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Evaluating fruit morphological and physicochemical characteristics in different banana (*Musa* spp.) cultivars using multivariate analysis

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Abstract. *Sa'diyah H, Waluyo B, Rusdiana RY, Sari VK, Hadi AF. 2026. Evaluating fruit morphological and physicochemical characteristics in different banana* (Musa *spp.*) *cultivars using multivariate analysis. Biodiversitas 27 (4): d270435. https://doi.org/10.13057/biodiv/d270435*. Banana (*Musa* spp.) are an important tropical fruit in Indonesia, widely cultivated and contributing significantly to local food production. Indonesia hosts numerous banana cultivars with diverse morphological and physicochemical characteristics; however, comprehensive trait-based evaluations of local cultivars, particularly those integrating multiple traits within a single analytical framework, remain limited. This study aimed to assess the morphological and physicochemical characteristics of 20 banana cultivars collected from traditional markets in East Java and to explore their variability using a multivariate statistical approach. Sixteen quantitative traits, including fruit biometric attributes and nutrient composition, were measured at a standardized ripening stage to enable meaningful cultivar comparisons at market-ready maturity. Cluster analysis using Euclidean distance with complete linkage and Principal Component Analysis (PCA) was applied to examine trait distributions and similarities among cultivars. The results showed clear phenotypic and nutritional variation among cultivars. Several cultivars were separated from others, each exhibiting a distinct profile. These cultivars had high levels of several quality-related traits, including high Fruit Firmness (FF), Total Soluble Solids (TSS), and nutrient content, indicating potential value for improving fruit quality. Meanwhile, several cultivars formed clusters characterized by more moderate trait values. *Berlin* was identified as an outlier with a distinctive profile, specifically in its moisture, ash, and carbohydrate content. The clustering patterns observed in the PCA biplot were consistent with the cluster heatmap, supporting the use of the methods for integrated characterization. Overall, this study demonstrates that combining morphological and physicochemical traits can uncover complex patterns of variability that may not be apparent through univariate assessment. These findings provide useful information for cultivar differentiation, utilization, and the conservation of local banana germplasm, while also highlighting the need for future studies integrating molecular approaches to better disentangle genetic and environmental influences on key quality traits and to support precision breeding for improved nutrition and stress adaptation.

Keywords: Banana cultivars, East Java, fruit quality, multivariate analysis, physicochemical traits

INTRODUCTION

Banana (*Musa* spp.) is one of the most important tropical fruits worldwide, serving not only as a staple food but also as a vital source of income and nutrition in tropical and subtropical regions. This fruit is culturally important and nutritionally valuable, providing carbohydrates, vitamins, minerals, and bioactive compounds essential for human health. Indonesia is recognized as one of the major centers of banana diversity and ranks among the world's leading producers, with the rich agroecological diversity (Hastuti et al. 2019; Acevedo et al. 2021). The favorable climatic and edaphic conditions, such as high rainfall, abundant sunshine, and fertile soil, support the long-term cultivation of diverse banana cultivars across the archipelago (Wahyudi et al. 2020; Rozaki et al. 2025). The long process of domestication and farmer selection has led to a wide range of landraces, with unique fruit qualities and characters that contribute to their ecological resilience and local preferences (Joshi et al. 2023).

Banana cultivars in Indonesia are unique due to their high diversity, partly the result of long-term hybridization between *Musa acuminata* Colla and *Musa balbisiana* Colla across various agroecological zones (Hastuti et al. 2019; Joshi et al. 2023). These bananas have adapted, resulting in numerous local cultivars with diverse morphologies, textures, and physicochemical properties. Some local cultivars, such as *Kepok*, *Raja*, and *Mas*, are valued for their distinctive taste, texture, and superior micronutrient content (Hapsari and Lestari 2016; Borges et al. 2019). These attributes underscore Indonesian germplasm as an important genetic resource for developing superior and climate-resistant banana varieties.

Despite this diversity, a comprehensive characterization of banana germplasm remains limited, particularly for local cultivars. Most existing studies focus on the general nutritional content or agronomic performance of commercial cultivars, such as *Cavendish* and *Kepok*. Meanwhile, morphological and physicochemical variations among local cultivars are still scarce. This limitation affects the use of local germplasm in breeding programs, conservation planning, and the development of banana-based functional food products. Banana cultivars exhibit considerable variation in morphology and physicochemical attributes. Traits such as fruit length, shape, peel color, pulp texture, moisture content, pH, and sugar content can vary significantly among genotypes (Maseko et al. 2024; Kurnianingsih et al. 2025). These differences influence consumer preferences, shelf life, and processing suitability. However, previous studies often focus on a narrow set of traits, such as the nutritional profiles of *Cavendish* and *Kepok* varieties (Sapei 2023; Cheng et al. 2024) or selected morphological traits in local varieties (Trimanto et al. 2022; Sa'diyah et al. 2025). These investigations often concentrate on restricted variables, such as physical or nutritional characteristics, limiting a broader understanding of trait interrelationships and the implications to breeding, agronomy, and conservation programs. Therefore, the analysis must consider morphological and physicochemical characters to better capture the complexity of banana diversity.

Research integrating morphological and physicochemical traits through multivariate analysis is still rare in Indonesia, specifically in regions such as East Java, which harbor substantial local banana diversity. Previous studies have highlighted variation in mineral and nutrient contents. For example, Christelová et al. (2017) reported variation in Magnesium (Mg) content in Indonesian banana, suggesting potential for nutritional improvement through breeding. However, these analyses are rarely extended to a broader multivariate framework.

Multivariate statistical approaches such as Principal Component Analysis (PCA) and cluster analysis provide a useful means for simultaneously evaluating multiple traits and capturing complex relationships within trait datasets. The use of biplots further enhances interpretation by providing additional information on variables, facilitating the identification of key attributes and cultivar relationships (Jellife et al. 2015; Saranya and Poonguzhali 2024). While these methods are often used to evaluate genetic diversity and agronomic traits in bananas, aiding the identification of superior cultivars for breeding and conservation (Nyine et al. 2017; Selvaraj et al. 2020; Wei et al. 2025), their application to combined fruit morphology and physicochemical traits of local East Javanese cultivars remains scarce.

Therefore, this research aims to evaluate 20 banana cultivars from East Java, Indonesia using an integrated multivariate approach, by combining fruit morphology and nutritional traits within a single analytical framework. This research provides an integrated phenotypic assessment that can inform cultivar selection, support breeding programs, germplasm conservation, and the development of high-quality functional banana products.

MATERIALS AND METHODS

Plant material

A total of 20 banana (*Musa* spp.) cultivars were evaluated, including *Raja*, *Susu*, *Candi*, *Ambon*, *Berlin*, *Kepok*, *Kepok Makassar*, *Kayu*, *Nangka*, *Kepok Banyuwangi*, *Mas*, *Mas Kirana*, *Ijo*, *Musang*, *Janten*, *Agung*, *Sri Ayu*, *Goroito*, *Kepok Australia*, and *Talun*. Most of these cultivars are hybrids of *M. acuminata* and *M. balbisiana*, the primary wild progenitors of edible bananas.

The banana cultivars were collected from three traditional markets in Jember and Lumajang Regencies, East Java. For morphological and physicochemical analysis, a total of three separate biological replicates per cultivar were gathered from different bunches, purchased either from the same or different vendors. Each replicate consisted of three fruit fingers taken from the right, center, and left positions of the middle comb of the bunch to reduce positional variation among fruits. Sampling from the middle portion of the bunch follows the principles of the IPGRI/INIBAP technical guidelines and is commonly applied in banana postharvest studies to obtain representative samples (Dadzie and Orchard 1997). Nearly all cultivars were purchased from separate vendors, with each vendor supplying bananas originating from different cultivation sites. Consequently, the observed variation may reflect phenotypic differences influenced by both genetic background and environmental or pre-harvest factors rather than controlled growing conditions.

All fruit samples were selected to be free of ethrel and other artificial ripening agents, based on information provided by the seller and supported by visual inspection of the absence of typical signs of artificial ripening agent application. Visual inspection was based on the absence of uneven peel coloration, excessively uniform bright yellow color without natural brown speckling, and inconsistency between peel color and fruit firmness, which are commonly associated with artificial ripening.

Although the cultivars were obtained from traditional markets, their identity and genetic background have been well documented in previous taxonomic and genetic studies of Indonesian bananas. The cultivars examined in this study represent established genome groups commonly found in Indonesia, including AA, AAB, and ABB types, which are associated with both dessert and cooking bananas (Hapsari and Lestari 2016; Christelová et al. 2017). These cultivar names are locally standardized and widely recognized across regions, reflecting long-term farmer selection, historical cultivation practices, and relatively stable phenotypic expression.

Physicochemical nutrient analytical testing

Physicochemical analysis was performed on ripe banana pulp with ripeness level of 6 (scale 1-7) following Bantayehu and Alemayehu (2024). The analyzed variables included protein, carbohydrate, fat, fiber, Mg, K, vitamin C, pH, Total Soluble Solids (TSS), Fruit Firmness (FF), water content, and ash content.

Morphological characteristics included Fruit Length (FL), Fruit Diameter (FD), Fruit Peel Thickness (FPT), and Fruit Flesh Thickness (FFT). The Fruit Length (FL) and Fruit Diameter (FD) were measured on fully ripe fruits using a digital caliper. Fruit length was recorded from the base to the tip of the fruit, while diameter was measured at the mid-section. Fruit Flesh Thickness (FFT) was assessed at the same mid-section after the peel had been removed.

Fruit Peel Thickness (FPT) was then estimated indirectly by measuring the fruit diameter at the mid-section with the peel intact and subtracting the corresponding flesh thickness value, using the same instrument. Physicochemical measurements were performed in duplicate as technical replicates from the same homogenized pulp sample to ensure reproducibility and improve measurement accuracy.

Protein and fat contents were determined using the Kjeldahl digestion and Soxhlet extraction methods, respectively, following AOAC (2005) and SNI 01-2891-1992 procedures (BSN 1992). Carbohydrate content was estimated using the AOAC carbohydrate-by-difference method, calculated as 100 minus the sum of protein, fat, moisture, and ash contents. Vitamin C (ascorbic acid) content was measured quantitatively using UV-VIS spectrophotometry. Mineral contents (Mg and K) levels were determined using Atomic Absorption Spectrophotometry (AAS). Moisture and ash contents were analyzed according to AOAC (2005) and SNI 01-2891-1992 standards (BSN 1992).

The firmness was assessed using a penetrometer through a puncture test. Measurements were taken at three points along the tip, middle, and base of the fruit. Crude fiber content was analyzed using the standard acid-alkali digestion method after defatting banana pulp with n-hexane (AOAC 2005). The samples were sequentially treated with dilute acid and alkali, filtered, dried at 105°C, and weighed to determine the fiber content. The pH and Total Soluble Solids (TSS) were measured by a pH meter and refractometer, respectively.

Data analysis

A total of 16 variables, including four morphological traits (FL, FD, FPT, FFT) and 12 physicochemical traits (protein, carbohydrate, fat, fiber, Mg, K, vitamin C, pH, TSS, fruit firmness, moisture, and ash), were included in the analysis. Descriptive statistics were used to summarize each variable. Cluster analysis was performed using the complete linkage method and Euclidean distance as a measure of dissimilarity, which was visualized through a clustered heatmap. Prior to clustering, all variables were standardized (mean = 0, standard deviation = 1) to eliminate scale effects, as shown in Equation 1. The Euclidean distance between two observations x and y in an n-dimensional space is defined as shown in Equation 1. Data standardization was performed as shown in Equation 2.

$$d(x,y) = \sqrt{\sum_{j=1}^{p} (x_j - y_j)^2} \qquad [1]$$

Where:

x_j, y_j : The values of the attribute j of *x* and *y*

To avoid scale-related bias and ensure that all traits contributed equally, the data were standardized prior to clustering. Each observation was transformed by subtracting the mean and dividing by the standard deviation of the respective variable, as shown in Equation 2.

$$z_{ij} = \frac{x_{ij} - \mu_j}{\sigma_j} \qquad [2]$$

Where:

z_{ij} : The standardized value of the variable j for the observation i

μ_j, σ_j : The mean and standard deviation of the variable j

Principal Component Analysis (PCA), based on correlation matrix, was applied, which was visualized by PCA biplots. Multivariate analyses (cluster analysis and PCA) were conducted using cultivar-level mean values averages across biological replicates.

All analyses were performed using R software version 4.4.1 within the Rstudio integrated development environment (version 2025.05). The pheatmap package (Kolde 2025) was used to generate hierarchical clustering heatmaps to visualize the results of the cluster analysis and the relationships between variables. The factoextra package (Kassambara and Mundt 2020) was used to create PCA biplots as a visualization of the PCA.

RESULTS AND DISCUSSION

Descriptive analysis of fruit morphological characters

Figure 1 shows the banana cultivar analyzed in this research. Table 1 presents the descriptive statistics for morphological characteristics of 20 banana cultivars. Considerable variation was observed among cultivars in terms of fruit size and structure, i.e. fruit length, fruit diameter, fruit peel thickness, and fruit flesh thickness. *Kepok Australia* possesses generally thicker peels and flesh, while *Agung* and *Talun* have the longest fruit. When compared to other bananas, the *Goroito* has the thinnest flesh and the smallest fruit diameter. The coefficients of variation indicated moderate to high variability in morphological traits across cultivars, particularly in peel thickness.

Descriptive analysis of physicochemical characteristics

Table 2 shows the variation in physicochemical properties among cultivars. There is considerable diversity in nutrient composition and postharvest quality indicators. This indicates that *Musang* banana has the highest protein content and the lowest fat content, and is distinguished by its reddish skin. *Ambon* banana, commonly consumed as a dessert banana, exhibits relatively low protein and K levels. *Agung* banana has the highest Mg and TSS content. *Kayu* banana records the lowest pH and vitamin C levels, while *Kepok* banana possesses the highest fat content, supporting the traditional use in infant nutrition. The coefficient of variation was particularly high in fat (111.34%) and Mg (127.90%), indicating substantial variability across cultivars for these traits, based on mean values calculated for each cultivar, which can be explored for breeding and nutritional improvement.

Table 1. The summary statistics of banana fruit morphological characters

Variable	Minimum	Cultivar	Maximum	Cultivar	Mean	Coefficient of variation (%)
Fruit Length (FL, cm)	9.00	*Mas*	31.70	*Talun*, *Agung*	17.25	33.14
Fruit Diameter (FD, cm)	2.96	*Goroito*	5.64	*Kepok Australia*, *Agung*	3.935	15.84
Fruit Peel Thickness (FPT, mm)	1.17	*Berlin*	4.60	*Kepok Australia*	2.620	35.66
Fruit Flesh Thickness (FFT, mm)	18.90	*Goroito*	34.70	*Kepok Australia*	24.975	13.75

Table 2. The summary statistics of banana fruit physicochemical characters

Variable	Minimum value	Cultivar (min)	Maximum value	Cultivar (max)	Mean	CV (%)
Protein (%)	0.82	*Ambon*	1.92	*Musang*	1.36	21.62
Carbohydrate (%)	21.80	*Berlin*	34.06	*Susu*	28.25	14.44
Fat (%)	0.07	*Musang*	1.81	*Kepok*	0.34	111.34
Fiber (%)	0.19	*Candi*	1.66	*Ijo*	0.72	54.01
Magnesium (Mg, mg/100 g)	0.07	*Talun*	39.00	*Agung*	8.93	127.90
Potassium (K, mg/100 g)	Not detected	*Mas*, *Ambon*	765.80	*Ijo*	392.10	64.01
Vit C (mg/100 g)	10.55	*Kayu*	39.36	*Kepok Australia*	24.82	37.14
pH	3.50	*Kayu*	6.40	*Sri Ayu*	5.33	15.79
Total Soluble Solids (TSS, Brix)	22.00	*Janten*	30.40	*Agung*	26.23	8.70
Fruit Firmness (FF, kg cm^{-2})	1.20	*Ijo*	6.00	*Talun*	3.24	45.98
Moisture (%)	62.74	*Kepok Banyuwangi*	74.54	*Berlin*	68.43	6.14
Ash (%)	0.72	*Susu*	1.22	*Berlin*	0.90	13.10

Note: Values represent the range (minimum and maximum) observed across 20 banana cultivars. Mean and Coefficient of Variation (CV) were calculated based on cultivar means (n = 20)

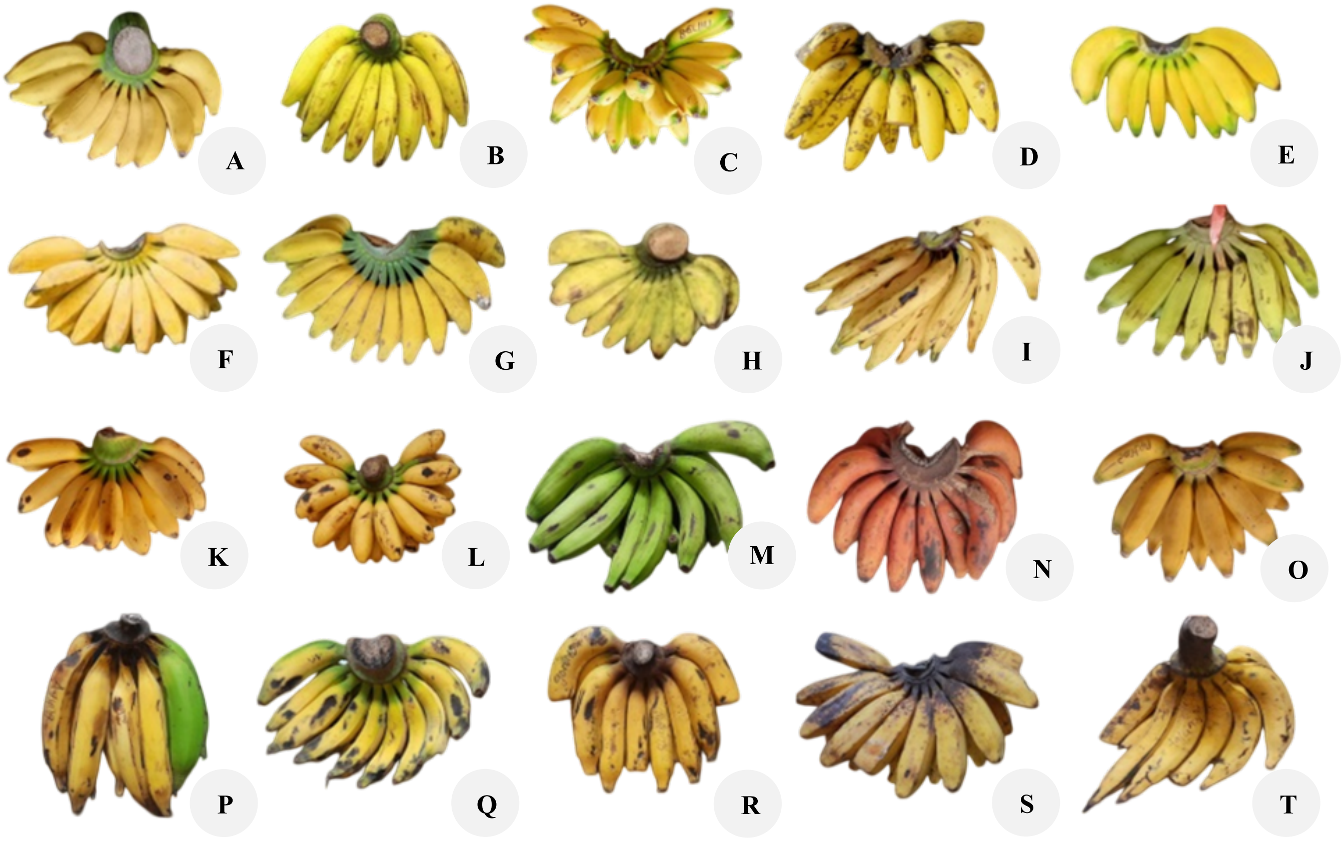

Figure 1. Banana cultivars. A. *Susu*, B. *Ambon*, C. *Berlin*, D. *Kayu*, E. *Raja*, F. *Kepok*, G. *Kepok Banyuwangi*, H. *Kepok Makassar*, I. *Candi*, J. *Nangka*, K. *Mas*, L. *Mas Kirana*, M. *Ijo*, N. *Musang*, O. *Janten*, P. *Agung*, Q. *Sri Ayu*, R. *Goroito*, S. *Kepok Australia*, T. *Talun*

The protein content of banana cultivars showed low variability among the tested varieties. This is in line with the general range reported from studies on edible bananas. Previous research by Laksemi et al. (2023) reported protein levels in local Balinese cultivars ranging from 1.57% to 1.91%, with *Bali Mas* having the highest value and *Buluh* the lowest. Compared with findings from the Balinese cultivar, the results of this study showed similar or slightly lower protein levels, with *Mas* having values below the overall average. This variation may be related to genotype and ripeness, as protein accumulation in banana flesh tends to decrease during ripening (Li et al. 2019).

Cultivars differ greatly in their carbohydrate content, with *Susu* having the highest content and *Berlin* having the lowest. Compared with cultivars from Sri Lanka (Nadeeshani et al. 2021), Indonesian banana exhibit greater variability in carbohydrate metabolism. This variability may be due to differences in starch accumulation and conversion during ripening. Cooking bananas are characterized by a higher proportion of starch, whereas dessert bananas contain carbohydrates predominantly in the form of sugars, explaining differences in processing requirements and consumption patterns (Hapsari and Lestari 2016). Banana flesh contains carbohydrates mainly in the form of starch and sugars, along with fiber and cellulose. During fruit development, starch accumulates and is subsequently converted into glucose, sucrose, and fructose during ripening. Starch content decreases from 15-25% to below 5% in ripe banana, but sugar content increases significantly (Netshiheni et al. 2019).

Fat content exhibited substantial variability (Coefficient of variation exceeding 100%), with values ranging from negligible amounts to nearly 2%. This is relatively high compared to other physicochemical characteristics, except for magnesium. The value is higher than the reported fat content range for Northern Tanzanian cultivars (Dotto et al. 2019), but the value is lower than previous results by Pragati et al. (2014) in Indian banana, and Ohizua et al. (2017) in Nigerian banana, where reported fat content ranges from 0.5% to 2.34%. Variation in fat content is likely influenced by genetic differences among cultivars and environmental factors (Annor et al. 2016). Despite the variations, fat remained a minor component, reinforcing the banana's status as a low-fat fruit. However, fat plays a vital role in energy storage and the absorption of fat-soluble vitamins (Borges et al. 2019).

Fiber content varied notably among cultivars, ranging from approximately 0.2% to 1.7%, with *Ijo* showing the highest level. The broad range aligns with reports that fiber levels depend on cultivar and ripening stage. Phillips et al. (2021) reported a fiber content of approximately 2% using the Enzymatic-Gravimetric (EG) method, which remained stable in ripening stages. The modified EG (mEG) method indicated a fiber content of approximately 18 g/100 g in unripe fruit, decreasing to approximately 2 g/100 g at mature fruit. Dietary fiber supports gastrointestinal health, blood sugar regulation, and cholesterol reduction (Dotto et al. 2019). Current nutrition trends emphasize the consumption of low-fat, high-fiber foods due to dual benefits for nutrition and health (Tapsell et al. 2016). The relatively high variability observed here suggests that certain cultivars may provide greater nutritional value in terms of dietary fiber.

Mineral content, particularly Magnesium (Mg) and Potassium (K), also varied among the banana cultivars analyzed. Mg levels showed the highest variability, ranging from approximately 0.07 to 39.00 mg/100 g (Table 2). The Coefficient of Variation above 100% indicates a standard deviation greater than the mean (Jellife et al. 2015). Meanwhile, K was abundant in all cultivars, reaching up to approximately 765.8 mg/100 g in *Ijo*, indicating a strong mineral accumulation potential. Wulandari et al. (2023) found that ripe *Ambon Kuning* and unripe *Kepok* varieties had the highest and lowest K contents, respectively. Suchitra and Parthasarathy (2021) found that some cultivars had nearly double the K value of other cultivars. This mineral content variability may be influenced by soil nutrition and plant genotype. In all samples, K content exceeded Mg, indicating that bananas are a potential source of potassium (Emmanuel et al. 2025). This is important for cardiovascular health and blood pressure regulation (Huang et al. 2024).

The vitamin C (ascorbic acid) content is within the general range of ripe banana, although some cultivars exhibit higher antioxidant potential. Previous studies have reported larger variation in vitamin C content in unripe banana or banana peel flour (Indrasari et al. 2017; Syukriani et al. 2021). Ascorbic acid significantly enhances the antioxidant potential of the fruit, thereby contributing to the protection of cellular components, including DNA, from oxidative damage (Wekti and Khanifa 2021). By mitigating oxidative stress, antioxidants support physiological balance and help reduce the risk of chronic diseases such as cancer, arthritis, autoimmune disorders, and cardiovascular or neurological conditions (Kaźmierczak-Barańska et al. 2020).

For pH and Total Soluble Solids (TSS), values correspond to the range for ripe bananas. The pH tends to decrease with fruit ripening, indicating an increase in sugar content, as starch is converted to simple carbohydrates (Simkova et al. 2024). Widodo et al. (2019) explained that the decrease in pH during ripening is related to the accumulation and decarboxylation of ascorbic and oxalic acids, respectively. Conversely, TSS increases with fruit ripening, indicating a higher sugar concentration. Higher TSS, as in *Agung*, is associated with a sweeter taste and shorter shelf life, while bananas with lower TSS tend to ripen more slowly and remain stable for a longer period (Iqbal et al. 2025). TSS primarily represents sugars resulting from starch breakdown during ripening, which affect fruit flavor and shelf life (Burdon et al. 2016). Proper storage conditions can slow sugar accumulation and delay softening, thereby extending shelf life (Souza et al. 2024). Moisture and ash contents vary moderately between cultivars, with *Berlin* showing relatively high levels for both traits. Moisture content influences texture, while ash content reflects the inorganic residue after roasting and can affect starch color and texture. Physicochemical composition results from the interaction between genetic traits and environmental conditions. Soil nutrient availability, plant health, and mineral bioavailability significantly influence the physicochemical quality of bananas (Hapsari and Lestari 2016; Durgadevi et al. 2019). Overall, the study results demonstrate extensive physicochemical diversity among Indonesian banana cultivars. Variability in protein, carbohydrate, and mineral levels suggests the influence of genetic factors and the local growing environment. This diversity provides valuable insights for breeding, nutritional selection, and conservation strategies aimed at improving banana quality and health-related traits.

Multivariate analysis of fruit characters

Heatmaps provide a color-coded overview of data, and dendrograms add hierarchical clustering to simplify the interpretation of complex relationships as well as aid in pattern recognition and hypothesis generation (Fernandez et al. 2017; Yu et al. 2020). The clustered heatmap comprehensively visualizes the physicochemical characteristics of 20 banana cultivars. Rows represent the cultivars, while the columns indicate the 16 measured variables. A color gradient from orange (low) to red (high) allows for the quick identification of cultivars with unique trait profiles. Figure 2 shows the clustering of banana cultivars based on standardized trait values, revealing groups with similar physicochemical characteristics as well as several cultivars with distinct profiles.

Similarly, *Kepok Australia*, *Agung*, and *Talun* showed higher values for several variables, including carbohydrates and protein. In contrast, cultivars such as *Nangka*, *Kepok Makassar*, and *Kayu* reported predominantly lower values for most of the measured traits, as reflected by the yellow to blue colors, showing different compositional profiles suitable for alternative uses or consumer preferences.

Among these cultivars, *Kepok* displayed a remarkably high fat content, as reflected by the intense red coloration in the heatmap. Such characteristics make this cultivar a promising candidate for value-added industrial uses where higher fat content enhances texture, shelf-life or processing stability (Vu et al. 2025). It is particularly valuable for processed food industries, such as banana chips or bakery fillings, where higher fat content improves flavor and texture stability (Damanhuri et al. 2023). Likewise, *Kepok Australia*, *Agung*, and *Talun* showed elevated values for multiple nutritional and morphological traits (e.g., carbohydrates, protein and fruit size). This multi-trait advantage suggests they could be prioritized in breeding programs aimed at combining high compositional quality with desirable size or firmness traits.

Conversely, cultivars such as *Nangka*, *Kepok Makassar*, and *Kayu* showed lower overall values, which may be associated with slower ripening rates and denser tissue structure, as inferred from their relatively lower TSS and higher firmness. Such trait combinations may contribute to extended shelf life and align with local market preferences for firmer fruit, highlighting their potential for niche markets and for germplasm conservation to maintain genetic diversity (Ma et al. 2022). However, such implications are inferred from physicochemical patterns and should be validated through dedicated postharvest and storage studies.

Figure 2 shows close clustering between *Berlin* and *Goroito*, *Candi* and *Ambon*, as well as *Susu* and *Mas*. Close clustering in a dendrogram reflects comparable nutritional profiles, which can simplify selection for specific quality traits in breeding programs or targeted market segments. Such similarity also suggests the potential interchangeability in breeding or product development programs, specifically when uniformity of quality traits is desired for specific industrial or consumer applications (Tesfaye 2021; Rosmahadi and Hamdan 2022). This pattern also presents the cultivar groups with similar physicochemical attributes related to genetic background, agroecological conditions, or post-harvest handling practices (Singh et al. 2016; Rosmahadi and Hamdan 2022; Silué and Fawole 2025). Principal Component Analysis (PCA) is a widely used method in multivariate analysis to reduce the dimensionality of complex data sets without significant loss of information. This is achieved by transforming the original set of potentially correlated variables into a new set of uncorrelated Principal Components (PCs). The components are constructed orthogonally to each other and ordered by the amount of variance explained in the data. The first principal component captures the largest portion of the total variation. By concentrating variation into a few components, PCA allows for the representation of high-dimensional data in a simplified two-dimensional space. This facilitates the visualization of patterns, relationships, and clusters that may not be apparent in the raw data (Michael et al. 2025). In this study, the percentage of variability in the dataset explained by PC1 and PC2 is 26% and 17.2%, respectively, and the cumulative variance explained by PC1+PC2 is 43.2% (Figure 3).

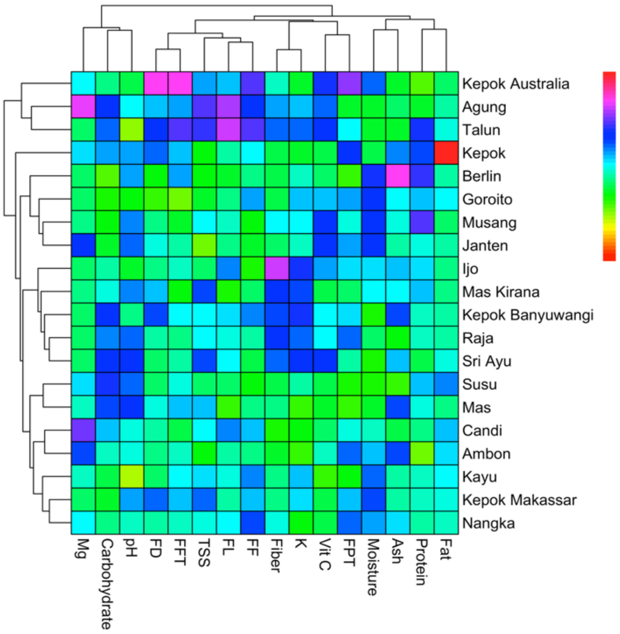

Figure 2. Clustered-Heatmap representing 20 banana cultivars and morphological-physicochemical characters using complete linkage and Euclidean distance to the standardized data. FL: Fruit Length, FD: Fruit Diameter, FF: Fruit Firmness, TSS: Total Soluble Solids, FFT: Fruit Flesh Thickness, FPT: Fruit Peel Thickness, K: Potassium, Mg: Magnesium

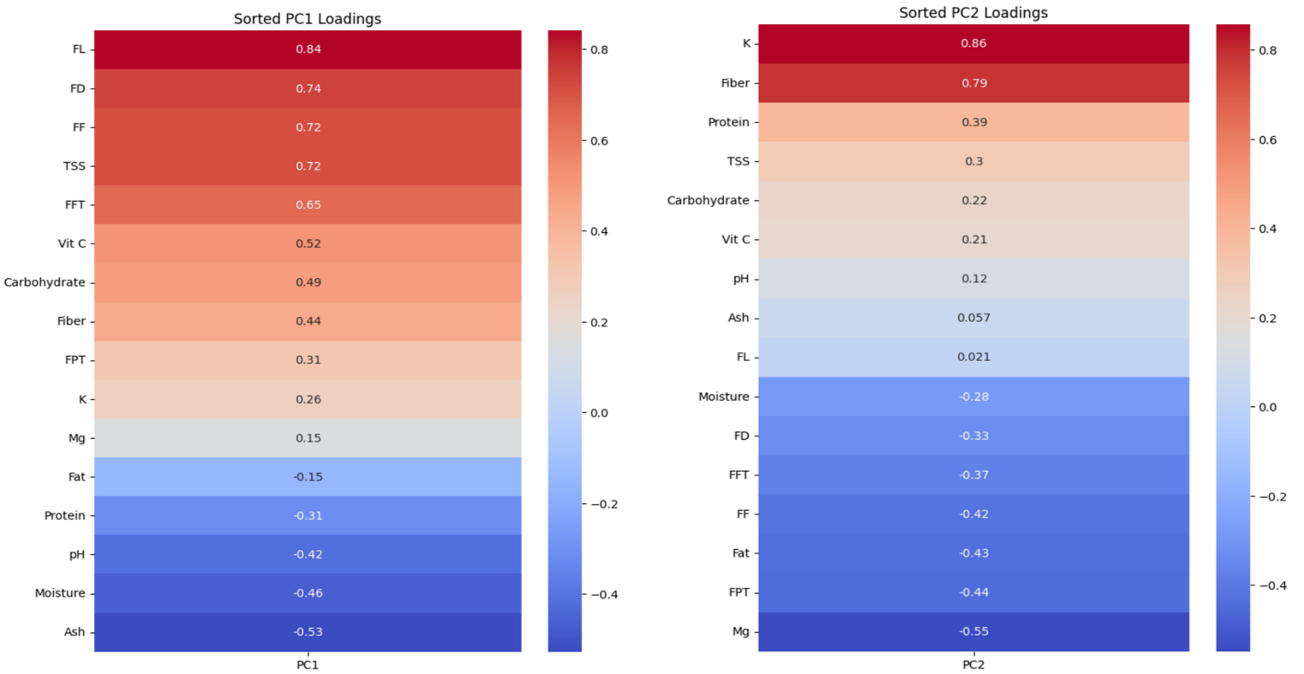

Figure 3. Traits importance represented by the Principal Components' Loading. FL: Fruit Length, FD: Fruit Diameter, FF: Fruit Firmness, TSS: Total Soluble Solids, FFT: Fruit Flesh Thickness, FPT: Fruit Peel Thickness, K: Potassium, Mg: Magnesium.

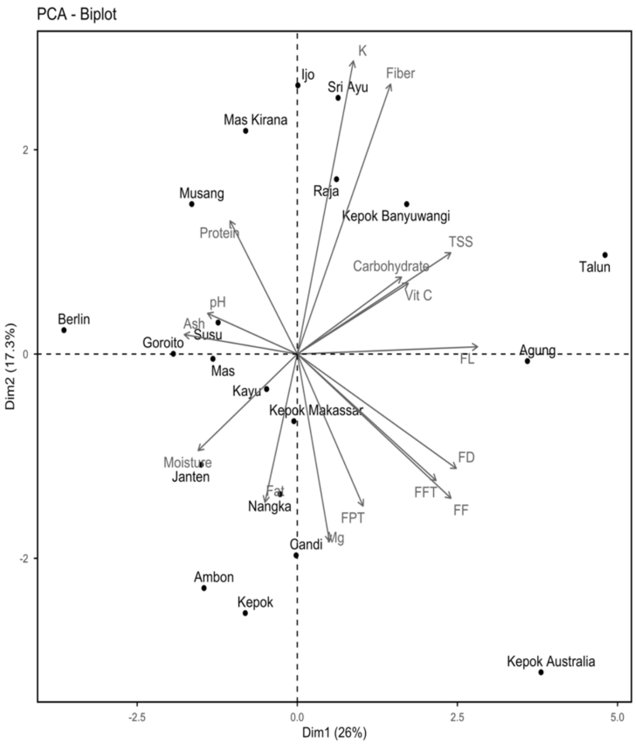

Figure 4. PCA Biplot of morphological and physicochemical characters of 20 banana cultivars. FL: Fruit Length, FD: Fruit Diameter, FF: Fruit Firmness, TSS: Total Soluble Solids, FFT: Fruit Flesh Thickness, FPT: Fruit Peel Thickness, K: Potassium, Mg: Magnesium

The first Principal Component (PC1) is mainly associated with high values of fruit length, fruit diameter, fruit firmness, total soluble solids, fruit flesh thickness, fruit peel thickness, vitamin C, carbohydrate, fiber, potassium, and magnesium. Furthermore, PC1 shows negative loadings for ash, moisture content, and pH. The second Principal Component (PC2) is characterized by high values for several physicochemical properties, such as potassium, fiber, protein, total soluble solids, carbohydrate, vitamin C, pH, ash, and fruit length, and by low values for several morphological traits. Overall, Figure 3 highlights that both morphological and physicochemical traits jointly contribute to cultivar differentiation, with fruit size, firmness, sugar content, and mineral composition emerging as key drivers of variation among the evaluated banana cultivars.

A common visualization tool used in PCA is a biplot, which shows objects (such as individuals, samples, or varieties) and variables (such as original traits or features) simultaneously in a space defined by the first two principal components. A biplot can evaluate the contribution of a variable to the formation of principal components and the relative positioning of objects. This dual representation makes biplot very useful for exploring the structure of multivariate data, identifying influential variables, and interpreting similarities or differences between observations (Castura et al. 2023; Saranya and Poonguzhali 2024). In this research, the PCA biplot shows which characteristics most clearly distinguish different banana varieties. This identifies distinct or potentially valuable genetic types. The information is important for breeders selecting parent plants with complementary beneficial traits. Conservation efforts are also assisted in focusing on varieties to preserve genetic and physical diversity.

Figure 4 illustrates the separation and clustering of banana cultivars based on their morphological and physicochemical traits, with several cultivars positioned away from the main group, indicating distinct phenotypic profiles. In the biplot (Figure 4), *Talun*, *Kepok Australia*, and *Berlin* are positioned farther from the other banana cultivars, indicating a low level of similarity in morphological and physicochemical characteristics. This difference suggests that these cultivars have unique trait profiles compared to others.

Talun stands out for its relatively large fruit size and firm texture, accompanied by lower magnesium levels. *Kepok Australia*, in contrast, exhibits consistently high values across multiple physical attributes and vitamin C content, pointing to a cultivar with strong firmness and nutritional appeal. *Berlin* shows a different pattern, with thinner pulp and lower carbohydrate content. The distance between data points indicates the degree of similarity. Closer cultivars have more similar characteristics, while those further apart tend to be more different. *Kepok Makasar* was positioned close to Nangka and Kayu since the three cultivars had comparable morphological and physicochemical properties. *Ambon* and *Candi* were closely clustered with Susu and Mas cultivars, indicating a high degree of similarity within each pair. *Raja*, *Sri Ayu*, *Kepok Banyuwangi*, *Mas Kirana*, and *Ijo* were also clustered, indicating phenotypic similarity that may reflect shared genetic background or similar selection practices rather than direct evidence of genetic kinship. Even though *Berlin* was located outside the main cluster, the cultivar was relatively close to *Goroito*, *Musang*, and *Janten*, showing a moderate degree of similarity. This spatial pattern is consistent with the clustered heatmap (Figure 2), where cultivars positioned close to each other in the biplot appeared in the same cluster. The orientation and proximity of cultivars to the variable vector provide valuable insights into the dominance of certain traits. Cultivars positioned in the direction of a particular vector show higher values since the direction reflects the influence of the variable on the principal component (Saranya and Poonguzhali 2024).

In this research, *Kepok* was closely associated with the fat vector, suggesting a higher fat content. *Kepok* Australia was strongly associated with fruit firmness, while Agung and Talun were oriented toward the FL vector. Berlin was consistent with the ash vector, reflecting the relatively high ash content. This trend is consistent with the clustered heatmap (Figure 2), where a darker red hue represented higher trait values.

The relationships among different cultivars, as shown in the biplot and heatmap, indicate that some groups, such as *Ambon-Candi* and *Susu-Mas*, exhibit strong trait similarities and are phenotypically related. This resemblance is likely due to shared ancestry or similar selection practices. In contrast, several cultivars, such as *Berlin*, *Talun*, *Agung*, and *Kepok Australia*, were positioned as outliers in the biplot. This indicates their distinct morphological and physicochemical profiles. *Talun*, *Agung*, and *Kepok Australia* represent valuable genetic resources with notable traits, including larger fruit size, firmer texture, and higher vitamin C content. From a biological and quality standpoint, larger fruit size and higher firmness are widely associated with greater resistance to mechanical damage during handling and transport, as well as improved shelf stability during postharvest storage. In addition, elevated vitamin C content enhances the fruit's nutritional value and positively influences consumer perceptions of freshness and health benefits. Cultivars combining these traits are therefore particularly attractive for fresh consumption and for distribution systems that require extended storage and transport durability. Such attributes may increase their market potential beyond local consumption and support their selection in breeding programs targeting both quality and post-harvest performance.

Berlin displayed lower carbohydrate content but higher moisture and ash levels, suggesting a distinctive metabolic profile that may be related to differences in growing conditions or cultivar-specific physiological characteristics, as suggested in previous studies (Hapsari and Lestari 2016; Li et al. 2019). Lower carbohydrate content is often associated with reduced sweetness, which may shape consumer preference, whereas higher moisture content can influence fruit texture and postharvest stability. Despite these potential limitations, such trait combinations may be advantageous for specific culinary applications or niche markets. From a conservation perspective, the presence of these contrasting attributes underscores the importance of retaining these cultivars in germplasm collections to preserve both functional and genetic diversity.

Although *Berlin* differs markedly from most cultivars, it shares moderate similarity with *Goroito*, *Musang*, and *Janten*. These unique cultivars collectively broaden the phenotypic spectrum within the banana germplasm. Understanding such relationships is crucial for making informed decisions about preserving genetic diversity, where unique varieties should be prioritized for conservation. From a breeding perspective, cultivar conservation with complementary traits can be used to select parents that enhance nutritional and physical characteristics in offspring.

The results of this study indicate that an integrated multivariate approach is effective for characterizing complex phenotypic and nutritional variation among banana cultivars, enabling the identification of cultivars with distinct, application-relevant trait profiles. A clearer understanding of cultivar relationships, trait distribution, and nutritional potential can be examined by integrating morphological and physicochemical traits. The combined use of cluster analysis, PCA, heatmaps, and biplots enabled the identification of distinct cultivar groupings and trait associations that are difficult to discern with univariate methods.

Several cultivars, such as *Agung*, *Talun*, *Kepok Australia*, and *Berlin*, exhibited trait combinations, suggesting potential relevance for targeted use in functional foods or cultivar improvement programs, including improvements in fruit size, firmness, or micronutrient content. These findings highlight the practical value of local germplasm for designing parent combinations and prioritizing conservation of genetically valuable landraces. Because the analysis relied on phenotypic and physicochemical traits, the observed clustering patterns may reflect a combination of genetic background and environmental influences. Integrating molecular data would help disentangle these effects and further refine the interpretation of cultivar relationships.

Although post-harvest handling and storage conditions are known to influence banana physicochemical properties —such as sugar accumulation, vitamin C degradation, and textural softening—these effects were partially controlled in this study by standardizing fruit maturity at ripening stage 6 of 7. This standardization enabled cultivar comparisons under comparable physiological conditions, allowing more comparable comparisons of genetic and phenotypic differences rather than storage-related effects. Previous studies have shown that storage temperature and humidity can alter carbohydrate metabolism, moisture content, and nutrient stability (Li et al. 2019; Brizzolara et al. 2020). While post-harvest dynamics were beyond the scope of this work, the results provide an initial reference point for evaluating cultivar-specific quality traits at market-ready ripeness.

Indonesian banana landraces are commonly cultivated under low-input traditional systems and show broad adaptation to diverse agroecological conditions, including variable rainfall and marginal soils (Hapsari and Lestari 2016; Joshi et al. 2023). Maintaining locally adapted cultivars can enhance agroecological resilience and reduce dependence on intensive inputs, such as irrigation and chemical fertilizers. From a sustainability perspective, aligning cultivar-specific traits with intended uses—for example, firm-textured cultivars for extended distribution chains and softer types for local consumption—may improve both environmental efficiency and economic viability. Although sustainability indicators were not directly assessed in this study, the observed phenotypic diversity provides a useful basis for selecting cultivars that balance fruit quality with ecological adaptability.

Despite its contribution to banana characterization, this research remains limited to the use of phenotypic and physicochemical traits measured across a limited set of cultivars and growing environments. Nevertheless, the results provide a clear phenotypic baseline relevant to cultivar differentiation, utilization, and conservation at market-ready ripeness. The use of larger samples from a broader region, along with standardized postharvest handling, would further strengthen the robustness of cultivar comparisons. Future research should integrate genomic, metabolomic, or transcriptomic approaches to better disentangle genetic and environmental influences, elucidate the molecular mechanisms underlying key quality traits and support precision breeding for improved nutrition and stress adaptation.

In conclusion, this study showed clear phenotypic and nutritional variation among cultivars. Several cultivars were separated from others, each exhibiting a distinct profile. These cultivars had high levels of several quality-related traits, including high Fruit Firmness (FF), Total Soluble Solids (TSS), and nutrient content, indicating potential value for improving fruit quality. Meanwhile, several cultivars formed clusters characterized by more moderate trait values. *Berlin* was identified as an outlier with a distinctive profile, specifically in its moisture, ash, and carbohydrate content. The clustering patterns observed in the PCA biplot were consistent with the cluster heatmap, supporting the use of the methods for integrated characterization. Overall, this study demonstrates that combining morphological and physicochemical traits can uncover complex patterns of variability that may not be apparent through univariate assessment. These findings provide useful information for cultivar differentiation, utilization, and the conservation of local banana germplasm, while also highlighting the need for future studies integrating molecular approaches to better disentangle genetic and environmental influences on key quality traits and to support precision breeding for improved nutrition and stress adaptation.

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REFERENCES

Annor GA, Asamoah-Bonti P, Sakyi-Dawson E. 2016. Fruit physical characteristics, proximate, mineral, and starch characterization of FHIA 19 and FHIA 20 plantain and FHIA 03 cooking banana hybrids. SpringerPlus 5: 796. https://doi.org/10.1186/s40064-016-2465-1.

Acevedo SA, Carrillo ÁJD, Flórez-López E, Grande-Tovar CD. 2021. Recovery of banana waste-loss from production and processing: A contribution to a circular economy. Molecules 26 (17): 5282. https://doi.org/10.3390/molecules26175282.

AOAC [Association of Analytical Chemists]. 2005. Official Methods of Analysis of the Association of Analytical Chemists, 18th Edition. Washington DC: AOAC International.

BSN [Badan Standardisasi Nasional]. 1992. SNI 01-2891-1992: Cara Uji Makanan dan Minuman. Badan Standardisasi Nasional, Jakarta.

Bantayehu M, Alemayehu M. 2024. Stability of fruit ripening traits of banana (*Musa* species) across postharvest environments. Heliyon 10 (17): e37143. https://doi.org/10.1016/j.heliyon.2024.e37143.

Borges CV, Amorim EP, Leonel M, Gomez HAG, dos Santos TPR, da Silva Ledo CA, Belin MAF, de Almeida SL, Minatel IO, Lima GPP. 2019. Post-harvest physicochemical profile and bioactive compounds of 19 banana and plantains genotypes. Bragantia 78 (2): 284-296. https://doi.org/10.1590/1678-4499.20180252.

Brizzolara S, Manganaris GA, Fotopoulos V, Watkins CB, Tonutti P. 2020. Primary metabolism in fresh fruits during storage. Front Plant Sci 11: 80. https://doi.org/10.3389/fpls.2020.00080.

Burdon J, Pidakala P, Martin P, Billing D, Boldingh H. 2016. Fruit maturation and the soluble solids harvest index for 'Hayward' kiwifruit. Sci Hortic 213: 193-198. https://doi.org/10.1016/j.scienta.2016.10.027.

Castura JC, Varela P, Næs T. 2023. Evaluation of complementary numerical and visual approaches for investigating pairwise comparisons after principal component analysis. Food Qual Prefer 107: 104843. https://doi.org/10.1016/j.foodqual.2023.104843.

Cheng YT, Huang PH, Chan YJ, Chiang PY, Lu WC, Hsieh CW, Liang ZC, Yan BW, Wang CCR, Li PH. 2024. Investigate the composition and physicochemical properties attributes of banana starch and flour during ripening. Carbohydr Polym Technol Appl 7: 100446. https://doi.org/10.1016/j.carpta.2024.100446.

Christelová P, De Langhe E, Hřibová E, Čížková J, Sardos J, Hušáková M, Van den Houwe I, Sutanto A, Kepler AK, Swennen R, Roux N, Doležel J. 2017. Molecular and cytological characterization of the global *Musa* germplasm collection provides insights into the treasure of banana diversity. Biodivers Conserv 26: 801-824. https://doi.org/10.1007/s10531-016-1273-9.

Dadzie BK, Orchard JE. 1997. Routine Post-Harvest Screening of Banana/Plantain Hybrids: Criteria and Methods. INIBAP Tech Guidelines 2. International Plant Genetic Resources Institute, Rome; International Network for the Improvement of Banana and Plantain, Montpellier; ACP-EU Technical Centre for Agricultural and Rural Cooperation, Wageningen.

Damanhuri MK, Purwayantie S, Hartanti L. 2023. Quality characteristics of kepok banana chips (*Musa paradisiaca*) from various methods. FoodTech Jurnal Teknologi Pangan 6 (2): 18-26. http://doi.org/10.26418/jft.v4i1.74275.

Dotto J, Matemu AO, Ndakidemi PA. 2019. Nutrient composition and selected physicochemical properties of fifteen Mchare cooking bananas: A study conducted in northern Tanzania. Sci Afr 6: e00150. https://doi.org/10.1016/j.sciaf.2019.e00150.

Emmanuel JK, Mtashobya LA, Mgeni ST. 2025. Potential contributions of banana fruits and residues to multiple applications: An overview. Nat Prod Commun 20 (2): 1934578X251320151. https://doi.org/10.1177/1934578X251320151.

Fernandez NF, Gundersen GW, Rahman A, Grimes ML, Rikova K, Hornbeck P, Ma'ayan A. 2017. Clustergrammer, a web-based heatmap visualization and analysis tool for high-dimensional biological data. Sci Data 4: 170151. https://doi.org/10.1038/sdata.2017.151.

Hapsari L, Lestari DA. 2016. Fruit characteristic and nutrient values of four Indonesian banana cultivars (*Musa* spp.) at different genomic groups. Agrivita J Agric Sci 38 (3): 303-311. https://doi.org/10.17503/agrivita.v38i3.696.

Hastuti H, Purnomo P, Sumardi I, Daryono BS. 2019. Diversity wild banana species (*Musa* spp.) in Sulawesi, Indonesia. Biodiversitas 20 (3): 824-832. https://doi.org/10.13057/biodiv/d200328.

Huang L, Li Q, Wu JHY, Tian M, Yin X, Yu J, Liu Y, Zhang X, Wu Y, Paige E, Trieu K, Marklund M, Rodgers A, Neal B. 2024. The contribution of sodium reduction and potassium increase to the blood pressure lowering observed in the Salt Substitute and Stroke Study. J Hum Hypertens 38: 298-306. https://doi.org/10.1038/s41371-024-00896-4.

Indrasari SD, Kristamtini K, Wiranti EW. 2017. Vitamin C and total sugar content characterization on 31 accessions of banana collection of banana germplasm plants of Yogyakarta. Biol Med Nat Prod Chem 6 (2): 53-57. https://doi.org/10.14421/biomedich.2017.62.53-57.

Iqbal M, Khan A, Ali S, Ahmad Z. 2025. Impact of various ripening agents on shelf life and quality of banana. J Agron Food Chem 45(3): 112-125. https://doi.org/10.1016/j.agrofood.2025.10.12

Jellife RW, Schumitzky A, Bayard D, Xiaowei MD, Neely M. 2015. Describing assay precision—reciprocal of variance is correct, not CV percent: Its use should significantly improve laboratory performance. Ther Drug Monit 37: 389-394. https://doi.org/10.1097/ftd.0000000000000168.

Joshi RU, Singh AK, Singh VP, Rai R, Joshi P. 2023. A review on adaptation of banana (*Musa* spp.) to cold in subtropics. Plant Breed 142 (3): 269-283. https://doi.org/10.1111/pbr.13088.

Kassambara A, Mundt F. 2020. Factoextra: Extract and visualize the results of multivariate data analyses. R Package Version 1.0.7. https://CRAN.R-project.org/package=factoextra.

Kaźmierczak-Barańska J, Boguszewska K, Adamus-Grabicka A, Karwowski BT. 2020. Two faces of vitamin C—Antioxidative and pro-oxidative agent. Nutrients 12 (5): 1501. https://doi.org/10.3390/nu12051501.

Kolde R. 2025. Pheatmap: Pretty heatmaps. R package version 1.0.13. CRAN. https://doi.org/10.32614/CRAN.package.pheatmap.

Durgadevi PSKS, Saravanan A, Uma S. 2019. Antioxidant potential and antitumour activities of *Nendran* banana peels in breast cancer cell line. Indian J Pharm Sci 81 (3): 464-473. https://doi.org/10.36468/pharmaceutical-sciences.531.

Kurnianingsih R, Mastuti R, Nikmatullah A, Arumingtyas EL. 2025. Morphological characterization of the banana indigenous cultivar '*Haji*' (*Musa* × *paradisiaca*) for germplasm development in Indonesia. Sabrao J Breed Genet 57 (2): 668-682. https://doi.org/10.54910/sabrao2025.57.2.24.

Laksemi IGAA, Rai IN, Mayadewi NNA. 2023. Identifikasi karakter morfologi dan analisis kandungan nutrisi buah pisang Mas, Buluh, dan Lumut lokal Bali. Agrotrop J Agric Sci 13 (1): 27-39. https://doi.org/10.24843/AJoAS.2023.v13.i01.p03. [Indonesian]

Li T, Yun Z, Wu Q, Qu H, Duan X, Jiang Y. 2019. Combination of transcriptomic, proteomic, and metabolomic analysis reveals the ripening mechanism of banana pulp. Biomolecules 9 (10): 523. https://doi.org/10.3390/biom9100523.

Yu C-S, Lin C-H, Lin Y-J, Lin S-Y, Wang S-T, Wu JL, Tsai M-H, Chang S-S. 2020. Clustering heatmap for visualizing and exploring complex and high-dimensional data related to chronic kidney disease. J Clin Med 9 (2): 403. https://doi.org/10.3390/jcm9020403.

Ma L, Liang C, Cui Y, Du H, Liu H, Zhu L, Yu Y, Lu C, Benjakul S, Brennan C, Brennan MA. 2022. Prediction of banana maturity based on the sweetness and color values of different segments during ripening. Curr Res Food Sci 5: 1808-1817. https://doi.org/10.1016/j.crfs.2022.08.024

Maseko KH, Regnier T, Meiring B, Wokadala OC, Anyasi TA. 2024. *Musa* species variation, production, and the application of its processed flour: A review. Sci Hortic 325: 112688. https://doi.org/10.1016/j.scienta.2023.112688.

Michael NA, Al Ibrahim MA, Scheibe C, Craigie N. 2025. Best practices of utilizing principal component analysis in chemostratigraphic studies. Appl Geochem 186: 106355. https://doi.org/10.1016/j.apgeochem.2025.106355.

Nadeeshani H, Samarasinghe G, Silva R, Hunter D, Madhujith T. 2021. Proximate composition, fatty acid profile, vitamin and mineral content of selected banana varieties grown in Sri Lanka. J Food Compos Anal 100: 103887. https://doi.org/10.1016/j.jfca.2021.103887.

Netshiheni RK, Omolola AO, Anyasi TA, Jideani AIO. 2019. Banana bioactives: Absorption, utilisation and health benefits. In: Jideani AIO, Anyasi TA (eds). Banana Nutrition: Function and Processing Kinetics. IntechOpen, London. https://doi.org/10.5772/intechopen.83369.

Nyine M, Uwimana B, Swennen R, Batte M, Brown A, et al. 2017. Trait variation and genetic diversity in a banana genomic selection training population. PLoS One 12 (6): e0178734. https://doi.org/10.1371/journal.pone.0178734.

Ohizua ER, Adeola AA, Idowu MA, Sobukola OP, Afolabi TA, Ishola RO, Ayansina SO, Oyekale TO, Falomo A. 2017. Nutrient composition, functional, and pasting properties of unripe cooking banana, pigeon pea, and sweetpotato flour blends. Food Sci Nutr 5 (3): 750-762. https://doi.org/10.1002/fsn3.455.

Phillips KM, McGinty RC, Couture G, Pehrsson PR, McKillop K, Fukagawa NK. 2021. Dietary fiber, starch, and sugars in bananas at different stages of ripeness in the retail market. PLoS One 16 (7): e0253366. https://doi.org/10.1371/journal.pone.0253366.

Pragati S, Genitha I, Ravish K. 2014. Comparative study of ripe and unripe banana flour during storage. J Food Process Technol 5 (11): 1000384. https://doi.org/10.4172/2157-7110.1000384.

Rosmahadi NAS, Hamdan MF. 2022. Statistical analysis of food nutrition by using K-means clustering. IEEE Xplore 8: 159-169.

Rozaki Z, Hartanto MIR, Triyono, Rahmawati N, Man N, Ardila RA, Ariffin AS, Ramli MF, Santoso WI. 2025. Assessing the environmental impacts of banana farming in Yogyakarta Special Region using Life Cycle Assessment (LCA). Intl J Des Nat Ecodyn 20 (1): 159-167. https://doi.org/10.18280/ijdne.200117.

Sa'diyah H, Sari VK, Rusdiana RY, Khofi AC. 2025. Cluster analysis to explore morphological variation of banana (*Musa* spp.): A case study in Jember and Lumajang, East Java, Indonesia. J Kultivasi 24 (1): 47-58. https://doi.org/10.24198/kultivasi.v24i1.61853.

Sapei L. 2023. Proximate composition and functional properties of banana flour at different ripening stages. Jurnal Litbang Industri 13 (1): 41-49. https://doi.org/10.24960/jli.v13i1.8021.41-49.

Saranya S, Poonguzhali S. 2024. Principal component analysis biplot visualization of electromyogram features for submaximal muscle strength grading. Comput Biol Med 182: 109142. https://doi.org/10.1016/j.compbiomed.2024.109142.

Selvaraj MG, Vergara A, Montenegro F, Ruiz HA, Safari N, Raymaekers D, Ocimati W, Ntamwira J, Tits L, Omondi AB, Blomme G. 2020. Detection of banana plants and their major diseases through aerial images and machine learning methods: A case study in DR Congo and Republic of Benin. ISPRS J Photogramm Remote Sens 169: 110-124. https://doi.org/10.1016/j.isprsjprs.2020.08.025.

Silué Y, Fawole OA. 2025. Cluster analysis of Japanese plum cultivars for optimizing export handling conditions. Sci Hortic 346: 114185. https://doi.org/10.1016/j.scienta.2025.114185.

Simkova K, Veberic R, Hudina M, Grohar MC, Pelacci M, Smrke T, Ivancic T, Weber NC, Jakopic J. 2024. Non-destructive and destructive physical measurements as indicators of sugar and organic acid contents in strawberry fruit during ripening. Sci Hortic 327: 112843. https://doi.org/10.1016/j.scienta.2024.112843.

Singh S, Prakash A, Chakraborty NR, Wheeler C, Agarwal PK, Ghosh A. 2016. Trait selection by path and principal component analysis in *Jatropha curcas* for enhanced oil yield. Ind Crops Prod 86: 173-179. https://doi.org/10.1016/j.indcrop.2016.03.047.

Souza EG, Sasaki FFC, Pereira MEC, do Nascimento MN, Silva LEP, Lopes JP, Lima MB. 2024. Extension of the shelf-life of 'BRS-

Princesa' bananas through refrigerated storage. Rev Caatinga 37: e12233. https://doi.org/10.1590/1983-21252024v3712233rc.

Suchitra MR, Parthasarathy S. 2021. Estimation of potassium content of different varieties of banana fruit in an Indian delta: Is there a clinical relevance. J Med Pharm Allied Sci 10 (6): 3853-3855. https://doi.org/10.22270/jmpas.v10i6.1620.

Syukriani L, Febjislami S, Lubis DS, Hidayati R, Asben A, Suliansyah I, Jamsari J. 2021. Physicochemical characterization of peel, flesh and banana fruit cv. Raja (*Musa paradisiaca*). IOP Conf Ser: Earth Environ Sci 741: 012006. https://doi.org/10.1088/1755-1315/741/1/012006.

Tapsell LC, Neale EP, Satija A, Hu FB. 2016. Foods, nutrients, and dietary patterns: Interconnections and implications for dietary guidelines. Adv Nutr 7 (3): 445-454. https://doi.org/10.3945/an.115.011718.

Tesfaye A. 2022. Genetic divergence and cluster analysis for bulb yield and related traits in garlic (*Allium sativum*) accessions at Dorze, southern Ethiopia. Agrosyst Geosci Environ 5 (2): e20269. https://doi.org/10.1002/agg2.20269.

Trimanto T, Renjana E, Lestari DA, Firdiana ER, Mas'udah S, Rahadiantoro A, Ningrum LW, Hapsari L. 2022. Morphological characterization and seed germination study of wild banana *Musa acuminata* var. *flava* (Ridl.) Nasution. J Trop Biodivers Biotechnol 7 (1): 66645. https://doi.org/10.22146/jtbb.66645.

Vu ND, Hang NT, Mi KD, Anh NH, Pham BA. 2025. Exploring the nutritional composition, physicochemical properties, and biological characteristics of mature banana varieties (*Musaceae*). Food Chem X 28: 102594. https://doi.org/10.1016/j.fochx.2025.10.2594.

Wahyudi D, Uslan, Rifliyah K. 2020. Genome evaluation of banana cultivars based on morphological character and Inter-Simple Sequence Repeat (ISSR) molecular marker. Biodiversitas 21 (7): 2982-2990. https://doi.org/10.13057/biodiv/d210715.

Wei J, Liu G, Sun M, Wang H, Yang P, Cheng S, Huang L, Wei S, Liu D. 2025. Comprehensive analysis of morphology, transcriptomics, and metabolomics of banana (*Musa* spp.) molecular mechanisms related to plant height. Front Plant Sci 16: 1509193. https://doi.org/10.3389/fpls.2025.1509193.

Wekti C, Khanifah F. 2019. Kadar vitamin C pada buah pisang raja (*Musa paradisiaca* L.) sebelum dan sesudah penambahan kalsium karbida (CaC_2). Jurnal Insan Cendekia 6 (1): 13-17. https://doi.org/10.35874/jic.v6i1.527. [Indonesian]

Widodo WD, Suketi K, Rahardjo R. 2019. Evaluasi kematangan pascapanen pisang Barangan untuk menentukan waktu panen terbaik berdasarkan akumulasi satuan panas. Buletin Agrohorti 7 (2): 162-171. https://doi.org/10.29244/agrob.7.2.162-171. [Indonesian]

Wulandari NPAN, Rai IN, Mayadewi NNA, Efendi D. 2023. The effect of differences in fruit maturity levels of three Balinese banana cultivars (*Musa* spp.) on the quality of fruit flesh flour produced. GSC Biol Pharm Sci 22 (1): 105-113. https://doi.org/10.30574/gscbps.2023.22.1.0478.