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Quality Classification of Candied Bilimbi Using Principal Component Analysis and Linear Discriminant Analysis: Effects of Storage and Packaging

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ABSTRACT

This study aimed to classify quality characteristics of candied bilimbi based on packaging type and storage temperature using Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA). A factorial design with two factors was applied: packaging type (vacuum, polypropylene (PP), edible film) and storage temperature (26 °C and 10 °C). Observations were conducted every three days over 48 days. The study began with edible film preparation, followed by packaging and storage of samples. Physicochemical analyses included moisture content, vitamin C, pH, and total soluble solids (TSS). Results indicated that moisture content increased over storage time, whereas vitamin C, pH, and TSS decreased across treatments. Vacuum packaging with cold storage (10 °C) provided the best physicochemical stability of candied bilimbi, and the PCA-LDA approach proved effective for evaluating and optimizing food packaging systems. PCA revealed that PC-1 (81%) and PC-2 (11%) explained 92% of the total variability, with moisture content contributing to PC-1 and TSS to PC-2. The score plot showed clear separation by packaging type, with vacuum packaging exhibiting the most stable clustering and PP the greatest variability. LDA achieved a classification accuracy of 94.12%, confirming packaging type as the main discriminating factor. The edible film group displayed the most consistent pattern within the discriminant space.

1. INTRODUCTION

Candied fruit is a form of fruit preservation intended to extend shelf life while enhancing the product's sensory quality [1]. Bilimbi (Averrhoa bilimbi L.) is a highly acidic fruit with strong potential to be processed into candied products. This processing can reduce the excessive sour taste of fresh bilimbi and produce a more balanced sweet–sour flavor profile, thereby improving its acceptability and added value.

In candied fruit production, packaging is an important factor that determines product stability during storage. Appropriate packaging can protect the product from moisture vapor, oxygen exposure, physical contamination, and microbial deterioration, all of which directly influence shelf life and physicochemical quality. For semi-moist products such as candied bilimbi, changes in moisture content, vitamin C, pH, and total soluble solids (TSS) may occur when the packaging material does not provide sufficient protection against environmental conditions.

However, in practice, candied bilimbi packaging is still predominantly made from synthetic plastics. The use of conventional plastic materials poses significant environmental challenges, particularly due to limited recyclability across various plastic packaging types and their persistent nature, which prevents them from being readily biodegraded by soil microorganisms [2]. The accumulation of plastic waste increases environmental pollution and may pose health risks [3]. Therefore, more sustainable packaging alternatives are required, such as natural biopolymer-based materials, including edible films, without compromising product quality.

One promising alternative is the use of biodegradable packaging materials such as edible films. Edible films made from natural biopolymers, including starch, cellulose derivatives, proteins, and polysaccharides, can serve as protective barriers against moisture migration, oxygen transfer, and microbial contamination [4]. Their effectiveness is generally evaluated through water vapor permeability, oxygen permeability, mechanical strength, and microbial resistance [5]. Although bilimbi is naturally acidic, candied bilimbi may still experience quality deterioration during storage, especially when moisture content increases. High-acid food products can suppress the growth of certain bacteria, but molds and yeasts may still develop under favorable moisture and oxygen conditions [6]. Therefore, the application of edible film in high-acid candied fruit systems remains an important research area.

In this study, vacuum packaging, polypropylene (PP) packaging, and edible film were selected to represent three different packaging approaches. PP packaging represents conventional low-cost packaging commonly used by small-scale food industries. Vacuum packaging represents a protective system that reduces oxygen exposure and delays quality deterioration. Meanwhile, edible film represents a biodegradable alternative that supports the development of environmentally friendly packaging. The comparison of these three packaging systems under different storage temperatures provides a specific research niche, particularly for high-acid candied bilimbi products.

The quality of candied products is influenced by both packaging type and storage conditions, such as temperature, as reflected in changes in physicochemical parameters, including moisture content, vitamin C, pH, and TSS. The complexity of these multivariable relationships requires an analytical approach that can summarize key information while objectively distinguishing between treatment groups. In this context, Principal Component Analysis (PCA) is employed to identify the principal components in the physicochemical dataset that explain variations in candied bilimbi quality across packaging treatments and storage temperatures. Furthermore, Linear Discriminant Analysis (LDA) is applied to classify and confirm the separation among treatment groups. LDA enables the determination of the most optimal conditions for maintaining product quality, thereby clarifying significant differences in candied bilimbi quality influenced by these factors [7, 8].

This study aimed to classify the quality characteristics of candied bilimbi based on packaging type (vacuum, PP), and edible film) and storage temperature (room temperature at 26 °C and cold storage at 10 °C) using PCA and LDA.

2. MATERIAL AND METHOD

2.1 Research tools and materials

This study employed a set of laboratory equipment for sample preparation, packaging, and physicochemical analyses. The instruments used included gloves, scissors, a spatula, a heat sealer, a vacuum packaging sealer, a pH meter, a refractometer, and an analytical balance. Laboratory glassware consisted of Erlenmeyer flasks, volumetric flasks, beakers, droppers, graduated cylinders, and burettes. In addition, a hot plate, porcelain crucibles, an oven, a desiccator, and forceps were utilized to support heating, drying, and sample handling processes.

The materials used in this study included candied bilimbi obtained from UMKM SIEERA ATJEH as the research sample, as well as three types of packaging materials: vacuum packaging, PP plastic packaging, and edible film. Chemical reagents used for analysis included ascorbic acid, distilled water, iodine solution, and starch indicator.

2.2 Research procedure

This study was conducted in two main stages: (1) preparation of edible film following the methsod described by Rusli et al. [9], and (2) packaging, storage, and monitoring of quality changes.

Edible film preparation was carried out by dissolving corn starch and carboxymethyl cellulose (CMC) in distilled water, followed by heating under continuous stirring until a homogeneous solution was obtained. After homogenization, the mixture was supplemented with glycerol as a plasticizer, then cast onto a mold surface using the casting method. The film was subsequently dried in an oven until a uniform sheet was formed. The dried edible film sheets were then used as one of the packaging materials.

Candied bilimbi was packaged using three types of packaging materials: vacuum packaging (P1), PP packaging (P2), and edible film (P3). The packaged samples were then stored at two temperatures: room temperature (26 °C; T1) and cold storage (10 °C; T2). Quality evaluation was conducted every three days by measuring physicochemical parameters, including moisture content, vitamin C, pH, and TSS.

The experiment was arranged in a two-factor Completely Randomized Design (CRD) with packaging type (P1–P3) and storage temperature (T1–T2) as factors. All treatment combinations (3 × 2) were replicated twice, resulting in experimental units as presented in Table 1.

Table 1. Design experiments

Experiments	Storage Temperature			
Packaging	Room Temperature (T1) 26 °C		Cold Temperature (T2) 10 °C	
Vacuum (P1)	P1T1U1	P1T1U2	P1T2U1	P1T2U2
PP (P2)	P2T1U1	P2T1U2	P2T2U1	P2T2U2
Edible Film (P3)	P3T1U1	P3T1U2	P3T2U1	P3T2U2

To maintain randomness, candied bilimbi samples from the same production batch were randomly assigned to each packaging treatment and storage temperature. Each treatment combination was coded before analysis to minimize handling bias. The position of samples in the storage chamber was randomized and periodically rotated to reduce the effect of temperature or humidity gradients. Potential confounding variables, including sample size, initial product condition, storage duration, analytical method, and measurement interval, were controlled across all treatments [10].

2.3 Data analysis

Data analysis was performed using PCA and LDA to evaluate quality changes and classify candied bilimbi samples based on packaging type and storage condition. PCA was first applied to map the interrelationships among physicochemical parameters during storage and to identify the main variables responsible for sample variation. PCA was selected because it is widely used in food analysis to reduce multivariable datasets into fewer principal components without losing the main information contained in the data [8]. In this study, PCA was conducted using Unscrambler X version 10.3 with moisture content, vitamin C, pH, and TSS as input variables. The results were interpreted using score plots and loading plots. Score plots were used to visualize the separation of samples or treatment groups, while loading plots were used to determine the contribution of each physicochemical variable to group differentiation [11].

If the PCA results showed unclear separation among treatment groups, the analysis was further extended using LDA. LDA was applied as a supervised classification method to improve discrimination among treatments and to evaluate whether candied bilimbi samples could be classified based on packaging type and storage condition. LDA is commonly used to reduce redundant information and maximize separation among predefined groups, making it suitable for classification analysis [12].

The combination of PCA and LDA was considered appropriate because the dataset consisted of a limited number of physicochemical variables and treatment groups. PCA was used to identify dominant quality patterns, whereas LDA was used to confirm group separation and classification performance. Compared with more complex machine learning methods such as Random Forest and Support Vector Machines, PCA and LDA are more interpretable and suitable for exploratory classification in relatively small experimental datasets. Although these machine learning methods have strong potential for food quality and authenticity analysis, they are generally more effective for larger and more complex datasets [13]. Therefore, future studies with larger sample sizes and broader quality parameters may apply these advanced machine learning methods to validate and improve classification robustness.

The physicochemical parameters analyzed included moisture content, vitamin C, pH, and TSS. Moisture content and vitamin C were determined using the oven-drying method in accordance with the AOAC [14]. The pH was measured using a calibrated pH meter, while TSS were determined using a digital refractometer and expressed as °Brix [15].

3. RESULT AND DISCUSSION

3.1 Moisture content

The results showed that the moisture content of candied bilimbi increased during storage across all treatments, with varying rates depending on packaging type and storage temperature (Figure 1). At the beginning of storage, the product's moisture content was approximately 25.00%. However, by day 48, a substantial increase was observed, particularly in PP packaging (P2) stored at room temperature (T1), reaching 42.15%. This value was higher than those recorded for vacuum packaging (P1T1) and edible film (P3T1), which reached 32.10% and 37.25%, respectively. Under cold storage conditions (T2), the increase in moisture content was generally slower for all packaging types, indicating that lower temperatures effectively reduced the rate of moisture changes in the product during storage.

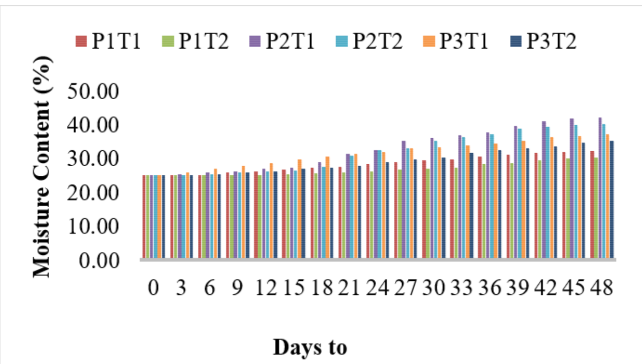


Figure 1. Changes in moisture content of candied bilimbi during 48 days of storage under different packaging types and storage temperatures

These findings indicate that packaging type and storage temperature play significant roles in the dynamics of moisture content during storage. The increase in moisture content at room temperature is likely attributed to differences in relative humidity between the surrounding environment and the product. When ambient humidity exceeds the product's equilibrium moisture level, moisture absorption occurs, increasing moisture content [16]. This condition has direct implications for product stability, as elevated moisture levels can accelerate the growth of molds and yeasts, potentially reducing product quality and compromising food safety [17].

From a packaging performance perspective, vacuum packaging demonstrated the greatest ability to suppress the increase in moisture content compared with the other treatments. The reduction of oxygen within the package headspace not only inhibits the activity of aerobic microorganisms but also minimizes oxidative reactions that may trigger structural changes in the product matrix [18]. In contrast, PP packaging, although widely used for its good mechanical performance, still allows gas and water-vapor transfer, and the barrier properties of polymeric films are known to strongly influence physicochemical stability during storage [19]. Consequently, moisture diffusion from the surrounding environment may still occur in PP-packed samples, particularly at room temperature, leading to a more pronounced increase in moisture content. Under cold storage conditions, permeation and diffusion processes through packaging materials generally proceed more slowly, thereby reducing the rate of moisture increase during storage [20].

Edible film packaging exhibited performance intermediate between vacuum and PP packaging. This finding indicates that the film's water vapor barrier properties play a significant role in maintaining moisture stability. Biopolymer-based edible films with adequate water resistance and stability against microbial degradation have strong potential as environmentally friendly packaging alternatives while still preserving product quality [21].

When compared with the Indonesian National Standard (SNI, 1996), which recommends that the moisture content of candied products should not exceed 25%, the results of this study indicate that most treatments exceeded this limit by the end of storage, with values ranging from 25.00% to 42.15% [22]. These findings suggest that controlling the combination of packaging type and storage temperature is a critical factor in maintaining candied bilimbi quality in accordance with established standards.

The higher variance observed in PP packaging can be attributed to its relatively lower barrier performance against water vapor and gas transfer compared with vacuum packaging. Barrier properties against oxygen and water vapor are critical factors in food packaging because they directly influence moisture migration, oxidation, microbial stability, and shelf-life extension [23]. Candied bilimbi contains soluble sugars that may exhibit hygroscopic behavior, allowing the product to absorb moisture from the surrounding environment when the external humidity is higher than the product equilibrium moisture content. This phenomenon is commonly observed in intermediate-moisture foods and osmotically dehydrated fruit products, in which sugar concentration, water activity, and environmental humidity strongly affect moisture transfer during storage [24].

This moisture uptake can dilute soluble solids, accelerate physicochemical changes, and create less uniform quality profiles during storage. In contrast, vacuum packaging reduces oxygen availability inside the package and may slow oxidative reactions as well as the growth of aerobic microorganisms [25]. Consequently, PP-packaged samples, especially under room temperature, showed wider dispersion in PCA and LDA plots, indicating greater quality instability.

3.2 Vitamin C

The results demonstrated that the vitamin C content of candied bilimbi decreased progressively during storage across all treatments, with degradation rates varying depending on packaging type and storage temperature. The most pronounced decline occurred in PP packaging stored at room temperature (P2T1), where vitamin C decreased from 7.92 mg on day 0 to 2.64 mg on day 48. In contrast, vacuum packaging at room temperature (P1T1) retained a higher vitamin C level of 3.52 mg over the same period. Edible film packaging exhibited better performance than PP, particularly under cold storage conditions (P3T2), where vitamin C remained at 3.52 mg on day 48. Overall, storage at 10 °C effectively slowed the rate of vitamin C degradation compared with storage at 26 °C, as illustrated in Figure 2.

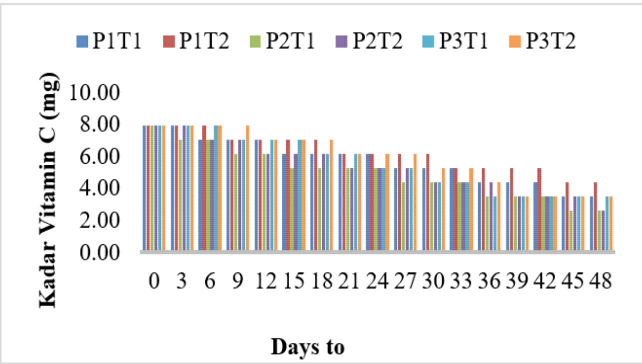


Figure 2. Changes in vitamin C of candied bilimbi during 48 days of storage under different packaging types and storage temperatures

These findings confirm that storage temperature and the barrier properties of packaging play critical roles in vitamin C stability. Vitamin C (ascorbic acid) is highly sensitive to oxygen, light, and elevated temperatures, making it susceptible to oxidation into dehydroascorbic acid and other biologically inactive derivatives. Storage at lower temperatures can effectively slow oxidative reactions and enzymatic activity that contribute to vitamin C degradation [26]. This explains why cold storage treatments showed higher vitamin C retention than room-temperature conditions.

Differences in performance among packaging types are associated with each material's ability to limit oxygen and water vapor transfer. Vacuum packaging proved more effective at preserving vitamin C because reduced oxygen within the package suppresses oxidative reactions, which are the primary mechanism of ascorbic acid degradation [27]. In contrast, PP packaging still allows oxygen diffusion from the surrounding environment, resulting in a greater decline in vitamin C, particularly at room temperature. Edible film packaging exhibited relatively good protective performance, likely due to its oxygen barrier properties and ability to maintain a stable micro-moisture environment around the product.

In addition to packaging type and storage temperature, vitamin C stability is also influenced by the product's internal conditions. Vitamin C tends to be more stable in acidic environments; therefore, candied bilimbi, which naturally possesses acidic characteristics, is more likely to retain its vitamin C content compared with systems having a higher pH [28, 29]. However, an increase in moisture content during storage may accelerate oxidation and hydrolysis reactions, particularly when the packaging is not completely airtight [30]. Therefore, the interactions among moisture content, pH, temperature, and packaging barrier properties simultaneously determine the degradation pattern of vitamin C.

Overall, the results of this study indicate that the combination of vacuum packaging and cold storage represents the most effective condition for maintaining the vitamin C content of candied bilimbi during storage. These findings highlight the importance of controlling the packaging atmosphere and storage temperature as key strategies for preserving the nutritional quality of fruit-based products.

3.3 pH

The pH of candied bilimbi showed a gradual decreasing trend during storage across all treatments, indicating an increase in product acidity. The most pronounced decline occurred in PP packaging stored at room temperature (P2T1), where the pH reached 2.75 on day 48. In contrast, vacuum packaging under cold storage (P1T2) maintained a relatively more stable pH of 2.65 at the end of storage. Edible film packaging exhibited a higher initial pH compared with the other treatments, and under cold storage (P3T2) it maintained a pH of 3.02 on day 48, whereas under room temperature (P3T1) it decreased to 2.69. Overall, the pH range observed during the study was between 2.4 and 4.8, which falls within the acidic category, as shown in Figure 3.

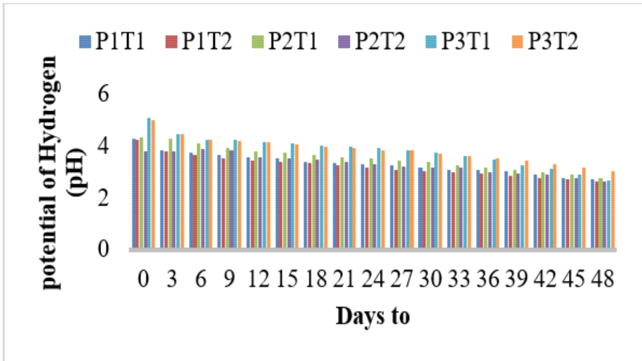


Figure 3. Changes in pH of candied bilimbi during 48 days of storage under different packaging types and storage temperatures

The decrease in pH during storage indicates the accumulation of organic acids, which may result from natural fermentation processes or the degradation of organic compounds within the product matrix [31]. Microbial activity that persists at certain moisture levels can contribute to the formation of additional organic acids, leading to a continuous decline in pH over time [32]. This phenomenon is more pronounced at room temperature, which provides more favorable conditions for microbial growth compared with cold storage.

Differences in pH stability among packaging types are associated with the ability of each material to limit the exchange of gases and water vapor with the surrounding environment. Vacuum packaging demonstrated better performance than PP in maintaining pH stability, particularly under cold storage conditions. The reduction of oxygen in the vacuum system creates an anaerobic environment with effective barrier properties against air and moisture [33] thereby suppressing the activity of aerobic microorganisms and slowing biochemical reactions that generate acidic compounds [34]. In contrast, PP packaging still allows gas diffusion, leading to faster chemical and microbiological changes, especially at room temperature.

Storage temperature significantly influences the dynamics of product acidity, where an increase in temperature generally accelerates the decline in pH [35]. Storage at 10 °C was found to be more effective in slowing the decrease in pH compared with storage at 26 °C [36], as lower temperatures can inhibit enzymatic activity and microbial metabolism. Although a decrease in pH occurred during storage, the pH range remained within the acidic category, which is consistent with the natural characteristics of bilimbi fruit that is rich in organic acids. These organic acids inherently contribute to the preservation and shelf-life stability of the product [37].

Overall, the results indicate that the combination of packaging type and storage temperature influences the pH stability of candied bilimbi. Among the treatments, vacuum packaging combined with cold storage provided the most stable condition for maintaining the acidity of the product throughout the storage period.

3.4 Total soluble solids

The TSS of candied bilimbi showed a decreasing trend during the 48 days of storage across all treatments, as illustrated in Figure 4. At the beginning of the observation period, TSS values ranged from 23.7 to 28.35 °Brix, with the highest value recorded in PP packaging under cold storage (P2T2) and the lowest in edible film packaging stored at room temperature (P3T1). Over time, all treatments exhibited a decline in TSS, with the lowest value observed in P3T1 (13.55 °Brix) and the highest in vacuum packaging under cold storage (P1T2), reaching 15.10 °Brix on day 48. This pattern indicates that the combination of vacuum packaging and low storage temperature was the most effective in maintaining the TSS content during storage.

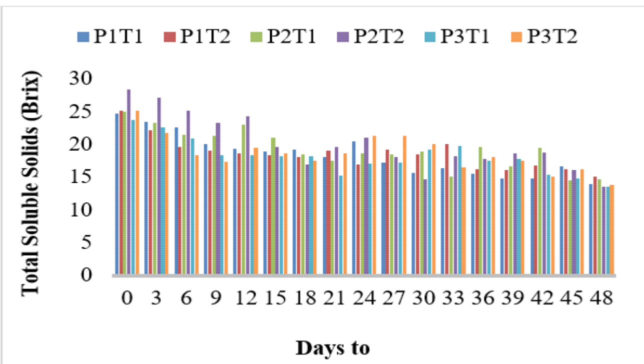


Figure 4. Changes in total soluble solids (TSS) of candied bilimbi during 48 days of storage under different packaging types and storage temperatures

The decline in TSS indicates changes in soluble components, particularly sugars, which may be attributed to respiration processes, microbial activity, and chemical reactions occurring during storage. At higher temperatures, the rate of respiration and sugar degradation reactions tends to increase, resulting in a faster reduction of soluble sugar content [38]. This explains why treatments stored at room temperature exhibited a more pronounced decrease in TSS compared with those stored under cold conditions. Storage at 10 °C can slow microbial metabolism and chemical reactions, thereby maintaining the stability of soluble solids for a longer period [31].

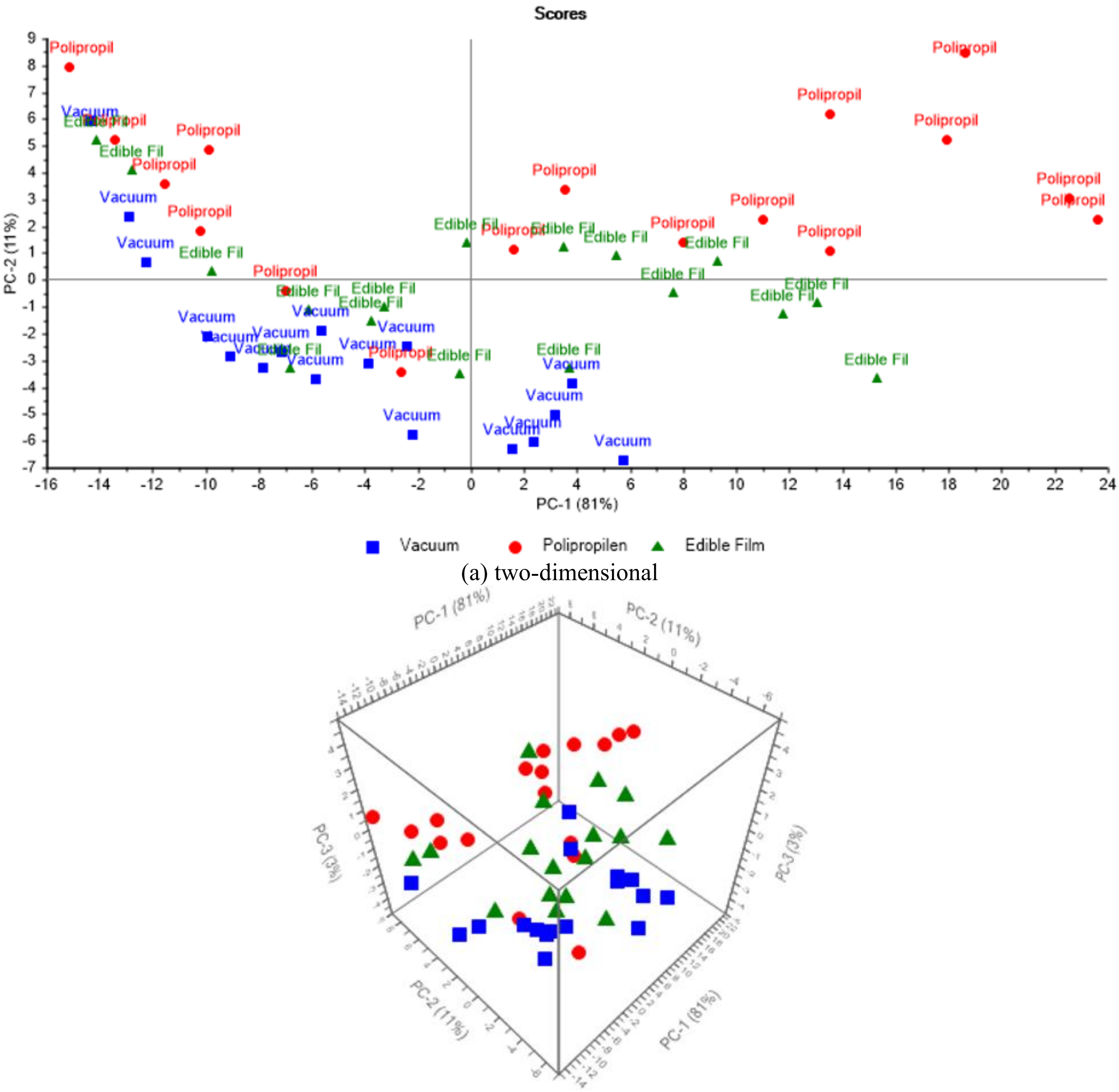
From a packaging perspective, the superior performance of vacuum packaging in maintaining TSS is likely associated with its ability to reduce oxygen within the package, thereby delaying oxidation processes and inhibiting the growth of oxygen-dependent microorganisms [39]. In addition, vacuum conditions help minimize water vapor migration that may influence the concentration of dissolved substances. In contrast, PP and edible film packaging still allow gas and moisture exchange with the surrounding environment, making them more susceptible to changes in sugar composition and soluble solids content, particularly under room temperature conditions [40].

Overall, the results indicate that TSS stability is influenced by the interaction between storage temperature and the barrier properties of packaging materials. The combination of vacuum packaging and cold storage provided the best TSS retention, which directly contributes to maintaining the sweetness stability and sensory quality of candied bilimbi. These findings emphasize that controlling storage conditions and selecting appropriate packaging materials are important strategies for preserving product quality during distribution and storage.

3.5 Effect of packaging and storage temperature on candied bilimbi analyzed using Principal Component Analysis

PCA is a dimensionality reduction technique used to simplify data while preserving important information (variance) within the dataset, commonly visualized through score plots and loading plots. The PCA score plot is a graphical representation used to display the position of data points (samples) in the space of the principal components calculated by PCA [41]. The PCA results indicated that the physicochemical characteristics of candied bilimbi varied depending on the type of packaging used. The two-dimensional score plot (Figure 5(a)) shows that PC-1 and PC-2 together explain 92% of the total data variability (PC-1: 81%, PC-2: 11%). Samples packaged in PP are more widely distributed on the right side of the plot, indicating greater variability in physicochemical characteristics compared with other packaging types. Edible film packaging is located near the central axis of PC-1, whereas vacuum-packaged samples are more concentrated on the left side of the plot, suggesting greater stability in their characteristics. The wider distribution observed for PP packaging indicates higher variability in the physicochemical properties of the candied bilimbi, while vacuum packaging is more effective in maintaining product stability [42].

The three-dimensional score plot analysis (Figure 5(b)) further shows that the first three principal components (PC-1, PC-2, and PC-3) explain 95% of the total variability in the dataset, with contributions of 81%, 11%, and 3%, respectively. Vacuum-packaged samples exhibit a more clustered data distribution, indicating stable physicochemical characteristics during storage. In contrast, samples packaged in PP display a broader distribution, suggesting greater differences among samples, with several points even detected as outliers. The main factor influencing this pattern is the agent factor, where edible film exhibits a positive factor, while vacuum and PP packaging fall into the negative factor category, indicating differences in their contributions to the principal components of the PCA [43].



(a) two-dimensional

(b) three-dimensional

Figure 5. Principal Component Analysis (PCA) score plot results of candied bilimbi based on physicochemical characteristics during storage

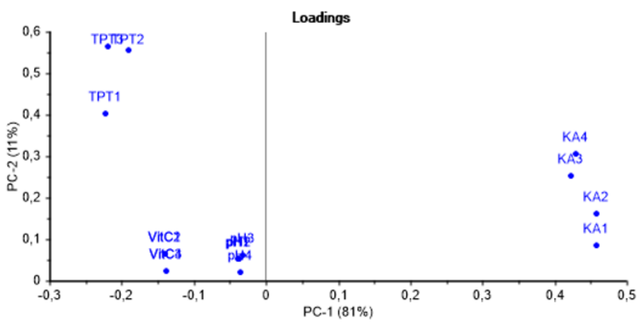


Figure 6. Principal Component Analysis (PCA) loading plot showing the contribution of moisture content, vitamin C, pH, and total soluble solids (TSS) to the principal components

The loading plot or biplot (Figure 6) in PCA is used to understand the relationship between the dimension-reduced data and the original variables [44]. In this study, the loading plot of candied bilimbi with three types of packaging illustrates the contribution of each variable to the principal components. PC-1 explains 81% of the total data variability, while PC-2 accounts for 11%. Moisture content shows a high positive loading on PC-1, indicating a significant contribution to the variation in the dataset. Meanwhile, TSS play a greater role in explaining variability along PC-2. Vitamin C and pH exhibit smaller loading values, suggesting that these parameters contribute less to distinguishing among samples. The points in the plot indicate that the farther a point is from the origin (0,0), the greater its contribution to the principal components. Based on this analysis, moisture content and TSS are identified as the dominant factors influencing the physicochemical characteristics of candied bilimbi during storage [45].

The loading plot illustrates the correlation between the measured parameters and the principal components. Moisture content is located in the first quadrant (PC-1 positive, PC-2 positive), indicating a strong influence on PC-1. TSS are positioned in the second quadrant (PC-1 negative, PC-2 positive), suggesting a greater contribution to PC-2. Meanwhile, vitamin C and pH are located in the third and fourth quadrants with relatively low loading values, indicating that these parameters do not play a dominant role in distinguishing the characteristics of the candied samples [46].

It also revealed distinct grouping patterns among the four physicochemical parameters, allowing for a mechanistic interpretation of their roles in quality deterioration. Moisture content exhibited the highest positive loading on PC-1 loading coefficient > 0.85, positioning it as the dominant variable driving sample separation along the first principal component. This strong contribution aligns with the experimental observations that moisture absorption was the most pronounced quality change over the 48-day storage period, particularly under suboptimal packaging conditions. The magnitude of the moisture loading suggests that water migration and vapor transmission through packaging materials were the primary degradation pathways influencing product stability.

TSS demonstrated the highest loading on PC-2 loading coefficient > 0.70, indicating that changes in soluble sugar composition contributed most significantly to the secondary axis of variation. The orthogonal relationship between moisture content and TSS in the loading space moisture positioned in the first quadrant, TSS in the second quadrant reflects the inverse correlation often observed in dried and semi-moist food products: as moisture increases due to hygroscopic absorption, the concentration of soluble solids decreases through dilution and metabolic consumption. This inverse relationship was corroborated by the temporal trends shown in Figures 1 and 4, where treatments with the highest moisture gain (PP at room temperature) also exhibited the steepest decline in TSS.

Vitamin C and pH, in contrast, displayed loading coefficients of relatively lower magnitude, approximately 0.3 and 0.4, and were positioned closer to the origin of the loading plot. This placement indicates that while these parameters contributed to the overall dataset variance, they were less influential than moisture and TSS in discriminating among packaging treatments. Notably, both variables were oriented in the negative quadrants of PC-1 and PC-2, suggesting that their degradation patterns were inversely associated with the positive direction of the principal components. This inverse relationship is consistent with the observed decline in vitamin C and pH over storage time, whereas moisture content increased.

The PCA model extracted three principal components (PCs) with eigenvalues exceeding 1, cumulatively accounting for 95% of the total variance in the candied bilimbi dataset. PC-1 dominated the variance structure, explaining 81% of the total variability, which strongly indicates that the primary source of differentiation among samples is associated with the most dynamic physicochemical changes occurring during storage. PC-2 contributed an additional 11%, while PC-3 added a further 3%, collectively capturing nearly all systematic variation within the experimental data. The high cumulative variance explained by the first two PCs (92%) confirms that the dimensionality reduction was effective, preserving the essential information needed to discriminate among treatments without significant loss of data integrity.

3.6 Linear Discriminant Analysis results of candied bilimbi

LDA and PCA are two multivariate analysis methods that are commonly used for dimensionality reduction and pattern recognition, but they have different analytical objectives. PCA is an unsupervised method that focuses on maximizing total data variance and identifying the main variables contributing to quality variation [47]. In contrast, LDA is a supervised method that aims to maximize separation among predefined groups using class information [48]. In this study, PCA was first applied to explore the general distribution pattern of candied bilimbi samples based on physicochemical variables, while LDA was subsequently used to improve group discrimination and confirm whether the samples could be classified according to packaging type. The LDA results, presented in Figure 7, showed that the model achieved an overall classification performance of 94.12%, indicating that packaging type had a strong discriminating effect on the physicochemical characteristics of candied bilimbi [49].

Although the LDA model showed high classification performance, this result should be interpreted carefully. Possible classification bias may arise from the limited number of samples, repeated observations during storage, and overlapping physicochemical characteristics among treatments. Classical LDA is known to be sensitive to small sample size, noise, outliers, and overlapping class structures, which may reduce classification reliability [50]. In addition, repeated observations during storage may produce correlated data, and ignoring this dependency can lead to biased interpretation of model performance [51]. Therefore, the classification accuracy obtained in this study should be considered an initial indication of model performance rather than a final predictive model. Further validation using larger datasets, independent samples, or cross-validation is recommended to reduce the risk of overfitting and improve model generalizability.

This limitation was also reflected in the confusion matrix. Although the model showed an overall classification performance of 94.12%, the confusion matrix indicated an actual classification accuracy of 82.35%, suggesting that several samples were misclassified due to overlapping physicochemical characteristics among packaging treatments. Among the three packaging types, edible film was the only group that was classified perfectly. This result indicates that edible film produced a more consistent physicochemical profile than vacuum and PP packaging. Edible films can function as barriers against moisture transfer, oxygen diffusion, and dissolved substances, thereby helping to maintain product quality and extend shelf life [52]. The more homogeneous quality profile of edible film-packaged samples contributed to clearer group separation in the LDA discriminant space.

In contrast, PP packaging exhibited wider data dispersion within the discriminant space, indicating greater variability in physicochemical characteristics among samples compared with the edible film group. This wider dispersion explains the occurrence of misclassification in the confusion matrix, as some PP-packaged samples showed overlapping quality characteristics with other treatments. This condition can be attributed to the properties of PP, which has relatively higher permeability to water vapor and gases, allowing greater moisture transfer between the product and the surrounding environment. As a result, changes in moisture content and TSS tended to occur more rapidly and less uniformly during storage. In line with this, Lee and Robertson [53] reported that packaging materials such as PP exhibit varying levels of water vapor permeability that can influence the stability of moisture-sensitive products.

Meanwhile, vacuum packaging showed a more clustered distribution pattern compared with PP, although some overlap with other groups was still observed, particularly under certain storage conditions. This suggests that vacuum packaging was more effective than PP in maintaining physicochemical stability, likely due to reduced oxygen availability within the package. However, the overlap observed in the LDA space indicates that vacuum packaging did not completely prevent quality changes during storage, especially when storage temperature and moisture-related changes influenced the physicochemical profile of the product. Therefore, the LDA results confirm that packaging type plays an important role in differentiating candied bilimbi quality, with edible film showing the most homogeneous classification pattern, PP showing the highest variability, and vacuum packaging demonstrating intermediate to high stability.

Confusion m	Actual	Vacum	Polipropilen	Edible Film
Predicted		1	2	3
Vacum	1	16	2	0
Polipropilen	2	1	15	0
Edible Film	3	0	0	17

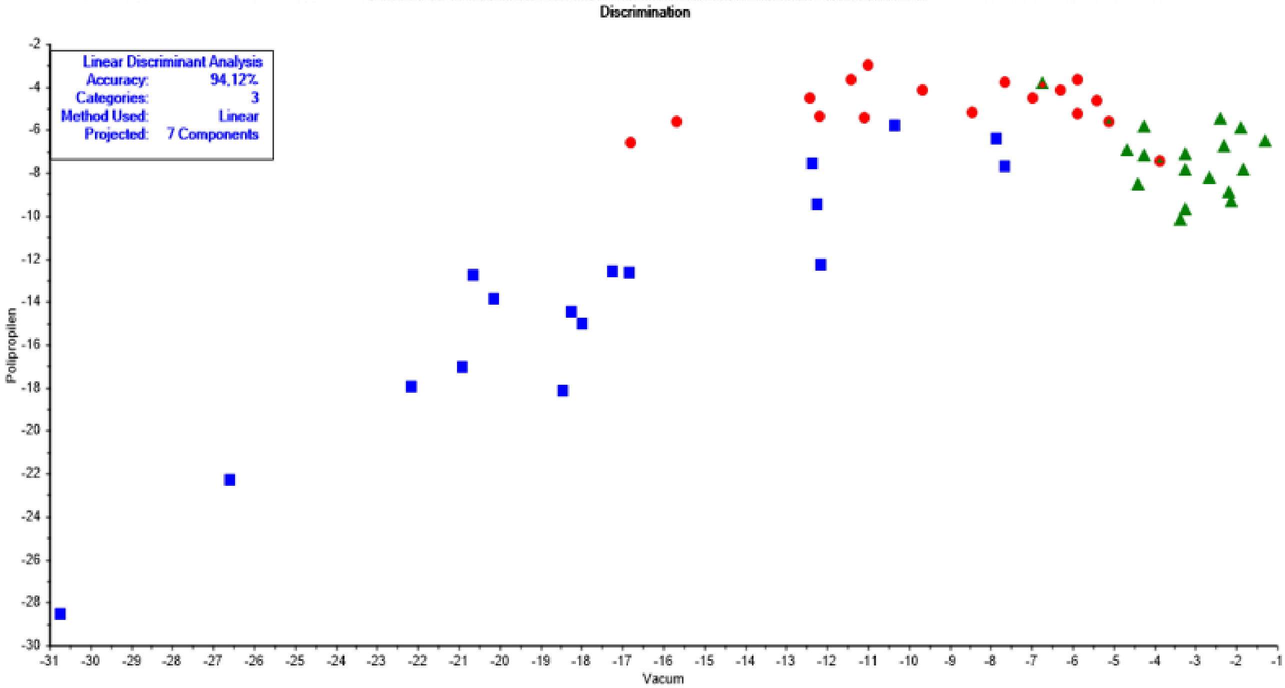


Figure 7. Linear Discriminant Analysis (LDA) classification plot of candied bilimbi samples under different packaging treatments

The PCA results provide the foundation for the subsequent LDA classification, as the principal components derived from PCA served as input variables for the discriminant analysis. The high classification accuracy achieved by LDA (94.12%) validates that the variance structure captured by PCA effectively preserves the discriminative information necessary to distinguish among packaging treatments. Notably, the edible film group, which exhibited moderate dispersion in the PCA score plot, was perfectly classified in the LDA model, suggesting that while this group showed some internal variability, its overall multivariate profile was sufficiently distinct from both vacuum and PP groups. The misclassifications observed in the PP group, where some samples were incorrectly assigned to the edible film or vacuum categories, correspond to the greater overlap observed in the PCA score plot between PP samples and other treatment groups, particularly under cold storage conditions where the quality differences between packaging types were less pronounced.

This integrated PCA-LDA approach demonstrates the complementary roles of these multivariate methods: PCA provides an unsupervised exploration of data structure and identification of variance-contributing variables, while LDA offers a supervised classification framework that quantifies the ability of the measured parameters to discriminate among predefined treatment groups. Together, these methods provide a comprehensive analytical strategy for evaluating and optimizing food packaging systems, as demonstrated in the current study of candied bilimbi quality under varying storage and packaging conditions.

Overall, the LDA results confirm that packaging type is the dominant factor influencing the physicochemical characteristics of candied bilimbi during storage, as reflected by the model's ability to accurately classify the samples. The combined application of PCA and LDA in this study proved to be an effective chemometric approach for evaluating the effects of packaging treatments and storage conditions on food product quality. This approach is consistent with current trends in food engineering that utilize multivariate analysis as a decision-support tool for selecting optimal packaging systems.

4. CONCLUSIONS

This study demonstrated that packaging type and storage temperature significantly influenced the physicochemical stability of candied bilimbi during storage. Changes in moisture content, vitamin C, pH, and TSS indicated that product quality gradually deteriorated over time, particularly under less protective packaging conditions. PCA results showed that PC-1 and PC-2 explained 92% of the total variability, with moisture content and TSS as the dominant variables contributing to sample differentiation. The PCA score plot clearly separated samples based on packaging type, where vacuum packaging showed the most stable clustering pattern, while PP packaging exhibited the widest dispersion, indicating higher variability and lower stability.

LDA further confirmed that packaging type was the main discriminating factor in the quality classification of candied bilimbi, with high overall classification performance. Although some misclassification occurred due to overlapping physicochemical characteristics among treatments, edible film showed relatively homogeneous characteristics in the discriminant space. Overall, vacuum packaging combined with cold storage at 10 °C was the most effective strategy for maintaining product quality, while PP packaging may be more suitable for short-term distribution due to its low cost and availability. Edible film offers potential as an environmentally friendly packaging alternative, but further improvement in barrier properties, mechanical strength, microbial safety, and production consistency is required. Future studies should include longer storage durations, sensory and microbiological evaluations, shelf-life modeling, and economic feasibility analysis to support commercial application, particularly for small- and medium-scale food industries.

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