due to the semi-hydrophobic properties and the ability to form cross-links with starch molecules [18]. Chitosan, a natural polymer with antibacterial and hydrophobic properties [19], was also added to enhance water resistance and strengthen the tensile strength of the biofoam.

Previous studies have been limited to using cassava starch with only 1 filler or modifier, untreated biomass, or an inorganic filler. Therefore, the novelty of this study is in the use of cellulose isolated from bagasse as a purer and more reactive natural reinforcement, combined with PVA and chitosan as modifying agents. The combination is expected to enhance both the physical and mechanical properties of biofoam without sacrificing the biodegradability.

2. Research Methods

2.1 Tools and Materials

A series of laboratory equipment was used to support the study process. All glassware was referred to as a set, while the mixing and foam-formation process used a measuring pipette, a hot plate with a magnetic stirrer, an 80-mesh sieve, an oven, a bowl, a mixer, and a 20x20 cm mold. Mechanical characterization was performed using an HT 8172/90 Adhesion Tearing Strength Tester and precision measuring instruments, including calipers and desiccators.

Some of the materials used were bagasse obtained from sugarcane juice traders in Palembang, cassava starch (local), distilled water (local), sodium hydroxide (NaOH, Merck, Germany), hydrogen peroxide (H_2O_2, Merck, Germany), acetic acid (Merck, Germany), magnesium stearate (Merck, Germany), shrimp chitosan (local), carrageenan (local), PVA (polyvinyl alcohol) used was a product of Sigma-Aldrich (United States), and glycerin (Merck, Germany).

2.2 Sugarcane Bagasse Pre-Treatment

The bagasse pre-treatment process was carried out to reduce particle size and increase specific surface area to support efficient alpha-cellulose isolation. The process started with washing the bagasse with clean water to remove dirt and residual sugar, followed by brushing to eliminate the outer layer of fibers. Subsequently, the bagasse was cut into small pieces of approximately 3–4 cm, dried in an oven at 105°C for 1 hour, and ground with a mixer to produce fine particles. The resulting powder was sieved through an 80-mesh sieve to obtain a uniform fraction, which was ready for use in the isolation process.

2.3 Isolation of Sugarcane Bagasse Cellulose

The sugarcane bagasse pre-treatment results were delignified by soaking in a 10% NaOH solution at a 1:10 ratio at 95°C for 1 hour. Subsequently, the fiber was washed with water until the pH reached neutrality. The bleaching stage used a 30% H_2O_2 solution at a 1:10 ratio, at 100°C for 2 hours, to remove residual lignin and increase

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cellulose purity. The fiber was washed again and dried in an oven at 105°C for 30 minutes.

2.4 Biofoam Synthesis

Biofoam was synthesized through baking by dissolving chitosan at concentrations of 1.5%, 2.0%, and 2.5% in 1% acetic acid. The solution was homogenized using a magnetic stirrer to ensure complete mixing. Additional ingredients were added, comprising 2.08% carrageenan, 5.56% magnesium stearate, 20% distilled water, 16.67% glycerin, PVA at concentrations of 10% and 15%, respectively, and 5% bagasse cellulose by weight of the total cassava starch.

The ingredients were added gradually while stirring with a high-speed mixer for 20 minutes, followed by water to adjust the mixture's viscosity. Once the mixture was homogeneous, 36 g of cassava starch was added, and the mixture was stirred again at low speed. After being poured into a 20x20 cm mold, the mixture was heated at 100°C for 1 hour. This was followed by conditioning at room temperature for 4 days to achieve physical stability before conducting characteristic analysis.

2.5 Water Absorption Analysis

This water absorption analysis follows the Indonesian National Standard (SNI) 1969:2008. Initially, samples measuring 2.5 x 5 cm were oven-dried at 50°C for 5 minutes, cooled for 10 minutes to stabilize the weight. All samples were weighed to determine the dry weight (W_0), immersed in water for 1 minute, surface-dried, and re-weighed to find the wet weight (W_1). The water absorption value was calculated using equation 1.

2.6 Density Analysis

This density analysis adhered to the ASTM D792-08 standard. The sample was cut into 3 x 3 cm pieces and weighed to determine its mass (m). Subsequently, the sample volume was calculated based on its length, width, and thickness using a vernier caliper. The density value was calculated using equation 2.

2.7 Tensile Strength Analysis

Tensile strength analysis was performed using the tensile test method specified in ISO 527-2 for sheet-shaped polymer specimens. The test samples were cut to a size of 10 × 2 cm and clamped at both ends for a length of 1.5 cm. The test was carried out by gently pulling until the sample broke. The tensile strength value was calculated using equation 3.

$$\%\text{Water Absorption} = \frac{W1-W0}{W0} \times 100\% \quad \text{.....(1)}$$

$$\rho = \frac{m}{v} \quad \text{.....(2)}$$

$$\sigma = \frac{Fmaks}{A} \quad \text{.....(3)}$$

$$\%\text{Biodegradation Rate} = \frac{M0-M1}{M0} \times 100\% \quad \text{.(4)}$$

Description:

W_0 : Dry weight before immersion (g)
W_1 : Wet weight after immersion (g)
ρ : Density (g/cm^3)
m : Mass (g)
v : Volume (cm^3)
σ : Tensile stress (MPa)
F_{maks} : Maximum force applied to the sample before breaking (N)
A : Cross-sectional area of the specimen (mm^2)
M_0 : Initial mass (g)
M_1 : Final mass (g)

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2.8 Biodegradation Rate Analysis

Biodegradation rate analysis used the soil burial method following ASTM D5988 standards. The test medium consisted of topsoil placed in plastic cups. Furthermore, the specimens measured 2.5 x 5 cm and were buried at a depth of 10 cm for 2 weeks. The samples were conditioned in a desiccator for 10 minutes and weighed initially (M_0). After the testing period, the samples were cleaned of soil and reweighed (M_1). The percentage biodegradation rate was calculated using equation 4.

3. Result and Discussion

3.1 Biofoam Water Absorption Capacity

The water absorption test was carried out to evaluate the water absorption capacity of biofoam and examine the effects of chitosan as well as PVA concentrations on its hydrophobic characteristics. The data obtained are presented in Figure 1.

As shown in Figure 1, increasing the concentration of chitosan and PVA reduced the water-holding capacity of the biofoam material. At a PVA concentration of 10%, water absorption decreased from 14.2% (chitosan 1.5%) to 11.9% (chitosan 2.0%) and 8.9% (chitosan 2.5%).

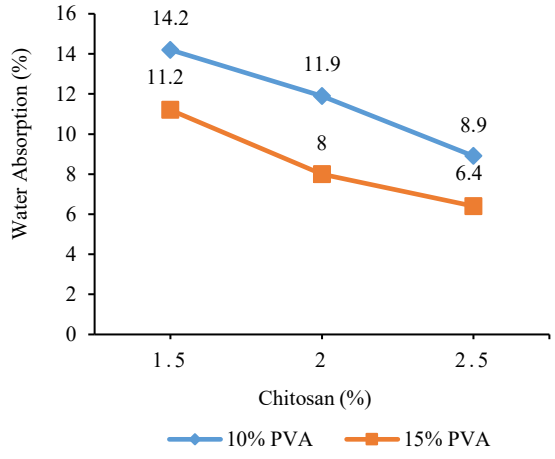

Figure 1. Effect of chitosan and PVA variations on the water absorption capacity of biofoam

A similar decrease was observed at a PVA concentration of 15%, from 11.2% (chitosan 1.5%) to 8.0% (chitosan 2.0%) and 6.4% (chitosan 2.5%). The water absorption values of all samples after 1-minute immersion ranged from 6.4% to 14.2%. These values remained below the maximum limit according to the SNI (26.12%), indicating good water resistance.

The decrease in water absorption can be attributed to the hydrophobic nature of chitosan, whose amine and hydroxyl groups form bonds with other molecules such as starch and cellulose. These intermolecular interactions reduce the number of free hydrophilic groups, thereby inhibiting water penetration into the material's structure [20].

The water absorption capacity was reduced due to increasing PVA concentration, a semi-hydrophobic synthetic polymer with good film-forming properties [21]. As a reinforcing agent, PVA promotes intermolecular interactions through hydrogen bonding. It also helps form a more compact and dense foam structure, reducing the space available for water to enter [22].

The presence of cellulose fibers from bagasse reduces pore size in the foam structure, thereby inhibiting water penetration into the material [23]. The addition of cellulose also increases the crystallinity of the matrix, which significantly slows the rate of water diffusion into the biopolymer structure [24].

3.2 Density Test

A density test was conducted to measure the density of the biofoam structure and analyze the effect of varying chitosan and PVA concentrations on the material's internal structure. The test results are shown in Figure 2.

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As shown in Figure 2, the density of biofoam increased with rising chitosan at all PVA concentrations. At 10% PVA, the density increased from 0.370 g/cm³ to 0.449 g/cm³, while at 15% PVA, density rose from 0.486 g/cm³ to 0.613 g/cm³. The highest value is close to the commercial product, Synbra Technology's biofoam, at 0.66 g/cm³ [25].

This increase is related to the ability of chitosan to form a gel that seals the cavities between particles, leading to a more compact and stronger matrix [26]. Meanwhile, PVA supports the formation of a dense polymer network by increasing the mixture's viscosity, allowing the pores in the structure to fill more completely [27].

Another factor that contributes to high density is the addition of cellulose fibers from bagasse, which helps prevent expansion during foam formation and fills gaps in the matrix [28][29]. The cellulose fibers from bagasse also enhanced intermolecular interactions, particularly through hydrogen bonding, increasing the overall cohesion of the foam structure [30].

PVA and chitosan can form physical crosslinks through hydrogen bonding between the –OH groups in PVA and the –NH_2 groups in chitosan [20]. Although this study did not directly measure crosslink formation, the interaction was expected to increase the density and stability of the biofoam structure. However, this interaction plays a significant role in affecting the foam structure and pore distribution, supporting higher density.

3.3 Tensile Strength Test

Tensile strength test was conducted to assess the ability of biofoam to withstand tensile forces without deforming or breaking. The test also analyzed the effect of varying chitosan and PVA concentrations on the mechanical properties of the foam produced, with the results presented in Figure 3.

Based on the results shown in Figure 3, increasing the chitosan concentration had varying effects depending on the PVA concentration used. At 10% PVA, the tensile strength increased significantly from 0.061 MPa (1.5% chitosan) to 0.49 MPa (2.0% chitosan) and 0.613 MPa (2.5% chitosan). This increase shows the formation of intermolecular bonds, such as hydrogen bonds between chitosan and starch, which strengthen the foam structure [3].

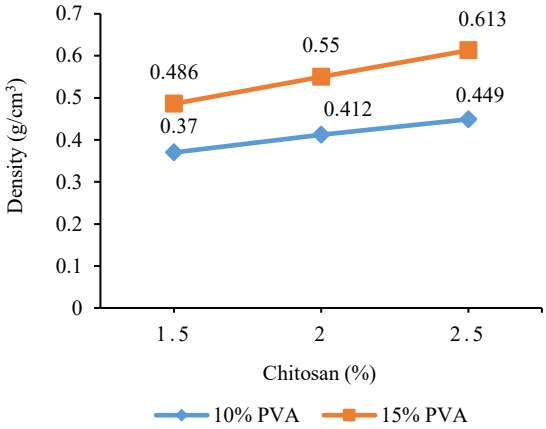

Figure 2. Effect of chitosan and PVA variations on biofoam density

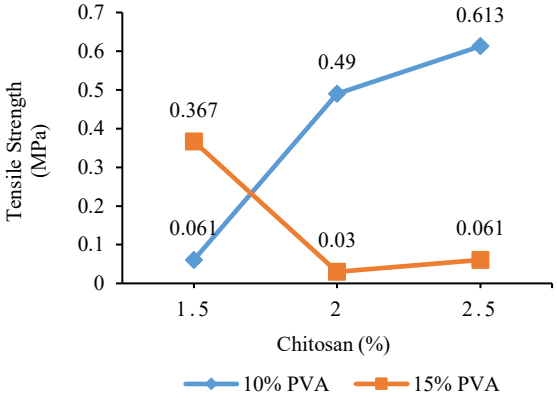

Figure 3. Effect of chitosan and PVA variations on the tensile strength of biofoam

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At other PVA concentrations, increasing the chitosan to 15% PVA caused a decrease in tensile strength from 0.367 MPa (1.5% chitosan) to 0.030 MPa (2.0% chitosan) and 0.061 MPa (2.5% chitosan). This is due to the unbalanced PVA-chitosan ratio, which disrupts the formation of a stable polymer network [21]. Furthermore, less homogeneous mixing weakens the interactions between components [28].

As a semi-crystalline polymer, PVA has the ability to form films and serve as a matrix binder. However, at high concentrations (15%), it can reduce compatibility with chitosan [18]. Cellulose fibers from sugarcane bagasse also contribute to structural reinforcement because of the ability to form bonds between components [24], with fiber quality and blend homogeneity being essential for their effectiveness [31]. Similarly, Hamine et al. [6] observed that variations in pore structure, blend homogeneity, and heat distribution during baking affected the mechanical properties of foam.

In this study, the tensile strength values for all samples ranged from 0.030 to 0.613 MPa. The combination of 10% PVA with 2.5% chitosan produced the highest value, while 15% PVA with 2.0% chitosan had the lowest. However, the tensile strength values obtained were still significantly below the minimum standard reference of 29.16 MPa for conventional polymer packaging materials.

The value of 29.16 MPa is used only as a general comparison, not as a specific standard for biofoam, due to the absence of an SNI specifically regulating the mechanical properties of starch-based biofoam. Although certain combinations can increase tensile strength, starch-based biofoam still requires further modification to meet the mechanical requirements of conventional packaging materials.

3.4 Biodegradation Rate Test

Biodegradation test was conducted to assess the biodegradability of biofoam and to examine how varying chitosan and PVA concentrations influence the material's degradation rate. The study data are presented in Figure 4.

As shown in Figure 4, increasing the PVA concentration from 10% to 15% generally reduced the biodegradation rate. At 10% PVA, all chitosan variations (1.5%–2.5%) experienced complete degradation (100%) after 2 weeks, producing a stable graph. In comparison, at 15% PVA, the biodegradation rate gradually declined, reaching 84.0% (1.5% chitosan), 78.6% (2.0% chitosan), and 74.4% (2.5% chitosan).

The decrease in biodegradation rate is due to the nature of PVA, which is more resistant to microbial attack than starch, despite being biodegradable [32]. Additionally, increasing the chitosan concentration contributes to reduced degradation. This factor is related to the NH_3^+ group in chitosan, which forms stronger hydrogen bonds with starch molecules, thereby strengthening the matrix structure and inhibiting microbial penetration [3].

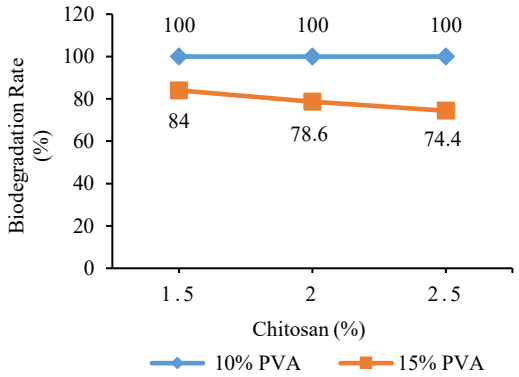

Figure 4. Effect of chitosan and PVA variations on the biodegradation rate of biofoam

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Cellulose fibers from bagasse slow the biodegradation process because of their relatively hydrophobic nature, which inhibits water absorption and limits the access of decomposing enzymes to the matrix [33]. In comparison, cassava starch, the main component, is easily degraded due to the rapid metabolization in soil environments [34].

Compared to the study by Amaraweera et al. [35], cassava starch biofoam produced using microwave and freeze-drying methods only showed approximately 50–60% biodegradation after 15 days. The results suggest that adding bagasse cellulose, chitosan, and PVA in this study can increase porosity and microbial accessibility.

All tested biofoam formulations met biodegradability standards set by the SNI, degrading in less than 2 months. The formulation with 10% PVA performed the best, with a degradation rate of approximately 100% for all chitosan variations (1.5%, 2.0%, and 2.5%) within 2 weeks.

Formulations containing 15% PVA showed lower degradation rates, ranging from 74.4% to 84.0%, which indicated a slower process. However, all biofoam formulations still met SNI standards, showing degradation in less than 2 months.

4. Conclusion

In conclusion, this study achieves the optimal formulation based on a balance of physical, mechanical, and biodegradation properties with a combination of 2.5% chitosan and 10% PVA. The formulation shows water absorption of 8.9%, a density of 0.449 g/cm³, the highest tensile strength of 0.613 MPa, and a biodegradation rate of 100%. These results suggest that the biofoam has potential as an environmentally friendly alternative to styrofoam, particularly for single-use packaging applications. Moreover, further studies are recommended to enhance the mechanical performance of biofoam by optimizing material composition and adjusting the production process, thereby meeting higher quality standards.

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