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Physical Characteristics and Ripening Effects of a Banana Peel Powder–Na-CMC Bio-patch on Kepok Banana

[1]Ruspeni Daesusi, [2*]Ajeng Retno Kustianingrum, [3]Elmi Tri Yuliandari
[1,2]Department of Biology Education, Faculty of Education, Communication, and Sciences, Universitas Muhammadiyah Surabaya, Surabaya, Indonesia.
[3]Department of Elementary School Teacher Education, Faculty of Education, Communication, and Sciences, Universitas Muhammadiyah Surabaya, Surabaya, Indonesia.
*Corresponding Author e-mail: retnorum07@gmail.com
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Abstract: This study aimed to develop a cellulose-based bio-patch utilizing banana peel waste as a natural ethylene precursor to promote uniform fruit ripening. The research involved the processing of banana peel waste to obtain bioactive compounds associated with ethylene-mediated ripening, followed by the fabrication of a cellulose matrix as a carrier material. The developed bio-patches were applied to climacteric banana fruits to evaluate their effectiveness in accelerating and synchronizing the ripening process. The evaluated parameters included ripening duration, peel color development, texture softening, and physicochemical properties, including total soluble solids (TSS) and pH. The results demonstrated that the bio-patch containing 1.5% banana peel powder (P3) significantly improved ripening uniformity (96.30%) compared with other treatments and the control, while maintaining fruit physical quality and reducing weight loss during storage. This approach provides an eco-friendly and cost-effective postharvest strategy by converting agricultural waste into functional biomaterials. These findings highlight the potential application of cellulose-based bio-patches as an innovative technology for sustainable postharvest management and improved supply chain efficiency.
Keywords: Banana waste; ethylene precursor; cellulose matrix; bio-patch; postharvest ripening

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INTRODUCTION

The horticultural sector plays a strategic role in supporting national food security and economic development, with bananas representing the largest fruit commodity in Indonesia. According to the Ministry of Agriculture, national banana production reached 9.45 million tons in 2024, accounting for approximately one-third of the country's total fruit production (Kementerian Pertanian, 2025). However, as a climacteric fruit, bananas are highly vulnerable to postharvest deterioration, which leads to uneven ripening, quality decline, and substantial economic losses during handling, distribution, and storage (Geng et al., 2024). Therefore, the development of sustainable postharvest technologies based on locally available biomass resources is essential to minimize postharvest losses while preserving fruit quality.

A major challenge in the postharvest management of climacteric fruits is the lack of precise control over ripening processes, resulting in inconsistent fruit quality. Banana ripening is commonly performed using traditional methods in enclosed environments without accurate regulation of temperature, humidity, and ethylene concentration. Consequently, fruits often exhibit heterogeneous ripening stages, with some fruits becoming overripe while others remain underdeveloped (Ali et al., 2022). In Indonesia, postharvest losses during storage and distribution remain considerable due to accelerated senescence and fruit decay. In some regions, calcium carbide is still applied as an inexpensive ripening agent because of its rapid ripening effect.

However, its use has raised food safety concerns due to the release of acetylene gas and the potential contamination by toxic impurities, including arsenic and phosphorus hydrides, in commercial calcium carbide products (Deshi et al., 2024).

Several commercial ripening technologies, including ethylene gas chambers, ethephon treatments, ethylene-releasing sachets, and controlled-release systems, have been developed to improve ripening uniformity. Nevertheless, these approaches often require specialized facilities, imported materials, or relatively high investment and operational costs, limiting their accessibility for small- and medium-scale producers (Shinga & Fawole, 2023). In contrast, edible coating technologies have predominantly been designed to delay fruit ripening by restricting gas exchange rather than actively stimulating ripening. Therefore, the development of an affordable, environmentally friendly, and locally sourced ripening system capable of providing controlled ripening while remaining accessible to smallholder farmers is highly desirable (Shinga et al., 2025).

One potential solution is the utilization of banana peel waste, an abundant agricultural by-product that remains largely underexploited despite the substantial volume of banana production (Bhavani et al., 2023). As a renewable biomass resource, banana peel provides valuable raw materials for the development of biodegradable materials. Its lignocellulosic composition, particularly its cellulose-rich fraction, contributes to the structural properties of biodegradable matrices (Kumari et al., 2023). Based on this potential, the present study incorporates banana peel powder into a sodium carboxymethyl cellulose (Na-CMC)-based biodegradable matrix to develop bio-patches. Previous studies have explored banana peel as a natural ripening agent and reported improvements in ripening performance and several postharvest quality parameters, suggesting that processed banana peel may retain bioactive compounds associated with fruit ripening. However, the stability and activity of these bioactive compounds after drying and incorporation into a biodegradable Na-CMC matrix, as well as the mechanism underlying their ripening effects, remain insufficiently understood and require further investigation (Manigo, 2026).

Although banana peel-derived biomaterials and biodegradable films have been extensively studied, previous research has primarily focused on the development of biodegradable packaging materials or edible coatings derived from banana peel. Studies investigating the integration of banana peel powder into a localized edible paper bio-patch for controlled ripening of Kepok banana remain limited. The novelty of this study lies in the development of a banana peel powder–Na-CMC bio-patch in a discrete patch format that is attached to a specific area of the fruit surface, rather than covering the entire fruit as in conventional edible coatings or films. The Na-CMC matrix serves as a biodegradable carrier for banana peel powder and is expected to facilitate localized exposure of the fruit surface to ripening-associated bioactive compounds during storage. This system was specifically designed for Kepok banana (*Musa paradisiaca* L.). The developed bio-patches were characterized based on their physicochemical properties, including thickness, flexibility, homogeneity, and color, while their effectiveness in promoting fruit ripening was evaluated through peel color uniformity, firmness, weight loss, and total soluble solids (TSS). These integrated assessments of material characteristics and fruit quality provide a comprehensive evaluation of the proposed bio-patch system.

Based on this background, this study aimed to: (1) fabricate banana peel powder–Na-CMC bio-patches containing different concentrations of banana peel powder and characterize their physicochemical properties, including thickness and color; (2) evaluate the effects of the developed bio-patches on Kepok banana ripening by assessing peel color uniformity, firmness, weight loss, and total soluble solids (TSS); and (3) determine the optimal bio-patch formulation for achieving the most uniform ripening of Kepok banana. The findings of this study are expected to contribute to the development of sustainable postharvest biomaterials that enhance ripening uniformity and fruit quality while promoting the value-added utilization of banana peel waste within a circular bioeconomy framework.

METHOD

Time and Location

This study was conducted from March to May 2025 at the Biology Laboratory, Faculty of Education, Communication and Sciences, Universitas Muhammadiyah Surabaya, Indonesia.

Research Design

This laboratory-based experimental study employed a Completely Randomized Design (CRD) with a single-factor treatment arrangement to evaluate the effectiveness of cellulose matrix-based bio-patches containing different concentrations of Kepok banana peel powder on the postharvest ripening process of Kepok bananas (*Musa paradisiaca* L.) (Permata Sari, 2023). The treatments consisted of four bio-patch formulations containing banana peel powder at concentrations of 0% (P0), 0.5% (P1), 1.0% (P2), and 1.5% (P3) (w/v), incorporated into the bio-patch matrix.

A total of 24 mature-green Kepok bananas with uniform size, weight, physiological maturity, and free from physical defects were selected, labeled, and randomly assigned to four treatment groups. Each treatment consisted of six fruits, with one fruit considered as one experimental unit, resulting in a total of 24 experimental units (Dasumiati et al., 2025). This experimental design was used to determine the effect of different concentrations of banana peel powder incorporated into the bio-patch matrix on postharvest quality parameters of Kepok bananas.

The number of replications was determined using the Federer f ormula, $(t-1)(r-1) \geq 15$, where t is the number of treatments and r is the number of replications. With four treatments, the minimum number of replications required was six $[(4-1)(6-1)=15]$. Thus, six replications were used for each treatment, resulting in a total of 24 experimental units (Kusuma et al., 2016).

Materials and Equipment

The materials used in this study included Kepok banana peel waste as the raw material for bio-patch fabrication, mature-green Kepok bananas (*Musa paradisiaca* L.) as the test fruit, Sodium Carboxymethyl Cellulose (Na-CMC), glycerol, distilled water, and edible paper as the carrier medium. The identity of Kepok bananas was verified by a plant taxonomist based on morphological characteristics.

Kepok banana peels were collected from traditional market vendors using purposive sampling based on the following criteria: freshly peeled on the same day, free from bruises, pests, diseases, and chemical contamination. The test fruits were selected based on uniformity in size, weight, shape, and physiological maturity to minimize experimental variation and were confirmed to be free from physical damage. The equipment used included a laboratory drying oven, blender, magnetic stirrer, digital balance, texture analyzer, digital refractometer, and a standard Von Loesecke banana peel color chart.

Preparation of Banana Peel Powder

The preparation of banana peel powder began with washing the Kepok banana peels, cutting them into small pieces, and drying them in a low-temperature oven at

50–60 °C for 24 h until sufficient moisture reduction was achieved and the peels became brittle. The dried peels were subsequently ground using a blender to obtain fine banana peel powder, which was used as the active component in the bio-patch formulation (Elisusanti et al., 2020).

Bio-patch Formulation

The bio-patch matrix solution was prepared by dissolving 2% (w/v) Sodium Carboxymethyl Cellulose (Na-CMC) in 100 mL of distilled water under mild heating conditions. Subsequently, 30% glycerol was added as a plasticizer (Amanda, 2023). Banana peel powder was then incorporated into the matrix solution according to the designated treatment concentrations (0%, 0.5%, 1.0%, and 1.5%) and homogenized using a magnetic stirrer.

The homogenized solution was uniformly coated onto edible paper as the carrier substrate and dried until bio-patch sheets were formed. The complete experimental procedure is illustrated in Figure 1.

Figure 1. Flowchart of the experimental procedure

Bio-patch Application and Storage

Each bio-patch sheet, measuring approximately 4 × 4 cm with a contact area of approximately 16 cm², was attached to the central region of the banana peel surface, with one bio-patch applied to each fruit (Syakri, 2019). The bio-patches remained attached throughout the storage period without replacement.

The treated fruits were stored individually at room temperature under ambient laboratory humidity conditions for seven consecutive days and protected from direct sunlight. Fruit quality parameters were evaluated daily throughout the storage period.

Parameter Measurement

The physical characteristics of the fabricated bio-patches were evaluated based on thickness and visual color assessment.

Fruit quality was evaluated daily by measuring weight loss, peel color, pulp firmness, and Total Soluble Solids (TSS). Weight loss was calculated as the percentage reduction in fruit weight relative to the initial fruit weight using a digital balance according to the following equation:

$$Weight\ loss\ (\%) = \frac{W_{0-}\ W_t}{W_0} \times 100$$

where W_0 is the initial fruit weight (g) and W_t is the fruit weight (g) at each observation day.

Fruit firmness was determined using a texture analyzer by applying compression at the equatorial region of the peeled fruit pulp. Measurements were performed once for each fruit, and the maximum force was recorded and expressed in Newton (N).Total Soluble Solids (TSS) were determined from freshly extracted pulp juice using a digital refractometer and expressed as °Brix (Nur Azizah et al., 2025).

Peel color was assessed using the Von Loesecke banana ripening scale (Stages 1–7). The Von Loesecke peel color index is a standardized and widely accepted method for evaluating banana ripening and has been validated in previous postharvest studies (Bora et al., 2015).

Ripening uniformity was defined as the percentage of fruits within each treatment reaching the same ripening stage on the same observation day based on the peel color index. Ripening uniformity was calculated using the following equation:

$$\text{Ripening Uniformity (RU, \%)} = \frac{n}{N} \times 100$$

Where *n* is the number of fruits reaching the same ripening stage within a treatment group on the same observation day, and *N* is the total number of fruits in that treatment group.

Statistical Analysis

The independent variable in this study was the concentration of Kepok banana peel powder incorporated into the bio-patch matrix (0%, 0.5%, 1.0%, and 1.5%). The dependent variables included bio-patch characteristics (thickness and color) and fruit quality parameters, including weight loss, peel color, pulp firmness, and total soluble solids (TSS).

The collected data were processed through editing, coding, and tabulation before statistical analysis. Prior to hypothesis testing, data normality and homogeneity of variance were evaluated. Data that met the assumptions of normal distribution and homogeneity were analyzed using one-way analysis of variance (ANOVA), followed by Duncan's Multiple Range Test (DMRT) at a 95% confidence level (α = 0.05). Data that did not meet the assumptions of parametric analysis were analyzed using the Kruskal–Wallis test (Efendi & Hidayat, 2018).

RESULTS AND DISCUSSION

Physical Characteristics of Cellulose Matrix-Based Bio-patch from Kepok Banana Peel Waste

The physical characteristics of the cellulose matrix-based bio-patch incorporating Kepok banana peel powder are presented in Table 1.

Table 1. Descriptive physical characteristics of the cellulose matrix-based bio-patch

Treatment	Thickness (mm)	Flexibility	Homogeneity	Visual Color
P0 (Control, 0%)	0.18 +- 0.01	Good	Very homogeneous	Clear white
P1 (0.5% Peel Powder)	0.20 +- 0.01	Good	Homogeneous	Light cream
P2 (1.0% Peel Powder)	0.22 +- 0.01	Very good	Homogeneous	Cream
P3 (1.5% Peel Powder)	0.24 +- 0.02	Very good	Homogeneous	Light brown

Based on Table 1, all fabricated bio-patches exhibited intact sheet forms, excellent flexibility, and ease of application onto the fruit surface using edible paper as a carrier medium without visible defects. The addition of Kepok banana peel powder caused a gradual color alteration in the sheets, shifting from clear white in the control (P0) to light cream (P1), cream (P2), and light brown at a 1.5% concentration (P3). This color transition was influenced by natural pigments and organic components inherent in the banana peel biomass.

Furthermore, an increase in banana peel powder concentration was directly proportional to a slight increment in bio-patch thickness, increasing from 0.18 mm in P0 to 0.24 mm in P3. Nonetheless, the sheets maintained excellent flexibility and structural integrity, ensuring they did not tear easily when applied to curved fruit surfaces. The cellulose matrix proved capable of forming a homogeneous layer that adhered strongly to the edible paper, thus demonstrating potential as a controlled-release system for active precursors.

The findings regarding bio-patch characteristics are consistent with previous studies demonstrating the potential of cellulose-based matrices to produce flexible films with favorable mechanical properties, making them suitable as carriers for bioactive compounds (Ridho Zuchrillah et al., 2020). The incorporation of plant-derived biomass into cellulose-based materials has also been reported to increase film thickness while maintaining structural integrity and flexibility when the filler concentration is appropriately optimized (Sharma et al., 2025). In addition, lignocellulosic biomass, including banana peel waste, provides valuable cellulose fractions that contribute to the development of biodegradable and functional biomaterials (Kumari et al., 2023). The use of banana peel powder as an active component in a localized Na-CMC bio-patch represents a novel approach by integrating agricultural waste valorization with a targeted postharvest ripening management system. Unlike conventional edible coatings or films that cover the entire fruit surface, this patch-based system enables localized application of ripening-associated compounds, offering potential advantages for sustainable and efficient postharvest technology.

Effect of Bio-patch on the Uniformity of Kepok Banana Ripening

The ripening uniformity of Kepok bananas treated with different bio-patch formulations was evaluated to determine the effectiveness of each treatment in synchronizing the ripening process. The results are summarized in Table 2.

Table 2. Fruit ripening uniformity rates

Treatment	Days to Reach Maturity (Days)	Ripening Uniformity Rate (%)
P0	7.00 ± 0.00^{a}	61.20 ± 2.15^{d}
P1	6.00 ± 0.00^{b}	76.80 ± 1.85^{c}
P2	6.00 ± 0.00^{b}	88.50 ± 1.62^{b}
P3	5.00 ± 0.00^{c}	96.30 ± 1.25^{a}

Note: Values represent Mean ± SD ($n = 6$). Means within a column with different superscripts differ significantly ($p < 0.05$, DMRT).

The research results presented in Table 2 demonstrate that bio-patch application exerted a notable influence on the acceleration and uniformity of Kepok banana ripening. One-Way ANOVA confirmed highly significant treatment effects on days to reach maturity (F3,20 = 120.00, p < 0.001) and ripening uniformity (F3,20 = 414.65, p < 0.001). Treatment P3 (1.5%) accelerated full ripening to 5.00 +- 0.00 days compared to 7.00 +- 0.00 days in control P0, while producing the highest uniformity rate at 96.30 +- 1.25% compared to 61.20 +- 2.15% in control P0.

This increased uniformity was visually observed through synchronized peel color changes within the same treatment group. This response may be associated with ripening-related bioactive compounds derived from banana peel powder incorporated into the Na-CMC matrix. Ethylene plays a central role in regulating climacteric fruit ripening by activating physiological processes, including pigment degradation, cell wall modification, and carbohydrate metabolism (Kumar et al., 2022; Asrey et al., 2023). The Na-CMC matrix may facilitate localized exposure and gradual diffusion of these compounds, contributing to more uniform ripening. Moreover, biopolymer-based carrier systems have been reported to provide controlled delivery of active compounds and support sustainable postharvest applications (Yadav et al., 2021; Sharma et al., 2025).

Effect of Bio-patch on the Physical Quality of Kepok Bananas

To capture dynamic postharvest changes over time, fruit weight loss and pulp firmness were monitored longitudinally across storage (Table 3).

Table 3. Fruit weight loss and firmness

Treatment	Weight Loss (%) Day 3	Final Weight Loss (%) (At Maturity)	Firmness (N) Initial (Day 0)	Final Firmness (N) (At Maturity)
P0 (Control)	5.40 ± 0.21^a	12.80 ± 0.42^a (Day 7)	42.50 ± 1.10^a	8.60 ± 0.35^d (Day 7)
P1 (0.5% Peel Powder)	4.10 ± 0.18^b	10.70 ± 0.38^b (Day 6)	42.50 ± 1.10^a	10.20 ± 0.28^c (Day 6)
P2 (1.0% Peel Powder)	3.20 ± 0.15^c	9.10 ± 0.31^c (Day 6)	42.50 ± 1.10^a	11.40 ± 0.30^b (Day 6)
P3 (1.5% Peel Powder)	2.50 ± 0.12^d	8.20 ± 0.25^d (Day 5)	42.50 ± 1.10^a	12.60 ± 0.40^a (Day 5)

Note: Values represent Mean +- SD (n = 6). Means within a column with different superscripts differ significantly ($p < 0.05$, DMRT).

Based on Table 3, application of the cellulose matrix-based bio-patch provided a significant effect in maintaining the physical quality of Kepok bananas during storage. Treatment P3 (1.5%) generated the lowest final weight loss percentage (8.20 +- 0.25%) and the highest pulp firmness value at maturity (12.60 +- 0.40 N). In contrast, control P0 showed the highest degree of physical degradation, with weight loss reaching 12.80 +- 0.42% and drastic pulp softening (8.60 +- 0.35 N).

These results indicate that increasing banana peel powder concentration within the cellulose matrix improved the preservation of Kepok banana physical quality during storage. This effect may be attributed to the formation of a localized semi-permeable protective layer by the bio-patch, which can reduce moisture loss and regulate gas exchange at the fruit surface. Similar barrier effects of cellulose-based coatings and films have been reported to minimize transpiration, delay quality deterioration, and extend fruit shelf life by controlling water vapor and gas permeability (Ali et al., 2022; Geng et al., 2024). Maintaining water retention contributes to reduced weight loss, while the delayed degradation of cell wall components, including pectin polymers, helps preserve fruit firmness during storage (Eka et al., 2025). Furthermore, cellulose-based biomaterials have demonstrated potential as biodegradable protective matrices for postharvest applications due to their favorable barrier properties and structural stability (Sharma et al., 2025).

Effect of Bio-patch on Chemical Quality and Determination of Optimum Concentration

The effect of bio-patch treatments on the chemical quality of Kepok bananas was evaluated based on the total soluble solids (TSS) content at the maturity stage. The results are presented in Table 4.

Table 4. Final TSS Content of Kepok Banana Fruits at Maturity

Treatment	TSS (deg Brix)
P0 (Control)	18.50 +- 0.45d
P1 (0.5% Peel Powder)	20.20 +- 0.38c
P2 (1.0% Peel Powder)	21.40 +- 0.41b
P3 (1.5% Peel Powder)	22.10 +- 0.35a

Note: Values represent Mean +- SD (n = 6). Means within a column with different superscripts differ significantly (p < 0.05, DMRT).

Total Soluble Solids (TSS) values increased across all treatments in conjunction with the progress of fruit ripening (Table 4). Treatment P3 produced the highest TSS value at 22.10 +- 0.35 deg Brix with the most uniform ripening degree. This increase in soluble solids content indicates that starch hydrolysis into simple sugars (glucose, fructose, and sucrose) proceeded optimally due to effective natural ethylene induction from the bio-patch formulation.

This finding is consistent with the mechanism described by Asrey et al. (2023), in which ethylene-mediated ripening acceleration activates carbohydrate-degrading enzymes that promote the conversion of complex carbohydrates into soluble sugars, thereby increasing fruit total soluble solids (TSS). Similar responses have been reported in climacteric fruits, where ethylene signaling regulates metabolic processes associated with starch degradation, sugar accumulation, and fruit quality improvement during ripening (Kumar et al., 2022; Nur Azizah et al., 2025). The higher TSS value observed in treatment P3 (1.5%) indicates more effective ripening progression, which may be associated with enhanced synchronization of ripening-related biochemical processes. Overall, treatment P3 was identified as the optimum formulation, producing a bio-patch with stable physical characteristics, the highest ripening uniformity (96.30%), improved physical quality preservation, and optimal sugar accumulation (Zheng et al., 2023). These findings support the potential application of banana peel powder–Na-CMC bio-patches as a sustainable biomaterial system for postharvest ripening management.

CONCLUSION

Based on the research results, it can be concluded that a cellulose matrix-based bio-patch incorporating Kepok banana peel powder was successfully developed as an active carrier medium for a natural ethylene precursor capable of inducing a controlled and uniform postharvest ripening process in Kepok bananas. The bio-patch formulation applied to edible paper exhibited favorable physical characteristics (thickness 0.18–0.24 mm, high flexibility, homogeneity), ease of application, and gradual release capacity during storage. Increasing the concentration of Kepok banana peel powder positively influenced fruit ripening quality, as indicated by enhanced color uniformity, reduced weight loss, well-preserved firmness, and increased Total Soluble Solids (TSS) values. Among all evaluated treatments, the bio-patch formulated with 1.5% Kepok banana peel powder (P3) represented the optimum formulation, delivering the highest ripening uniformity (96.30%), accelerating full maturity to 5 days, effectively restricting final weight loss to 8.20%, maintaining pulp firmness at 12.60 N, and achieving an optimal TSS value of 22.10 deg Brix. These results highlight that valorizing banana peel waste as an active ethylene precursor in a cellulose bio-patch offers an eco-friendly and cost-effective biomaterial solution supporting circular bioeconomy principles in sustainable postharvest management.

RECOMMENDATION

Future studies are highly recommended to quantitatively investigate the ethylene release characteristics of the bio-patch using gas chromatography (GC) analysis, thereby providing a more comprehensive explanation of the precursor release mechanism. Furthermore, testing should be extended to various other climacteric fruits, such as mangoes, avocados, papayas, and tomatoes, to evaluate the effectiveness of the bio-patch across different commodities. Modifying the cellulose matrix formulations by varying plasticizers or incorporating other natural active ingredients is also necessary to enhance stability, adhesion, and overall performance during storage. Finally, conducting semi-commercial scale testing and economic feasibility analysis will be crucial to unlocking the broader implementation potential of this technology as a safe, eco-friendly, and sustainable alternative fruit ripening system.

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