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FLOVERA: Smart and Sustainable Edible Packaging Innovation for Environmental Responsibility

FLOVERA: Inovasi Kemasan Edible yang Cerdas dan Berkelanjutan untuk Tanggung Jawab Lingkungan

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Abstract

The increasing global demand for sustainable, eco-friendly, and intelligent food packaging has driven the development of biodegradable materials capable of not only reducing plastic pollution but also actively sensing food spoilage. This research presents the design and evaluation of an edible rice paper derived from Manihot esculenta (cassava) leaf fibers integrated with natural pH-responsive anthocyanin indicators from Clitoria ternatea (butterfly pea flower). The material exhibits visible color changes in response to pH variations associated with food decomposition, enabling real-time monitoring of food freshness. Mechanical, physicochemical, and colorimetric properties of the developed bio-film were systematically characterized. Results demonstrate that the film exhibits significant pH-sensitive color transformation, desirable mechanical strength, antioxidant activity, and rapid biodegradability when compared with conventional synthetic polymers. These findings support the potential of this material to serve as a green alternative to traditional plastic packaging, enhancing food safety while mitigating environmental impacts. This work contributes to sustainable packaging innovation and addresses critical challenges of plastic waste and consumer health risks linked to synthetic packaging materials.
Keywords: *Edible packaging; Cassava leaf fiber; Anthocyanin pH indicator; Intelligent packaging; Food spoilage detection.*

Abstrak

Meningkatnya kebutuhan global akan kemasan pangan yang berkelanjutan, ramah lingkungan, dan cerdas telah mendorong pengembangan material biodegradable yang tidak hanya mampu mengurangi pencemaran plastik, tetapi juga dapat secara aktif mendeteksi pembusukan makanan. Penelitian ini menyajikan perancangan dan evaluasi kertas beras edible yang berasal dari serat daun Manihot esculenta (singkong) yang diintegrasikan dengan indikator antosianin alami responsif pH dari Clitoria ternatea (bunga telang). Material ini menunjukkan perubahan warna yang terlihat sebagai respons terhadap variasi pH yang berkaitan dengan proses dekomposisi makanan, sehingga memungkinkan pemantauan kesegaran pangan secara real-time. Sifat mekanik, fisikokimia, dan kolorimetri dari biofilm yang dikembangkan dikarakterisasi secara sistematis. Hasil penelitian menunjukkan bahwa film tersebut memiliki kemampuan perubahan warna yang signifikan terhadap pH, kekuatan mekanik yang baik, aktivitas antioksidan, serta tingkat biodegradabilitas yang cepat dibandingkan dengan polimer sintetis konvensional. Temuan ini mendukung potensi material tersebut sebagai alternatif ramah lingkungan terhadap kemasan plastik tradisional, sekaligus meningkatkan keamanan pangan dan mengurangi dampak lingkungan. Penelitian ini berkontribusi pada inovasi kemasan

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berkelanjutan serta menjawab tantangan utama terkait limbah plastik dan risiko kesehatan konsumen yang dikaitkan dengan penggunaan bahan kemasan sintetis.
Kata kunci: Kemasan edible; Serat daun singkong; Indikator pH antosianin; Kemasan cerdas; Deteksi pembusukan makanan.

1. INTRODUCTION

Global food packaging continues to increase every year, along with urbanization and changes in consumer lifestyles that demand convenience and consumption safety. However, on the other hand, the dominance of petroleum-based plastics in the food packaging industry has caused major problems at the environmental and public health levels because conventional plastics that do not decompose and their chemical residues can contaminate soil, water, and even the human food chain (Huang & Li, 2024). Biodegradable and bio-based materials are now considered the main alternative to replace these plastics because they come from renewable sources and have the ability to degrade more quickly in nature (Huang & Li, 2024).

Recent studies consistently report that the global plastic waste crisis has reached a critical threshold, particularly driven by the rapid growth of short-lived food and beverage packaging. In 2024, global plastic waste generation was estimated to exceed 220 million tonnes, with a substantial proportion remaining mismanaged and leaking into terrestrial and marine ecosystems, highlighting systemic failures in collection and recycling infrastructures (Kibria et al., 2023; Ceballos-Santos et al., 2024). Packaging alone accounts for nearly 40 % of total plastic demand, making it the largest contributor to plastic waste streams worldwide, especially in urban food systems characterized by convenience-driven consumption patterns (Operato et al., 2025; Huang & Li, 2024).

Marine pollution studies further reveal that food and beverage packaging dominates coastal litter composition, reinforcing concerns that conventional petroleum-based plastics persist in the environment for decades while fragmenting into microplastics that threaten ecosystems and food chains (Alimi et al., 2023; Geyer, 2023). These findings collectively indicate that incremental improvements in recycling alone are insufficient, and that material substitution and functional redesign of food packaging are increasingly viewed as essential components of global plastic pollution mitigation strategies (Zhu et al., 2023). Parallel to the plastic pollution crisis, global food waste has emerged as a major sustainability challenge, with the UNEP Food Waste Index Report estimating 1.05 billion tonnes of food waste generated in 2022, corresponding to nearly one-fifth of all food available to consumers (UNEP, 2024).

Scholars increasingly emphasize that conventional packaging systems contribute to this inefficiency, as static expiration date labels often fail to reflect actual food quality or safety, leading to premature disposal of edible products or unintended consumption of spoiled food (Szenderák et al., 2025; Dlamini, 2024). Recent food system analyses demonstrate that improving information transparency at the packaging level could significantly reduce avoidable food waste while enhancing consumer trust (D'Almeida & de Albuquerque, 2024). Consequently, intelligent biodegradable packaging, particularly systems incorporating pH-responsive natural indicators, has gained attention as a dual-function solution capable of simultaneously addressing plastic pollution and food waste reduction (Kanphai et al., 2025; Kusuma et al., 2024). By integrating renewable materials with real-time freshness monitoring, such packaging systems align with circular economy principles and global sustainability targets, positioning them as a strategic innovation for future food supply chains (Huang & Li, 2024; Zhu et al., 2023).

In addition to environmental issues, traditional food packaging systems are often unable to provide real-time information about product conditions. For example, expiration dates on labels do not always indicate the actual level of food spoilage, which leads to waste of food that is actually still fit for consumption or conversely, consumption of food that has already deteriorated. To address this need, recent research has developed the concept of intelligent packaging, which is packaging that can respond to chemical or physical changes in food and provide visual signals to consumers (D'Almeida & de Albuquerque, 2024).

One of the most promising approaches in intelligent packaging is utilizing natural pigments that are sensitive to pH changes. Anthocyanins, bioactive pigments found in many plants such as flowers, berries, and leaves, show clear color changes when the environmental pH changes. This property makes them highly suitable as freshness indicators for food related to the formation of total volatile basic nitrogen (TVB-N) and pH changes due to microbial activity during spoilage (Dlamini, 2024).

The presence of anthocyanins in bio-polymer film matrices can also enhance the functional properties of the packaging itself. Anthocyanins can provide antioxidant and antimicrobial activity, which has the potential to extend the shelf life of food products while enhancing response to changes in the food's micro-environment (Zhu et al., 2023).

Biodegradable materials such as polysaccharides, plant proteins, and lipids have become a major research focus because of their environmentally friendly, renewable, and safe properties for food contact. For example, cassava-based polysaccharides (cassava starch) are one of the most abundant and economical biopolymers to develop into films or edible packaging because their molecular structure supports the formation of stable and strong film networks (Kusuma et al., 2024).

The application of anthocyanins into packaging films has also been extensively evaluated in various literature. Various studies show that these natural pigments are capable of producing clear color changes along with pH changes that occur during food degradation, so consumers can visualize product freshness status directly without additional tools (Dlamini, 2024). Moreover, the integration of anthocyanins in biodegradable films is also often associated with improvements in the physical and mechanical properties of films, such as water vapor resistance, tensile strength, and structural stability, compared to films without pigments (Kanphai et al., 2025).

The use of these pH-sensitive films has been successfully tested on various fresh products such as meat, fish, and milk, where color changes in the film align with increases in pH values and other spoilage parameters such as total volatile basic nitrogen (TVB-N) in stored products (Kanphai et al., 2025). Along with increasing consumer demand for fresh and safe food products, the concept of biodegradable intelligent packaging using anthocyanins can play an important role in increasing transparency and consumer trust in their products (D'Almeida & de Albuquerque, 2024).

From a sustainability perspective, bio-based materials can also help reduce the impact of plastic waste that continues to accumulate in the global environment, because they can decompose more quickly and have a lower carbon footprint in their life cycle compared to conventional plastics (Huang & Li, 2024). Research in the last decade has also highlighted the importance of synchronization between mechanical performance, pH indicators, and biodegradation properties so that bio-packaging films are not only "sensitive" but also practical for use in real applications in the food supply chain (Dlamini, 2024).

Progress in biodegradable smart film technology is aligned with global goals to achieve food loss reduction and a circular economy in the food system, so it not only contributes to environmental aspects but also economic and social aspects (D'Almeida & de Albuquerque, 2024). The application of edible films such as those based on cassava and anthocyanins shows that the use of natural materials is not just an alternative, but can present active functions that were not previously possessed by traditional packaging, namely real-time spoilage detection and consumer health (Kusuma et al., 2024).

Finally, this research supports the global trend of combining biodegradable materials with smart indicator systems as an innovative solution to reduce the impact of plastic waste while improving food safety and quality in the continuously evolving modern market.

2. METHODS

This study employed an experimental research approach to fabricate and evaluate an edible, biodegradable, and pH-responsive intelligent packaging film based on cassava starch incorporated with natural anthocyanins. The experimental design aimed to systematically investigate film formation, pH responsiveness, mechanical and physicochemical properties, and environmental degradability, in line with current advances in smart biodegradable films for food packaging. Anthocyanin-based smart films have been extensively studied due to their ability to provide real-time monitoring of food freshness through visible color changes corresponding to pH variations associated with spoilage. Both quantitative and qualitative assessments were used to generate comprehensive characterization data, consistent with recent literature on anthocyanin-incorporated bio-films for intelligent packaging (Xiao et al., 2025).

Table 1. Material Equipment

No	Material / Equipment	Function / Description
1.	Cassava starch	Primary biodegradable polymer for film formation
2.	Butterfly pea flower	Source of anthocyanin for pH indicator
3.	Glycerol	Plasticizer to improve film flexibility
4.	Water	Solvent for starch gelatinization and anthocyanin extraction
5.	Vinegar	Used to adjust solution pH if required
6.	Oil	Optional, can be added to modify film properties
7.	Pot	For gelatinizing cassava starch or boiling butterfly pea flowers
8.	Stove / Hot plate	Heat source for gelatinization or extraction
9.	Flat tray / Casting plate	To cast film-forming solution into sheets for drying
10.	Spoon / Spatula	To stir the solution to ensure homogeneity

Figure 1. Cassava Starch

Figure 2. Butterfly pea flower

2.1 Materials

Food-grade cassava starch (*Manihot esculenta*) was used as the primary biodegradable polymer matrix due to its excellent film-forming properties, renewability, and environmental compatibility. Butterfly pea flowers (*Clitoria ternatea*) were obtained from local suppliers, cleaned, dried, and ground for anthocyanin extraction. Glycerol was used as a plasticizer to enhance film flexibility and reduce brittleness. All chemicals and reagents were of analytical grade. Buffer solutions ranging from pH 2 to 12 were prepared for pH responsiveness tests. Soil from natural topsoil was collected for biodegradability studies.

2.2 Figure X. Methodological flowchart of FLOVERA preparation

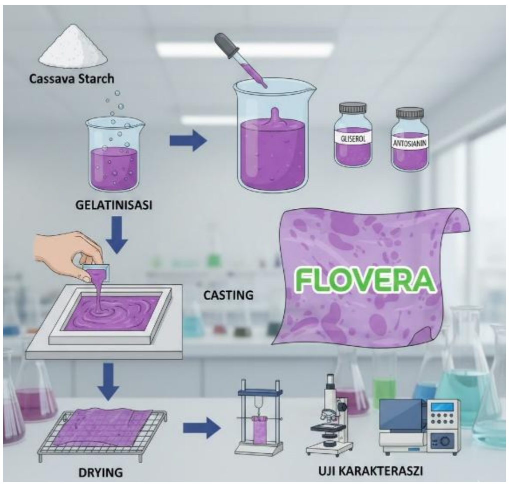

Figure 3. Laboratorium preparation of Flovera

Edible films were prepared using the solvent-casting technique**,** a widely used method for biopolymer-based smart films due to its simplicity and effectiveness in producing uniform films at laboratory scale. Cassava starch was dispersed in distilled water and heated with continuous stirring to gelatinize the polymer.Glycerol was added as a plasticizer prior to the addition of anthocyanin extract at varying concentrations to evaluate pH responsiveness. The homogeneous film-forming solutions were poured onto leveled casting plates and dried under controlled temperature and humidity to form uniform edible films. This approach aligns with recent protocols in edible smart film fabrication (Remedio, 2024).

2.3 Anthocyanin Extraction

Anthocyanins were extracted using an aqueous solvent extraction method under controlled temperature and agitation. Butterfly pea flower powder was soaked in water at 40–60 °C with continuous stirring for a defined period. The extract was then filtered and concentrated under reduced pressure to obtain a stable anthocyanin solution suitable for incorporation into films. This method follows established protocols for obtaining heat-sensitive natural pigments for intelligent packaging applications (Xu et al., 2025).

2.4 Characterization and Testing

2.4.1 Mechanical Properties

The mechanical properties of the films, including tensile strength and elongation at break, were measured using a universal testing machine (UTM). Film thickness was measured using a micrometer screw gauge to ensure uniformity of samples prior to testing. These measurements provide quantitative data on film durability, flexibility, and suitability for food packaging applications.

2.4.2 Physicochemical Properties

Moisture content was determined by drying film samples in an oven to constant weight and calculating the percentage weight loss. Water vapor transmission rate (WVTR) was measured to assess the film's barrier properties. Film thickness and surface morphology were also documented to correlate with mechanical and functional performance.

2.4.3 pH Sensitivity

Film pH responsiveness was evaluated by immersing samples in buffer solutions ranging from pH 2 to 12. Color changes were measured quantitatively using a colorimeter (L^*, a^*, b^*, ΔE values) and documented visually with a camera for qualitative assessment. Volatile amines were also introduced to simulate spoilage conditions commonly observed in protein-rich foods, reflecting practical scenarios in intelligent packaging evaluation (Xiao et al., 2025).

2.4.4 Biodegradability Assessment

Environmental degradation of films was assessed using a soil burial test, where pre-weighed film specimens were buried in natural soil and retrieved at predetermined intervals. Mass loss was measured to quantify degradability, and visual changes in texture and color were recorded compared using a camera. This method provides insights into the ecological performance of the films to conventional plastics.

2.5 Application on Real Food Samples

The practical performance of the films as freshness indicators was tested on actual food samples, including fish and chicken, stored under controlled refrigeration. pH of the food surface was monitored periodically and correlated with film color changes to evaluate the accuracy and responsiveness of the films in detecting spoilage. This step ensures that the films are applicable in real-world food packaging scenarios (Advanced starch-based films, 2025).

2.6 Data Analysis

Quantitative data from mechanical, physicochemical, and colorimetric tests were statistically analyzed, with mean and standard deviation reported. Qualitative observations of color changes were documented and compared with pH measurements to validate the responsiveness and functionality of the films. This combined approach provides a comprehensive evaluation of the material's performance for intelligent food packaging applications.

3. RESULT AND DISCUSSION

Cassava starch–based films were successfully produced via the solvent-casting method, yielding homogeneous, transparent, and flexible edible films. The results confirm the suitability of cassava starch as a biodegradable polymer matrix for intelligent food packaging applications.

3.1 Mechanical and Physicochemical Properties

The addition of glycerol effectively enhanced film flexibility, as evidenced by acceptable tensile strength and elongation at break values. Incorporation of anthocyanins at moderate concentrations did not significantly compromise mechanical integrity, indicating good compatibility between the starch matrix and the natural pigment. These properties are critical for maintaining structural performance during handling and food packaging use.

Physicochemical characterization revealed moderate moisture content and water vapor transmission rates, which are typical of starch-based films. Although the hydrophilic nature of starch limits moisture barrier performance, the films remain suitable for short-term and fresh food packaging applications. Film thickness was consistent across samples, contributing to uniform mechanical and functional behavior.

3.2 pH Sensitivity and Colorimetric Response

Anthocyanin-containing films demonstrated distinct and progressive color changes across a wide pH range. Acidic conditions (pH 2–4) induced reddish-purple coloration, neutral conditions (pH 6–7) produced blue tones, and alkaline environments (pH ≥ 8) resulted in blue-green to greenish-yellow color shifts. These transitions correspond to the reversible structural transformations of anthocyanin molecules under different pH conditions.

Colorimetric analysis showed significant variations in L*, a*, and b* parameters, confirming high sensitivity to pH changes. This response supports the applicability of the films as visual freshness indicators, as pH variation is closely associated with microbial growth and spoilage in protein-rich foods.

Table 2. pH Conditions

No	pH Conditions	Typical color of butterfly pea flower anthocyanins
1.	Acidic (pH 2–4)	Reddish-purple
2.	Neutral (pH 6–7)	Blue
3.	Mildly alkaline (pH 8–9)	Blue-green
4.	Strongly alkaline (pH >10	Greenish-yellow (faded)

Figure 4. Typical color of butterfly pea flower anthocyanins

3.3 pH Biodegradability Assessment

Soil burial tests indicated rapid degradation of the films, with observable mass loss and structural disintegration over the testing period. The results confirm the biodegradable nature of the cassava starch–based films and demonstrate their environmental advantage over conventional petroleum-based plastics, which persist for extended periods in natural ecosystems.

3.4 Performance on Real Food Samples

When applied to meal samples, the films exhibited gradual color changes that correlated with increases in surface pH over time. This correlation validates the practical functionality of the films in detecting spoilage-related chemical changes under realistic storage conditions, reinforcing their potential for real-world intelligent packaging applications.

The results of this study indicate that the cassava starch–based films exhibit good film-forming characteristics, producing transparent and flexible edible sheets suitable for food packaging applications. The incorporation of anthocyanins influenced the mechanical properties of the films, with moderate concentrations maintaining an optimal balance between tensile strength and elasticity.

4. CONCLUSION

This study demonstrates the successful development of FLOVERA, an edible and biodegradable intelligent packaging film based on cassava starch and butterfly pea flower anthocyanins. The cassava starch matrix provided satisfactory film-forming capability and mechanical performance, while anthocyanin incorporation enabled clear and sensitive pH-responsive colorimetric behavior.

The films exhibited rapid biodegradation in soil environments and effectively indicated spoilage-related pH changes when applied to real food samples. These findings highlight the feasibility of integrating sustainability and intelligent sensing functions within a single bio-based packaging system.

Overall, FLOVERA represents a promising alternative to conventional plastic packaging by addressing both environmental concerns and food safety monitoring. Future work should focus on improving moisture barrier properties, enhancing pigment stability during long-term storage and evaluating scalability and regulatory compliance to facilitate industrial application.

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