Current **A**pplied **S**cience and **T**echnology e-ISSN: 2586-9396

Curr. Appl. Sci. Technol. ….., Vol... (No...), e0269775

Research article

Agroecological Influence on Proximate Composition of Parakan Rambutan (*Nephelium lappaceum* L.)

Ady Daryanto[1], Haris Maulana[1]*, Araz Meilin[1], Riyadil Jinan[2], Lia Ratnawati[3], Enny Sholichah[4], Achmat Sarifudin[5], Asep Jatnika Sutrisno[6], Eman Sumarna[6], Andrew Yoel[7] and Dwinita Wikan Utami[1]

[1]Research Center for Horticulture, National Research, and Innovation Agency (BRIN), Jl. Raya Jakarta – Bogor km 46, Cibinong, Bogor Regency, West Java Province, Indonesia
[2]Directorate of Intellectual Property Management, National Research and Innovation Agency (BRIN), Indonesia
[3]Research Center for Processing Technology, National Research and Innovation Agency (BRIN), Indonesia
[4]Research Center for Molecular Chemistry, National Research and Innovation Agency (BRIN), Indonesia
[5]Research Center for Food Technology and Processing, National Research and Innovation Agency (BRIN), Indonesia
[6]Department of Agriculture and Food Security, Tangerang Regency, Indonesia
[7]Faculty of Agriculture, Universitas Padjadjaran, Indonesia

Received: 7 November 2025, Revised: 28 July 2026, Accepted:29 September 2026, Published: 20 November 2026

Abstract

Parakan rambutan (*Nephelium lappaceum* L.) is an important local cultivar in Indonesia, valued for its sweet flavor, thick aril, and desirable postharvest quality. This study evaluated the proximate composition and nutritional characteristics of Parakan rambutan collected from three production sites in Tangerang Regency, Indonesia, and compared them with the local cultivar Tangkue as a reference cultivar. Proximate components, caloric values, vitamin C, total sugars, and total soluble solids (TSS) were determined using AOAC-standardized methods, while soil physicochemical properties were characterized to provide environmental context. Significant differences ($p \leq 0.05$) were observed among the evaluated samples for moisture, ash, protein, fat, carbohydrate, vitamin C, total sugars, and TSS. Parakan rambutan from the BPP Caringin site (R3) exhibited the highest protein (1.71%), carbohydrate (22.31%), and caloric value (98.38 kcal/100 g), whereas Tangkue (R4) showed the highest vitamin C content (46.75 mg/100 g) and TSS. The observed differences in proximate composition among Parakan samples collected from different production sites suggest that agroecological conditions may contribute to nutritional variation, while comparison with Tangkue provides additional context for variation between cultivars. Principal component analysis (PCA) and the Multi-trait Genotype–Ideotype Distance Index (MGIDI) integrated multiple nutritional traits and identified Parakan rambutan from the BPP Caringin site (R3) as the sample with the most desirable overall

*Corresponding author: E-mail: hari061@brin.go.id
https://doi.org/10.55003/cast.2026.269775
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desirable overall nutritional profile. These findings provide a comprehensive nutritional characterization of locally important rambutan cultivars, suggest that agroecological conditions may contribute to variation in fruit nutritional composition, and demonstrate the usefulness of multivariate analysis for integrating multiple nutritional traits. The results also provide a foundation for future multi-location studies aimed at validating site-associated nutritional variation.

Keywords: fruit quality; MGIDI; nutritional composition; production site; tropical fruit

1. Introduction

Rambutan (*Nephelium lappaceum* L.) is one of the popular tropical fruits in Southeast Asia, including countries like Indonesia, Malaysia, Thailand, and Vietnam (Kuswandi et al., 2014). This fruit is known for its distinctive appearance, characterized by a unique, leathery skin covered with soft, hair-like structures, and also for its translucent, juicy, sweet flesh. This fruit is not only favored for its flavor but also valued for its nutritional content. Proximally, rambutan flesh contains approximately 78% water, 21% carbohydrates, and minor amounts of protein and fat, while its seeds are rich in crude fat (37.1-38.9%), protein (11.9-14.1%) (Augustin & Chua, 1988; Jahurul et al., 2020) and other bioactive components, including anti-cancer, anti-diabetic, and antibacterial properties. These bioactive compounds supports their potential for industrial applications (Mahmood et al., 2018; Biswas, 2021; Bhattacharjee et al., 2022)

Rambutan's bioactive components, such as phenolic acids (gallic and ellagic acids), flavonoids (catechin), and vitamin C, enhance its antioxidant, anti-inflammatory, and anticancer qualities, earning it recognition as a functional food (Palanisamy et al., 2008; Hernández-Hernández et al., 2019; Afzaal et al., 2023). The nutritional quality and bioactive composition of tropical fruits have become increasingly important not only for their health-promoting properties but also for improving postharvest quality and consumer acceptance, highlighting the need for comprehensive nutritional characterization of locally important fruit cultivars (Arif et al., 2026)

Rambutan by-products like the peel and seeds have shown considerable industrial potential in addition to the edible flesh. Phenolic compounds like geraniin and corilagin, which have anti-inflammatory and antimicrobial properties, are abundant in peel extracts. In contrast, rambutan seed fat is a good alternative to cocoa butter because it contains oleic and arachidic acids (Li et al., 2018; Jahurul et al., 2020). Manaf et al. (2013) further reported that rambutan seed oil contains approximately 38% crude fat, with a balanced composition of saturated and unsaturated fatty acids, including high levels of oleic acid (42.0%) and arachidic acid (34.3%), making it a potential alternative to conventional vegetable oils.

Indonesia is a center of genetic diversity for rambutan, harboring more than 30 identified local accessions from Sumatra, Java, and Kalimantan (Kuswandi et al., 2014). One notable variety is Parakan rambutan, which originates from Tangerang Regency and has been officially recognized as a superior variety under the Decree of the Minister of Agriculture No. 518 Kpts/PD.210/10/2003 (Department of Agriculture, 2003). Parakan rambutan is characterized by its distinct sweet taste, thick flesh, and the ease with which the flesh separates from the seed (Windarsih & Efendi, 2019). Additionally, the low water content in its dry flesh provides an added advantage, making Parakan rambutan highly desirable for both fresh consumption and processing. Studies have also indicated that genetic variations among rambutan cultivars significantly influence nutrient accumulation,

antioxidant properties, and secondary metabolite production, further highlighting the need for variety-specific nutritional analysis (Shahrajabian et al., 2020).

The quality, yield, and nutritional composition of rambutan fruit are influenced by multiple environmental and agronomic factors during plant growth and fruit development. According to Balai Penyuluhan Pertanian Cisauk (2016), Parakan rambutan is well adapted to humid tropical climates with evenly distributed rainfall, lowland elevations of up to 500 m above sea level, and moderate temperatures (22-30°C). Soil physicochemical properties and their interactions with beneficial microorganisms, including endophytic bacteria and arbuscular mycorrhizal fungi, are also known to influence nutrient availability and uptake, which may contribute to variation in fruit nutritional composition and the accumulation of bioactive compounds (Khastini et al., 2020; Afzaal et al., 2023). These factors provide a plausible ecological context for the variation observed among the evaluated samples, although their individual contributions were not assessed in the present study.

To comprehensively evaluate multiple correlated nutritional traits, this study employed multivariate techniques, including principal component analysis (PCA) and the Multi-trait Genotype–Ideotype Distance Index (MGIDI). Multivariate approaches have become valuable tools for integrating complex datasets and identifying overall response patterns among correlated variables, thereby providing a more comprehensive evaluation than single-trait analyses (Ambrósio et al., 2024; Putri et al., 2026). MGIDI enables the integration of multiple traits into a unified selection index, allowing the identification of samples that most closely approach an ideal nutritional profile based on overall trait performance (Debnath et al., 2024; Gowda et al., 2025). This approach is particularly valuable for evaluating underutilized genetic resources in which several nutritional and quality attributes must be considered simultaneously. Similar integrative breeding strategies that simultaneously evaluate agronomic performance and fruit quality have been successfully applied in tropical crop improvement programs to accelerate the identification and development of superior breeding materials (Olivoto & Nardino, 2021; Daryanto et al., 2025; Karthik & Hanamaratti, 2025).

The objective of this study was to characterize the nutritional composition of Parakan rambutan collected from three production sites in Tangerang Regency, Indonesia, and to compare their nutritional profiles using multivariate analytical approaches. Tangkue rambutan was included as a reference cultivar to provide additional context for interpreting nutritional variation among the evaluated samples. By integrating proximate composition, vitamin C, total soluble solids (TSS), and multivariate evaluation using the Multi-trait Genotype–Ideotype Distance Index (MGIDI), this study provides a comprehensive assessment of site-associated nutritional variation in locally important rambutan cultivars and establishes a basis for future multi-location validation and germplasm characterization. The findings contribute to the nutritional characterization of locally important rambutan cultivars and provide baseline information for future studies on multi-location evaluation and the development of cultivation strategies aimed at improving fruit nutritional quality.

2. Materials and Methods

2.1 Sample collection and preparation

Rambutan fruits used for proximate analysis were collected from four sample groups. The Parakan cultivar was collected from three commercial production sites in Tangerang Regency, Indonesia: UPTD Plant Seed Production (R1), Karya Alam Farmers Group (R2), and BPP Caringin (R3). The Tangkue cultivar was collected from the same UPTD Plant

Seed Production site (R4) and was included as a reference cultivar for comparative purposes. All rambutan fruits were freshly harvested in April 2024 at the commercial maturity stage, based on uniform peel coloration, characteristic fruit size, and marketable quality. Fruits from all locations were harvested at the same maturity stage to minimize variation due to fruit development. After collection, the fruits were manually peeled, and the edible flesh was separated from the seeds. The flesh was cut into small pieces using a clean stainless-steel knife and homogenized using an electric blender or food processor until a uniform consistency was obtained. The homogenized samples were immediately transferred into labeled airtight containers and stored under appropriate conditions until proximate analysis. All samples were prepared using the same protocol to ensure consistency among varieties and sampling locations and to minimize variation arising from sample preparation. Three independent laboratory replicates were performed for each analytical parameter.

2.2 Proximate analysis

All proximate analyses were conducted according to the AOAC (2000) guidelines.

2.2.1 Moisture content

A dried and cooled platinum dish was first weighed and recorded as w1. A precisely measured two grams portion of the rambutan flesh sample was then placed in the dish, and the total weight was recorded as w2. The dish, with the sample, was placed in an oven set at 105°C for approximately 3 h, ensuring that the sample reached a constant weight, after which the dish was reweighed as w3. Moisture content (%) was calculated using the formula:

$$\%\ \text{Moisture content} = \left(\frac{w2 - w3}{w2 - w1}\right)\ x\ 100$$

2.2.2 Ash content

A dried, cooled platinum dish was accurately weighed as (w_1), and approximately two grams of rambutan sample was evenly spread in the dish, with the combined weight recorded as (w_2). The dish was then transferred with tongs to a muffle furnace set to 550°C until the sample was fully ashed, turning to a gray color. The final weight of the ash and dish was recorded as (w_3). The ash content (%) was calculated as follows:

$$\%\ \text{Ash} = \left(\frac{W3 - W1}{W2 - W1}\right)\ x\ 100$$

2.2.3 Protein content

Approximately 0.25-0.35 g of the sample was analyzed for protein content following the Dumas combustion method using DuMaster protein analyzer (Buchi D-480, Switzerland) according to the manufacturer's instructions (BÜCHI Labortechnik AG, manual user). Crude protein content was calculated by multiplying the nitrogen content by a conversion factor of 6.25. The nitrogen content was calculated using the following formula:

$$\%\ \text{Protein}\ = \%N\ x\ F$$

Where F is the conversion factor = 6.25; %N =% Nitrogen.

2.2.4 Fat content

The Weibull method was used to determine crude fat according to SNI 011-2891-1992 (National Standardization Agency of Indonesia, 1992). A sample (2 g) was added with 30 mL of 20% HCl and 20 mL of distilled water. Then, the mixture was heated for the hydrolysis step and neutralization through washing. The fat extraction was conducted using a fat extractor (Buchi E-500, Switzerland) and hexane as the solvent. The extracted fat was dried at 105°C in an oven, cooled, and weighed (w_2). The percentage of fat content was calculated using the following formula:

$$\% \text{ Fat} = \left(\frac{W2 - W1}{W}\right) x\ 100$$

Where W = weight of the sample (g); W_1 = weight of the empty extraction flask (g); W_2 = weight of the extraction flask plus extracted fat after drying (g).

2.2.5 Carbohydrate content

Total carbohydrate content was calculated by using by difference method following this formula below:

Total Carbohydrate content (%) =100% − Moisture (%) - Ash (%) – Protein (%) – Fat (%)

2.2.6 Vitamin C

Vitamin C analysis was conducted using the titration methods (Sudarmaji et al., 1997). A homogenized slurry sample (10-30 g) was placed in a 100 mL volumetric flask, marked with distilled water, and filtered. A total of 5-25 mL of the filtrate was put into a 250 mL Erlenmeyer flask, added with 2 mL of 1% amylum solution and then titrated using 0.01 N iodium. The endpoint was indicated by the first appearance of a dark blue-black coloration resulting from the starch-iodine complex formation. Vitamin C (mg/100g) was calculated using the following equation:

$$Vitamin\ C\ (mg/100g) = \left(\frac{V\ I2\ x\ 0.88\ x\ df}{w}\right) x\ 100$$

where V I_2 is the iodium volume (mL), 0.88 is the value that 1 mL of 0.01 N iodine is equivalent to 0.88 mg of ascorbic acid, df is the dilution factor and w is sample weight (g)

2.2.7 Total sugars

Total sugars analysis was conducted using the hydrolysis and titration methods (Sudarmaji et al., 1997). A 2.5-25 g sample was weighed and transferred into a 100 mL volumetric flask, in which distilled water (50 mL) was added. Then, lead acetate solution was gradually added until turbidity was no longer observed. The flask contents were diluted to the mark with distilled water. The solution was transferred to a 200 mL volumetric flask, treated with anhydrous Na_2CO_3 to remove excess lead (Pb), diluted to the mark, homogenized, and filtered to obtain the clear filtrate. An aliquot of 25mL of the filtrate was mixed with 25 mL

of Luff Schoorl reagent, refluxed for 10 min, and then cooled down. After that, 15 mL of 20% KI and 25 mL of 25% H_2SO_4 were added to the mixture. 0.1 M $Na_2S_2O_3$ was used to titrate the solution until it turned pale yellow. The solution was made purple blue by adding 1% amylum indicator. The titration was continued until the purplish blue color disappeared. The amount of 0.1 M $Na_2S_2O_3$ was calculated. A blank solution was tested by replacing the filtrate with 25 mL distilled water. Total sugars (%) was calculated using the following equation:

$$Total\ sugars\ (\%) = \left(\frac{w1\ x\ df}{w2}\right)\ x\ 100$$

where w1 is the sugar weight (mg), *w2* is the sample weight (mg), and df is the dilution factor (Sudarmaji et al., 1997).

2.3 Statistical analysis

A completely randomized design (CRD) was used for the laboratory evaluation of the nutritional composition of rambutan samples collected from four production-site groups. Each nutritional parameter was analyzed using three replicates for each sample group. The production sites were treated as observational groups for statistical comparison of nutritional characteristics. Data were subjected to analysis of variance (ANOVA) at the 95% confidence level ($p \leq 0.05$) using STAR software. Significant differences among means were further examined using Tukey's Honestly Significant Difference (HSD) test.The Multi-trait Genotype–Ideotype Distance Index (MGIDI) was applied to evaluate the overall nutritional performance of the evaluated rambutan samples by simultaneously integrating all measured nutritional traits, including moisture, ash, protein, fat, carbohydrate, caloric attributes, total sugars, total soluble solids (TSS), and vitamin C. Trait values were first rescaled to a 0-100 range according to the desired selection direction, in which higher values were considered desirable for protein, carbohydrate, caloric attributes, total sugar, total soluble solids, and vitamin C, whereas lower values were preferred for moisture content. Equal importance (weight) was assigned to all evaluated traits.

Following the original MGIDI procedure proposed by Olivoto and Nardino (2021), a factor analysis based on the correlation matrix of the rescaled variables was performed to summarize correlated traits into latent factors and reduce data dimensionality prior to ideotype distance estimation. An ideotype was defined as a hypothetical sample combining the desired values for all evaluated traits. The Euclidean distance between each sample and the ideotype was then calculated from the factor scores, and samples were ranked according to their MGIDI values. Lower MGIDI values indicate samples closer to the ideotype and therefore exhibiting superior overall nutritional performance. Factor analysis was retained as an integral computational step of the MGIDI algorithm rather than as an independent multivariate analysis because MGIDI is fundamentally calculated from the latent factors generated during this procedure (Olivoto & Lúcio, 2020).

3. Results and Discussion

3.1 Nutritional composition variability across sites and genotypes

Significant differences ($p \leq 0.05$) were observed among the four rambutan samples (R1-R4) for all proximate traits, including moisture, ash, protein, fat, and carbohydrates (Table 1).

The consistently low coefficients of variation (0.16-9.37%) indicated reliable laboratory precision and reinforced the notion that the variation detected was primarily biological, not methodological. Similar low CV thresholds have been suggested as acceptable in fruit quality evaluation (Gomez & Gomez, 1984).

Moisture content ranged from 75.33% in R3 to 76.53% in R1 (Table 2). Although moisture content varied slightly among locations, the differences may reflect local environmental and agronomic conditions during fruit development. However, because environmental variables such as rainfall and temperature were not monitored in this study, the underlying causes cannot be confirmed. Similar variation in fruit moisture content associated with differences in local environmental conditions has been reported in other tropical fruits (Ubwa et al., 2014; Maldonado-Celis et al., 2019).

Ash content differed among sampling locations (Table 2). Although the three sites exhibited differences in soil chemical properties, including organic carbon, available phosphorus, exchangeable cations, and cation exchange capacity, the variation in fruit ash content cannot be attributed solely to soil mineral status. Mineral accumulation in fruit is influenced by multiple factors, including nutrient availability, plant uptake efficiency, and fruit physiological development (Blank et al., 2017).

Protein content differed among the evaluated rambutan samples, with R3 recording the highest value (1.71%). The elevated organic carbon and nitrogen at BPP Caringin site (2.78% and 0.23%, respectively) may have contributed to the higher protein content. Nitrogen availability is widely recognized as a determinant of protein synthesis in fleshy fruits (Tripathi et al., 2014; Tsong et al., 2021). Fat content in the rambutan flesh remained very low (0.15-0.26%) across samples. Previous studies reported that significant fat content was found in the seeds, which were often studied for their potential applications in food and cosmetics industries (Manaf et al., 2013; Chai et al., 2018; Ghobakhlou et al., 2019). The major fatty acids previously found in rambutan seed fat included oleic acid (33.35-46.64%) and arachidic acid (26.03-36.89%) (Manaf et al., 2013; Chai et al., 2018). Other fatty acids present in smaller amounts included stearic, palmitic, linoleic, and behenic acids (Manaf et al., 2013).

Carbohydrates, the major contributor to sweetness and energy, were highest in R3 (22.31%), followed by R4 (22.17%) and R2 (21.96%) (Table 2). The differences observed among the evaluated samples were consistent with previous reports showing that carbohydrate accumulation and sweetness-related traits in rambutan vary according to cultivar characteristics and production environments (Windarsih & Efendi, 2019; Shahrajabian et al., 2020). Environmental conditions during fruit development may also influence carbohydrate metabolism and sugar accumulation (Deng et al., 2023).

3.2 Caloric and sugar–antioxidant attributes

Caloric partitioning reflected proximate composition (Table 3). R3 recorded the highest total energy (98.38 kcal 100 g^{-1}), driven by higher carbohydrates (and modestly by protein), whereas R1 showed the lowest energy (93.14 kcal 100 g^{-1}), consistent with its higher moisture and lower dry matter (Gupta et al., 2012). The moisture content in various tropical fruits ranged from 65.70% to 93.30% in pulp and peel, which are typically lower in energy density compared to their dried counterparts (Morais et al., 2017).

Table 1. Recapitulation of analysis of variance for proximate composition and nutritional content of rambutan fruit

No	Parameter	MS	F Value	P Value	Significance	CV (%)
1	Moisture Content (%)	0.75	52.46	<.0001	**	0.16
2	Ash Content (%)	0.01	25.80	0.000	**	5.15
3	Protein Content (%)	0.02	20.36	0.007	**	1.99
4	Fat Content (%)	0.01	12.92	0.016	*	9.37
5	Carbohydrate Content (%)	0.56	38.49	0.002	**	0.55
6	Calories from Protein (kcal/100 g)	0.98	20.27	0.007	**	2.00
7	Calories from Fat (kcal/100 g)	0.46	12.98	0.016	*	9.32
8	Calories from Carbohydrates (kcal/100 g)	8.96	38.09	0.002	**	0.55
9	Total Calories (kcal/100 g)	9.36	32.13	0.003	**	0.56
10	Total Sugar (Titration) (%)	9.37	12.59	0.017	*	1.09
11	Total Soluble Solids (°Brix)	0.33	87.44	0.000	**	0.29
12	Vitamin C (mg/100g)	262.03	20.14	0.001	**	5.42

Notes: Mean Square (MS): Represents the middle square, used in ANOVA calculations, F Value (ANOVA): The calculated F statistic for ANOVA tests. P Value (Probability): The probability value, indicates statistical significance. Significance: * indicates significant, ** indicates highly significant results. CV (%) (Coefficient of Variation): Represents the variability relative to the mean in percentage.

Tabel 2. Proximate composition of rambutan genotypes

Rambutan	Moisture (%)	Ash (%)	Protein (%)	Fat (%)	Carbohydrate (%)
R1	76.53±0.06^{a}	0.52±0.02^{a}	1.57±0.06^{bc}	0.26±0.01^{a}	21.13±0.02^{b}
R2	75.89±0.08^{b}	0.48±0.02^{a}	1.47±0.03^{c}	0.23±0.04^{a}	21.96±0.07^{a}
R3	75.33±0.19^{c}	0.38±0.03^{b}	1.71±0.01^{a}	0.26±0.01^{a}	22.31±0.22^{a}
R4	75.71±0.08^{b}	0.40±0.01^{b}	1.61±0.01^{a}	0.15±0.01^{b}	22.17±0.08^{a}

Notes: Numbers followed by the same letter within the same column indicate no significant difference, as determined by the HSD (Honestly Significant Difference) test at the 5% level. R1 = Parakan Rambutan from UPTD Plant Seed Production, R2 = Parakan Rambutan from Karya Alam Farmers Group, R3 = Parakan Rambutan from BPP Caringin, R4 = Tangkue Rambutan from UPTD Plant Seed Production

Tabel 3. Distribution of caloric contribution in rambutan genotypes

Rambutan	Calories from Protein (kcal 100 g^{-1})	Calories from Fat (kcal 100 g^{-1})	Calories from Carbohydrates (kcal 100 g^{-1})	Total Calories (kcal 100 g^{-1})
R1	6.26±0.22^{bc}	2.37±0.07^{a}	84.51±0.09^{b}	93.14±0.38^{c}
R2	5.87±0.11^{c}	2.08±0.35^{ab}	87.84±0.27^{a}	95.78±0.04^{b}
R3	6.84±0.02^{a}	2.30±0.10^{a}	89.23±0.86^{a}	98.38±0.97^{a}
R4	6.43±0.04^{ab}	1.32±0.09^{b}	88.69±0.33^{a}	96.44±0.28^{ab}

Notes: Numbers followed by the same letter within the same column indicate no significant difference, as determined by the HSD (Honestly Significant Difference) test at the 5% level. R1 = Parakan Rambutan from UPTD Plant Seed Production, R2 = Parakan Rambutan from Karya Alam Farmers Group, R3 = Parakan Rambutan from BPP Caringin, R4 = Tangkue Rambutan from UPTD Plant Seed Production

Vitamin C differed markedly among the evaluated samples, with Tangkue (R4) showing the highest concentration (Table 4). This suggests genetic predisposition for ascorbate biosynthesis and/or ascorbate recycling pathways (Hernández-Hernández et al., 2019; Khastini et al., 2020). In apple cultivars, quantitative trait loci (QTL) studies identified specific genetic regions associated with higher ascorbate concentrations, further supporting the role of genetic factors in vitamin C accumulation (Mellidou et al., 2012)

Sugar-related traits also differed among the evaluated samples. R3 had the highest titration-based total sugars (19.42%), while R4 recorded the highest soluble solids (21.15 °Brix) (Table 4). Different genotypes exhibit significant variation in sugar content and composition, for instance in Japanese pears, genotypic differences significantly influenced the levels of sucrose, fructose, and glucose (Nishio et al., 2018; Saito et al., 2019).

Tabel 4. Total sugars and total soluble solids of rambutan genotypes

Rambutan	Vitamin C (mg/100g)	Total Sugars (Titration) (%)	Total Soluble Solids (° Brix)
R1	27.94±3.54^{c}	18.84±0.09^{ab}	20.90±0.00^{b}
R2	31.98±2.57^{bc}	18.20±0.32^{b}	21.05±0.07^{ab}
R3	34.85±1.74^{b}	19.42±0.22^{a}	20.25±0.07^{c}
R4	46.75±0.96^{a}	19.07±0.07^{a}	21.15±0.07^{a}

Notes: Numbers followed by the same letter within the same column indicate no significant difference, as determined by the HSD (Honestly Significant Difference) test at the 5% level. R1 = Parakan Rambutan from UPTD Plant Seed Production, R2 = Parakan Rambutan from Karya Alam Farmers Group, R3 = Parakan Rambutan from BPP Caringin, R4 = Tangkue Rambutan from UPTD Plant Seed Production

3.3 Soil properties and their influence on fruit composition

Soils differed meaningfully among the three Parakan sites (Table 5). All were slightly acidic, but UPTD had the lowest pH (5.79) and the highest Al saturation (13.60%). Aluminum toxicity is known to impair root growth, reduce P and Ca uptake, and constrain carbon assimilation (Ubwa et al., 2014; Tripathi et al., 2014), consistent with R1's comparatively lower protein, carbohydrates, and calories.

Table 5. Soil analysis in three Parakan rambutan planting areas

No.	Parameter	Unit	UPTD Plant Seed Production		Karya Alam Farmers Group		BPP Caringin	
			Result	Criteria	Result	Criteria	Result	Criteria
1	pH : H2O *)	-	5.79	Slightly Acidic	6.10	Slightly Acidic	6.14	Slightly Acidic
2	pH : KCl 1 N	-	4.45		4.89		5.39	
3	Organic – C *)	(%)	1.30	Low	2.48	Medium	2.78	Medium
4	Total – N *)	(%)	0.11	Low	0.20	Medium	0.23	Medium
5	C/N	-	9	Low	12	Medium	12	Medium
6	P_2O_5 HCl 25%	(mg/100g)	20.90	Low	103.49	Very High	137.13	Very High
7	P_2O_5 (Olsen)	(ppm P)	1.44	Very Low	32.97	Very High	37.49	Very High
8	K_2O HCl 25%	(mg/100g)	2.90	Very Low	18.85	Low	18.93	Low
9	Basic Cations:							
	K-dd	(cmol/kg)	0.07	Very Low	0.46	Medium	0.46	Medium
	Na-dd	(cmol/kg)	0.15	Low	0.25	Low	0.29	Low
	Ca-dd	(cmol/kg)	4.86	Low	8.22	Medium	8.80	Medium
	Mg-dd	(cmol/kg)	2.78	High	3.15	High	3.22	High
10	Cation Exchange Capacity (CEC)	(cmol/kg)	27	High	34.37	High	33.18	High
11	Base Saturation	(%)	29.10	Low	35.02	Low	38.47	Low
12	Al-dd	(cmol/kg)	1.31	-	0.44	-	0.33	-
13	H-dd	(cmol/kg)	0.43	-	0.18	-	0.08	-
14	Al-Saturation	(%)	13.60	High	3.44	Very Low	2.48	Very Low

By contrast, BPP Caringin (R3) soil combined higher organic C, N, and P with low Al saturation, conditions generally associated with improved nutrient availability, nutrient acquisition, and assimilate partitioning to the fruit (Chai et al., 2018; Muhammad et al., 2011). CEC was high at all sites (>27 cmol kg^{-1}), indicating good nutrient-holding capacity; however, at UPTD, Al toxicity likely offset the benefits of high CEC (Rahman & Upadhyaya, 2021).

Slightly elevated K at Karya Alam and BPP Caringin sites may have contributed to the higher sugar content observed in R2 and R3, as K plays central roles in phloem loading, starch–sugar interconversion, and osmotic regulation (Afzaal et al., 2023). Together, these patterns reinforce a G×E framework where genetic potential is either expressed or suppressed by edaphic context—a dynamic reported in mango, papaya, and rambutan nutrient profiles (Aziz & Jalil, 2019; Mistriyani et al., 2021).

3.4 Multivariate analyses: PCA and MGIDI evaluation

PCA condensed the twelve nutritional variables into three principal components explaining 100% of total variance (Table 6). PC1 (58.1%) was primarily associated with carbohydrate and caloric traits, confirming that carbohydrates are the primary drivers of nutritional differentiation and play a crucial role in various metabolic processes in these samples (Khakimov et al., 2016; Maldonado-Celis et al., 2019). PC2 (29.6%) grouped fat and vitamin C, suggesting co-regulation during ripening or metabolic trade-offs between lipid fractions and antioxidant pools (Villa-Rodríguez et al., 2011; Pal et al., 2012). The decline in antioxidant enzymes and the increase in lipid peroxidation during ripening indicate a

metabolic trade-off between maintaining lipid integrity and antioxidant defenses (Villa-Rodríguez et al., 2011). PC3 (12.3%) isolated protein-related variation, which is often soil-N-sensitive (Souza et al., 2016). The relationship between nitrogen and protein content highlights the importance of soil-N in determining protein levels and overall plant health (Souza et al., 2016; Asthir et al., 2017).

Table 6. Principal component analysis (PCA) of nutritional traits in rambutan fruit

PC	Eigenvalues	Variance (%)	Cumulative Variance (%)
PC1	6.97	58.1	58.1
PC2	3.55	29.6	87.7
PC3	1.47	12.3	100

As part of the MGIDI procedure, factor analysis (varimax rotation) was performed to summarize the correlation structure among the evaluated nutritional traits into latent factors prior to estimating the distance between each sample and the nutritional ideotype (Table 7). The extracted factors represent the computational basis of the MGIDI algorithm rather than independent biological groups. Their primary role is to integrate correlated variables into a reduced set of latent factors used for calculating the Multi-trait Genotype–Ideotype Distance (Olivoto & Nardino, 2021; Debnath et al., 2024; Nasution et al., 2025).

Table 7. Factor loadings obtained from the factor analysis used in the MGIDI procedure

No	Var	FA1	FA2	FA3
1	Protein Content (%)	-0.27	-0.04	**-0.96**
2	Fat Content (%)	0.20	**-0.98**	-0.05
3	Total Sugar (%)	-0.14	0.07	**-0.99**
4	Total Soluble Solids (°Brix)	0.39	**0.65**	0.65
5	Water Content (%)	**0.95**	-0.13	0.29
6	Ash Content (%)	0.64	-0.39	**0.66**
7	Carbohydrate Content	**-0.95**	0.28	-0.17
8	Calories from Protein	-0.27	-0.04	**-0.96**
9	Calories from Fat	0.20	**-0.98**	-0.05
10	Calories from Carbohydrates	**-0.95**	0.28	-0.17
11	Total Calories (kcal/100g)	**-0.93**	0.04	-0.36
12	Vitamin C (mg/100g)	-0.39	**0.89**	-0.24

Note: FA1 = Factor analysis1; FA2 = Factor analysis 2; FA3 = Factor analysis 3; Bolded values indicate contributions to the factor analysis

The latent factors generated through factor analysis were subsequently used to calculate the Multi-trait Genotype–Ideotype Distance Index (MGIDI). Among the evaluated samples, R3 ranked closest to the nutritional ideotype, indicating the most balanced combination of desirable nutritional characteristics, whereas R1 showed the greatest distance from the ideotype (Figure 1). Because factor analysis is an integral computational step of the MGIDI algorithm, the resulting ranking reflects the combined contribution of all evaluated nutritional traits rather than the influence of any single variable. This approach

enables a comprehensive assessment of overall nutritional quality by integrating correlated traits into a single selection index while reducing redundancy among variables (Olivoto & Nardino, 2021; D S Raj et al., 2024). Furthermore, the strengths and weaknesses of each sample are presented in Figure 2. R3 indicates strengths in FA3 associated with protein content, total sugar, ash content, and calories from protein.

Collectively, the results demonstrate substantial variation in the nutritional characteristics of the evaluated rambutan samples. Parakan rambutan from BPP Caringin site (R3) exhibited the most favorable nutritional profile, with higher protein, carbohydrate, and caloric values, whereas Tangkue (R4) was distinguished by its higher vitamin C content and total soluble solids (TSS). In contrast, Parakan from UPTD (R1) generally showed lower values for several nutritional traits. The observed differences among the three Parakan samples suggest that local production environments may be associated with distinct nutritional profiles, whereas the contrast between Parakan and Tangkue indicates additional cultivar-related variation. However, the relative contribution of cultivar characteristics and agroecological conditions could not be separated within the present experimental design. These findings demonstrate the value of integrating nutritional profiling with multivariate evaluation tools such as MGIDI to identify samples with superior overall nutritional performance. They also provide preliminary evidence supporting the hypothesis that Parakan rambutan may exhibit site-specific nutritional characteristics, which should be validated through controlled multi-location studies using identical planting materials.

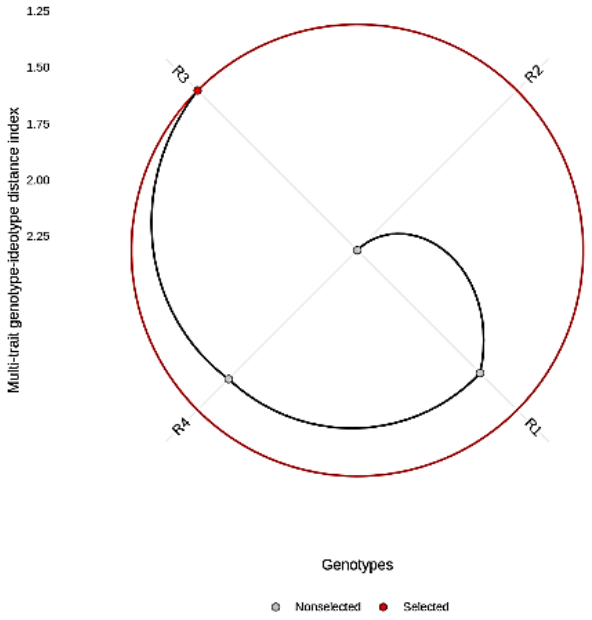


Figure 1. Multi-trait Genotype-Ideotype Distance Index (MGIDI) plot of rambutan genotypes based on proximity to the nutritional ideotype

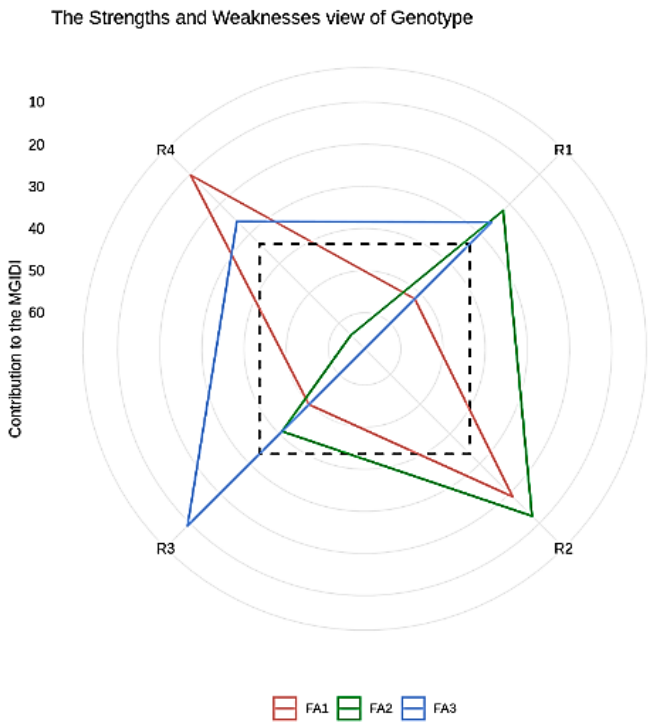


Figure 2. The strengths and weaknesses of the selected genotypes is shown as the proportion of each factor on the computed Multi-trait Genotype–Ideotype Distance Index (MGIDI).

4. Conclusions

This study demonstrated substantial variation in the nutritional composition of rambutan samples collected from different production locations. Among the evaluated samples, Parakan rambutan from the BPP Caringin site (R3) exhibited the most favorable overall nutritional profile, whereas Tangkue (R4) showed the highest vitamin C concentration and total soluble solids. The observed differences among the three Parakan production sites suggest that local agroecological conditions may be associated with site-specific nutritional profiles, although their effects could not be separated from cultivar characteristics within the scope of this study. MGIDI analysis successfully identified R3 as the sample closest to the predefined nutritional ideotype, demonstrating the usefulness of multivariate evaluation for integrating multiple nutritional traits into a comprehensive assessment. These findings provide a useful basis for future multi-location validation and for developing cultivation strategies aimed at improving rambutan fruit nutritional quality.

5. Acknowledgements

The authors extend their sincere gratitude to the Department of Agriculture and Food Security of Tangerang Regency for granting access to the research sites and supporting the fieldwork activities. Special thanks are also due to the technical staff and laboratory

personnel whose dedicated assistance in sample collection and analysis greatly contributed to the success of this study. This research was conducted under the ELSA program of the National Research and Innovation Agency (BRIN) and carried out as part of an ongoing collaboration with the Banten Regency Government.

6. Authors' Contributions

Conceptualization: D.W.U., A.J.S., A.M., A.S., and R.J.
Methodology: H.M., A.D., L.R., and E.S.
Investigation: H.M., A.D., L.R., E.Su., and A.M.
Data Curation and Software: A.D. and A.Y.
Formal Analysis: H.M., A.D., and A.M.
Resources and Field Coordination: R.J., A.S., A.J.S., and E.Su.
Project Administration: R.J. and A.S.
Supervision: D.W.U., A.M., and A.J.S.
Writing – Original Draft: A.D. and H.M.
Writing – Review & Editing: A.M., D.W.U., L.R., A.S., and E.S.

ORCID
Ady Daryanto https://orcid.org/0000-0001-6698-3300
Haris Maulana https://orcid.org/0000-0002-0446-6786
Araz Meilin https://orcid.org/0000-0001-7084-1540
Dwinita Wikan Utami https://orcid.org/0000-0002-5873-0570
Lia Ratnawati https://orcid.org/0000-0002-9293-6556
Enny Sholichah https://orcid.org/0000-0002-9902-7873
Achmat Sarifudin https://orcid.org/0000-0002-9964-517X
Andrew Yoel https://orcid.org/0000-0002-8876-6013

7. Conflicts of Interest

The authors declare no conflicts of interest related to the research, authorship, or publication of this manuscript. All authors have read and approved the final version of the manuscript.

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