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Nutritional and sensory characteristics of local and hybrid East African Highland cooking bananas: Implications for breeding programs

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Abstract

Background: Bananas (*Musa* species) are an important staple food and cash crop in many parts of the world. The East African Highland cooking bananas form the backbone of food security for millions of Ugandans. The demand for high quality cooking bananas is thus closely linked to their sensory characteristics (which drive consumer preference) and physicochemical properties, which, on the other hand, influence their nutritional and culinary values. We explored the relationship between nutritional composition, sensory characteristics, and physicochemical properties of 23 cooking banana cultivars from Uganda. These included officially released hybrids ($n = 2$), hybrids under evaluation ($n = 12$), female parent cultivars used in breeding ($n = 3$), and popular local East African Highland bananas ($n = 6$).

Results: Local cultivars (Mpologoma, Mbwazirume, and Muvubo) had significantly higher moisture, crude fat, ash, protein, and amylose contents compared to the hybrids ($p < 0.05$). Hybrid cultivars (N2, N6, and M33) had the highest dry matter contents, while the other hybrid cultivars had higher phenolic contents. Sensory evaluation identified key desirable characteristics of cooked bananas to be color, texture, aroma, taste, and astringency. Some hybrid cultivars (N21, N15, N11, N8, 17914S-24, N2, and N6) had lower sensory scores compared to others (M32, N17, M9, M33, and N24) and the local cultivars. Principal component analysis and Pearson correlation revealed positive relationships between physicochemical properties (titratable acidity, pH, phenols, tannins, starch, amylose, moisture, and minerals composition) and desirable sensory characteristics (yellow homogeneous color, sweet and matooke tastes, and low astringency).

Conclusion: Breeders could select for the attributes with positive relationships to enhance the adoption and consumption of the hybrid cooking bananas. However, further work is needed to establish the acceptability thresholds of the attributes.

KEYWORDS
astringency, East African Highland bananas, phenolic compounds, proximate composition

INTRODUCTION

Bananas are elongated edible berries that are informally considered to be fruits. They are produced by large tree-like vegetatively propagated herbaceous flowering plants in the *Musa* taxon.[1] Archaeological evidence indicates that bananas were first domesticated by farmers in Southeast Asia around 7000 years ago, and later spread to other parts of the world through migration and travel.[2,3] To date, bananas remain an important staple food and cash crop in many parts of the developing world.[4,5] In Uganda, the East African Highland cooking bananas (called matooke in the Luganda dialect) form the backbone of national food security.[6] They are used as cultural artifacts, a source of income and employment, and are consumed as a primary carbohydrate source.[7,8] The demand for high quality cooking bananas (COB) is thus closely linked to their sensory characteristics, which drive consumer preference, and physicochemical properties, which influence their nutritional and culinary values.[9] For example, cooked matooke is distinguished by its unique insipid taste, aroma, soft texture, and golden-yellow color, collectively referred to as "tookeness."[8,10]

In recent years, there has been increasing interest in banana breeding programs aimed at improving the agronomic performances, pests, diseases and drought resistance, and food quality of banana cultivars.[4,5,10–14] In Uganda, hybrid banana cultivars known as NARITAs have been developed to enhance resistance to pests and diseases while maintaining or improving the sensory and nutritional qualities expected by consumers.[15,16] However, the adoption of these hybrid varieties has been suboptimal due to the perception that their sensory attributes are inferior to those of local cultivars.[17] Therefore, understanding the relationship between the sensory characteristics and physicochemical properties of these hybrid and local COB is central to the success of breeding programs and meeting consumer preferences.[10,18–20]

The physicochemical properties of COB (such as moisture content, dry matter, starch composition, and phenolic compounds) are key determinants of their nutritional value and culinary performance. These could directly influence the sensory attributes of COB (for example, texture, taste, aroma, and appearance), which drive consumer acceptance.[14,20] Sensory evaluation using trained panelists provide valuable insights into consumer preferences and enable breeders to identify the most desirable traits for future cultivar development.[13,16,21] Furthermore, correlating sensory characteristics with physicochemical properties allow breeders to decisively select hybrids that meet both agronomic and sensory quality standards.

Previous studies in our group[9,10,14,19–21] used qualitative mixed and quantitative research methods to identify the preferred characteristics of COB by consumers. The present study focused on 23 COB cultivars to investigate the relationship between nutritional attributes, physicochemical and sensory properties. Nowakunda et al.[14] recently evaluated local and released hybrid COB. In contrast, the present study assessed 12 hybrids under evaluation alongside local and released cultivars with established characteristics. The focus was on genotypes still under selection at the time, and thus this study provides breeders with data on the physicochemical and sensory attributes that may influence adoption potential of the 12 improved hybrids.

MATERIALS AND METHODS

Banana samples

The hybrids and local cultivars were chosen based on our previous breeding programs, agronomic performance, and their role as female parents in hybrid development targeting improved yields and disease resistance. Three mature green bunches per cultivar of COB were harvested from Kawanda and Sendusu trial stations in Uganda. A total of 23 cultivars were evaluated and these included:

a. Two officially released hybrids (M30 and M9), which were selected due to their higher acceptability,[12,14,22,23]
b. Twelve hybrids of COB under evaluation, that is, NARITAs (N17, N24, N2, N6, N8, N11, N14, N15, N21), NABIOs (M32 and M33), and 17914S-24,
c. Three female parents used in breeding (Nakawere, Kabucuragye, and Enzirabahima),
d. Six local COB cultivars as controls (Nakitembe, Kibuzi, Muvubo, Nfuuka, Mbwazirume, and Mpologoma).

The bunches were labelled and transported to National Agricultural Research Laboratories-Kawanda, Uganda, between 8:00 am and 10:00 am for analysis.

Morphometric traits

A total of nine fingers from each experimental block were sampled for morphometric measurements according to the protocol of Dadzie and Orchard.[24] Briefly, finger circumference and length were measured using a tape measure. Pulp and peel weight were determined by hand peeling the fingers and then separately measuring their weights using a digital analytical balance. The weights of the pulp and peel were expressed as a ratio. Peel thickness was measured using a micro-caliper across the transversely cut banana fruit.

Preparation of banana flour

Banana flours of the individual cultivars were prepared according to the procedure of Belayneh et al.[25] The second hand of each cultivar was used to prepare a composite sample of 15 fingers for physicochemical analysis since fingers from the second hand have the least variations. Five fingers per cultivar were peeled and their pulp sliced with a stainless-steel knife, placed on sterile plastic petri plates, and kept in a drier (JW-1350ED, KOREA) for 48 h at 40°C. The dry slices were ground in a mortar and sieved throug a 0.2 mm mesh sieve (Kenpoly Manufacturers Ltd., Nairobi, Kenya). The fine powder was then kept in 15 mL plastic tubes at room temperature for further analysis of proximate and chemical composition.

Physicochemical composition of the banana flours

Total soluble solids

The total soluble solids (TSS) were measured following the method adopted from Ssemwanga et al.[11] The pulp sample (50 g) was thoroughly crushed using a blender (Snijders Labs, Tilburg, The Netherlands) in 50 mL of deionized water for 2 min. The blend was filtered through Whatman No. 1 filter paper. A single drop of the filtrate at room temperature (24°C) was placed on a prism of a calibrated handheld refractometer (Leica Buffalo, NY 14215 0-50 Brix, USA), and the reading was recorded.

Sample pH and titratable acidity

The pH of the filtrate from TSS sample preparation was determined using a calibrated EcoTestr pH 2 meter (Oakton 35423-10; Oakton Instruments, Vernon Hills, IL 60061, USA). Sample pH was measured at 24°C by submerging the tip of the probe into the sample for 2 min until a stable reading was registered on the pH meter LCD display.

Titratable acidity (TA) was determined by titrating 6 mL of the filtrate against 0.1 N sodium hydroxide solution to the phenolphthalein end point. The percentage TA was calculated as malic acid equivalent using the formula:

$$\mathrm{TA} = (\text{Titer volume} \times \text{Normality of sodium hydroxide} \times 0.067 \times 100)/\text{Sample volume}.$$

From which 0.067 is the factor of malic acid, the dominant acid in bananas.

Proximate analysis and chemical composition of banana flours

The following proximate parameters were determined and expressed on a dry weight basis using standard methods: dry matter content (AOAC, 2000; Method No. 44-15A), crude fat (AOAC, 2000; Method No. 920.39), crude protein content (micro-Kjeldahl; AOAC, 2004), total ash (AOAC, 2000; Method No. 923.03).[26,27] On the other hand, the chemical compositions of the flours were determined as follows: starch content (AOAC, 2000; Method No. 996.11), amylose content by spectrophotometric assay,[27] crude fibre (AOAC, 2000; Method No. 962.09), colour values (Minolta color meter; Minolta CR-10 72311054, Japan) using the L*a*b* notation.[11] Total carbohydrate was calculated by difference,[28] as follows

$$\text{Carbohydrate}\,(\%) = 100 - (\text{protein} + \text{fat} + \text{ash} + \text{crude fiber}).$$

Extraction of phytochemicals in banana flours

The dried sample (200 mg) was weighed out into a 15 mL falcon tube, and 1.8 mL of 80% methanol was added. The tube was gently sonicated in an ultrasonic water bath (Bandelin Sonorex, Berlin, Germany; 35 kHz, 25 ± 2°C) for 1 h to extract polyphenols. After extraction, the tube was allowed to stand overnight, and the supernatant was pipetted and kept in dark in a refrigerator at 4°C.

Quantification of total tannins

Total tannins were determined using the Folin–Denis method.[29] To the supernatant obtained above, 100 µL of Folin–Denis reagent (Sigma-Aldrich, St. Louis, MO 63118, USA) was added, followed by 200 µL of a 7.5% sodium carbonate solution. It was thoroughly mixed and diluted to a final volume of 2 mL with deionized water. The solution was mixed again, allowed to stand at room temperature for 30 min, and its absorbance was measured at 760 nm on a Jenway 7200 Visible 72 Series Diode Array Scanning Spectrophotometer (Cole-Parmer, Vernon Hills, IL, USA).

For standard solution preparation, a stock solution of 0.5 mg/mL tannic acid (Acros Organics Bvba, Geel, Belgium) was used. Standard solutions were prepared by pipetting 10, 20, 30, 40, and 50 µL of the stock solution into separate test tubes and diluting each to 1 mL with deionized water. Subsequently, 500 µL of Folin–Denis reagent and 2.5 mL of 20% sodium carbonate solution were added to each test tube, and the contents were mixed. After incubation at room temperature for 30 min, the absorbance of each solution was measured at 760 nm. A standard calibration curve was generated from the absorbance values, and the total tannin content of the samples was calculated in mg tannic acid equivalent per 100 g (TA mg/100 g).

Determination of total phenolic content

The total phenolic content (TPC) was determined using the Folin–Ciocalteu method.[30] Briefly, 20 µL of the banana extract solution was mixed with 900 µL of Folin–Ciocalteu reagent (Loba Chemie Pvt. Ltd., Mumbai, India). The reagent was diluted 10 times with deionized water. After standing at room temperature for 5 min, 600 µL of a 7.5% (w/v) sodium carbonate solution was added, and then thoroughly mixed. The solution was left to stand for 1 h at room temperature.

The absorbance was measured at 765 nm on an ultraviolet–visible (UV–Vis) spectrophotometer,[31] and the TPC was extrapolated from a standard curve generated using standard gallic acid solutions (20, 40, 60, 80, and 100 mg/L). The standard stock solution was prepared by dissolving 10 mg of gallic acid (Honeywell Research Chemicals, Seelze, Germany) in 1 mL of deionized water. Results were expressed on a dry weight basis as mg of gallic acid equivalents (GAE) per 100 g of sample.

Determination of total flavonoid content

The total flavonoid content (TFC) was determined colorimetrically following the method of Zhishen et al.[32] A pipetted 250 µL aliquot of

banana extract was transferred into a test tube and mixed with 1 mL of deionized water. Next, 75 µL of 5% (w/v) sodium nitrite was added, and after 5 min, 75 µL of 10% (w/v) aluminium chloride solution was introduced. After 1 min, 500 µL of 1 M sodium hydroxide solution was added, and the final volume was adjusted to 2.5 mL with deionized water. The solution was mixed thoroughly, and its absorbance was measured at 510 nm on a UV–vis spectrophotometer. A calibration curve was prepared using catechin (Sigma-Aldrich, Tokyo, Japan) at concentrations of 20, 40, 60, 80, and 100 mg/L. The TFC was expressed in mg catechin equivalents (CE) per 100 g of dry sample.

Mineral analysis

Mineral content was analyzed using the closed-tube digestion method followed by microwave plasma-atomic emission spectrometry.[33,34] For each cultivar, 250 mg of the dried sample was digested with 2 mL of 69% nitric acid and 500 µL of 30% hydrogen peroxide in a 15 mL HDPE tube. It was digested overnight, heated in a digestion block at 80°C for 30 min and then 125°C for 2 h. The digest was diluted to 25 mL with deionized water, agitated, and decanted for analysis using a microwave plasma-atomic emission spectrometer (4100 MP-AES; Agilent Technologies, Mulgrave, Australia). The instrument was configured with appropriate hollow cathode lamps for the target minerals and operated under standardized conditions: 1 kW power, plasma argon flow at 20 L/min, auxiliary argon flow at 1.5 L/min, nebulizer argon flow at 0.55–1 L/min, sample flow rate at 0.9 mL/min, axial optics, and an integration time of 3 s across 3 readings.

Texture and sensory analysis

Cooked bananas were prepared using the traditional steam-and-mash method described by Gafuma et al.[35] and Nowakunda et al.[36] with slight modifications. Clusters from the same bunch used for physicochemical analysis were sampled for texture evaluation. For each cultivar, 6 kg of green banana fingers was washed in potable water, peeled to obtain about 3 kg of peeled bananas, which was wrapped in a layer of fresh banana leaves. An aluminum saucepan was filled with 10 L of portable water, and the wrapped bananas were placed on a porous metallic tray inside the saucepan. The saucepan and its contents were warmed on a gas stove for 15 min to ensure uniform distribution of heat in the saucepan. Bananas were then cooked by steaming over water heated to 100°C in a saucepan for 1 h.[36] Steamed banana fingers were mashed manually for 2 min and then simmered for an hour before texture and sensory analysis. This was done at a very low fire to keep them from cooling.[36]

Hardness, cohesiveness (moldability), and adhesiveness (stickiness) of the cooked bananas were determined using the texture profile analysis method.[37] At the end of the simmering, the mashed steamed bananas were scooped from the banana leaves with a stainless-steel spoon and put into a metallic dish of 7 cm diameter and 1.5 cm height. The dish was leveled using a meter ruler. A hollow tube of diameter 4.5 cm and height 7.7 cm was used to cut out a cylindrically shaped sample, which was placed on a measuring table under a 6 cm cylindrical probe of the texture analyzer (Mecmesin RH13OSZ 18-1020-08, West Sussex, UK). The probe was operated in the downward movement at a rate of 60 mm/min and allowed to deform the sample 3 mm deep. The maximum force needed to cause the deformation was recorded as the hardness of the sample. The sample was rested for 10 s by upward movement of the probe to enable sample recovery from deformation. The sample was then subjected to the second compression, and the maximum negative and/or opposite force exerted on the probe was recorded as its adhesiveness.

Sensory profiling was done using Quantitative Descriptive Analysis.[38] A pre-selection survey of sensory panelists was done to collect panelist biodata, identify their days of availability during the week, eating habits, health status in regard to foods they are allergic to, and to get their consent to participate in the sensory training and evaluation exercise. Eighteen panelists were recruited and subjected to a 35-h training on basic tastes (sweet, salty, sourness, astringency, and bitterness). They were trained on the identification of basic tastes and aromas, basic taste thresholds, ranking tests, and triangle tests before they evaluated the cooked bananas. Panelists were trained and assessed on the basis of functional taste buds using dilute solutions of basic tastes: sourness (tartaric acid at 6 g/L), bitterness (quinine at 0.06 g/L), salty (sodium chloride at 7.5 g/L), sweetness (sucrose at 6 g/L), and astringency (aluminium potassium sulfate dodecahydrate at 5 g/L).

Panelists were evaluated for repeatability using XLSTAT (version 2019.3.2.62913) sensory analysis tool bar and only 13 panelists were retained based on screening tests assessing sensory acuity, consistency, and availability for all evaluation sessions. The selected panelists were taken through a series of tests involving non-experimental bananas to allow them to identify and learn the various descriptors of banana quality characteristics and to generate a sensory vocabulary from which sensory descriptors adopted on the scale were built. Experimental samples were coded with four digits to eliminate name bias and presented to the panelists in a random order. The samples were served to individual panelists along with an evaluation form, a pencil, and water for rinsing their mouths in between sample tasting. Panelists were tasked to assess the different cooked banana samples on the basis of eating qualities on an 11-point category scale with verbal anchors as category labels.[39] The scale ranged from 0 to 10, where 0 represented the complete absence of the quality characteristic, while 10 represented its extreme intensity. Panelists assessed one sample at a time. On a daily basis, a total of four cooked banana samples (inclusive of a control sample in each testing shift) were served in a random sequence to reduce bias. The sensory characteristics evaluated as generated by the panel included aroma, color, color uniformity, taste (sweetness and astringency), mouth feel (softness and smoothness), impression (mouth feel), texture by hand (stickiness and lumpiness), and texture in the mouth (softness).[20]

Statistical analysis

Results were presented as mean ± standard error of three independent determinations from biological replicates. One way analysis of

TABLE 1 Physical characteristics of selected local and hybrid banana cultivars sampled in the study.

Cultivar	Finger length (cm)	Finger circumference (cm)	Peel thickness (mm)	Pulp/peel ratio
N2	18.15 ± 0.61^{fghi}	12.60 ± 0.12^{fgh}	2.96 ± 0.06^{ef}	1.54 ± 0.04^{cdef}
N6	13.40 ± 0.09^{k}	11.10 ± 0.60^{l}	3.30 ± 0.33^{de}	1.37 ± 0.03^{ef}
N8	20.80 ± 0.33^{bcde}	12.15 ± 0.15^{hij}	2.25 ± 0.09^{g}	1.78 ± 0.12^{abcd}
N11	20.85 ± 0.42^{bcde}	11.35 ± 0.35^{kl}	3.61 ± 0.12^{bcd}	1.79 ± 0.09^{abcd}
N14	22.50 ± 0.41^{b}	12.00 ± 0.24^{hijk}	3.53 ± 0.17^{bcd}	1.69 ± 0.04^{abcde}
N15	18.90 ± 0.10^{defghi}	12.25 ± 0.12^{ghij}	2.93 ± 0.15^{f}	1.56 ± 0.03^{cdef}
N17	21.00 ± 0.33^{bcd}	13.60 ± 0.20^{de}	2.83 ± 0.18^{f}	2.03 ± 0.22^{a}
N21	17.70 ± 1.80^{ghij}	13.65 ± 0.21^{de}	3.33 ± 0.27^{d}	1.84 ± 0.00^{abcd}
N24	18.40 ± 0.62^{fghi}	11.75 ± 0.12^{ijkl}	1.83 ± 0.09^{h}	2.01 ± 0.34^{ab}
M9	20.17 ± 0.89^{bcdef}	14.00 ± 0.38^{cd}	2.13 ± 0.01^{gh}	1.54 ± 0.09^{cdef}
M30	19.10 ± 0.68^{cdefgh}	12.50 ± 0.30^{fghi}	2.13 ± 0.00^{gh}	1.57 ± 0.03^{cde}
M32	16.55 ± 0.87^{ij}	12.95 ± 0.12^{efg}	3.77 ± 0.50^{bc}	1.54 ± 0.19^{cdef}
M33	15.55 ± 0.52^{jk}	12.60 ± 0.12^{fgh}	3.61 ± 0.21^{bcd}	1.50 ± 0.03^{cdef}
17914S-24	17.00 ± 0.47^{hij}	12.05 ± 0.15^{hijk}	1.83 ± 0.07^{h}	1.74 ± 0.24^{abcde}
Muvubo	19.50 ± 0.39^{cdefg}	13.50 ± 0.22^{de}	4.42 ± 0.15^{a}	1.38 ± 0.13^{ef}
Kibuzi	20.80 ± 0.42^{bcde}	14.65 ± 0.15^{bc}	3.73 ± 0.06^{bc}	1.87 ± 0.04^{abc}
Nakitembe	21.30 ± 0.88^{bc}	14.90 ± 0.25^{b}	3.72 ± 0.14^{bc}	1.69 ± 0.05^{abcde}
Mpologoma	27.25 ± 0.46^{a}	13.65 ± 0.25^{de}	3.89 ± 0.18^{b}	1.64 ± 0.03^{bcde}
Nfuuka	19.20 ± 0.76^{cdefgh}	14.15 ± 0.05^{bcd}	3.65 ± 0.04^{bcd}	1.46 ± 0.04^{def}
Mbwazirume	13.25 ± 0.05^{k}	13.05 ± 0.15^{ef}	2.14 ± 0.01^{gh}	1.54 ± 0.01^{cdef}
Kabucuragye	18.55 ± 0.25^{efghi}	12.10 ± 0.10^{hijk}	3.51 ± 0.06^{cd}	1.36 ± 0.14^{ef}
Enzirabahima	17.15 ± 0.45^{ghij}	13.05 ± 0.25^{ef}	2.12 ± 0.01^{gh}	1.83 ± 0.05^{abcd}
Nakawere	16.95 ± 0.69^{hij}	11.60 ± 0.08^{jkl}	3.35 ± 0.09^{d}	1.18 ± 0.07^{f}

Note: Values are expressed as mean ± standard error ($n = 3$ biological replicates). Means within a column with different superscript letters differ significantly ($p < 0.05$).

variance (ANOVA) was performed to identify significant differences among the nutritional, physicochemical, and sensory characteristics of the cooked bananas. Pearson's bivariate correlation analysis was used to determine the sensory characteristics associated with the physicochemical properties of COB. Principal Component Analysis was further performed to visually explore the most important sensory characteristics and physicochemical properties of the different cultivars. Eigenvalues were used to establish clusters and explain the variability within each cluster. All statistical evaluations and data visualization proceeded in XLSTAT (version 2019.3.2.62913) and Origin Pro 2026 for Windows (OriginLab Corporation, Northampton, MA) at $p < 0.05$.

RESULTS AND DISCUSSION

Physical characteristics of the banana cultivars

Finger length ranged from 13.25 to 27.25 cm (Table 1). The morphological variations that were observed could be attributed to the size differences among the cultivars. Specifically, hybrids (M9, N8, N11, N14, and N17) produced significantly longer fingers than the local cultivars apart from Mpologoma, Nakitembe, and Kibuzi ($p < 0.05$). Based on encountered literature, Mpologoma and Nakitembe belong to the Musakala and Nakitembe clone sets which are characterised by fingers longer than 20 cm and 15–20 cm, respectively.[40] Our results indicate that the above hybrid cultivars might have a competitive advantage in the market over the local cultivars because consumers prefer COB with long fingers.[10,24,41]

The measured finger circumferences were between 11.10 and 14.90 cm (Table 1). Hybrids N6, N11, and the local cultivar Nakawere had the smallest finger circumferences. The finger circumferences of local cultivars such as Nakitembe, Mpologoma, Nfuuka, Muvubo, and Kibuzi were not significantly larger than some of the hybrid cultivars such as M9, N17, and N21 ($p > 0.05$). Cultivars with larger finger circumferences and lengths are mostly desired by consumers due to their high dry matter content, and thus higher yields of the edible portion.[10] This is usually dictated by banana growth conditions such as soil fertility, climate, and fruit maturity.[24,41]

Regarding the measured peel thickness, the values were between 1.83 and 4.42 mm (Table 1). Mpologoma, Kibuzi, Muvubo, and Nakitembe peels were not significantly thicker than the hybrids (N11, N14, M32, and M33) ($p < 0.05$). Hybrids (17914S-24, M9, M30, N8, and N24) had thin peels that were not significantly different from

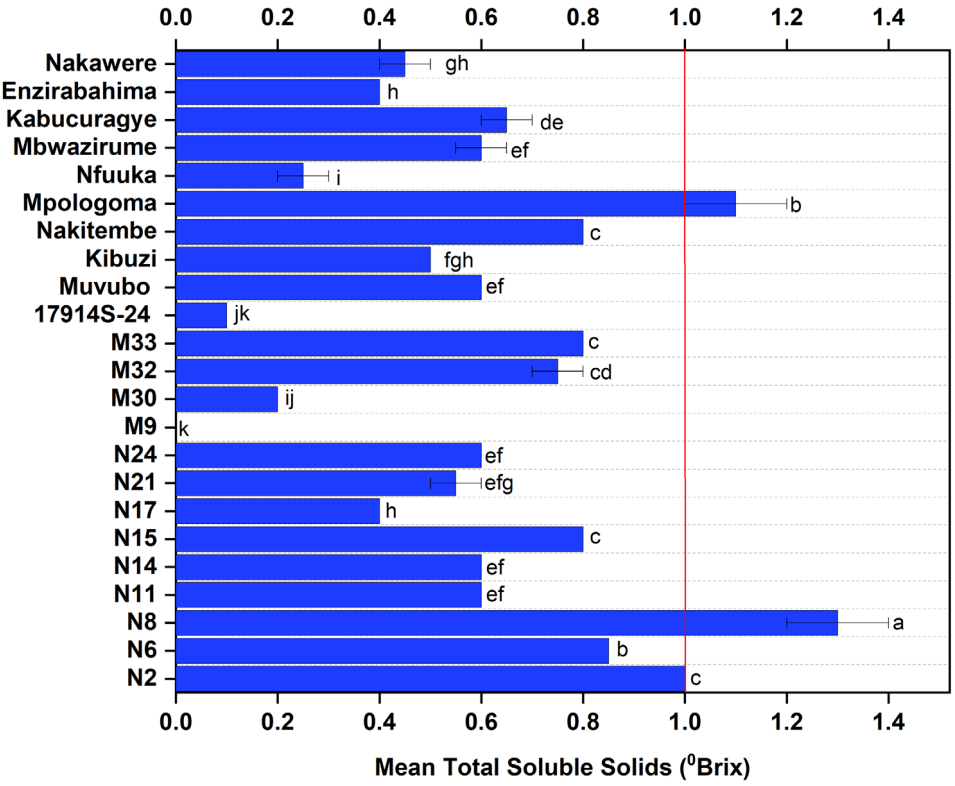

FIGURE 1 Mean total soluble solids of the banana cultivars. Means with no error bars had standard errors of 0.00. Bars with different alphabetical letters are statistically different as per one way analysis of variance (ANOVA) results ($p < 0.05$). The line at 1.0 °Brix indicates the threshold mentioned in the text.

Enzirabahima and Mbwazirume ($p > 0.05$). Banana fingers with thinner skins are easier to remove, making them more appealing to food preparers.[10,24,25,40]

The pulp to peel ratio was in the range of 1.18 to 2.03. Individually, hybrids (17914S-24, N2, N8, N17, and N24) and landraces (Enzirabahima and Kibuzi) had higher pulp to peel ratios, which were significantly different from the landraces (Nakawere, Kabucuragye, Muvubo, and Nfuuka) and hybrids (N6 and M33) ($p < 0.05$). These results agreed with previous reports, which found a pulp/peel ratio of 1.1–1.7 for COB at green physiological maturity.[24,25,42] A higher pulp to peel ratio is indicative of higher pulp yield for food preparation per unit fresh weight, since less material will be discarded as peels.[24,43] Hybrids (N17 and N24) and the landrace Kibuzi, which had the highest pulp to peel ratios, are advantageous for food preparation since consumers prefer bananas with more pulp relative to the peels.[25,44]

Physicochemical characteristics of the banana cultivars

Total soluble solids

The TSS of the raw banana pulp varied from 0.00x to 1.30 °Brix (Figure 1). Statistically, hybrids N8 and N2 had higher TSS (1.00–1.30 °Brix) than M30, 17914S-24, and local cultivars Nfuuka and Enzirabahima. The TSS (sugars) of COB are associated with the degree of their sweetness, which, together with organic acids, influence the sensory perception of taste.[11,45,46] The results obtained in the present study are comparable to those of Aquino et al.[47] who reported TSS of physiologically mature bananas in Brazil to be less than 1 °Brix. The data presented in our study are also close to 1.5–1.7 °Brix for Cardaba, Nijiru, Matoke, and Kitawira COB of Ethiopia.[25,48] Such differences in the TSS of COB may arise from cultivar-specific differences in the physiological maturity at the green stage maturity to analysis. Low TSS values of COB are obtained where samples are analysed at the green maturity stage when only a little starch was hydrolysed to sugars such as fructose, sucrose, and glucose.[49]

pH and titratable acidity

The pH of the raw banana pulp ranged from 5.50 to 6.75 and did not vary significantly ($p > 0.05$) among the COB (Figure 2). These results were comparable with preceding reports,[25,50,51] which found the pH of green mature COB in the range of 4.7 to 6.5. For titratable acidity, cultivars N14, N11, and Kibuzi had the highest values, which were significantly higher ($p < 0.05$) than M30, Enzirabahima, and 17914S-24 (Table 2). TA and pH indicate levels of malic and citric acids, which contribute to the taste of cooked bananas.[24,52]

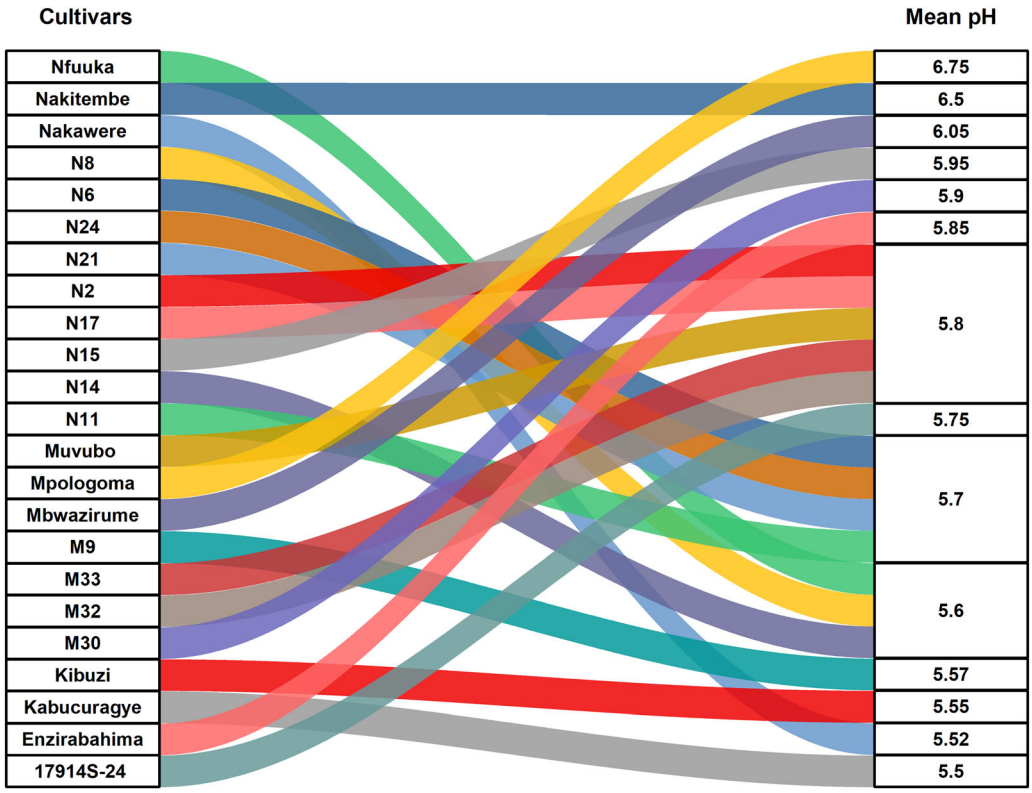

FIGURE 2 Alluvial plot of mean pH values of raw banana pulp from cultivars considered in the present study. The pH values did not vary significantly among the tested cultivars ($p > 0.05$).

Pulp colour

The lightness (L* values) of the banana pulps ranged from 23.45 to 48.00 (Table 2). Hybrids (N15, M33, and N6) had significantly ($p < 0.05$) higher lightness values than M30 and local cultivars (Enzirabahima and Mbwazirume). The a* scale indicated that hybrids were greener than the landraces, which tended to be red ($p < 0.0001$). Moreover, M30 and local cultivars (Enzirabahima and Mbwazirume) exhibited significantly different greenness from the rest of the samples ($p < 0.05$). Interestingly, hybrids (N15, N24, and 17914S-24) had the highest intensity of greenness. All samples under study had positive b* values, indicating a strong dominance of the yellow colour over blue. The data also indicated that there was no significant difference between local and hybrid COB on the basis of yellow pulp colour ($p > 0.05$).

By cultivar, landraces (Nakitembe, Kabucuragye, and Mpologoma) had the highest degree of yellowness, which was significantly higher than that of Enzirabahima, Mbwazirume, and M30 ($p < 0.05$). The yellowness of the pulp for the rest of the hybrids and local COB was not significantly different from each other ($p > 0.05$). The intensity of the yellowness of the pulp could contribute to the desired yellow colour of the cooked matooke meal. Although hybrids (N21, N6, and N11) were dominated by a reddish-brown colour, it was surprising that their intensity of yellowness was not significantly different from those of Nakitembe, Kabucuragye, and Mpologoma, which were completely yellow ($p > 0.05$). This could be due to higher phenolic, carotenoid, and flavonoid contents, and enzymatic oxidation rates in the hybrids, leading to mottled colours of yellow with red and brown.[52,53] Pulp colour of COB is a key quality characteristic in determining the acceptability of matooke.[11] In Uganda, if the pulp colour of matooke is white, it will be rejected by consumers as an immature banana. However, fruits with yellow or deep yellow pulp colour are often accepted as mature COB.[9,11,14,24,54]

Dry matter content

Dry matter content of the COB varied from 19.05% to 28.09% (Table 2). Mpologoma and hybrids N11 and N21 had the lowest dry matter contents. Local cultivars (Nakawere, Muvubo, and Mbwazirume) had strikingly higher dry matter contents, which were, however, not significantly different from those of hybrids N2, N6, and M33. Hybrids (N8, N24, M9, and N17) showed unexpected insignificant differences ($p > 0.05$) in their dry matter content when compared to the local cultivars (Nakitembe, Nfuuka, Kabucuragye, and Enzirabahima). Overall, the dry matter contents observed in this study align with the values reported by Agunbiade et al.[55] and Belayneh et al.,[25] which ranged from 22.9% to 29.0% for COB.

A high dry matter content indicates that the banana has good cooking qualities, a longer shelf life, and a bigger proportion that can be utilized for food preparation.[24,43,56,57] High dry matter content also translates into high bunch weight, yield, and starch content.[58] Since

TABLE 2 Titratable acidity, pulp color, and dry matter content of the banana samples.

Cultivar	Titratable acidity (%)	L*	a*	b*	Dry matter content (%)
N2	0.13 ± 0.01^{de}	46.60 ± 0.40^{abcde}	-14.60 ± 0.80^{cdef}	31.00 ± 0.90^{ab}	28.09 ± 0.31^{a}
N6	0.12 ± 0.01^{def}	47.30 ± 0.25^{abc}	-15.95 ± 0.65^{efg}	29.75 ± 1.95^{ab}	27.94 ± 0.02^{a}
N8	0.11 ± 0.02^{fghi}	45.05 ± 1.05^{bcde}	-14.80 ± 0.20^{def}	28.90 ± 0.10^{ab}	22.33 ± 0.13^{gh}
N11	0.16 ± 0.01^{ab}	46.50 ± 0.80^{abcde}	-15.65 ± 0.15^{efg}	29.80 ± 1.15^{ab}	20.86 ± 0.34^{i}
N14	0.17 ± 0.01^{a}	46.35 ± 1.65^{abcde}	-15.55 ± 0.75^{efg}	31.60 ± 0.00^{ab}	26.86 ± 0.02^{bc}
N15	0.11 ± 0.01^{fghi}	48.00 ± 0.20^{a}	-16.90 ± 0.1^{g}	28.45 ± 0.70^{ab}	24.07 ± 0.09^{f}
N17	0.12 ± 0.01^{efg}	45.80 ± 0.50^{abcde}	-15.25 ± 0.15^{efg}	29.80 ± 1.20^{ab}	23.21 ± 0.34^{fg}
N21	0.13 ± 0.01^{de}	44.55 ± 1.45^{cde}	-14.85 ± 1.15^{defg}	30.55 ± 2.95^{ab}	21.91 ± 0.28^{h}
N24	0.11 ± 0.01^{efgh}	45.80 ± 0.40^{abcde}	-16.25 ± 0.25^{fg}	30.70 ± 3.65^{ab}	22.09 ± 0.34^{h}
M9	0.12 ± 0.00^{def}	44.23 ± 0.85^{de}	-12.73 ± 0.25^{bc}	32.00 ± 0.65^{ab}	24.10 ± 0.33^{f}
M30	0.09 ± 0.01^{j}	23.45 ± 1.20^{f}	-9.60 ± 0.60^{a}	18.35 ± 0.25^{c}	25.19 ± 0.24^{e}
M32	0.15 ± 0.01^{bc}	46.15 ± 1.25^{abcde}	-15.10 ± 0.20^{efg}	31.25 ± 0.90^{ab}	26.24 ± 0.49^{cd}
M33	0.12 ± 0.01^{efg}	47.60 ± 0.50^{ab}	-16.10 ± 0.25^{efg}	30.45 ± 0.75^{ab}	27.49 ± 0.19^{ab}
17914S-24	0.09 ± 0.00^{hij}	47.05 ± 0.04^{abcd}	-16.25 ± 0.25^{fg}	27.25 ± 0.21^{b}	25.54 ± 0.13^{de}
Muvubo	0.14 ± 0.01^{cd}	45.45 ± 0.25^{abcde}	-12.90 ± 0.40^{bcd}	31.80 ± 1.15^{ab}	26.81 ± 1.02^{bc}
Kibuzi	0.16 ± 0.00^{abc}	46.50 ± 0.70^{abcde}	-14.95 ± 0.05^{defg}	31.20 ± 0.60^{ab}	22.82 ± 0.05^{gh}
Nakitembe	0.13 ± 0.01^{de}	44.00 ± 0.70^{e}	-12.05 ± 1.15^{b}	33.15 ± 1.55^{a}	22.06 ± 0.08^{h}
Mpologoma	0.11 ± 0.00^{efgh}	45.15 ± 0.75^{abcde}	-14.10 ± 0.20^{bcde}	32.15 ± 2.75^{ab}	19.05 ± 0.36^{j}
Nfuuka	0.11 ± 0.01^{fghi}	47.20 ± 0.10^{abc}	-16.15 ± 0.60^{efg}	30.00 ± 0.05^{ab}	23.24 ± 0.13^{fg}
Mbwazirume	0.10 ± 0.00^{fghij}	24.15 ± 1.15^{f}	-9.65 ± 0.25^{a}	19.55 ± 1.40^{c}	26.38 ± 0.21^{cd}
Kabucuragye	0.10 ± 0.00^{ghij}	43.80 ± 0.80^{e}	-12.20 ± 1.50^{b}	33.10 ± 1.90^{a}	23.91 ± 0.39^{f}
Enzirabahima	0.09 ± 0.00^{ij}	23.70 ± 0.80^{f}	-9.15 ± 0.50^{a}	20.25 ± 0.90^{c}	23.85 ± 0.37^{f}
Nakawere	0.10 ± 0.00^{ghij}	47.10 ± 1.30^{abcd}	-15.70 ± 0.40^{efg}	29.55 ± 2.20^{ab}	27.66 ± 0.24^{ab}

Note: Values are expressed as mean ± standard error ($n = 3$ biological replicates). L*, a*, and b* are CIE colour coordinates, where L* = lightness, a* = green (−) to red (+), and b* = blue (−) to yellow (+). Means within a column carrying different superscript letters differ significantly as per one way analysis of variance (ANOVA) ($p < 0.05$).

the dry matter contents of hybrids (N8, N24, and N17) were not significantly different from those of the locally consumed cultivars ($p > 0.05$), they are well suited for preparing cooked matooke. By implication, dry matter analysis could serve as a key determinant of consumer acceptability in future studies on matooke.

Proximate composition of the COB

The proximate composition of COB provides essential information about their nutritional value, which can be used to identify their potential applications in food product development and quality improvement. The individual components are discussed in the following:

Moisture and ash contents

Moisture content ranged from 71.91% to 80.95%, with Mpologoma having the highest value that was significantly different ($p < 0.05$) from that of N2. High moisture content is undesirable because it can lead to excessive softening and a mushy texture of cooked bananas.[59] The ash content varied between 2.61% and 4.93% (Table 3). Local COB (Mpologoma and Mbwazirume) had the highest ash contents, whereas hybrids (N6, N2, and M33) had the lowest ($p < 0.05$). When compared with data from mineral analysis, the former two local cultivars had higher levels of trace and macro elements compared to the rest of the samples. The ash contents obtained were mostly in the range of 0.46% to 4.30% for bananas reported in literature.[28,51,60–62]

Crude fat, proteins, fibres, and total carbohydrates

The crude fat content varied from 0.45% to 0.72%, with Nfuuka, Mpologoma, and Kibuzi having the highest levels, while hybrids (N24 and N11) had the lowest (Table 3). The crude fat contents obtained were consistent with findings from other studies (0.58%–0.94%).[28,60,61,63,64] The current results surpassed 0.0%–0.3% for FHIA hybrids,[62] which may be due to variations among the studied cultivars.

Considering the crude protein contents, the obtained values span from 2.08% to 4.94% on a dry weight basis (Table 3). It was clear that

TABLE 3 Proximate composition of the banana cultivars (expressed on a dry weight basis, except moisture).

Cultivars	Moisture (%)	Ash (%)	Crude fat (%)	Protein (%)	Dietary fiber (%)	Total carbohydrates (%)
N2	71.91 ± 0.31^{h}	2.80 ± 0.00^{k}	0.52 ± 0.02^{defghi}	4.78 ± 0.14^{ab}	1.11 ± 0.12^{de}	90.79 ± 0.03^{gi}
N6	72.07 ± 0.19^{gh}	2.61 ± 0.07^{l}	0.48 ± 0.02^{ghi}	2.97 ± 0.01^{ghi}	1.87 ± 0.37^{abc}	92.07 ± 0.29^{bc}
N8	77.67 ± 0.13^{bcd}	3.58 ± 0.09^{d}	0.47 ± 0.00^{hi}	3.73 ± 0.18^{d}	1.60 ± 0.13^{bcd}	90.67 ± 0.07^{gi}
N11	79.17 ± 0.34^{b}	3.48 ± 0.05^{e}	0.46 ± 0.00^{hi}	3.73 ± 0.05^{d}	1.49 ± 0.01^{bcde}	90.84 ± 0.02^{gi}
N14	73.14 ± 0.39^{fgh}	3.29 ± 0.03^{f}	0.51 ± 0.01^{defghi}	2.84 ± 0.10^{hij}	1.37 ± 0.13^{cde}	91.99 ± 0.18^{bc}
N15	75.93 ± 0.09^{de}	2.85 ± 0.09^{jk}	0.48 ± 0.02^{ghi}	4.00 ± 0.02^{c}	1.60 ± 0.38^{bcd}	91.07 ± 0.15^{fgh}
N17	76.80 ± 0.02^{cd}	2.83 ± 0.01^{jk}	0.49 ± 0.03^{fghi}	2.11 ± 0.07^{l}	1.99 ± 0.25^{ab}	92.58 ± 0.16^{ab}
N21	78.09 ± 0.28^{bc}	3.29 ± 0.00^{f}	0.51 ± 0.01^{efghi}	3.02 ± 0.05^{fghi}	1.96 ± 0.02^{ab}	91.22 ± 0.01^{efgh}
N24	77.90 ± 0.31^{bc}	3.29 ± 0.03^{f}	0.45 ± 0.05^{i}	4.00 ± 0.02^{c}	0.99 ± 0.02^{e}	91.27 ± 0.07^{dfg}
M9	75.94 ± 0.15^{de}	3.54 ± 0.15^{d}	0.58 ± 0.01^{bcdef}	2.13 ± 0.07^{l}	1.71 ± 0.02^{bc}	92.04 ± 0.18^{bc}
M30	74.82 ± 0.33^{ef}	3.73 ± 0.23^{c}	0.57 ± 0.04^{cdefg}	2.63 ± 0.04^{jk}	2.29 ± 0.11^{a}	90.78 ± 0.13^{gi}
M32	73.76 ± 0.49^{fg}	3.27 ± 0.01^{f}	0.59 ± 0.03^{bcde}	4.11 ± 0.14^{c}	1.62 ± 0.12^{bcd}	90.41 ± 0.19^{i}
M33	72.50 ± 0.24^{gh}	2.81 ± 0.13^{k}	0.55 ± 0.03^{defgh}	2.56 ± 0.06^{k}	1.37 ± 0.12^{cde}	92.71 ± 0.06^{a}
17914S-24	74.46 ± 0.02^{ef}	3.45 ± 0.18^{e}	0.58 ± 0.01^{bcdef}	3.43 ± 0.02^{e}	0.99 ± 0.01^{e}	91.55 ± 0.16^{cf}
Muvubo	73.19 ± 0.10^{fgh}	3.44 ± 0.62^{e}	0.58 ± 0.02^{bcdef}	4.94 ± 0.51^{a}	1.74 ± 0.24^{abc}	89.30 ± 0.20^{j}
Kibuzi	77.19 ± 0.05^{cd}	3.16 ± 0.30^{g}	0.67 ± 0.03^{ab}	2.53 ± 0.04^{k}	1.85 ± 0.13^{abc}	91.79 ± 0.03^{cde}
Nakitembe	77.94 ± 0.08^{bc}	2.88 ± 0.02^{j}	0.59 ± 0.03^{bcd}	2.08 ± 0.17^{l}	1.87 ± 0.13^{abc}	92.58 ± 0.10^{ab}
Mpologoma	80.95 ± 0.36^{a}	4.93 ± 0.04^{a}	0.69 ± 0.03^{a}	4.63 ± 0.22^{b}	1.86 ± 0.13^{abc}	87.89 ± 0.03^{k}
Nfuuka	76.76 ± 0.37^{cd}	2.95 ± 0.53^{i}	0.72 ± 0.02^{a}	3.75 ± 0.14^{d}	1.73 ± 0.02^{bc}	90.85 ± 0.16^{gi}
Mbwazirume	73.62 ± 0.21^{fgh}	4.02 ± 0.07^{b}	0.56 ± 0.07^{cdefg}	2.81 ± 0.05^{ij}	1.96 ± 0.27^{ab}	90.65 ± 0.27^{hi}
Kabucuragye	76.09 ± 0.24^{de}	3.09 ± 0.08^{h}	0.65 ± 0.02^{abc}	3.05 ± 0.02^{fgh}	1.37 ± 0.13^{cde}	91.84 ± 0.29^{cd}
Enzirabahima	76.16 ± 0.56^{de}	3.32 ± 0.07^{f}	0.53 ± 0.04^{defghi}	3.19 ± 0.11^{fg}	1.95 ± 0.04^{ab}	91.01 ± 0.01^{fi}
Nakawere	72.34 ± 0.13^{gh}	2.85 ± 0.48^{jk}	0.58 ± 0.02^{bcdef}	3.23 ± 0.09^{ef}	1.61 ± 0.10^{bcd}	91.73 ± 0.58^{cde}

Note: Values are expressed as mean ± standard error ($n = 3$ biological replicates). Means within a column carrying different superscript letters differ significantly as per one way analysis of variance (ANOVA) ($p < 0.05$).

landraces had significantly higher crude protein contents than hybrid cultivars ($p < 0.05$). Muvubo and Mpologoma had the highest crude protein contents, but these were not statistically different from that of N2 ($p > 0.05$). Cultivars N17, M9, and Nakitembe had the lowest crude protein contents. Interestingly, the crude protein content of hybrids (N6, N21, and N14) was not significantly different from that of local COB (Nakawere, Enzirabahima, and Kabucuragye) ($p > 0.05$). The crude protein contents obtained were comparable with literature values of 0.6% to 4.8%.[50,51,60–62,64,65]

The measured crude fibre contents were between 0.99% and 2.29%, with N2, N24, and 17914S-24 having the lowest crude fibre values. Conversely, local cultivars (Mbwazirume, Muvubo, and Kibuzi) had fiber contents that were not significantly different from hybrids such as M30, N17, and N21 ($p > 0.05$). These results were comparable to 0.65% to 2.92% for Ugandan COB.[60,61]

The total carbohydrate content of banana flours calculated by difference ranged from 87.89% ± 0.03% for Mpologoma to 92.71% ± 0.06% for M33 (Table 3). One Way ANOVA showed that there were statistical differences in the carbohydrate contents of the COB ($p < 0.05$), although these contents were comparable. The results showed that carbohydrates were the major nutrients in the COB.

Starch and its composition in the COB

Starch content of the COB was between 63.89% and 73.25% on a dry weight basis (Figure 3; Table S1). The local COB (Nfuuka, Mbwazirume, and Kibuzi) had relatively high starch contents, which were, however, not significantly different from hybrids N15, N17, M9, and M33 ($p > 0.05$). On the other hand, N8, 17914S-24, and N6 had the lowest starch contents. The results of the current study were higher than those reported by Aquino et al.[47] (11%–39.3% dry weight basis for 15 banana cultivars). Nevertheless, the starch content of COB in the present study is slightly lower than 70%–85% reported in previous studies.[51,62,66] High starch content in unripe bananas is associated with hardness after cooking due to starch retrogradation.[35,54,67]

The amylose content (11.73%–33.68%; Figure 4; Table S1) was highest in Mbwazirume, Nfuuka, and Muvubo than N8, M9, and N14 (11.73%, 18.47%, and 18.99%, respectively). In the United Kingdom, Qi et al.[66] also reported amylose contents of Green Cavendish dessert banana and Big Ebanga plantain pulp to be 27.35% and 33.37%, which are comparable to those observed in the present study. The lower amylose content of the hybrids in the present study could contribute to their high cooking abilities due to their low pasting and gelatinization temperatures.[68]

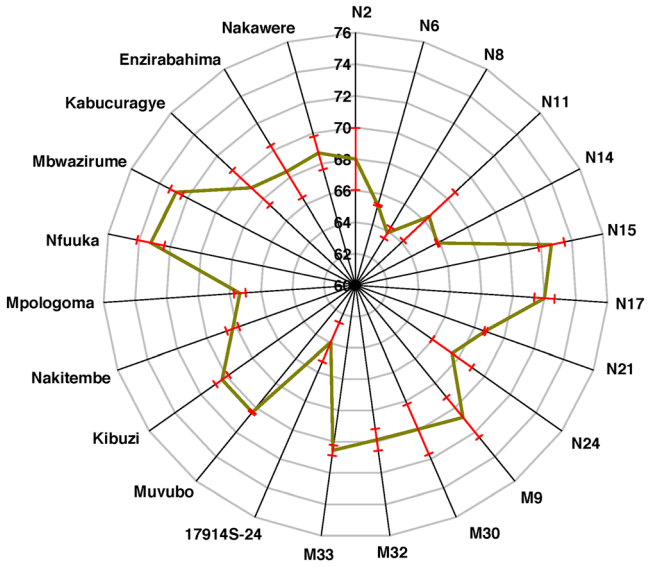

FIGURE 3 Mean starch content (%) of the cooking bananas investigated. Standard error bars are indicated in red.

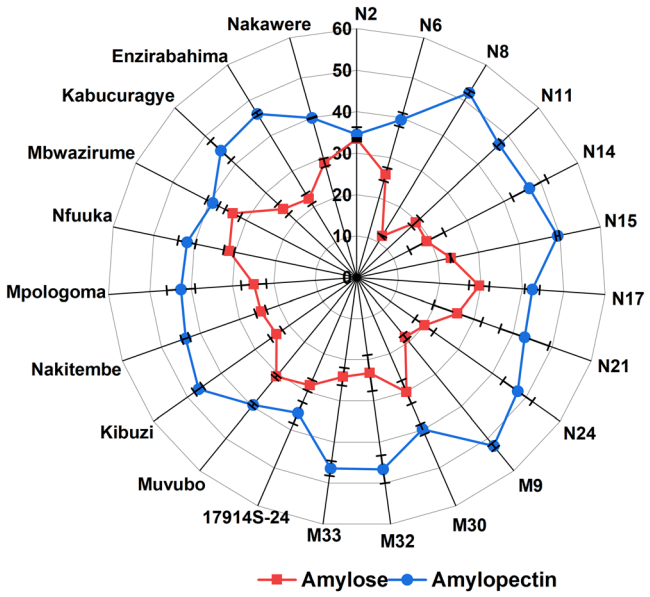

FIGURE 4 Radar plot of mean ± standard error of amylose and amylopectin contents (%) of the cooking banana cultivars.

Considering the amylopectin content, it ranged from 34.53% to 52.31% (Figure 4; Table S1). Hybrids (M9, N8, and N15) tended to have the highest amylopectin contents, while 17914S-24, N2, and Mbwazirume had the lowest contents. Local COB such as Mbwazirume, Nfuuka, Mpologoma, and Nakawere were not significantly ($p > 0.05$) different from some of the hybrid cultivars (M30, 17914S-24, N2, N6, N17, and N21) on the basis of their amylopectin contents. High levels of starch, amylose, and dry matter in food crops have been associated with a harder texture of cooked bananas.[67,69–71] Firmness in raw and cooked food products with high amylose content has been attributed to the transfer of calcium ions to galacturonan and the formation of hydrogen bonds within the plant tissue.[66,72,73] In the present study, Nfuuka and N2, which had high amylose contents, were found to be among the hardest when cooked. Thus, amylose and amylopectin content could be used as indices for predicting firmness in COB.[35] However, more studies are needed to investigate the effect of different amylose/amylopectin ratios on the cooling rate and hardening of cooked matooke products.

Essential mineral composition of the COB

Mineral composition of the banana flour samples in mg/100 g was Zn (0.13–2.53), Ca (10.44–38.59), Fe (0.46–1.25), K (308.29–877.05), Mg (32.90–110.09), and Na (1.83–10.92) (Table S2). Hybrid COB had significantly ($p < 0.05$) higher levels of Zn than local cultivars. Hybrids N11, N21, and N15 had significantly higher levels of Zn than local cultivars (Enzirabahima, Muvubo, and Mbwazirume), which had the lowest. Generally, the Fe content in hybrids was significantly higher than that in the landraces ($p < 0.05$). Cultivars N8, Mpologoma, and N15 had the highest levels of Fe, while Muvubo, Enzirabahima, and Nfuuka had the lowest. Mineral elements (Zn and Fe) together with polyphenols, vitamin C, and carotenoids are free radical scavengers in the human body, preventing loss of cell integrity.[47]

The Ca content of the hybrid cultivars was significantly ($p < 0.05$) different from that in local COB. In particular, N15, N11, and N6 had the highest Ca contents, while local cultivars Mpologoma and Enzirabahima, and hybrids (17914S-24 and N17) had the lowest. Magnesium content of hybrids was mostly higher than in local cultivars. Hybrids N11, N24, and N21 had the highest levels of Mg, while landraces (Nfuuka, Nakitembe, and Enzirabahima) had the lowest. There were no significant differences between local and hybrid COB on the basis of K content ($p > 0.05$). Mpologoma and the hybrids (N8 and M9) had the highest levels of K, while N6, N2, and Enzirabahima had the lowest contents. The local cultivar (Muvubo) and hybrids (N11 and N15) had the highest levels of Na, which were significantly different from those of M30, M9, and Enzirabahima ($p < 0.05$). Earlier studies on the mineral content of COB reported similar mineral compositions with Zn, Ca, Fe, K, Mg, and Na concentrations of 0.1–0.5, 10.1–132.4, 0.3–12.2, 259.0–733.9, 21.2–106.0, and 0.1–23.9 mg/100 g, respectively.[28,50,74–76]

Phytochemical composition of the COB

Total tannin content

Varietal significant differences were observed in the total tannin content of the selected COB under study (Table 4). Mbwazirume and hybrids (N15, N2, and M30) had significantly higher total tannin content ($p < 0.05$) than N24, Nakitembe, Nfuuka, and Kibuzi. Unlike juice bananas, COB are not expected to have high tannin content, which causes an astringent impression in the mouth.[52] In Uganda,

TABLE 4 Phytochemical composition of the selected cooking banana cultivars (expressed on a dry weight basis).

Cultivars	Total tannins (mg TA/100 g)	Total phenolic content (mg GAE/100 g)	Total flavonoid content (mg CE/100 g)
N2	8.68 ± 0.79^{abc}	37.36 ± 0.62^{a}	20.59 ± 1.65^{cde}
N6	8.60 ± 0.35^{abc}	14.86 ± 0.12^{fgh}	9.26 ± 0.41^{de}
N8	8.49 ± 1.04^{abcd}	17.84 ± 0.29^{cdefg}	6.85 ± 0.30^{b}
N11	8.22 ± 0.12^{abcd}	34.06 ± 0.56^{a}	11.65 ± 1.11^{de}
N14	8.47 ± 0.93^{abcd}	21.88 ± 0.20^{bc}	10.37 ± 0.96^{de}
N15	8.89 ± 0.46^{ab}	13.42 ± 0.71^{gh}	11.81 ± 0.04^{de}
N17	8.14 ± 1.50^{bcd}	18.58 ± 1.24^{cdef}	10.53 ± 0.02^{de}
N21	8.39 ± 0.93^{abcd}	19.61 ± 0.41^{cdef}	7.78 ± 0.03^{ab}
N24	7.76 ± 0.35^{d}	20.44 ± 0.21^{bcd}	15.48 ± 0.16^{cde}
M9	8.10 ± 0.58^{bcd}	13.01 ± 0.62^{h}	12.45 ± 0.96^{de}
M30	8.69 ± 0.46^{abc}	25.80 ± 0.73^{efgh}	7.34 ± 0.55^{e}
M32	8.28 ± 0.23^{abcd}	17.55 ± 0.21^{cdefg}	10.37 ± 0.48^{de}
M33	8.10 ± 0.58^{bcd}	15.69 ± 2.48^{efgh}	10.05 ± 0.16^{de}
17914S-24	8.51 ± 0.69^{abcd}	24.67 ± 0.15^{b}	9.58 ± 0.77^{a}
Muvubo	8.56 ± 0.35^{abcd}	17.34 ± 0.41^{defgh}	2.65 ± 0.13^{f}
Kibuzi	8.07 ± 0.81^{cd}	18.99 ± 0.10^{cdef}	10.85 ± 0.64^{de}
Nakitembe	7.95 ± 0.23^{cd}	14.66 ± 0.20^{fgh}	1.58 ± 0.05^{f}
Mpologoma	8.33 ± 0.12^{abcd}	17.55 ± 0.21^{cdefg}	15.48 ± 0.16^{cde}
Nfuuka	8.05 ± 0.23^{cd}	14.66 ± 0.21^{fgh}	1.88 ± 0.29^{f}
Mbwazirume	9.00 ± 0.69^{a}	35.29 ± 0.62^{a}	20.90 ± 1.44^{cd}
Kabucuragye	8.25 ± 1.28^{abcd}	29.61 ± 0.21^{cde}	18.51 ± 2.87^{cde}
Enzirabahima	8.53 ± 1.27^{abcd}	38.39 ± 0.83^{a}	14.36 ± 0.96^{cde}
Nakawere	8.16 ± 0.93^{bcd}	18.58 ± 0.28^{cdef}	12.13 ± 0.96^{de}

Note: Values are expressed as mean ± standard error ($n = 3$ biological replicates). Means within a column carrying different superscript letters differ significantly as per one way analysis of variance (ANOVA) ($p < 0.05$).

Kyamuhangire et al.[77] obtained average tannin contents of 54.4 and 52.1 mg/100 g for green Musakala and Kibuzi fresh banana pulp, respectively, which are close to those obtained in the current study. The differences in the tannin contents can be attributed to differences in the extraction and analysis methods since we worked on dry powder samples rather than fresh samples. The variation could also be due to differences in banana cultivars, growth conditions, and post-harvest storage conditions.[78] This data suggests that hybrid COB in the current study may not differ much from local cultivars with respect to the low astringent taste when cooked.

Total phenolic content

The TPC of the COB was 13.01–37.36 mg GAE/100 g (Table 4). Local COB (Enzirabahima and Mbwazirume) and hybrids (N2 and N11) had significantly higher TPC compared to hybrids M9, N15, and N6 ($p < 0.05$). The TPC of COB obtained was comparable with the findings of Aquino et al.[47] who reported TPC in unripe bananas grown in Brazil in the range of 23.15–33.28 mg GAE/100 g. Results of the present study were also close to those reported for Pisang Mas banana (51–56.1 mg GAE/100 g).[30,79] Phenolic compounds act as antioxidants, inhibiting the decomposition of hydroperoxides into free radicals[52,79] but they can also participate in undesirable enzymatic browning of bananas after peeling, affecting their colour and imparting a puckering taste.[80] For instance, the L* value for Enzirabahima and Mbwazirume (23.70 and 24.15) suggested that they were dark in colour yet the b* values were relatively low (20.25 and 19.55), which meant the darkness in colour was not due to the intensity of pulp yellowness (Table 2). The pulp darkness could have been due to phenolic compounds causing enzymatic browning in the banana pulp.[81]

Total flavonoid content

The TFC of the COB varied from 1.58 to 20.90 mg CE/100 g on a dry weight basis. Hybrids such as 17914S-24, N21, and N8 exhibited significantly higher TFC ($p < 0.05$) compared to local cultivars Kibuzi, Nakawere, and Enzirabahima. These values are comparable to the range reported by Alothman et al.[30] for Pisang Mas bananas in Malaysia (23.7–47.0 mg CE/100 g fresh weight) but lower than those observed by Fatemeh et al.[78] in the green and ripe pulp and peel of Cavendish and Dream banana cultivars in Malaysia (39.01–389.33 mg CE/100 g dry weight). Differences in TFC and TPC across

TABLE 5 Textural attributes of selected cooked bananas grown in Uganda.

Cultivars	Hardness (N)	Cohesiveness	Adhesiveness (N)
N2	4.43 ± 0.13^{c}	0.55 ± 0.09^{abcd}	-0.37 ± 0.02^{ab}
N6	8.66 ± 0.18^{a}	0.52 ± 0.06^{bcd}	-0.65 ± 0.11^{ab}
N8	3.16 ± 0.15^{defg}	0.53 ± 0.03^{abcd}	-0.69 ± 0.08^{abc}
N11	1.72 ± 0.07^{h}	0.46 ± 0.01^{d}	-0.36 ± 0.01^{ab}
N14	3.49 ± 0.15^{cdef}	0.51 ± 0.08^{bcd}	-0.91 ± 0.10^{abc}
N15	6.32 ± 0.04^{b}	0.41 ± 0.09^{d}	-0.59 ± 0.04^{ab}
N17	2.11 ± 0.12^{gh}	0.53 ± 0.03^{bcd}	-0.55 ± 0.09^{ab}
N21	1.34 ± 0.19^{h}	0.87 ± 0.02^{a}	-1.26 ± 0.06^{abc}
N24	1.56 ± 0.01^{h}	0.46 ± 0.07^{d}	-0.24 ± 0.02^{a}
M9	2.41 ± 0.11^{fgh}	0.82 ± 0.01^{abc}	-1.37 ± 0.11^{bc}
M30	3.02 ± 0.16^{efg}	0.78 ± 0.04^{abcd}	-1.31 ± 0.05^{bc}
M32	2.91 ± 0.29^{efg}	0.56 ± 0.07^{abcd}	-0.67 ± 0.01^{abc}
M33	4.01 ± 0.05^{cde}	0.51 ± 0.05^{bcd}	-0.72 ± 0.08^{abc}
Muvubo	3.01 ± 0.17^{efg}	0.48 ± 0.01^{d}	-0.47 ± 0.06^{ab}
Kibuzi	2.34 ± 0.14^{gh}	0.50 ± 0.04^{cd}	-0.52 ± 0.03^{ab}
Nakitembe	3.55 ± 0.03^{cde}	0.55 ± 0.02^{abcd}	-0.60 ± 0.07^{ab}
Mpologoma	2.99 ± 0.05^{efg}	0.49 ± 0.08^{cd}	-0.45 ± 0.03^{ab}
Nfuuka	2.32 ± 0.12^{gh}	0.52 ± 0.01^{bcd}	-0.54 ± 0.01^{ab}
Mbwazirume	3.50 ± 0.07^{cdef}	0.61 ± 0.05^{abcd}	-0.61 ± 0.04^{ab}
Kabucuragye	3.01 ± 0.04^{efg}	0.73 ± 0.03^{abcd}	-1.72 ± 0.12^{cd}
Enzirabahima	2.94 ± 0.09^{efg}	0.51 ± 0.02^{bcd}	-0.65 ± 0.02^{ab}
Nakawere	4.16 ± 0.05^{cd}	0.84 ± 0.06^{ab}	-1.74 ± 0.05^{d}

Note: Hardness and adhesiveness are expressed in Newtons (N), while cohesiveness is a dimensionless ratio. Values are expressed as mean ± standard error ($n = 3$ biological replicates). Means within a column carrying different superscript letters differ significantly as per one way analysis of variance (ANOVA) ($p < 0.05$). More negative adhesiveness values indicate greater stickiness of the cooked banana sample.

studies can be attributed to variations in cultivars, physiological maturity at harvest, postharvest storage conditions, chemical composition of the banana fruit, and soil fertility.[82] Furthermore, flavonoids together with other metabolites contribute to the pulp color of matooke,[52] suggesting that TFC may influence consumer acceptability for food preparation.

Textural characteristics of the cooked bananas

Hardness

Hardness of COB varied considerably from 1.34 to 8.66 N (Table 5). For instance, N6, N15, and N2 were significantly harder than local cultivars Kibuzi, Mpologoma, and Kabucuragye ($p < 0.05$). Hardness data indicated that N21, N24, and N11 produced the softest cooked bananas among all the cultivars studied, while hybrids (M30, M32, and N8) were not significantly different ($p < 0.05$) from local cultivars (Kabucuragye, Muvubo, and Mpologoma). Gafuma et al.[35] concluded that Kibuzi and Mpologoma were the softest local COB in Uganda. The differences in experimental results could be due to differences in the method of analysis used since the TPA method involved moulding the sample into a cylindrical shape for uniformity before analysis, which could have led to the observed slight hardening.

Hardness of cooked bananas is an undesirable characteristic. Ssemwanga et al.[11] reported that the banana hybrid FHIA 3 was rejected as a cooking cultivar in Uganda due to its hardness and astringent taste. Hardness in cooked bananas is typically linked to high dry matter content, elevated starch levels, high amylose content, and low pectin content in the cell walls, which increases starch-starch interactions within the banana matrix.[67] Notably, hybrids (N21, N24, and N11), which had the softest texture, also had the lowest dry matter contents (20%–22%; Table 2). High dry matter content is further associated with reduced water-holding capacity of starch, resulting in lower water activity and hardening of cooked bananas.[35,71] Based on their soft texture, comparable to or nearing that of local AAA-EA COB, hybrids (N21, N24, N11, M30, M32, and N8) would be suitable as COB.

Cohesiveness

Cohesiveness of cooked bananas varied from 0.41 to 0.84. Results showed that N21, Nakawere, and M9 had the highest degree of cohesiveness, while N24, N11, and N15 had the lowest. Overall, there were significant differences ($p < 0.05$) in cohesiveness among the COB (Table 5). Cohesiveness is desirable in lower amounts by consumers.[41] A high degree of cohesiveness is associated with elevated pectin content, which causes cooked bananas to stick together, making them less resistant to stress during processing, packaging, and delivery.[35] Hybrid N15 exhibited the lowest degree of cohesiveness, rendering it less moldable into a bolus, a less desirable quality of cooked bananas. Future research should prioritize quantifying and optimizing pectin levels in both the local and hybrid COB to enhance their processing and handling characteristics for consumers.

Adhesiveness

Adhesiveness of cooked bananas varied from −1.74 to −0.24 N (Table 5). Nakawere, Kabucuragye, and the hybrid M9 had the highest degree of adhesiveness to the probe (−1.74, −1.72, and −1.37 N). Excessive adhesiveness in cooked bananas has been reported as an undesired sensory quality characteristic.[41] High starch content provides more gelatinizable material that can create binding sites via hydroxyl groups. In practice, adhesiveness is determined by a complex interplay between starch composition, dry matter content, and moisture availability. For example, samples with higher amylose and dry matter contents may form stronger internal gel networks upon cooling, reducing surface stickiness and resulting in lower adhesiveness.[83]

Sensory characteristics of the cooked bananas

Descriptors for the quality characteristics

During sensory analysis, panelists generated 40 descriptors for the quality characteristics of COB, which were grouped into six categories used in our previous study.[20] The list of descriptors was used as the quality screening tool to measure the differences in consumer eating quality attributes of the cooked bananas. The core sensory quality characteristics of the cooked bananas included a yellow homogeneous colour by appearance, moist smooth soft texture by mouth, a soft cooked banana that sticks between fingers, which is easily moldable by hand, an aroma of cooked banana leaves, a mild sweet taste tending to flatness, and a very low sensation of astringency. Panelists also mentioned that sourness "sap like taste" was considered a bad sensory quality characteristic since it is associated with the immaturity of the bananas, while astringency was associated with juice bananas and good for beer brewing but not cooked bananas. An astringent taste due to tannins in cooked bananas was reported previously in FHIA 03, IITA hybrids, and Yangambi KM5.[54] The astringent taste caused by tannins in cooked bananas is an undesirable eating characteristic, predominantly observed in Ugandan hybrid banana varieties.[45,46]

The other inferior sensory characteristics of cooked bananas mentioned by panelists were a pale yellow colour, blackish, and mottled colour homogeneity, which gave a visual impression of immaturity. Firm and hard texture was undesired. Panelists desired moderate softness; excessive softness was regarded as an inferior quality attribute. Similar textural desirability was reported about Ugandan COB by preceding authors.[11,20,35,54]

Sweet taste and banana juice aroma were classified as undesirable characteristics of the cooked matooke since they gave an impression of ripeness. Cooked bananas are superior in sensory characteristics when prepared from physiologically green mature bananas with a relatively blunt taste. When asked about the taste of bananas, panelists indicated that some samples were mildly sweet. These findings are in agreement with previous reports of Ssemwanga.[84] In the study, the author identified a total of 80 quality characteristics of COBs falling under three categories, that is, physical, sensory, and socio-economic descriptors. The majority of this sensory descriptors were identical to the ones we obtained in the current study.

Taste and aroma

Sensory evaluation indicated that generally hybrid COB had significantly ($p < 0.0001$) lower scores for the desired eating attributes than the local cultivars (Table S3). All hybrid cultivars were scored significantly lower ($p < 0.05$) in regard to sweetness compared to local cultivars, except for Nfuuka and Kabucuragye, which were not significantly different from hybrid cultivars such as N2, N11, N17, and N24. Local bananas were scored similarly to each other in respect to astringency with exception of *Muvubo*. The perceived sweetness of cooked products was not related to the°Brix of raw bananas, which may arise from interference of the sugar: acid balance by phenols and tannins in the fruit pulp.[80]

In regards to matooke taste, hybrids were perceived to be significantly inferior to local cultivars. Hybrid cultivars M9 and N17 were not significantly ($p > 0.05$) different from local cultivars Kabucuragye and Nakawere (Table S3). The cultivars M32, N17, and N8 were not significantly ($p > 0.05$) different from local cooking cultivars (Nakitembe, Muvubo, and Musakala), suggesting that these hybrids are advantageous. These results also indicated that cultivars N8, N21, N15, N11, N2, and N6 are undesirable with respect to yellow colour intensity and uniformity.

Texture

Panelists mentioned an uneven mouth feel of hybrid cultivars such as N6, N2, and N15, indicating that they were of an inferior eating quality as COB. The same hybrids were also described as the hardest cultivars, significantly different ($p < 0.05$) from local cultivars Kibuzi, Musakala, and Nakitembe, which were scored as the softest cooked bananas (Table S3). Hardness is an undesirable sensory characteristic of bananas among Ugandan consumers. The results of this part of the study were congruent with instrumental measurement of hardness, which indicated that hybrids were harder than local cultivars.

Stickiness between cultivars was scored in the range 2.56 to 7.22, with cooked products of N21, N8, and Musakala scored as the stickiest cooked bananas, significantly ($p < 0.05$) higher than hybrids N2, N6, and N15 and the local cultivar Nfuuka. The stickiness of bananas is only desired in low amounts; too much of it is referred to as a poor quality attribute by consumers.[41] Hybrid cultivars N2, N6, and N15 were lumpier than the rest of the samples studied. Hybrid cultivars M33, N24, and N17 were not significantly different from local cultivars *Nakitembe*, *Kibuzi*, and *Kabucuragye*, with respect to stickiness. This therefore showed that these hybrids could be preferred for their sensory stickiness since consumers of cooked bananas prefer moderately sticky cooked bananas.

Yellowness

Colour of cooked bananas ranged from 1.50 to 9.08 with local cultivars Muvubo, Musakala, and Kibuzi having the deepest intensity of yellow colour (9.08, 8.89, and 8.78, respectively), while hybrids 17914S-24, N21, and N8 had the lowest (Table S3). This could therefore imply that local cultivars are still being preferred for cooking on the basis of yellow colour. To some extent, the results of this section were in agreement with the instrumental colour measurements. However, much as the measured yellowness of the banana pulp indicated no major differences between local and hybrid cultivars, panelists scored hybrids N8, N21, 17914S-24, and N15 as inferior in intensity of the yellow colour compared to their local counterparts. Nowakunda and Tushemereirwe[54] earlier reported that

Kisansa, a local AAA-EA banana, was superior in eating quality characteristics than hybrids under their study (Pita-14, Pita-17, FHIA 01, FHIA 03, FHIA 17, FHIA 21, FHIA 23, and KM5). In the present study, however, hybrids M32, N17, N24, M33, and M9 were not significantly different ($p > 0.05$) from local cultivars Kibuzi, Nakawere, Kabucuragye, Nakitembe, and Enzirabahima on the basis of yellow colour. This indicates that the above hybrids could be easily adopted by banana consumers since they do not vary much from local AAA-EA COBs on the basis of colour of the cooked bananas.

Sweetness

Landraces (Musakala, Kibuzi, and Muvubo) had significantly higher mean scores for sweetness, while hybrids 17914S-24, N15, and N21 had the lowest ($p < 0.05$). However, the results were in disagreement with measurements, which indicated that N2, Mpologoma, and N8 raw pulp had the highest levels of sugar that were significantly lower than Kibuzi and Muvubo (Table S3). The differences could be attributed to the interferences from astringent chemicals disrupting the sugar: acid balance in the pulp, and hence a reduction in the perception of sweetness.[80] This probably explains why N2, N6, and Mpologoma were not perceived as the sweetest cooked products even though their raw banana pulps had the highest brix.

Matooke taste

Local COB (Kibuzi, Musakala, Muvubo, and Nakitembe) had the highest mean scores for matooke taste, while hybrids N21, N8, and 17914S-24 had the lowest. Earlier studies[11,41,84] indicated that consumers of COB prefer those that are slightly sweet and not highly astringent. Bugaud et al.[85] reported that sweetness in bananas is best predicted as a function of pH and TSS, while sourness is often a function of TA. Results of the current study agree with the foregoing report since Kibuzi, Musakala, Muvubo, and Nakitembe, which had the highest scores for taste also had relatively lower values of these physicochemical properties.

Astringency

Panelists cited an astringent taste of the cooked samples, which was significantly higher ($p < 0.0001$) in hybrid cultivars than the local COB (Table S3). Hybrids N11, N21, and N24 were more astringent ($p < 0.05$) than local cultivars (Kibuzi, Nakawere, and Nakitembe). These results agreed with the analytical tests, which indicated that the hybrid COB had higher phytochemicals than local cultivars (Table 4). The results were concordant with the findings of Nowakunda et al.[45,46] who reported higher astringency due to higher levels of tannins (20.7–67.0 g/100 g) in hybrid bananas than 0.8 and 1.0 g/100 g for Mbwazirume and Kisansa local COB. However, the astringency of the cooked hybrids (N24, M9, N17, N14, and N8) was not significantly different from the local COB (Musakala, Enzirabahima, Nakitembe, and Nfuuka). Thus, N24, N2, M9, M33, M32, N17, N14, and N8 could be adopted by consumers of COB for food preparation on the basis of their astringency.

Relationships among physicochemical properties and sensory characteristics of cooked bananas

Principal component analysis was performed to determine the relative importance of the major sensory quality characteristics of cooked bananas in relation to their chemical properties (Figure S1). The first two principal components (PC1 and PC2) had eigenvalues greater than 1 and together explained 76.2% of the total variance. This indicates that they adequately captured the major variability among the cultivars of COB.

As shown, PC1 accounted for 46.3% of the total variance and was positively associated with starch content, amylose proportion, and dry matter, while negatively associated with moist texture, smoothness, moldability, astringency, tannin content, and titratable acidity. This principal component thus represents a structural–textural axis contrasting firm, hard, starch-rich banana cultivars with softer, moist, and more astringent samples. The strong contribution of starch and dry matter confirms their central role in determining firmness and mouthfeel perception. The second principal component (PC2) explained 29.9% of the total variance and separated cultivars characterized by sour and astringent sensory attributes, higher total phenolics, and greater cohesiveness from those exhibiting yellow homogeneous colour, characteristic matooke and sweet tastes, higher amylopectin proportion, thicker peels, and longer fingers. This component reflects a sensory-compositional dimension, linking phenolic-driven astringency with structural cohesiveness, versus sweetness and desirable traditional matooke flavor associated with amylopectin-rich starch.

For breeding purposes, cultivars positioned positively along PC1 (M32, N8, N21, N18, N14, N24) can be targeted for desirable attributes such as yellow colour, sweetness, lower stickiness, and matooke taste. Selection of cultivars such as N2, N6, N15, and N11 along PC2 will allow for differentiation between phenolics-induced astringency and undesirable attributes such as firmness and hardness. The PCA biplot loading thus provided multivariate relationships among starch composition, phenolic content, and sensory attributes, providing a framework for simultaneous improvement of texture and consumer acceptability.

Astringency showed negligible correlation with TFC ($r = 0.014$) and total tannins ($r = -0.006$). The TFC and ash content were weakly correlated with stickiness ($r = 0.310$, $r = 0.402$), mouldability ($r = 0.121$, $r = 0.226$), and smoothness ($r = 0.130$, $r = 0.295$) of hybrids N8, N21, and 17914S-24. On the other hand, the correlation of ash content with a sticky, moldable smooth texture is explained by the effect of minerals such as calcium and sodium in the fruit pulp of bananas.[66] For instance, calcium ions induce the formation of ionic Ca^{2+} gels that cement the pectin chains and reduce their hydration

and solubilization abilities, hence delaying cell wall softening and separation.[86]

Total tannin content was moderately correlated with moistness ($r = 0.454$) of cooked bananas as observed in Nakitembe, M32, and Enzirabahima. Amylopectin is a highly branched water-soluble glucose polymer but is weakly correlated with moistness ($r = 0.190$). Hydrolysable tannins are generally water-soluble phenolics; therefore, the water absorption capacity of both amylopectin and tannins could have contributed to the moist texture of the cooked bananas.[77]

Sourness showed a moderate positive correlation with total phenol content ($r = 0.453$) in hybrids N11 and N15. This could have been due to interference of the sugar/acid balance by organic acids in the fruit pulp, leading to increased intensity of sourness in cooked bananas.[80] The correlation between polyphenols, sugars, and taste suggested that the levels of phenolic compounds significantly ($p < 0.05$) reduce the consumer preferred taste of the cooked bananas.[41,46]

Finger circumference was not present in the same principal component as dry matter and amylose content and had very weak negative and positive correlations ($r = -0.064$ and $r = 0.090$) in N11 and N15. Zhang et al.[58] indicated that a high dry matter content leads to high bunch weight and yield as well as high starch content since starch is a principal component in bananas. In the present study, N24 was the most closely related to the starch content and finger circumference. Similarly, firmness and hardness could be explained by high amylopectin ($r = 0.244$ and $r = 0.282$) content mainly in hybrids (N2, N6, M9, and M33) and a local cultivar, Nfuuka. More amylopectin and amylose are correlated with a firm tissue due to a cementing effect of amylose via hydrogen bonding with other polysaccharides within the cell walls.[66]

Matooke taste was correlated with high TA ($r = 0.404$), while sweetness, yellow, and homogeneous colour were associated with TSS ($r = 0.405$, $r = 0.581$ and $r = 0.578$) in Kibuzi, Nakitembe, Nakawere, Muvubo, Enzirabahima, Kabucuragye, N14, and N17. As banana berries grow, the sugar content and organic acids increases, and more carotenoids are formed, responsible for a yellow homogeneous colour and desired taste due to a well-balanced ratio of acids/sugars.[43,52,80] The PCA results indicated that high tannin content could influence the homogeneity of the desired yellow colour of cooked bananas since tannins, pale yellow, and mottled yellow colours are associated with immature bananas.[46]

The hybrids (N14, N17, N24, and M32) had physicochemical properties (thick peels, long fingers, high pulp/peel ratio, high titratable acidity, and high amylopectin content) similar to or close to those of the female parents Kabucuragye, Nakawere, and Enzirabahima.

The correlation between dry matter, starch content, and hard texture suggested that cultivars with high starch content and high dry matter exhibited a hard texture, dry and rough mouth feel, and were not easy to mould with the hand. The correlation between polyphenols, sugars, and taste suggested that the levels of phenolic compounds reduces the taste of cooked bananas.[41,46]

Taken together, sensory and physicochemical results supported that the hybrid bananas were superior to local cultivars on the basis of physical characteristics but of inferior eating quality. The promising hybrids identified in the present study (N14, N17, N24, and M32) would benefit from integration into ongoing biotechnology and tissue culture programs in the Eastern African region. Micropropagation approaches using meristem-derived explants to *Musa* species could ensure rapid multiplication of disease-free planting materials and year-round availability. Furthermore, growth regulators such as 6-benzylaminopurine and naphthalene acetic acid could be used to enhance shoot proliferation in the matoke cultivars, supporting large-scale dissemination of improved hybrids.[87] Integrating sensory-preferred and nutritionally superior hybrids with tissue culture propagation systems could accelerate adoption among farmers while maintaining phytosanitary quality.

The present study has some limitations that need to be taken into consideration while interpreting its results. The cultivars were evaluated from two trial stations and a single harvest period. Thus, the influence of environments and seasons on the physicochemical and sensory characteristics of the COB may not be fully captured. Furthermore, sensory assessment was conducted under controlled experimental conditions to ensure consistency in sample preparation and evaluation. Although this approach was intended to enhance comparability among cultivars, it may not fully capture variability in consumer perception under typical household preparation conditions. Thus, future research efforts need to consider samples from different locations, which can be evaluated across several seasons.

CONCLUSIONS

Overall, hybrids tended to have superior physical characteristics (e.g., finger length, pulp/peel ratio) but showed variable eating quality. Hybrids (N14, N17, N24, M32) approached local cultivars in sensory acceptability, making them promising candidates for adoption. The local cultivars tended to have superior proximate composition, which still makes them more desirable from a nutritional point of view. Principal component analysis indicated that correlations existed between certain physicochemical properties (flavonoids, tannins, and amylopectin contents) and sensory characteristics, indicating their potential as screening parameters for food quality and consumer acceptability in COB breeding programs. Since physicochemical characteristics of TSS, titratable acidity, pH, phenols, tannins, starch, amylose, moisture, and minerals composition were associated with a yellow homogeneous colour, sweet and matooke tastes, low astringency, low sourness, moist, soft, and moldable texture with a smooth mouth feel, breeders could select for these attributes to enhance the adoption and consumption of the hybrid COB. However, further work is needed to establish acceptability thresholds of these parameters.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data supporting the conclusions of this study are within this article and its Supporting Information.

ETHICS STATEMENT

This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of Department of Food Science and Technology, Faculty of Science, Kyambogo University (18/U/GMFT/19497/PD). The study was conducted under the National Agriculture Research Organization of Uganda, which has the legal authority to conduct research in the local communities and engage with farmers. On the day of the ranking exercises, every participant gave their consent to take part in the preference ranking.

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REFERENCES

1. Sardos J, Breton C, Perrier X, Van den Houwe I, Carpentier S, Paofa J, et al. Hybridization, missing wild ancestors and the domestication of cultivated diploid bananas. Front Plant Sci. 2022;13:969220.
2. Li LF, Wang HY, Zhang C, Wang XF, Shi FX, Chen WN, et al. Origins and domestication of cultivated banana inferred from chloroplast and nuclear genes. PLoS One. 2013;8:e80502.
3. Jenny C, Sachter-Smith G, Breton C, Rivallan R, Jacquemoud-Collet JP, Dubois C, et al. Musa species in mainland Southeast Asia: from wild to domesticate. PLoS One. 2024;19:e0307592.
4. Batte M, Swennen R, Uwimana B, Akech V, Brown A, Tumuhimbise R, et al. Crossbreeding East African Highland bananas: lessons learnt relevant to the botany of the crop after 21 years of genetic enhancement. Front Plant Sci. 2019;10:81.
5. Madalla N, Swennen R, Brown A, Carpentier SC, Van den Bergh I, Crichton RJ, et al. Farmers' preferences for East African Highland cooking banana 'Matooke' hybrids and local cultivars. Agric Food Secur. 2023;12:1–20.
6. Amaral MM, Herrin WE, Gulere GB. Using the Uganda National Panel Survey to analyze the effect of staple food consumption on undernourishment in Ugandan children. BMC Public Health. 2018;18:32.
7. Ssennoga F, Mugurusi G, Nagitta OP. Food insecurity as a supply chain problem. Evidence and lessons from the production and supply of bananas in Uganda. Sci Afr. 2019;3:e00076.
8. Lee H. Overview of the current status of Uganda's Banana sector: formalizing the Matooke sector may not be the best policy option. Open Agric J. 2023;17:e18743315252945.
9. Khakasa E, Muyanja C, Mugabi R, Nowakunda K. Profiling culinary properties of East African Highland cooking bananas to enhance hybrid selection efficiency. Afr J Food Agric Nutr Dev. 2024;24:26583–607.
10. Akankwasa K, Marimo P, Tumuhimbise R, Asasira M, Khakasa E, Mpirirwe I, et al. The East African Highland cooking bananas 'Matooke' preferences of farmers and traders: implications for variety development. Int J Food Sci Technol. 2021;56:1124–34.
11. Ssemwanga J, Thompson A, Aked J. Quality and acceptability of the new banana cultivar fhia 3 compared to indigenous Uganda cultivars for matooke preparation. Acta Hortic. 2000;540:561–7.
12. Nowakunda K, Barekye A, Ssali R, Namaganda J, Tushemereirwe WK, Nabulya G, et al. 'Kiwangaazi' (syn 'KABANA 6H') black Sigatoka nematode and Banana weevil tolerant 'Matooke' hybrid banana released in Uganda. HortScience. 2015;50:621–3.
13. Nasirumbi SL, Ssali RT, Namuddu MG, Kyotalimye M, Marimo P, Mayanja S. Why gender matters in breeding: lessons from cooking bananas in Uganda. Sustainability. 2023;15:7024.
14. Nowakunda KA-O, Khakasa EA-O, Ceballos H, Kenneth AA-O, Tumuhimbise R, Bugaud CA-OX, et al. East African Highland cooking banana: towards an efficient selection of hybrids with user-preferred food quality traits. J Sci Food Agric. 2024;104:4551–60.
15. ProMusa. NARITA Hybrids. [Accessed 21st January 2025]. Available from: https://www.promusa.org/NARITA+hybrids
16. Tushemereirwe W, Batte M, Nyine M, Tumuhimbise R, Barekye A, Tendo S, et al. Performance of NARITA banana hybrids in the preliminary yield trial for three cycles in Uganda. Kampala, Uganda: International Institute of Tropical Agriculture (IITA); NARO; 2015. 35 p.
17. Sanya LN, Sseguya H, Kyazze FB, Diiro GM, Nakazi F. The role of variety attributes in the uptake of new hybrid bananas among smallholder rural farmers in central Uganda. Agric Food Secur. 2020;9:1.
18. Khakasa E, Muyanja C, Mugabi R, Mukasa Y, Babirye MP, Balikoowa B, et al. Internal quality assessment of East African Highland cooking banana (*Musa* spp.) flour: significance for breeding and industrial applications. Foods. 2023;12:4323.
19. Bechoff AAO, Adinsi LAO, Ngoh Newilah GA-O, Nakitto M, Deuscher Z, Ssali RA-O, et al. Combined use of sensory methods for the selection of root, tuber and banana varieties acceptable to end-users. J Sci Food Agric. 2024;104:4700–8.
20. Khakasa E, Muyanja C, Mugabi R, Bugaud C, Forestier-Chiron N, Uwimana B, et al. Sensory characterization of the perceived quality of East African Highland cooking bananas (matooke). J Sci Food Agric. 2024;104:4907–14.
21. Marimo P, Karamura D, Tumuhimbise R, Shimwela M, Van den Bergh I, Batte M, et al. Post-harvest use of banana in Uganda and Tanzania: product characteristics and cultivar preferences of male and female farmers. RTB working paper no. 3. Lima: CGIAR Research Program on Roots, Tubers and Bananas (RTB); 2019. [Accessed 28th November 2025]. Available from: https://cgspace.cgiar.org/server/api/core/bitstreams/a5fd3135-f075-4f5d-a3fa-028f4200ecc5/content
22. Tumuhimbise R, Buregyeya H, Barekye A, Ssali RT, Talengera D, Kubiriba J, et al. Selection of cooking banana genotypes for yield and black Sigatoka resistance in different locations in Uganda. J Plant Breed Crop Sci. 2016;8:60–71.
23. Tumuhimbise R, Barekye A, Kubiriba J, Akankwasa K, Arinaitwe IK, Karamura D, et al. New high-yield cooking banana cultivars with multiple resistances to pests and diseases ('NAROBan1', 'NAROBan2', 'NAROBan3', and 'NAROBan4') released in Uganda. HortScience. 2018;53:1387–9.
24. Dadzie BK, Orchard JE. Routine post harvest screening of banana/plantain hybrids: criteria and methods. INIBAP Technical Guidelines 2. Rome; Montpellier; Wageningen: International Plant Genetic Resources Institute; International Network for the Improvement of Banana and Plantain; ACP-EU Technical Centre for Agricultural and Rural Cooperation; 1997.
25. Belayneh M, Workneh TS, Belew D. Physicochemical and sensory evaluation of some cooking banana (*Musa* spp.) for boiling and frying process. J Food Sci Tech. 2014;51:3635–46.

26. Shehaj A, Marku K, Morina A, Rama A. Evaluation of quality parameters in some types of wheat flour used for different purposes. J Biol Stud. 2022;5:229–36.
27. Bartkienė E. Plant food analysis methods: methodical book. Vol 1. Kaunas: Lietuvos sveikatos mokslų universitetas; 2012. 70 p. [Accessed 18th March 2026]. Available from: https://hdl.handle.net/20.500.12512/90057
28. Haslinda WH, Cheng LH, Chong LC, Aziah AAN. Chemical composition and physicochemical properties of green banana (*Musa acuminata* × *balbisiana Colla* cv. *Awak*) flour. Int J Food Sci Nutr. 2009;60:232–9.
29. Wiesneth S, Jürgenliemk G. Total phenolic and tannins determination: a modification of Ph. Eur. 2.8.14 for higher throughput. Pharmazie. 2017;72:195–6.
30. Alothman M, Bhat R, Karim AA. UV radiation-induced changes of antioxidant capacity of fresh-cut tropical fruits. Innov Food Sci Emerg Technol. 2009;10:512–6.
31. Omara T, Kiprop AK, Kosgei VJ. Intraspecific variation of phytochemicals, antioxidant, and antibacterial activities of different solvent extracts of *Albizia coriaria* leaves from some agroecological zones of Uganda. Evid Based Complement Alternat Med. 2021;2021:2335454.
32. Zhishen J, Mengcheng T, Jianming W. The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals. Food Chem. 1999;64:555–9.
33. Wheal MS, Fowles TO, Palmer LT. A cost-effective acid digestion method using closed polypropylene tubes for inductively coupled plasma optical emission spectrometry (ICP-OES) analysis of plant essential elements. Anal Methods. 2011;3:2854–63.
34. Vysetti B, Vummiti D, Roy P, Taylor C, Kamala CT, Satyanarayanan M, et al. Analysis of geochemical samples by microwave plasma-AES. At Spectrosc. 2014;35:154–62.
35. Gafuma S, Byarugaba-Bazirake GW, Mugampoza E. Textural hardness of selected Ugandan banana cultivars under different processing treatments. J Food Res. 2018;7:98.
36. Nowakunda K, Khakasa E, Maraval I, Forestierchiron N, Bugaud C. Standard operating protocol for sensory evaluation on matooke. Biophysical characterization of quality traits, WP2. Kampala: RTBfoods Laboratory; 2019. https://doi.org/10.18167/agritrop/00593
37. Trinh T, Tuoc K, Glasgow S. On the texture profile analysis test. New Zealand, Wellington: Institute of Food Nutrition and Human Health, Massey University; 2012. [Accessed 18th March 2026]. Available from: https://ibf.iuh.edu.vn/wp-content/uploads/2019/09/tpatest.pdf
38. ASTM. Manual on sensory testing methods, sponsored by ASMT Committee E-18 on sensory evaluation of materials and product. Philadelphia, PA, US: American Society for Testing and Materials; 1968.
39. Lawless HT, Popper R, Kroll BJ. A comparison of the labeled magnitude (LAM) scale, an 11-point category scale and the traditional 9-point hedonic scale. Food Qual Prefer. 2010;21:4–12.
40. Karamura DA. Numerical taxonomic studies of the East African Highland bananas (Musa AAA-East Africa) in Uganda. PhD thesis, University of Reading, Reading; 1998.
41. Ssemwanga J, Thompson A. Investigation of postharvest and eating qualities likely to influence acceptability of matooke banana cultivars to be introduced in Uganda. Asp Appl Biol. 1994;39:207–13.
42. Kachru RP, Kotwaliwale N, Balasubramanian D. Physical and mechanical properties of green banana (*Musa paradisiaca*) fruit. J Food Eng. 1995;26:369–78.
43. Muchui MN, Njoroge CK, Kahangi EM, Onyango CA. Determination of maturity indices of tissue cultured bananas (*Musa* spp.) "williams" and "grande naine". Acta Hortic. 2010;879:425–30.
44. Forster M, Rodríguez Rodríguez E, Darias Martín J, Romero CD. Distribution of nutrients in edible banana pulp. Food Technol Biotechnol. 2003;41:167–71.
45. Nowakunda K. Determination of consumer acceptability of introduced bananas. Master's thesis, Makerere University, Kampala; 2001.
46. Nowakunda K, Rubaihayo P, Ameny M, Tushemereirwe W. Consumer acceptability of introduced bananas in Uganda. Infomusa. 2000;9:22–5.
47. Aquino FC, Carlos L, Salomão C, Machado S, Ribeiro R, Lopes D, et al. Carbohydrates, phenolic compounds and antioxidant activity in pulp and peel of 15 banana cultivars. Rev Bras Frutic. 2016;38:e090.
48. Zerihun M, Minuye M. Physicochemical profiling of different released and improved desert and cooking banana varieties. Bioprocess Eng. 2019;3:12–21.
49. Abraham B, Saleh B, Zelelew D. Effect of post-harvest handling and ripening methods on quality and shelf-life of banana. Am J Plant Sci. 2022;13:175–92.
50. Arvanitoyannis IS, Mavromatis A. Banana cultivars, cultivation practices, and physicochemical properties. Crit Rev Food Sci Nutr. 2009;49:113–35.
51. Gibert O, Dufour D, Giraldo A, Sánchez T, Reynes M, Pain JP, et al. Differentiation between cooking bananas and dessert bananas. 1. Morphological and compositional characterization of cultivated Colombian Musaceae (*Musa* sp.) in relation to consumer preferences. J Agric Food Chem. 2009;57:7857–69.
52. Stewart D, McDougall GJ, Sungurtas J, Verrall S, Graham J, Martinussen I. Metabolomic approach to identifying bioactive compounds in berries: advances toward fruit nutritional enhancement. Mol Nutr Food Res. 2007;51:645–51.
53. Abbas FMA, Saifullah R, Azhar ME. Assessment of physical properties of ripe banana flour prepared from two varieties: Cavendish and dream banana. Int Food Res J. 2009;16:183–9.
54. Nowakunda K, Tushemereirwe W. Farmer acceptance of introduced banana genotypes in Uganda. Afr Crop Sci J. 2004;12:1–6.
55. Agunbiade SO, Olanlokun JO, Olaofe OA. Quality of chips produced from rehydrated dehydrated plantain and banana. Pak J Nutr. 2006;5:471–3.
56. Ferris RSB, Adeniji TA, Chukwu U, Akalumhe YO, Vulsteke D, Ortiz R. Postharvest quality of plantains and cooking bananas. In: Ortiz R, Akoroda M, editors. Plantain and banana production and research in West and Central Africa: proceedings, Regional Workshop, Onne, Nigeria, 23–28 Sep 1995. Ibadan: IITA; 1996. p.15–22.
57. Falade KO, Oyeyinka SA. Color, chemical and functional properties of plantain cultivars and cooking banana flour as affected by drying method and maturity. J Food Process Preserv. 2015;39:816–28.
58. Zhang P, Whistler RL, BeMiller JN, Hamaker B. Banana starch: production, physicochemical properties, and digestibility—a review. Carbohydr Polym. 2005;59:443–58.
59. Abedi FM, Takhar PS. Stress relaxation properties of bananas during drying. J Texture Stud. 2022;53:146–56.
60. Walugembe J, Buah S, Runo S, Ateka E, Kubiriba J, Tushemereirwe W. Genetically engineered East African Highland bananas–proximate analysis and effect of cooking on the enhanced provitamin A levels. Afr J Food Agric Nutr Dev. 2020;20:15205–21.
61. Bukusuba J, Muranga FI, Nampala P. Effect of processing technique on energy density and viscosity of cooking banana: implication for weaning foods in Uganda. Int J Food Sci. 2008;43:1424–9.
62. Annor GA, Asamoah-Bonti P, Sakyi-Dawson E. Fruit physical characteristics, proximate, mineral and starch characterization of FHIA 19 and FHIA 20 plantain and FHIA 03 cooking banana hybrids. SpringerPlus. 2016;5:796.
63. Khawas P, Das AJ, Sit N, Badwaik LS, Deka SC. Nutritional composition of culinary Musa ABB at different stages of development. Am J Food Sci Tech. 2014;2(3):80–7.
64. Batista ALD, Silva R, Cappato LP, Ferreira MVS, Nascimento KO, Schmiele M, et al. Developing a synbiotic fermented milk using probiotic bacteria and organic green banana flour. J Funct Foods. 2017;38:242–50.

65. Cano MP, de Ancos B, Matallana MC, Cámara M, Reglero G, Tabera J. Differences among Spanish and Latin-American banana cultivars: morphological, chemical and sensory characteristics. Food Chem. 1997;59:411–9.
66. Qi B, Moore KG, Orchard J. Effect of cooking on banana and plantain texture. J Agric Food Chem. 2000;48:4221–6.
67. Gafuma S, Mugampoza D, Byarugaba G. Starch and pectin affect hardness of cooked bananas. J Food Res. 2018;7:107.
68. Dufour D, Gibert O, Giraldo A, Sanchez T, Reynes M, Pain JP, et al. Characterisation of bananas and cooking bananas cultivated in Colombia: morphological, physicochemical and functional differentiation between genetic groups, consumption patterns and preferences. In: International Meeting Bio-Ethanol: Status and Future, 25–27 Mar, 2009, Hanoi. 47 p.
69. McComber DR, Homer HT, Chamberlin MA, Cox DF. Potato cultivar differences associated with mealiness. J Agric Food Chem. 1994;42:2433–9.
70. Sharma MK, Isleib DR, Dexter ST. The influence of specific gravity and chemical composition on hardness of potato tubers after cooking. Am Potato J. 1959;36:105–12.
71. Homayouni A, Amini A, Keshtiban AK, Mortazavian AM, Esazadeh K, Pourmoradian S. Resistant starch in food industry: a changing outlook for consumer and producer. Star. 2014;66:102–14.
72. Linehan DJ, Hughes JC. Texture of cooked potato: III.—Intercellular adhesion of chemically treated tuber sections. J Sci Food Agric. 1969;20:119–23.
73. Keijbets MJH, Pilnik W, Vaal JFA. Model studies on behaviour of pectic substances in the potato cell wall during boiling. Potato Res. 1976;19:289–303.
74. Hardisson A, Rubio C, Baez A, Martin M, Alvarez R. Mineral composition of the banana (*Musa acuminata*) from the Island of Tenerife. Food Chem. 2001;73:153–61.
75. Deshmukh MH, Pai SR, Nimbalkar MS, Patil RP. Biochemical characterization of banana cultivars from Southern India. Int J Fruit Sci. 2009;9:305–22.
76. Khoza M, Kayitesi E, Dlamini BC. Physicochemical characteristics, microstructure and health promoting properties of green banana flour. Foods. 2021;10:2894.
77. Kyamuhangire W, Krekling T, Reed E, Pehrson R. The microstructure and tannin content of banana fruit and their likely influence on juice extraction. J Sci Food Agric. 2006;86:1908–15.
78. Fatemeh SR, Saifullah R, Abbas FMA, Azhar ME. Total phenolics, flavonoids and antioxidant activity of banana pulp and peel flours: influence of variety and stage of ripeness. Int Food Res J. 2012;19:1041–6.
79. Lim YY, Lim TT, Tee JJ. Antioxidant properties of several tropical fruits: a comparative study. Food Chem. 2007;103:1003–8.
80. Joslyn MA, Goldstein JL. Astringency of fruits and fruit products in relation to phenolic content. Adv Food Res. 1964;13:179–217.
81. Jaramillo-Garcés Y, Sacchet-Pérez M, Manjarres-Pinzon G, Manjarres-Pinzon K, Correa-Londoño G, Rodríguez-Sandoval E. Effect of low-temperature storage time on rejected green banana for flour production. Rev Fac Nac Agron Medellin. 2023;76:10517–26.
82. Sabuz AA, Molla MM, Khan MHH, Chowdhury MGF, Pervin S, Alam M, et al. Comparison of physicochemical composition, antioxidant activity and common phytochemicals of selected BARI mango varieties and commercial cultivar, Langra. Food Chem Adv. 2024;4:1–12.
83. Sozer N, Dalgıç AC, Kaya A. Thermal, textural and cooking properties of spaghetti enriched with resistant starch. J Food Eng. 2007;81:476–84.
84. Ssemwanga JK. Quality attributes of matooke banana cultivars according to farmers and traders in Uganda. Musa Africa. 1995;7:7–9.
85. Bugaud C, Daribo MO, Deverge E. Chemical predictors of sweetness and sourness in banana. Chemical predictors of sweetness and sourness in banana. Acta Hortic. 2012;928:211–5.
86. Wu HC, Bulgakov VP, Jinn TL. Pectin methylesterases: cell wall remodeling proteins are required for plant response to heat stress. Front Plant Sci. 2018;9:1612.
87. Demissie AG. Effects of different combinations of BAP (6-benzyl amino purine) and NAA(naphthalene acetic acid) on multiple shoot proliferation of plantain (*Musa* spp.) cv. Matoke from meristem derived explant. Acad J Biotechnol. 2013;1:71–80.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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