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Physicochemical, Nutritional, and Antinutritional Characterization of Banana Peels Processed Using Two Drying Methods

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ABSTRACT: Banana peels, 30−40% of the fruit, often discarded, can be sustainably valued depending on postharvest quality preserved or modified by processing. This study aimed at evaluating the effect of two drying methods (drying at room temperature and in an oven at 45 °C) on the physicochemical, nutritional, and antinutritional properties of four clones of banana peels (*Batard, Grande naine, PITA 14,* and *CARBAP K74*) at different ripening stages. Fresh and dried peels were analyzed at five ripening stages based on color. Drying significantly influences ($p < 0.05$) these parameters. Dried peels had higher acidity, pH, and soluble solids. Drying could either increase or decrease the nutritional parameters, with protein (4.32−10.89%), lipid (2.72−14.97%), carbohydrate (55.64−70.17%), and dry matter (11.29−92.44%). Cyanide content remained below 1%. The study suggests that banana peels, particularly *Batard* and *CARBAP K74*, are rich in nutrients. Drying at 45 °C best preserves their nutritional and physicochemical properties while reducing cyanide in *CARBAP K74* and *Grande naine*. These findings highlight banana peels as a valuable resource in human and animal feeding.

KEYWORDS: *banana peels, ripening stage, drying methods, postharvest qualities*

INTRODUCTION

Bananas (*Musa* AAA), plantains (*Musa* AAB), and other cooking bananas (*Musa* AAB, ABB) are one of the world's most important food resources, after wheat and maize.[1] They are staple foods for millions of people in Central and West Africa and are produced all year round in Cameroon.[2] In 2023, Cameroon stands out as a key player on the continent Africa, with production rising to 4.6 million tons, despite a slight decrease in cultivated areas.[3] In Cameroon, the consumption of banana fruit varies according to the production zone. This consumption was estimated at 109−128 kg/year/inhabitant.[4] Bananas are eaten raw as a dessert, while plantains are most often used in culinary recipes and other food products specific to the populations of different regions of Cameroon.[5,6] Large quantities of banana or plantain peels, equivalent to around 40% of the total weight of fresh fruit, are generated as waste in households, markets, and industries producing banana-based products.[7] These wastes cause unpleasant odors due to the anaerobic digestion of the biomass, which generates gases that disturb the natural balance of the air.[8] Around 36 million tonnes of banana peels are produced every year, and their current end point is associated with unfavorable environmental impact and economic losses.[9] Banana peels contain many nutrients (proteins, lipids, carbohydrates, and fibers) and minerals (zinc, copper, calcium, potassium, and phosphorus).[10] To date, very little scientifically verifiable information exists on the use of banana peels in Cameroon. However, it is clear that in some communities, dried banana peels constitute the raw material for the production of a basic solution used in the preparation of a yellow sauce accompanying certain meals. Some studies have revealed that banana peels can be used in a variety of ways, mainly for soap making,[11] in livestock and poultry feed (7.5%) due to their low tannin and high fiber contents,[7] and in biogas production.[12] However, these previous works were carried out only with banana peels at the green stage (stage 1) of ripening and did not consider the other ripening stages (stages 3, 5, 7 and 9), hence the interest of our study. During the ripening of banana fruits, the chemical composition of the peel undergoes several important changes. Simple sugar content increases in the peels at advanced stages of ripening.[13] Drying is a key step in preservation and processing. It can improve stability but also alter nutritional and functional quality (variations in pH and acidity). Ripening stage and drying method are likely to influence the nutritional value of banana peels. Understanding the effect of drying according to the ripening stage on the composition of banana peels is key to optimizing and choosing the most suitable

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Figure 1. Banana clones analyzed within the framework of the study. A: Batard bunch; B: Grande Naine bunch; C: CARBAP K74 bunch; and D: PITA bunch.

process to best preserve nutrients while reducing antinutritional factors for their valorization in human or animal nutrition. The aim of this study was to assess the effect of two drying methods, room temperature drying (26 °C−30 °C) and oven drying (45 °C), on the physicochemical, nutritional, and antinutritional characteristics of banana peels during postharvest ripening. The objective was to identify the most suitable drying technique for preserving nutritional quality while minimizing antinutritional factors, thereby enhancing the potential use of banana peels in the food industry.

MATERIALS AND METHODS

Plant Material. The plantain and dessert banana bunches were harvested at optimal physiological maturity (presence of ripe fruit on the first or second hand of the bunch) from plots located in Njombé (latitude: 4° 34′ 59.99" N, longitude: 9° 39′ 59.99" E, Littoral, Cameroon). The peels used in this study were obtained from four banana clones presented in Figure 1 and namely *Batard* (a local plantain), *Grande naine* (a commercial dessert banana,), *CARBAP K74* (a plantain-like hybrid), and *PITA 14* (a plantain-like hybrid). The plantain clones were cultivated in an experimental plot set up at the *Centre Africain de Recherches sur Bananiers et Plantains* (CARBAP, Douala, Cameroon) within the framework of Component 5 - RTBfoods Project, while the dessert banana was obtained free of charge from a company exporting dessert bananas, namely *Plantations du Haut Penja* (PHP, Njombe, Cameroon).

These peels were obtained from bananas at 5 ripening stages based on peel color changes, as recommended by Dadzie and Orchard,[14] controlled in the laboratory at ambient temperature between 26 and 30 °C: stage 1 (green), stage 3 (light green), stage 5 (yellow), stage 7 (yellow with black spots), and stage 9 (more black than yellow) (Figure 2).

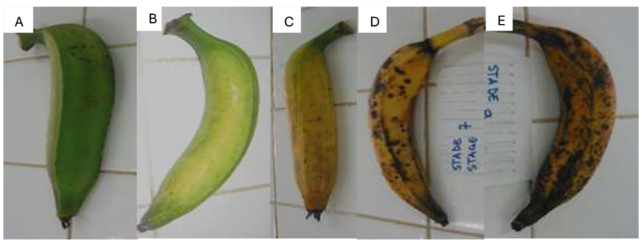

Figure 2. Ripening stages of *Batard* (cv) fruit based on plantain peel color: A: fruit at stage 1 of postharvest ripening; B: fruit at stage 3 of postharvest ripening; C: fruit at stage 5 of postharvest ripening; D: fruit at stage 7 of postharvest ripening; and E: fruit at stage 9 of postharvest ripening.

METHODS

After harvesting the bunches at the laboratory, banana fruits were removed from the bunches, separated, randomized, and placed in boxes at room temperature. Three bunches per clone were used. From each ripening stage, 8−11 fingers were taken to obtain about 400 g of fresh banana peels, which were homogenized and split equally for drying in ambient air or in an oven at 45 °C. For the peels at stage 1, banana fruits were washed after harvesting, peeled, and their peels were cut into small pieces and dried. Peels obtained at ripening stages 3, 5, 7, and 9 were collected after postharvest ripening of fruits for each banana clone.

The latter were dried in a Memmert drying oven at 45 °C for 72 h and at room temperature (26 °C − 30 °C) for a period ranging from 1 to 2 weeks at a relative humidity of 67−74%, depending on the ripening stage of the fruit. The dried peels obtained were ground using a Royalty Line brand blender, then sieved through a 1 mm diameter mesh sieve, and packed in polypropylene plastic bags before being stored in a desiccator for later analysis.

Physicochemical Parameter Analysis. The pH of the flours was measured using a nondestructive method with a pH meter, a combined electrode, and a temperature probe, following ISO standard 2917:1999.[15] Five (5) grams of sample were taken and placed in a beaker, and then 30 mL of distilled water was added. The mixture was homogenized using a magnetic stir bar on a Fisherbrand magnetic stirrer for about 5 min. The electrode of the Jenway Legallais pH meter was then immersed in the beaker containing 45 mL of solution at 25 °C, and the result was read on the pH meter display.

The refractive index was determined using a hand-held refractometer (REF 113, °Brix, 0−32 ATC), and the device was aligned toward a light source to read the refractive index (RI), which was then used to determine the soluble solids content.[14] Total titratable acidity was measured through titration using a 0.1 N sodium hydroxide (NaOH) solution until a persistent pink color was observed for approximately 10 s.[14] Dry matter content (DMC) was assessed using the A.O.A.C. method, based on the measurement of the mass loss of the samples after drying at 105 °C until complete removal of free water and volatile compounds.[16]

Nutritional Parameter Analysis. The crude protein content of the samples was determined by the Kjeldahl method.[16] This method involves three main steps: wet digestion, distillation with Bioblock Scientific, semiautomatic distiller 1001, and titration. For the digestion step, 3 g of sample were placed in a boiling tube with 25 mL of concentrated sulfuric acid and one catalyst tablet (containing 5 g K_2SO_4, 0.15 g $CuSO_4$, and 0.15 g TiO_2). The mixture was

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Table 1. pH of Fresh Peels without Drying (WD) and Dried Banana Peels at Room Temperature (DRT) and at 45 °C in an Oven (D45)[i]

Cultivars	Treatments	Postharvest ripening stages				
		Stage 1	Stage 3	Stage 5	Stage 7	Stage 9
Batard	WD	6.51 ± 0.27^{b}	6.53 ± 0.07^{c}	6.65 ± 0.06^{c}	6.67 ± 0,15^{a}	6.84 ± 0.11^{a}
	DRT	6.82 ± 0.03^{b}	7.67 ± 0.20^{b}	7.70 ± 0.58^{b}	6.94 ± 0,37^{a}	6.98 ± 0.03^{a}
	D45	8.93 ± 0.14^{a}	8.60 ± 0.13^{a}	9.04 ± 0.46^{a}	6.94 ± 0,37^{a}	6.58 ± 0.29^{a}
CARBAP K74	WD	6.78 ± 0.2 2^{b}	7.23 ± 0. 10^{c}	7.43 ± 0.13^{b}	7.11 ± 0,13^{b}	7.43 ± 0.25^{a}
	DRT	6.48 ± 0.26^{b}	7.72 ± 0.56^{b}	7.65 ± 0.01^{b}	7.59 ± 0,14^{a}	5.83 ± 0.21^{b}
	D45	8.06 ± 0.06^{a}	8.23 ± 0.27^{a}	7.99 ± 0.14^{a}	7.59 ± 0,14^{a}	7.68 ± 0.03^{a}
Grande naine	WD	6.88 ± 0.90^{a}	6.24 ± 0.15^{b}	6.33 ± 0.17^{b}	6.47 ± 0,19^{b}	6.72 ± 0.25^{a}
	DRT	6.63 ± 0.15^{a}	7.38 ± 0.15^{a}	7.09 ± 0.26^{a}	7.09 ± 0,12^{a}	6.04 ± 0.26^{a}
	D45	7.84 ± 0.13^{a}	7.07 ± 0.03^{a}	7.13 ± 0.03^{a}	6.69 ± 0,14^{a}	6.77 ± 0.61^{a}
PITA 14	WD	6.78 ± 0.25^{c}	7.12 ± 0.31^{a}	6.83 ± 0.52^{a}	6.52 ± 0,08^{b}	6.75 ± 0.35^{a}
	DRT	7.65 ± 0.10^{b}	7.47 ± 0.15^{a}	7.27 ± 0.04^{a}	6.88 ± 0,07^{b}	6.59 ± 0.27^{a}
	D45	8.81 ± 0.06^{a}	7.12 ± 0.3^{a}	7.27 ±0.04^{a}	7.19 ± 0.25^{a}	5.46 ± 0.06^{b}

[i]The results are an average of three trials; the means ± standard deviations with the same exponents per ripening stage and per variety are not significantly different at the 5% significance level (Tukey test).

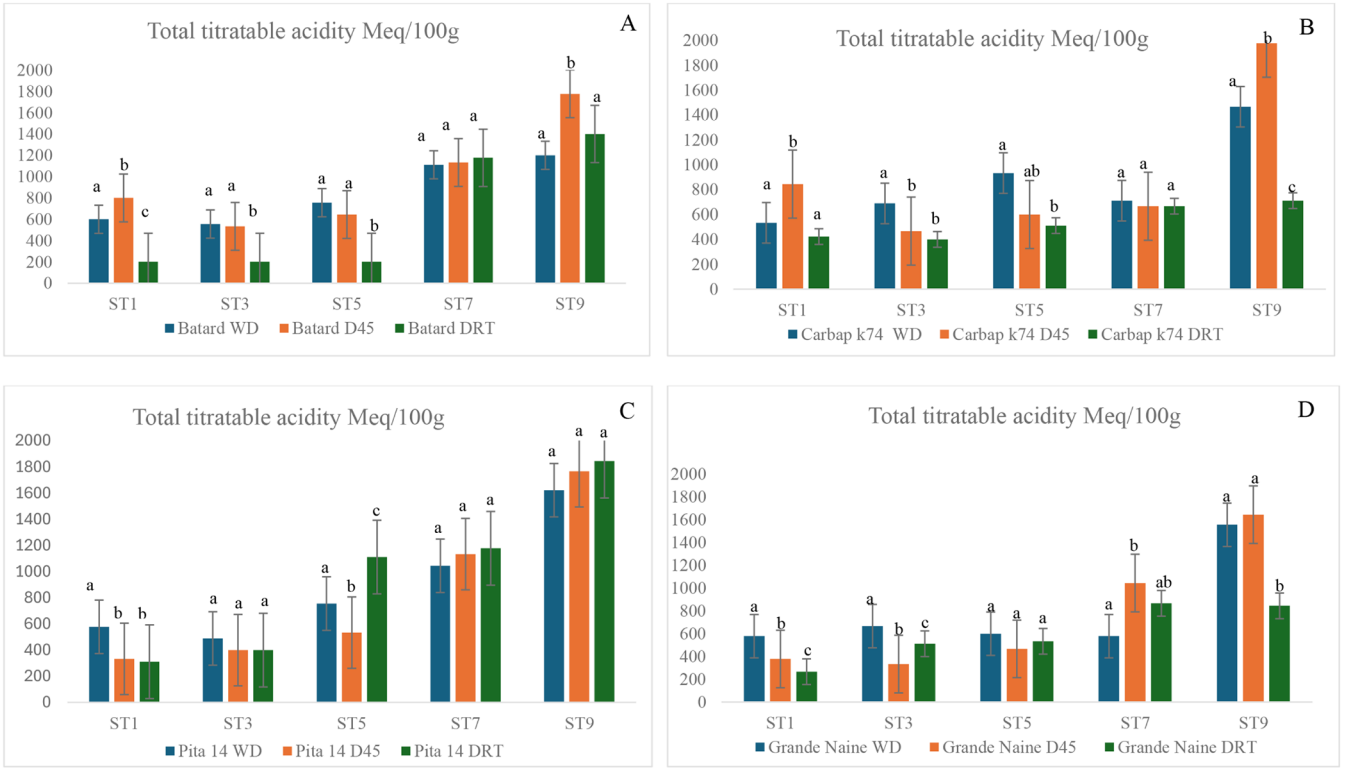

Figure 3. Total titratable acidity (mequiv/100g) of fresh peels and dried banana peels for the clones: A: Batard; B: CARBAP K74; C: Pita14; and D. Grande naine. WD: without drying; DRT: drying at room temperature; D45: drying at 45 °C in the oven.

heated at a low temperature until complete digestion was achieved. The digest was then diluted with 100 mL of distilled water, followed by the addition of 10 mL of 40% NaOH and 5 mL of $Na_2S_2O_3$ (antibumping agent). The liberated ammonia was collected into 10 mL of boric acid solution. The protein content was then calculated using the following formula:

$$\text{Proteins (\%)} = \frac{(\text{Volume HCl sample} - \text{Volume HCl blank}) \times N \times 1.401 \times 6.25}{\text{sample weight}}$$

where N = normality of HCl (0.1 N).

The lipid content was determined using the Soxhlet method.[16] Filter paper bags used for the analysis were first predried in an oven at 105 °C for 2 h, cooled in a desiccator for 1 h, and weighed (M). Subsequently, 5 g of sample (me) were introduced, and the sealed assembly was weighed again ($M1$). After 7 h of extraction, the assemblies were dried in an oven at 105 °C for 1 h 30 min, cooled in a desiccator for 30 min, and weighed once more ($M2$). The lipid content was then determined using the following formula:

$$\%\text{Lipids (\%)} = \frac{(M1 - M2)}{M1 - M} \times 10$$

The total carbohydrate content of dry peels was determined by differentiation, according to the AOAC method.[16]

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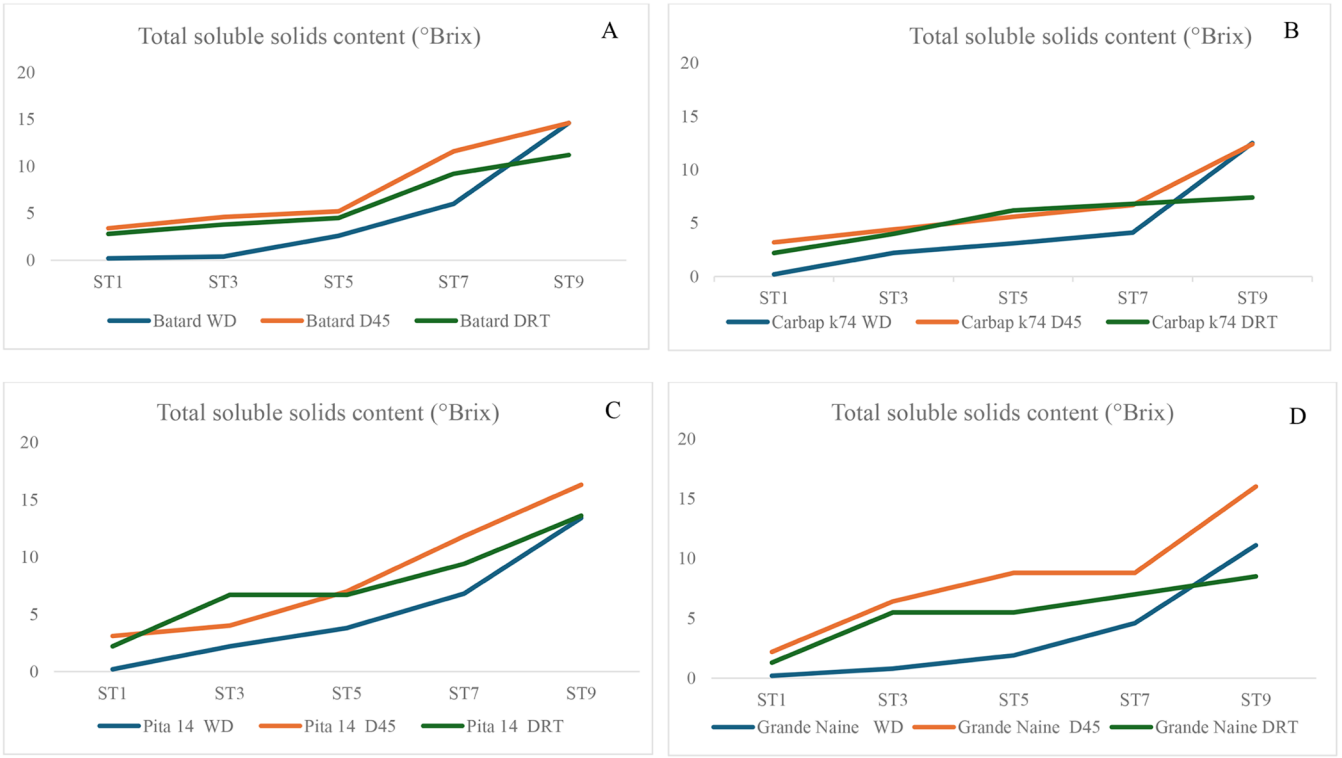

Figure 4. Total soluble solids content (°Brix) of fresh peels and dried banana peels for the clones: A: Batard; B: CARBAP K74; C: PITA14; and D. Grande naine. WD: without drying; DRT: drying at room temperature; D45: drying at 45 °C in the oven.

Carbohydrate content % = 100% − (moisture + proteins + fat + ash) %.

Ash content was determined by burning around 5 g of a sample at 550 °C for 24 h in a muffle furnace, according to the AOAC method.[16]

Determination of Antinutritional Factors. The oxalate content was determined using the modified titration method of Aina et al.[17] In the presence of sulfuric acid and under heat, oxalic acid is oxidized by potassium permanganate. The oxidation of oxalic acid is marked by a color change to a persistent pink lasting for a few seconds, which indicates the end of the reaction.

The determination of phytate content in the flours was performed using the method described by AOAC.[16] This method is based on the property of phytates to form stable, insoluble complexes with ferric ions in an acidic pH solution, where the source of phosphorus is phytic acid. Total tannins were evaluated using the protocol described by Ndhlala et al.[18] This method is based on the complexation of tannins with a ferric reagent in an acidic alcoholic medium, resulting in a red coloration that is measured at 550 nm using a spectrophotometer model 752G752N. The intensity of the coloration is proportional to the tannin concentration in the sample.

Cyanide contents of the dry peels were assessed using the A.O.A.C. method.[16] 10 g of flour were soaked in a mixture of 200 mL of water and 10 mL of orthophosphoric acid. The mixture was left to stand for 12 h to release all bound hydrocyanic acid. A drop of antifoaming agent (paraffin) and an antibumping agent (6 mm glass beads) was added, and the solution was distilled until 150 mL of distillate was collected. 20 mL of the distillate were transferred to a conical flask and diluted with 40 mL of water. Then, 8.0 mL of 6.0 M ammonium hydroxide (NH_4OH) and 2.0 mL of 5% (w/v) potassium iodide (KI) solution were added. The mixture was titrated with 0.02 M silver nitrate ($AgNO_3$) from a burette until permanent turbidity appeared (1 mL of 0.02 M $AgNO_3$ corresponds to 1.08 mg HCN).

Statistical Analysis. Data statistical analysis was carried out using XLSTAT 2014 software. Analysis of variance (ANOVA) enabled the comparison of means using the post hoc Tukey test at a significance level of 5%. Results from three replicates were expressed as the mean ± standard deviation. The histograms and curves were created by using Excel software.

RESULTS AND DISCUSSION

Physicochemical Characteristics of Banana Fruit Peels. Table 1, Figure 3A−D, and Figure 4A−D show the physicochemical characteristics of banana fruit peels before and after drying. In general, both the drying method and the ripening stage have a significant influence on total titratable acidity, total soluble solids content, and pH of banana fruit peels.

The pH of fresh banana peels was below 6.88 at harvest and varied depending on the banana clones and postharvest ripening stage (Table 1). After drying, peel pH values ranged from 6.24 to 9.04, with significant differences observed between drying methods. Overall, drying tended to increase the peel pH, particularly at 45 °C, where peels became more basic across most cultivars, except for *PITA 14* at stage 9. These results indicate that both ripening and drying methods influence peel acidity. The general increase in pH with ripening observed in this study contrasts with results obtained by Dedo Adi et al.[19] The increase in pH following drying can be explained by the degradation of heat-sensitive organic acids, such as ascorbic acid, leading to a reduction in acidity. These

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Table 2. Protein Content of Dried Banana Fruit Peels—Drying at Room Temperature (DRT) and at 45 °C (D45)—Expressed as g per 100 g of Dry Matter (DM)[i]

Protein content (g/100 g DM)						
		Postharvest ripening stages				
Cultivars	Treatments	Stage 1	Stage 3	Stage 5	Stage 7	Stage 9
Batard	D45	8.50 ± 2.08[a]	9.36 ± 0.11[a]	10.46 ± 0.46[a]	10.89 ± 0.00[a]	6.71 ± 0.46[b]
	DRT	6.28 ± 1.11[b]	8.07 ± 0.75[b]	7.82 ± 0.38[b]	8.68 ± 1.33[b]	9.04 ± 0.63[a]
CARBAP k74	D45	6.59 ± 0.46[a]	6.35 ± 0.28[a]	5.36 ± 0.49[a]	5.55 ± 0.80[a]	4,69 ± 1,23[b]
	DRT	5.30 ± 0.38[b]	6.28 ± 0.49[a]	6.41 ± 0.11[b]	6.71 ± 1.74[a]	8.00 ± 0.70[a]
Grande naine	D45	4.38 ± 0.21[a]	5.73 ± 0.37[a]	5.49 ± 0.87[a]	7.33 ± 1.41[a]	5,85 ± 0.85[a]
	DRT	4.32 ± 0.28[a]	5.55 ± 0.96[a]	7.33 ± 1.25[a]	6.84±0.37[a]	7.21 ± 2.03[a]
PITA 14	D45	8.13 ± 1.44[a]	6.35 ± 0.65[a]	8.80 ± 0.28[a]	6.71 ±2.18[a]	5.85 ± 1.11[a]
	DRT	6.22 ± 1.59[a]	6.71 ± 0.77[a]	9.05 ± 1.47[a]	9.54 ± 0.87[a]	7.02 ± 0.18[a]

[i]The results are an average of three trials; the means ± standard deviations with the same exponents per treatments and per variety are not significantly different at the 5% significance level (Tukey test).

Table 3. Dry Matter Content of Fresh Peel (WD) and Dried Banana Fruit Peels—Drying at Room Temperature (DRT) and at 45 °C (D45)—Expressed as g per 100 g of Dry Matter (DM)[i]

Dry matter content (g/100 g DM)						
		Postharvest ripening stages				
Cultivars	Treatments	Stage 1	Stage 3	Stage 5	Stage 7	Stage 9
Batard	D45	88.79 ± 0.21[a]	88.33 ± 0.24[a]	86.41 ± 3.01[a]	83.75 ± 1.23[a]	84.32 ± 1.24[a]
	DRT	86.48 ± 0.91[a]	86.23 ± 0.89[b]	85.01 ± 0.81[a]	85.38 ± 1.18[a]	85.98 ± 1.03[a]
	WD	15.06 ± 0.31[b]	11.29 ± 0.11[c]	13.05± 0.11[b]	19.30 ± 0.22[b]	27.39 ± 0.91[b]
CARBAP k74	D45	89.00 ± 0.91[a]	89.35 ± 0.45[a]	86.94 ± 0.12[b]	89.52 ± 0.29[a]	84.04 ± 0.44[b]
	DRT	87.90 ± 0.39[a]	89.71 ± 0.76[a]	90.56 ± 0.75[a]	90.18 ± 1.31[a]	92.44 ± 0.78[a]
	WD	9.3 ± 0.20[b]	12.14± 0.12[b]	18.37 ± 0.3[c]	18.09 ± 0.10[b]	34.64 ± 0.12[c]
Grande naine	D45	91.91 ± 0.47[a]	88.42 ± 1.40[a]	89.77 ± 0.48[a]	87.35 ± 0.56[a]	80.35 ± 0,56[b]
	DRT	85.27 ± 0.68[b]	85.73 ± 1.06[a]	88.01 ± 0.10[b]	88.79 ± 0.47[a]	90.79 ± 0,47[a]
	WD	10.52 ± 0.20[c]	11.43 ± 0.18[b]	12.30 ± 0.40[c]	13.77 ± 0.48[c]	22.17 ± 0.13[c]
PITA 14	D45	88.86 ± 0.60[a]	88.81 ± 0.77[a]	88.81 ± 0.77[a]	81.38 ± 1.95[b]	81.38 ± 1.95[a]
	DRT	85.27 ± 0.68[a]	85.73 ± 1.06[a]	85.73 ± 1.06[a]	88.79 ± 0.47[a]	84.12 ± 0.98[a]
	WD	13,47 ± 0.60[b]	15,30± 0.80[b]	14,13 ± 0.18[b]	18,95± 0.42[c]	28,80 ± 0.68[b]

[i]The results are an average of three trials; the means ± standard deviations with the same exponents per treatments and per variety are not significantly different at the 5% significance level (Tukey test).

variations in pH are particularly relevant to the technological valorization of banana peels. Acidity influences the microbial stability and shelf life of products.

At harvest, TTA of all the *Musa* peels analyzed are above 200 mEq/100 g (Figure 3). During ripening, TTA values increased gradually and significantly according to the ripening stage, ranging from 1200 to 1600 mEq/100 g for fresh peels and from 1400 and 1977 mEq/100 g for dried peels at stage 9, depending on the cultivar, with *CARBAP K74* exhibiting the highest value. At each ripening stage, drying significantly influenced TTA values. Generally, peels dried at 45 °C in an oven presented highest values of TTA at harvest, stage 7, and stage 9 compared to those dried at ambient temperature. The acidity of the fruit influences its sensory qualities, which are measured by total titratable acidity and pH.[20] The increase in total titratable acidity with ripening is due to the breakdown of starch into sugars during ripening, resulting in the synthesis of acids such as malic, oxalic, and citric acid in banana fruit peels.[21] Nevertheless, the high TTA values observed during drying at 45 °C are due to peel water content reduction, resulting in an increase in acidity caused by the hydrolysis of carbohydrates into sugars and other organic compounds.

Figure 4 shows the soluble solid content of fresh and dry banana peels. They increased with ripening depending on cultivar and drying mode. The soluble solids content varied from 0.2°Brix (stage 1) to 14.6°Brix (stage 9) in the fresh banana peels. With drying, these values increase and vary from 2.8 to 16.3°Brix for peels, with the highest value obtained by drying at 45 °C peels. Drying at 45 °C makes the different compounds (sugars and acids) in banana peels more soluble. Total soluble content refers to the amount of sugars present in a food. It is also an indicator of the ripeness of banana fruits. Studies by Huang et al.[13] showed that total soluble solids content increased with ripening from 4.2 to 38.3°Brix in the peels of *Big ebanga* (a local plantain). The increase in SSC with drying is thought to be due to the breakdown of starch into sugars during ripening, resulting in an increase in soluble solids in banana fruit peels.[22]

Dry matter (Table 2) content of banana peels ranged from 83.75 to 92.44% in dried peels and from 9.3 to 34.64% in fresh peels. In general, this value was higher in peels dried at 45 °C in an oven, confirming the effectiveness of drying in eliminating free water and concentrating solid constituents. Fresh peels have lower contents (9.3%−34.64% g/100 g), which reflects the high water proportion in fresh banana peels (more than 66%). These values are close to 91% obtained by Agbabiaka and Okorie,[23] in peels sun-dried for 2 weeks. The data obtained by Oduje et al.[24] are similar to the dry matter of

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Table 4. Lipid Content of Dried Banana Fruit Peels—Drying at Room Temperature (DRT) and at 45 °C (D45)—Expressed as g per 100 g of Dry Matter (DM)[i]

Lipid content (g/100 g DM)						
		Postharvest ripening stages				
Cultivars	Treatments	Stage 1	Stage 3	Stage 5	Stage 7	Stage 9
Batard	D45	3.71 ± 0.12[a]	5.52 ± 0.29[a]	6.76 ± 0.03[a]	10.57 ± 0.18[a]	6.15 ± 1.03[a]
	DRT	3.70 ± 0.12[a]	4.65 ± 0.40[b]	5.52 ±0.30[b]	8.52 ± 0.74[b]	7.48 ± 0.56[a]
CARBAP k74	D45	9.76 ± 0.33[b]	12.16 ± 0.04[b]	12.48 ± 0.10[a]	13.97 ± 0.59[a]	10.25 ± 0.57[b]
	DRT	12.13± 0.05[a]	8.55 ± 0.04[a]	13.03 ± 0.08[b]	13.69 ± 0.70[a]	14.93 ± 0.54[a]
Grande naine	D45	3.18 ± 0.01[a]	4.65 ± 0.12[a]	9.08 ± 0.15[a]	6.65 ± 1.13[a]	7.83 ± 0.41[b]
	DRT	2.72 ± 0.30[a]	3.72 ± 0.30[b]	7.71 ± 0.10[b]	6.66 ± 0.61[a]	8.83 ± 0.31[a]
PITA 14	D45	6.79 ± 0.22[a]	8.13 ± 0.11[a]	9.33 ± 1.19[a]	7.64 ± 1.10[b]	9.00 ± 0.67[a]
	DRT	6.71 ± 0.10[a]	8.90 ± 0.64[a]	9.57 ± 1.83[a]	11.27 ± 0 63[a]	10.31 ±1.38[a]

[i]The results are an average of three trials; the means ± standard deviations with the same exponents per treatments and per variety are not significantly different at the 5% significance level (Tukey test).

Table 5. Carbohydrate Content of Dried Banana Fruit Peels—Drying at Room Temperature (DRT) and at 45 °C (D45)—Expressed as g per 100 g of Dry Matter (DM)[i]

Total carbohydrate content (g/100 g DM)						
		Postharvest ripening stages				
Cultivars	Treatments	Stage 1	Stage 3	Stage 5	Stage 7	Stage 9
Batard	D45	62.91 ± 2.30[a]	58.64 ± 0.42[a]	53.62 ± 4.74[a]	45.57 ± 1.21[b]	55.62 ± 0.77[a]
	DRT	63.35 ± 2.42[a]	59.21 ± 1.86[a]	55.68 ± 2.02[a]	50.09 ± 1.05[a]	54.10 ± 0.40[b]
CARBAP k74	D45	59.13 ± 2.03[a]	57.44 ± 0.72[a]	53.68 ± 1.31[a]	54.12 ± 2.19[a]	54.93 ± 0.36[a]
	DRT	55.96 ± 1.06[a]	59.80 ± 1.99[a]	55.29 ± 2.61[a]	54.08 ± 2.54[a]	55.82 ± 0.95[a]
Grande naine	D45	70.17 ± 0.90[a]	65.62 ± 2.49[a]	59.63 ± 3.51[a]	58.30 ± 1.82[a]	57.08 ± 2.99[a]
	DRT	67.03 ± 0.18[b]	62.32 ± 4.08[a]	57.51 ± 0.29[a]	57.94 ± 0.34[a]	60.91 ± 2.43[a]
PITA 14	D45	63.31 ± 2.28[a]	64.26 ± 1.89[a]	56.04 ± 1.81[a]	55.29 ± 0.79[b]	56.12 ± 0.67[b]
	DRT	61.14 ± 1.81[a]	55.76 ± 2.11[b]	53.93 ± 3.35[a]	50.64 ± 1.22[a]	59.61 ± 1.59[a]

[i]The results are an average of three trials; the means ± standard deviations with the same exponents per treatments and per variety are not significantly different at the 5% significance level (Tukey test).

Table 6. Ash Content of Dried Banana Fruit Peels—Drying at Room Temperature (DRT) and at 45 °C (D45)—Expressed as g per 100 g of Dry Matter (DM)[i]

		Postharvest ripening stages				
Cultivars	Treatments	Stage 1	Stage 3	Stage 5	Stage 7	Stage 9
Batard	D45	13.67 ± 0.56[a]	14.30 ± 0.30[a]	15.56 ± 1.70[a]	16.72 ± 0.78[a]	15.82 ± 0.69[a]
	DRT	13.13 ± 0.71[a]	15.56 ± 1.70[a]	15.99 ± 1.59[a]	18.09 ± 1.54[a]	15.35 ± 0.51[a]
CARBAP K74	D45	13.52 ± 0.91[a]	13.40 ± 0.54[b]	15.41 ± 0.98[a]	15.88 ± 0.83[a]	14.18 ± 1.84[a]
	DRT	14.50 ± 1.37[a]	15.07 ± 0.80[a]	15.83 ± 1.88[a]	15.70 ± 0.81[a]	13.68 ± 0.17[a]
Grande naine	D45	14.19 ± 1.15[a]	12.41 ± 1.61[a]	15.57 ± 2.96[a]	15.07 ± 1.76[a]	9.00 ± 1.25[b]
	DRT	11.19 ± 0.28[b]	14.35 ± 3.75[a]	15.45 ± 1.53[a]	17.35 ± 0.27[a]	13.18 ± 1.37[a]
PITA 14	D45	10.63 ± 0.52[a]	10.07 ± 0.46[a]	13.78 ± 0.35[a]	13.42 ± 0.37[b]	10.48 ± 0.37[a]
	DRT	11.19 ± 0.28[a]	14.35 ± 3.75[a]	15.45 ± 1.53[a]	17.35 ± 0.27[a]	13.18 ± 1.37[b]

[i]The results are an average of three trials; the means ± standard deviations with the same exponents per treatments and per variety are not significantly different at the 5% significance level (Tukey test).

peels from cultivar *PITA 14* (86%) at stage 5 and cultivar *Batard* (87%) at stage 9. Drying at high temperatures could significantly reduce the amount of water in the product, thereby increasing its dry matter content. Genetic differences are also evident; *Grande naine* and *CARBAP K74* maintain high and consistent contents, suitable for industrial valorization (powder, flour, and fiber-rich additives), while *Batard* and *PITA 14* show more pronounced variations, reflecting variability in postharvest physiology.[25]

Nutritional Composition of Banana Fruit Peels. Tables 3−456 shows the nutritional parameters (proteins, lipids, carbohydrates, and ash) of banana peels dried at 45 °C in an oven and at room temperature. The table shows a significant difference between all the parameters analyzed, depending on the drying method. The peels of the *Batard* and hybride *CARBAP K74* varieties have higher nutrient contents than those of the *PITA 14* and *Grande naine* varieties. Whether dried at 45 °C in an oven or at room temperature, protein content increased with ripening. However, all the peels dried at 45 °C in the oven had a higher protein content than those dried at room temperature. The protein contents of the peels of the four banana cultivars studied ranged from 4.32 to 10.89%. These values are close to those obtained by Abou-

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Table 7. Phytate and Oxalate of Dried Banana Fruit Peels—Drying at Room Temperature (DRT) and at 45 °C (D45)—Expressed as g per 100 g of Dry Matter (DM)[i]

Phytate content (g/100 g DM)						
		Postharvest ripening stages				
Cultivars	Treatments	Stage 1	Stage 3	Stage 5	Stage 7	Stage 9
Batard	D45	1.03 ± 0.00[a]	0.19 ± 0.01[a]	0.18 ± 0.01[a]	0.11 ± 0.01[a]	0.07 ± 0.01[a]
	DRT	0.51 ± 0.00[b]	0.12 ± 0.01[b]	0.09 ± 0.01[b]	0.13 ± 0.01[a]	0.08 ± 0.01[a]
CARBAP K74	D45	0.88 ± 0.03[a]	0.17 ± 0,02[a]	0.19 ± 0.0[a]	0.25 ± 0.03[a]	0.07 ± 0.00[a]
	DRT	0,35 ± 0.00[b]	0.12 ± 0.00[b]	0.10 ± 0.01[b]	0.38 ± 0.07[a]	0.08 ± 0.00[a]
PITA 14	D45	0.91 ± 0,01[a]	0.13 ± 0.01[a]	0.12 ± 0.00[a]	0.14 ± 0.01[a]	0.14 ± 0.02[a]
	DRT	0.28 ± 0,00[b]	0.08 ± 0.01[a]	0.14 ± 0.01[a]	0.12 ± 0.00[a]	0.16 ± 0.01[a]
Grande naine	D45	1.04 ± 0.01[a]	0.21 ± 0.02[a]	0.27 ± 0,04[a]	0.14 ± 0,02[a]	0.12 ± 0.03[a]
	DRT	0.32 ± 0.01[b]	0.09 ± 0.01[b]	0.09 ± 0.00[b]	0.18 ± 0.01[a]	0.12 ± 0.00[a]
Oxalate content (g/100 g DM)						
		Postharvest ripening stages				
Cultivars	Treatments	Stage 1	Stage 3	Stage 5	Stage 7	Stage 9
Batard	D45	2.43 ± 0.16[a]	4.06 ± 0.08[a]	3.79 ± 0.08[a]	5.65 ± 0.08[a]	7.15± 0.08[a]
	DRT	2.49 ± 0.39[a]	4.55 ± 0,20[a]	2.53 ± 0.08[a]	4.72 ± 0.08[a]	4.09 ± 0.12[b]
CARBAP K74	D45	1.87 ± 0.16[a]	4.04± 1,05[a]	3.73 ± 0.08[a]	3.44 ± 0.16[a]	7.15 ± 0.08[a]
	DRT	2.49 ±0.05[a]	2.83 ± 0,12[b]	3.07 ± 0.20[a]	4.29 ± 0.08[a]	4.09 ± 0.20[b]
Grande naine	D45	1.75 ± 0.00[a]	4.55 ± 0,01[a]	4.88 ± 0.01[a]	5.00 ± 0.01[a]	10.98± 0.03[a]
	DRT	1.90 ± 0.00[a]	5.56 ± 0,01[a]	3.45 ± 0.00[a]	4.02 ± 0.00[a]	5.68 ± 0.00[b]
PITA 14	D45	2.20 ± 0.01[a]	5.3 0± 0,01[a]	5.47 ± 0.00[a]	5.95 ± 0.00[a]	6.94 ± 0.02[b]
	DRT	2.52 ±0.00[a]	3.81 ± 0,00[b]	4.41 ± 0.00[a]	4.76 ± 0.00[b]	7.22 ± 0.00[a]

[i]The results are an average of three trials; the means ± standard deviations with the same exponents per ripening stage and per variety are not significantly different at the 5% significance level (Tukey test).

Table 8. Tannin and Cyanide Content of Dried Banana Fruit Peels—Drying at Room Temperature (DRT) and at 45 °C (D45)—Expressed as g per 100 g of Dry Matter (DM)[i]

Tannin content (g/100 g DM)						
		Postharvest ripening stages				
Cultivars	Treatments	Stage 1	Stage 3	Stage 5	Stage 7	Stage 9
Batard	D45	1.65 ± 0.07[a]	3.82 ± 0.06[a]	1.75 ± 0.03[a]	1.20 ± 0.07[a]	7.41 ± 0.03[a]
	DRT	1.28 ± 0.03[a]	3.24 ± 0.05[a]	0.57 ± 0.03[b]	1.41 ± 0.07[a]	1.72 ± 0.06[b]
CARBAP K74	D45	1.62 ± 0.03[b]	4.27 ±0.05[a]	1.80 ±0.03[a]	1.15 ± 0.05[a]	7.41 ± 0.09[a]
	DRT	2.80 ±0.04[a]	1.96 ±0.03[a]	3.14 ± 0.05[a]	0.73± 0.10[a]	1.72 ± 0.03[b]
Grande naine	D45	0.57 ± 0.07[b]	1.31 ± 0.04[a]	9.03 ± 0.0[a]	1.15 ± 0.07[a]	0.70 ± 0.07[b]
	DRT	0.80 ± 0.09[a]	1.31 ± 007[a]	2.59 ± 0.07[b]	1.38 ± 0.05[a]	1.59 ± 0.07[a]
PITA 14	D45	2.54 ± 0.07[a]	2.82 ± 0.07[a]	2.75 ± 0.12[a]	0.99 ± 0.07[a]	2.48 ± 0.07[a]
	DRT	2.04 ± 0.07[a]	1.57 ±0.07[a]	1,23 ± 0.28[a]	0.89± 0.28[a]	0.31 ± 0.07[b]
Cyanide content (mg/100 g DM)						
		Postharvest ripening stages				
Cultivars	Treatments	Stage 1	Stage 3	Stage 5	Stage 7	Stage 9
Batard	D45	0.50 ± 0.07[a]	0.38 ± 0.05[a]	0.56 ± 0.02[a]	0.52 ± 0.07[a]	0.29 ±0.02[a]
	DRT	0.52 ± 0.03[a]	0.34 ± 0.01[a]	0.43 ± 0.01[b]	0.46 ± 0.02[a]	0.28 ± 0.09[a]
CARBAP K74	D45	0.52 ± 0.05[b]	0.58 ± 0.02[a]	0.31 ± 0.01[a]	0.39 ±0.03[a]	0.29 ± 0.03[a]
	DRT	0.72 ± 0.03[a]	0.32 ± 0.02[b]	0.34 ± 0.04[a]	0.44 ±0.09[a]	0.27 ± 0.09[a]
Grande naine	D45	0.57 ± 0.03[b]	0.50 ± 0.10[a]	0.29 ± 0.04[b]	0.34 ± 0.04[b]	0.31 ± 0.04[a]
	DRT	0.80 ± 0.09[a]	0.40 ± 0.0[b]	0.46 ± 0.02[a]	0.44 ± 0,04[a]	0.24 ± 0.04[a]
PITA 14	D45	0.50 ± 0.09[a]	0.65 ± 0.05[a]	0.36 ± 0.04[a]	0.31 ± 0.05[a]	0.21 ± 0.05[a]
	DRT	0.40 ± 0.03[b]	0.36 ± 0.01[b]	0.46 ± 0.06[b]	0.43 ± 0,01[b]	0.34 ± 0.03[b]

[i]The results are an average of three trials; the means ± standard deviations with the same exponents per ripening stage and per variety are not significantly different at the 5% significance level (Tukey test).

Arab and Abu-Salem[26] on microwave-dried banana peels (10.82%).

The lipid content of dried peels increased with ripening and varied from 2.72% (*Grande naine*) to 14.93% (*CARBAP K74*). Drying in the oven at 45 °C increased the lipid content of peels of *Batard* and *Grande naine*, whereas for *CARBAP K74* and *PITA 14*, drying at room temperature increased their lipid content during postharvest ripening. The increase in peel lipid content observed during drying is similar to the trend obtained by Wordu and Akusu[27] on plantain peels during ripening.

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However, the values obtained (<4%) by the latter are lower than those obtained in this study (2.72 −12.16%). The lipid contents in dried peels obtained in this study are higher than those obtained (3.8−5.23%) by Oduje et al.[24] This difference is due to the cultivar, variety, and stage of ripeness of the fruit, which determines the nutritional composition of the banana peel.[28]

The total carbohydrate content of dried banana peels varied from 70.17% (stage 1) to 50.64% (stage 7) and decreased with postharvest ripening. Drying methods had no significant influence on the carbohydrate content of *Batard, CARBAP K74, Grande naine, and PITA 14 peels*. Total carbohydrates in dried banana fruit peels decreased during postharvest ripening This decrease is similar to that obtained by Oduje et al.,[24] however, the values obtained are low (<50%). The high level of carbohydrates helps improve baked characteristics, such as their texture and structure, which might be attractive in baked goods.[29]

Table 6 highlights the ash contents, which vary according to cultivar, ripening stage, and drying method. Overall, drying at 45 °C and room temperature drying produced comparable values, with slight differences depending on the stage and cultivar. The ash content of dried peels tended to increase with ripening stage across all cultivars. The ash content ranged from 9 to 17%, which is lower than the 15−20% reported by Abou-arab and Abu-salem[26] in microwave-dried banana peels. This discrepancy might be attributed to differences in the varieties of the cultivars studied.

Antinutritional Parameters of Banana Fruit Peels. The antinutritional parameters (phytate, oxalate, tannin, and cyanide) of banana fruit peels dried at 45 °C and at room temperature are presented in Tables 7 and 8. There was a significant difference between the parameters studied depending on the drying mode.

The phytate content varied from 1.04% (stage 1) to 0.07% (stage 9) and decreased with ripening. Drying at room temperature significantly reduced the phytate content of the peels of all Musa clones, contrary to drying at 45 °C in an oven. Phytic acid or phytates form a complex with proteins and chelate essential dietary minerals such as iron, zinc, copper, and magnesium, reducing their absorption during digestion. Phytate levels in this study decreased during ripening and varied between 0.12 and 1.03%. These values are very low compared to 4.7% obtained by Abou-arab and Abu-salem in microwave-dried banana peels.[26] Kumar et al. mentioned a lower level in phytic acid contents of plant foodstuffs when they were subjected to various thermal treatment like microwave, autoclave etc. They attributed the decrease in phytate content to the formation of insoluble complexes between phytates and other compounds.[30]

The oxalate content increased with the stage of postharvest ripening and varied from 1.75% at stage 1 to 10.98% at stage 9. At stage 1, drying at 45 °C reduced the oxalate content in the peels of all Musa clones, whereas at stage 3, this effect was observed only in the peels of the local plantain (*Batard*) and dessert banana (*Grande naine*). From stages 5 to 9, room temperature drying reduced the levels of oxalate in the peels of all banana clones. Oxalate ions or oxalic acid are antinutrient capable of forming strong bonds with certain minerals such as calcium, making it inaccessible, while their soluble salts can crystallize in the urinary tract and form kidney stones.[26] Oxalate levels increased with postharvest ripening. oxalate contents (0.8−1.87%) found by Abou-arab and Abu-salem[26] are lower than those obtained in this study (1.75−10.98%).

Tannin levels varied from 0.57 to 9.03 g/100 g. In most cases, tannin levels obtained after drying at 45 °C in an oven were higher than those measured after drying at room temperature. The tannin content of peels after drying increased from stage 1 to stage 3, decreased at stages 5 and 7, and increased again at stage 9. This trend was observed in the peels of all banana cultivars, except *Grande naine* peels. Tannins are antinutrients that inhibit digestive enzymes, reducing the digestibility of most nutrients, particularly proteins and carbohydrates,[31] and are also responsible for a decrease in amino acid availability and an increase in fecal nitrogen. The tannin contents obtained are lower than those obtained by Adeniji and Tenkouano[32] (9.8% and 12.0%) after drying for *Agbagba* and *PITA 14* cultivars, respectively. This difference can be attributed to the varietal effect, as the physiological and biochemical characteristics inherent to each cultivar influence the tannin content.

The cyanide content of banana fruit peels assessed after drying varied from 0.21 to 0.80 mg/100 g, which was very low. Cyanide levels decreased during postharvest ripening. At stage 1 of ripening, the drying mode at 45 °C reduced the cyanide content in banana peels. For advanced ripening stages (3, 5, 7, and 9), the same effect was produced in the peels by drying at room temperature. Hydrogen cyanide is a highly toxic substance formed by the activity of acids on metal cyanides.[33] High doses of hydrogen cyanide can lead to death within minutes, while low doses can cause palpitations and muscle weakness.[27] The hydrogen cyanide levels obtained in this study were very low (<1 mg/100 g) compared to the cyanide content of 6.42 mg/100 g found by Onyenweaku and Kesa[34] in the peels of fruits. This low level, below the safety limit of 3.5 mg/g,[35] predispose dried peels to be used without danger of hydrogen cyanide poisoning in the production of flour. Dried banana peels can be safely incorporated into food applications. The simultaneous reduction in cyanide content and enhancement of nutritional properties further support their potential use in infant foods, bakery products, and other value-added formulations, thereby reinforcing the prospects for banana peel valorization while ensuring consumer safety.

Studies on the Correlations between the Different Observations and Variables of Banana Peels. Figure 5

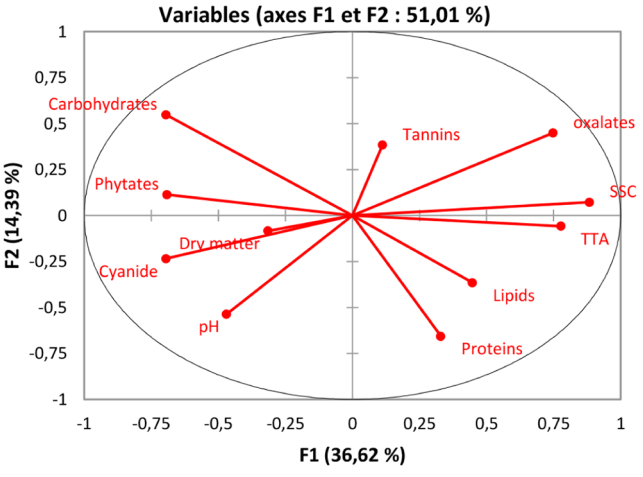

Figure 5. Principal component analysis (PCA) of the physicochemical, nutritional, and antinutritional variables of banana peels.

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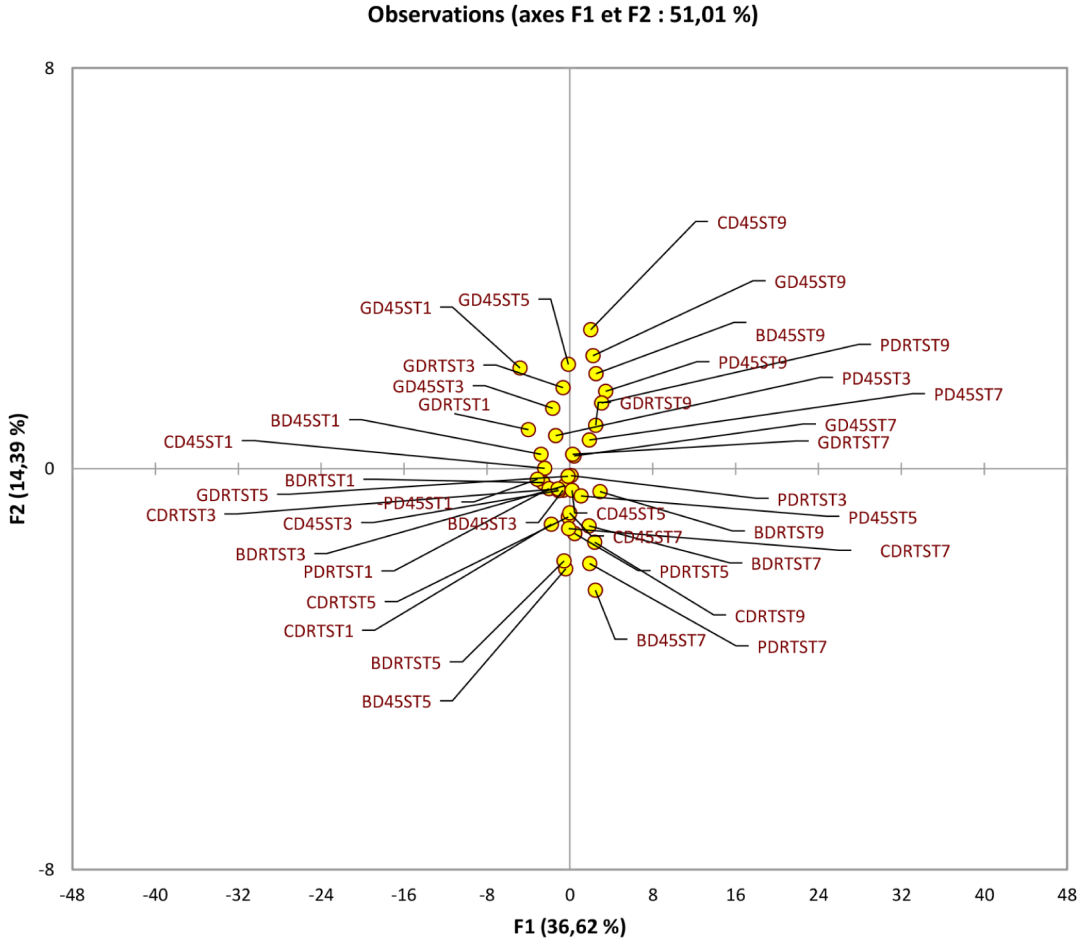

Figure 6. PCA score plot of banana peel samples according to maturity stage, drying method, and variety.

shows the projection of the studied variables on the first two principal components of the PCA, which explain 51.01% of the total variance (F1 = 36.62% and F2 = 14.39%). This figure highlights the associations among nutritional properties (proteins, lipids, and carbohydrates), physicochemical parameters (pH, TSS, TTA, and dry matter), and antinutritional factors (phytates, tannins, oxalates, and cyanide), enabling an integrated interpretation of the data according to peel maturity stages and drying treatments. Axis F1 is mainly positively correlated with oxalates, total soluble solids (TSS), titratable acidity (TTA), lipids, and proteins, and negatively correlated with pH and cyanide. Axis F2 is primarily to carbohydrates and, to a lesser extent, tannins, while the other variables contribute weakly. The proximity of vectors indicates positive correlations (between TSS, TTA, and oxalates), while opposite directions indicate negative correlations (between proteins/lipids and cyanide/pH).

The principal component analysis (PCA) performed on the observations (Figure 6) shows a clear discrimination among banana peel samples according to maturity stage, drying method, and banana variety. Samples from the intermediate ripening stages (ST3−ST5) are mainly grouped at the center of the factorial plane, reflecting a balanced profile between nutritional variables (proteins, lipids, and carbohydrates) and a moderate content of antinutritional factors (phytates, oxalates, and tannins). In contrast, the advanced ripening stages (ST7−ST9) show greater dispersion, associated with an increase in soluble solids and titratable acidity, but also with higher levels of tannins and oxalates. Regarding the drying methods, drying at 45 °C (D45) ensures better preservation of nutrients and a relative limitation of antinutritional compounds, whereas drying at room temperature (DRT) is characterized by higher levels of oxalates and tannins, which are less favorable for food valorization. Overall, the results indicate that stage ST5, combined with oven drying at 45 °C (D45) and the *CARBAP K74* variety, represents the most advantageous compromise, allowing the optimization of nutritional quality while minimizing antinutritional compounds.

All physicochemical, nutritional, and antinutrient parameters analyzed vary according to drying modes and ripening stages depending on banana clones. In fact, oven drying at 45 °C results in higher protein, carbohydrate, and ash contents at all ripening stages and promotes the reduction of antinutritional substances in the banana peels studied. From this work, the peels of the plantain landrace (*Batard*) and the plantain-like hybrid (*CARBAP K74*) should be chosen in preference to the *PITA 14* and *Grande naine* varieties in the production of whole fruit flour, given their high nutrient content and low antinutritional factors. Based on this work, the dried peels of the four banana cultivars show potential for use in food formulations. Further studies on microbiological safety, fiber content, digestibility, and amino acid profiles are needed to support their valorization as sustainable food ingredients.

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Notes

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ABBREVIATIONS:

(DMC), dry matter content; (DRT), drying at room temperature; (D45), drying at 45 °C; (pH), potential of hydrogen; (TTA), total titratable acidity; (TSS), total soluble solids; (WD), without drying; (ST1), ripening stage 1; (ST3), ripening stage 3; (ST5), ripening stage 5; (ST7), ripening stage 7; (ST9), ripening stage 9

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