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The Effect of Adding Variations in the Combination of Anthocyanin Extract and Curcumin Volume Fraction on the Mechanical Properties and Biodegradability of Seaweed-Based Bioplastic Materials

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Abstract: The environmental issues caused by conventional plastic waste are becoming increasingly serious, driving the development of more eco-friendly bioplastics. This study examines the mechanical properties, solubility, and biodegradability of seaweed-based bioplastics with the addition of curcumin and anthocyanin as additives. The results indicate that bioplastics containing only anthocyanin exhibit the best tensile strength (3.78 ± 0.26 MPa) and elasticity (12.48 ± 0.49 MPa). In contrast, bioplastics containing only curcumin show the lowest mechanical properties. The addition of anthocyanin enhances tensile strength and elasticity through the formation of strong hydrogen bonds with seaweed polymers, whereas curcumin decreases mechanical properties due to less stable molecular interactions. In terms of solubility, anthocyanin recorded the highest value (72.04%), while curcumin had the lowest (37.61%) due to its lower water stability. Regarding biodegradability, the combination of anthocyanin (1.25%) and curcumin (3.75%), as well as pure curcumin (5%), showed the highest degradation rates, whereas a balanced mixture (2.5%:2.5%) exhibited the lowest biodegradability. In conclusion, anthocyanin improves the mechanical properties and solubility of bioplastics, while curcumin supports biodegradability. Seaweed-based bioplastics with added curcumin and anthocyanin show potential as eco-friendly antibacterial materials.

Keywords: Anthocyanin; Bioplastic; Curcumin; Seaweed

Introduction

Conventional petroleum-based plastics have caused serious environmental problems and damaged the global ecosystem. Since 1950, plastic production has reached 1.3 billion tons, with an annual increase of 2.70 times (Antelava et al., 2019; Ciuffi et al., 2020; Coppola et al., 2023; Pan et al., 2020). The Covid-19 pandemic has worsened this situation, with estimates of global plastic waste reaching 1.6 million tons per day, mostly originating from food packaging and shipping (Benson et al., 2021). The development of bioplastics is one of the solutions to address this issue. Bioplastics, made from renewable materials and naturally degradable by microorganisms, have the potential to reduce the negative impacts of conventional plastics (Gilani et al., 2023).

Seaweed is one of the more environmentally friendly alternative raw materials for bioplastics (Ali et al., 2023). In addition, seaweed is chosen due to its abundant availability. Indonesia, as a major producer of *Eucheuma cottonii* seaweed, has great potential in developing seaweed-based bioplastics (BPS, 2021; FOA, 2019; Lim et al., 2021; Padam & Chye, 2020;

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Venkatachalam & Palaniswamy, 2020). In its development, bioplastics can be made into active packaging that can extend food shelf life, reduce spoilage, and preserve the nutritional content of food (Merino et al., 2022).

Active packaging is made by adding specific substances (Yolanda et al., 2020). The addition of active compounds such as anthocyanins and curcumin to bioplastics can provide antioxidant and antibacterial properties, thus increasing the safety of food products (Micó-Vicent et al., 2021; Roy & Rhim, 2021; Shahid-ul-Islam et al., 2023; Wang et al., 2024). By combining seaweed with these antioxidant and curcumin compounds, it is expected that the resulting bioplastic will not only reduce environmental impact but also enhance the safety and quality of packaged food products.

Eucheuma cottonii was selected as the primary material for bioplastic synthesis due to several significant advantages. First, this type of seaweed is very abundant in Indonesian waters, making it a raw material source that is not only easily accessible but also economical. Second, the biodegradability of *Eucheuma cottonii* is one of its key attributes; bioplastics produced from this seaweed can be naturally decomposed by microorganisms, offering an environmentally friendly solution and reducing the negative impacts of plastic pollution (Schmaltz et al., 2020).

Third, *Eucheuma cottonii* has great potential for applications such as cling wrap, a type of active packaging that can extend the shelf life of food and preserve its quality (Hamid et al., 2018). By utilizing *Eucheuma cottonii*, we not only contribute to reducing plastic waste but also provide innovation in the packaging industry, leading toward more sustainable and efficient solutions.

The addition of anthocyanins is used because of their ability to inhibit water vapor from entering food and prevent the formation of volatile compounds, thereby extending the food's shelf life (Mohammadalinejhad et al., 2023; Yao et al., 2021; Zhong et al., 2020). The combination of anthocyanins and curcumin plays a crucial role in improving the functional and aesthetic properties of bioplastics. Anthocyanins, which are natural pigments found in various fruits and vegetables, not only provide attractive colors but also act as strong antioxidant agents, protecting bioplastics from damage caused by free radicals and ultraviolet (UV) rays (Guzman-Puyol et al., 2022). With the addition of anthocyanins, bioplastics not only gain bright and natural colors but also show improved resistance to UV degradation, thereby extending their lifespan and stability under light exposure.

On the other hand, curcumin, the main bioactive compound in turmeric, adds an important dimension in terms of antimicrobial activity. This compound is known for its strong antibacterial properties due to its hydrophobic phenolic content (Bouloumpasi et al., 2024). The incorporation of curcumin into bioplastics not only enhances the mechanical strength of the material but also provides additional protection against microbial growth, maintaining the safety of packaged food products.

The combination of anthocyanins and curcumin creates bioplastics that are not only aesthetically pleasing and functional but also safer and more durable, making them an ideal solution for environmentally friendly active packaging applications.

This study aims to synthesize bioplastics based on *Eucheuma cottonii* by utilizing a combination of anthocyanins and curcumin, and to identify the functional groups and antibacterial properties of the resulting bioplastics. The main objective of this research is to develop bioplastics that not only capitalize on the advantages of natural raw materials but also improve their functional and aesthetic performance by incorporating anthocyanins as antioxidant agents and curcumin as antibacterial agents.

This study is highly relevant to reducing dependency on conventional plastics, supporting environmental sustainability, and fostering innovation in material technology. Conventional plastics, which are generally petroleum-based, have caused a global environmental crisis, including plastic pollution that harms ecosystems and human health (Kumar et al., 2021; Pilapitiya & Ratnayake, 2024). By synthesizing bioplastics from *Eucheuma cottonii*, this study offers a more environmentally friendly alternative, as these seaweed-based bioplastics can naturally decompose and reduce the accumulation of plastic waste (Lomartire et al., 2022; Moshood et al., 2022).

With innovation in material technology, this research has the potential to pave the way for the development of more advanced and sustainable packaging materials. The integration of anthocyanins and curcumin in bioplastics not only adds functional value but also aesthetic appeal, making it an attractive option for the packaging industry and supporting the development of more innovative and ecological material technologies (D'Almeida & de Albuquerque, 2024; Khandeparkar et al., 2024). Therefore, this research not only offers practical solutions to address the problems of conventional plastics but also promotes progress in sustainable material technologies.

Method

Anthocyanin Extraction from Dragon Fruit Peel Waste

The cleaned dragon fruit peel was dried at 100°C for 8 hours, ground using a blender until it became powder, and 50 g of the peel was measured. The peel powder was then put into 500 mL of 70% ethanol solution and stirred. The maceration process was carried out for 24 hours at room temperature. The resulting extract was filtered using a filter cloth which was then concentrated by heating in a beaker on a magnetic stirrer at 90 rpm until the temperature reached 70°C.

Synthesis of Seaweed-Based Bioplastics with a Combination of Anthocyanins and Curcumin

Curcumin Extraction from Turmeric

The turmeric was washed and cut into small pieces, then dried at 100°C for 8 hours. The dried turmeric rhizome was then blended to obtain turmeric powder. As much as 50 g of turmeric powder obtained was dissolved in 0.5 L of ethanol and stored at room temperature. The resulting solution was then filtered using filter paper and transferred to a glass bottle. The filtrate obtained was then heated in a beaker on a magnetic stirrer at a rotation speed of 90 rpm until the temperature reached 70°C.

Bioplastic Synthesis Process

Table 1. Composition of Anthocyanin and Curcumin Volume Fractions in Bioplastic

Code	Seaweed (m/v) (%)	Antosianin (v/v) (%)	Curcumin (v/v) (%)
A	3	5	0
B	3	1.25	3.75
C	3	2.50	2.50
D	3	3.75	1.25
E	3	0	5
O	3	0	0

A total of 3% w/v of extracted seaweed cellulose was dissolved in 100 mL of distilled water, the process was carried out using a magnetic stirrer at a speed of 100 rpm until the temperature reached 70°C for 30 minutes. The solution was then cooled until the temperature reached 50oC and glycerol 1.50% of the total volume of seaweed was added and homogenized for 5 minutes (Tran et al., 2020). Combination of two modified extracts, Next, the solution was cooled again until the temperature reached 40°C, and a combination of anthocyanin/curcumin extract mixture and glycerol was added which functioned as a plasticizer and then homogenized for 15 minutes using a magnetic stirrer at a speed of 100 rpm (Khoiriyah et al., 2022). Finally, the bioplastic material solution was printed on a 18×18 cm² baking sheet, then left at a temperature of 50oC for 24 hours before being released from the baking sheet and then dried. The composition of the basic ingredients of the bioplastic in this study with their respective sample codes is presented in Table 1.

Tensile Strength Characterization and Elastic Modulus of Bioplastics

The tensile test was carried out with the following steps: First, the bioplastic sample was cut into a size of 10 × 2 cm². Then, the sample was placed on the UTM HT-SF093A1kN tool for tensile testing. The tensile test was carried out with a crosshead speed of 1.0 mm/min and a distance between the clamps on the sample of 5.0 cm. The tensile test results were then analyzed to determine the tensile strength and elastic modulus of the synthesized bioplastic material (Pramitasari et al., 2022).

Bioplastic Solubility Test

The solubility of bioplastics was determined using the method as described by (Nigam et al., 2021). The dry bioplastic mass was weighed and the results were recorded. Furthermore, it was soaked in a container containing 50 mL of water with stirring for each light bioplastic periodically for 2 hours. The insoluble part was collected and dried at 60°C for 24 hours to obtain the final dry weight of the film. The total percentage of soluble matter (FS) was calculated using the following equation:

$$FS\ (\%) = \frac{ID - FD}{ID} \times 100 \quad (1)$$

Where ID (Initial Dry) is the dry mass before dissolving, and FD (Final Dry) is the dry mass after dissolving.

Antibacterial Activity Analysis

Biodegradability testing was carried out to determine the initial degradation of plastic samples. This biodegradability test applies a soil technique called the soil planting test (Hidayati et al., 2021). A 4×4cm2 sample was planted in a pot filled with soil, and the pot was left open to the air without a glass cover. Sample observations were carried out once every 5 days for a period of 15 days. According to (Tarique et al., 2021), the mass of bioplastic lost (m_l or mass loss) after being planted in the soil can be measured using the following equation:

$$m_l\ (\%) = \frac{m_0 - m_t}{m_0} \times 100 \quad (2)$$

Where m_0 is the mass of bioplastic before burial, and m_t is the mass of bioplastic after burial.

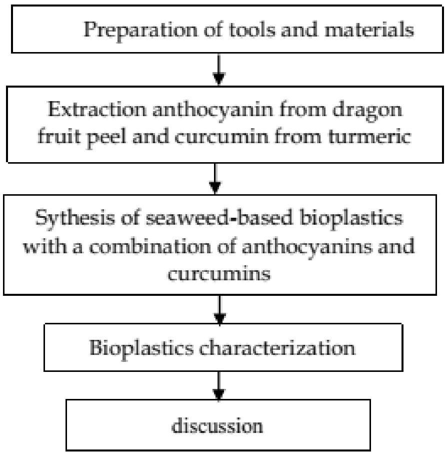

Figure 1. Research Flowchart

Result and Discussion

The addition of variations of anthocyanin and curcumin extracts has an effect on the color of the Eucheuma cottoni-based bioplastic that has been made. Figure 2 is a bioplastic with anthocyanin and curcumin extracts. The color of the bioplastic produced is significantly different from that without anthocyanin and curcumin extracts. Bioplastic without anthocyanin and curcumin extracts looks clear. Bioplastic with the addition of anthocyanin alone is pale white, because the bright color of anthocyanin causes the color of the bioplastic to not be too significant. Bioplastic with the addition of curcumin alone is dark orange. This happens because the phenol content in anthocyanin is smaller than curcumin, causing the color of curcumin to be more concentrated (Uto-Kondo et al., 2024).

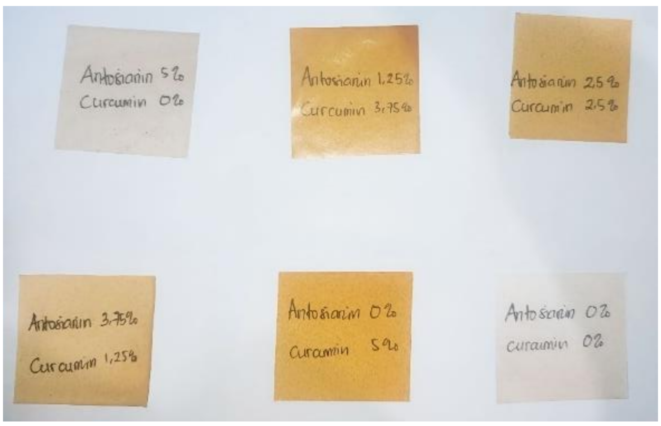

Figure 2. Bioplastic with anthocyanin and curcumin extracts

Tensile Strength and Elastic Modulus of Bioplastics

Based on Figure 3 it can be seen that the most optimal Tensile strength value of bioplastics is the addition of anthocyanins alone, which is 3.78 ± 0.26 MPa. While the smallest Tensile strength is the combination of Antocyanins 3.75%: Curcumin 1.25%, which is 1.29 ± 0.19 MPa. In addition, based on Figure 1, we can see that the addition of anthocyanins can increase the Tensile strength of bioplastics, while the addition of curcumin can decrease the tensile strength of bioplastics as stated by Negrete-Bolagay et al. (2024), Jayarathna et al. (2022), and Almeida et al. (2018). This happens because anthocyanins have hydroxyl groups so that they can form hydrogen bonds with polymers derived from seaweed. Where this hydrogen bond can increase the mechanical properties of a material (Oliveira Filho et al., 2021). Basically, curcumin has a hydroxyl group like anthocyanin, but as seen in Figure 3, it appears that the structure of curcumin itself is larger and more complex than the structure of anthocyanin in Figure 3. The large and complex structure of curcumin makes it less effective in forming strong hydrogen bonds or stable interactions with polymer chains compared to anthocyanins. This can reduce the attachment of curcumin molecules to the polymer matrix, creating weak points in bioplastics (Perera et al., 2023; Falcão et al., 2022).

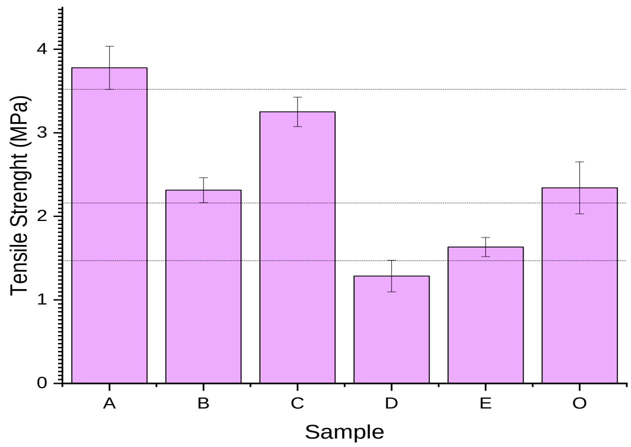

Figure 3. Tensile strength of bioplastic

Based on Figure 4 it can be seen that the most optimal elasticity value of bioplastic is the addition of anthocyanin alone, which is 12.48 ± 0.49 MPa. While the smallest elasticity is the combination of Antocyanin 3.75%: Curcumin 1.25%, which is 7.90 ± 049 MPa. In addition, based on Figure 4 we can see that the addition of anthocyanin can increase the tensile strength of bioplastic, while the addition of curcumin can reduce the tensile strength of bioplastic. This is like the assumption that the hydroxyl group that causes hydrogen bonds in bioplastic can increase interactions with polymers and increase stress distribution, while curcumin reduces stress due to aggregation, namely weak interactions with polymers so that the stress distribution is uneven and because of its inability to form a homogeneous structure with polymers from seaweed.

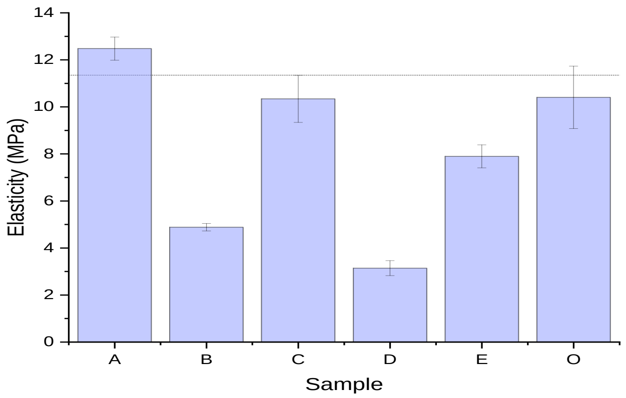

Figure 4. Elasticity of bioplastics

Bioplastic Solubility

Figure 5 shows that the highest solubility was obtained from sample A with a value of 72.04% and a standard error of 1.89, indicating high consistency with very low variation. Sample B has a solubility close to sample A, which is 71.17% with a standard error of 2.11, which also reflects good stability. Meanwhile, sample C shows a solubility of 63.32% with a standard error of 2.25, below A and B but still has a controlled level of variability. Samples D and O have almost similar solubility, which are 51.11% and 49.56% respectively, but sample D shows a greater variation with a standard error of 4.74 compared to sample O which has a standard error of 3.21. The lowest solubility was recorded in sample E with a value of 37.61% and a standard error of 3.70, indicating that the solubility in this sample is lower than the other samples, although it is still within the moderate variability limit. Thus, samples A and B showed the highest and most stable solubility results, while sample E showed the lowest solubility.

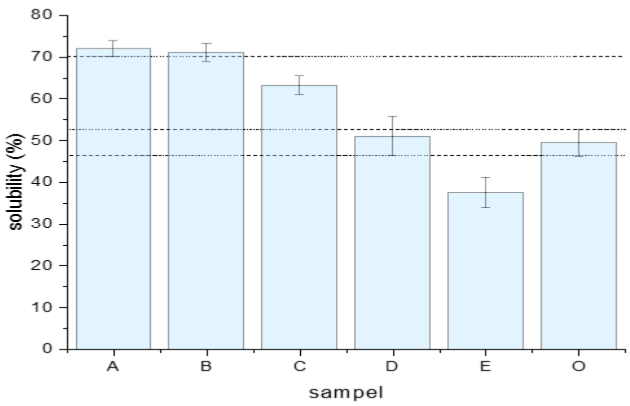

Figure 5. Graph of bioplastic solubility properties

The solubility of bioplastics with the addition of curcumin alone has the smallest solubility properties due to the nature of curcumin itself (Górnicka et al., 2023; Xie et al., 2021). In general, curcumin is almost insoluble in water at acidic and neutral pH, making it difficult to absorb in solution form in this environment. However, curcumin can dissolve well in organic solvents, both polar and nonpolar, such as methanol, ethanol, or benzene (Mondal et al., 2016; Slaček et al., 2023). In addition, curcumin also shows better solubility in alkaline solvents, where high pH can help break down the structure of curcumin, increasing its solubility. In very acidic conditions, such as in glacial acetic acid, curcumin can also dissolve effectively (Lestari & Indrayanto, 2014). Based on Figure 5, it is known that the best solubility is possessed by the addition of anthocyanin alone. Anthocyanin is able to dissolve well in water (Shi et al., 2024; Taghavi et al., 2022).

Biodegradability of Bioplastics

The results in Figure 6 show that the level of biodegradability of each bioplastic sample varies greatly. Samples B (Anthocyanin 1.25%: Curcumin 3.75%) and E (anthocyanin 0%: curcumin 5%) have the highest level of biodegradability, while sample C (Anthocyanin 2.50%: curcumin 2.50%) has the lowest level. In general, most samples show good potential for biological degradation. This is a positive indication that this bioplastic has the potential to reduce environmental impacts compared to conventional plastics. Figure 6 shows the appearance of bioplastic biodegradability.

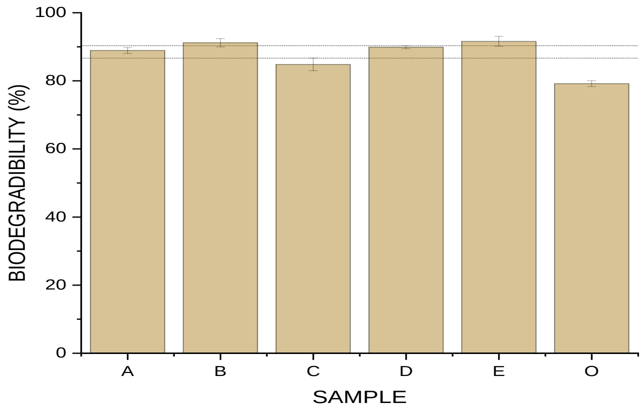

Figure 6. Biodegradability graph of bioplastics

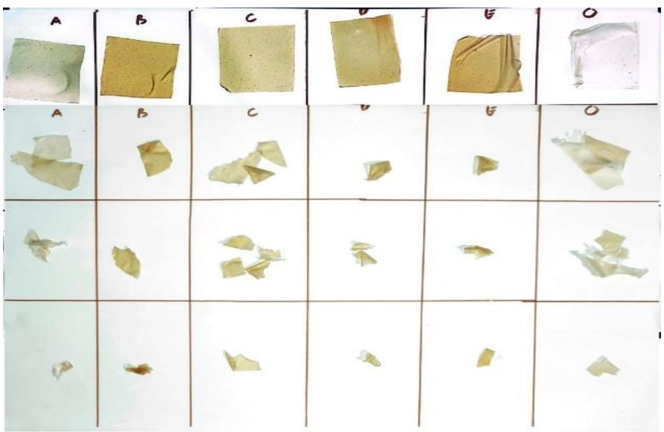

Figure 7. Appearance of bioplastic after being buried in the soil.

Conclusion

The conclusion of this study shows that bioplastic with the addition of anthocyanin alone showed the best performance in terms of tensile strength (3.78 ± 0.26 MPa) and elasticity (12.48 ± 0.49 MPa), while the combination of anthocyanin (3.75%) and curcumin (1.25%) produced the lowest values for both properties. The addition of anthocyanin increases tensile strength and elasticity due to the presence of hydroxyl groups that are able to form strong hydrogen bonds with seaweed polymers, while curcumin, with its more complex molecular structure, decreases mechanical properties due to less stable interactions with polymers. In terms of solubility, anthocyanin showed the best solubility (72.04%), due to its water-soluble nature, while curcumin had the lowest solubility (37.61%) due to its instability in water at acidic or neutral pH. In terms of biodegradability, the combination of anthocyanin (1.25%) and curcumin (3.75%) and curcumin alone (5%) showed the highest biological degradation rate, while the mixture of anthocyanin and curcumin in balanced proportions (2.50%:2.50%) had the lowest biodegradability. Overall, bioplastics with the addition of anthocyanins have superior mechanical properties and solubility, while curcumin makes a positive contribution to biodegradability. Therefore, the right formulation between anthocyanin and curcumin is needed to produce bioplastics with an optimal balance between mechanical strength, solubility, and biodegradability.

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Author Contributions
Conceptualization and design of the research work; field/laboratory experiments and data collection; N. R., S. Data analysis and interpretation; Manuscript preparation; Y. C. H.

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Conflicts of Interest
The author declares no conflict of interest.

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