Research Article

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Influence of contrasting cultivation altitudes on the physicochemical, digestive, and functional properties of four *Musa* starches produced in Cameroon

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Abstract

BACKGROUND: Bananas and plantains are important food sources for many people in the world. Their high starch content places them among the highest energy providers. This study aimed to determine the effects of altitude on banana starch properties in Cameroon. A dessert banana, a cooking banana, a plantain cultivar, and a plantain-like hybrid were grown at low and high altitudes (respectively at 80 m and 1300 m above sea level).

RESULTS: Starch analyses showed an increase in moisture and pH values against a drop in total titratable acidity and dry matter content with respect to altitude. Amylose content, as well as water absorption capacity, oil absorption capacity and syneresis of high-altitude plantain and plantain-like hybrid, were significantly higher. Starch digestibility was low and ranged between 13.4% and 37.9% after 2 h of incubation. High-altitude plantain starches contained more amylose and were more resistant to enzymatic hydrolysis.

CONCLUSION: Starches from CARBAP K74 and Kelong mekintu, grown at high altitude, showed good water and oil absorption capacities, low digestibility, and high resistance. The adequate properties of these banana starches predispose them for use as thickeners and gelling agents as well as ingredients for the formulation of low-calorie foods. This study highlights the importance of altitude when discussing banana and plantain starch properties.

Keywords: bananas and plantains; starch properties; environmental influence; genotype-by-environment interaction

INTRODUCTION

Bananas (*Musa* spp.) are important foods and income sources for many people in tropical areas. They represent an important source of energy for more than 70 million people in West and Central Africa.[1] In Cameroon, the daily energy from banana consumption is up to 173 kcal per person per day, making it one of the principal sources of dietary energy. Between 2018 and 2019, the national production was estimated at 2.76 million tons, but only 13% of this production was marketed and/or processed.[2] The limit uses of bananas, their highly perishable nature, and their low processing together promote post-harvest losses, severely limit their potential for added value, and reduce their real impact on economic growth. It is therefore necessary to explore new fields for the valorization of bananas.

Bananas could have alternative uses based on their high starch content if more scientific data were available.[3] Numerous studies

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on the physicochemical, techno-functional, and digestive characterizations of banana starches have been conducted all over the world.[4-9] These studies generally focused on their particle size, composition, susceptibility to hydrolysis, water and oil retention capacities, as well as syneresis, rheological and thermal properties. Sivirihauma *et al*. reported that high altitude enhance suckering and significantly reduced plantain yields in North Kivu,[10] while Suzuno and Ishida showed that starch content was higher (7.9% fresh weight) at high altitudes (1000 m) than at middle and low altitudes.[11] However, none of these studies has so far focused on starches derived from bananas, plantains, and plantain-like hybrids cultivated in Cameroon. Furthermore, the influence of altitude on the various properties studied remains unknown. The current study aims to evaluate the physicochemical, functional, and digestive properties of starches extracted from four banana cultivars produced in two contrasting localities of Cameroon.

MATERIALS AND METHODS

Biological materials

The biological material consisted of unripe fruits from a cooking banana Maduranga (ABB), a dessert banana Banane cochon (AAA), a local plantain cultivar Kelong mekintu (AAB), and a plantain-like hybrid CARBAP K74 (AAA). They were grown in two experimental plots set up in Njombe in the Littoral Region and in Bansoa in the West Region (80 and 1300 m above sea level, respectively). Characteristics of the study sites are shown in Table 1. The study was conducted within the RTBfoods Project (https://rtbfoods.cirad.fr/) conducted by CARBAP (Centre Africain de Recherches sur Bananiers et Plantains).

Sampling

Three to four bunches at their optimal physiological maturity (characterized by the appearance of a start ripe finger on the first or second hand of the bunch) were harvested and immediately transported to the CARBAP Post-harvest Technology Laboratory in Njombe. For each bunch, unripe fruits from the second and third hands were selected and randomized before being subdivided into two batches. The first batch was used for physicochemical characterization that was carried out immediately after harvest, while those from the second batch were used for starch extraction, determination of extraction yields, evaluation of amylose and amylopectin contents, digestibility studies, and determination of predicted glycemic index (pGI). Kinetics parameters, as well as rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) fractions, were also determined from the second batch.

Table 1. Agro-ecological characteristics of the locations used for this study

	Locality	
Characteristics	Bansoa	Njombe
Agro-ecological zone (AEZ)	Western highlands (AEZ III)[12]	Humid forest (AEZ IV)[12]
Altitude (m)	1300–1440[13]	80[14]
Soil texture	Sandy loam[13,15]	Highly organic[14]
Soil type	Alfisol[13] Ustic Oxisol[15]	Andisol[14]
Soil pH	5–6,[13] 5.2[15]	6[14]
Temperature (°C)	16–21[13]	26–28[14]
Rainfall (mm)	1883[13]	2300–3200[14]

Starch extraction

Pulp starches from the different genotypes were extracted using a modified protocol.[16] In the laboratory, samples from the second batch described above were weighed and washed before being peeled with a stainless-steel knife. The unripe pulps obtained were weighed, cut into cubes, and ground with tap water (1 kg pulp for 1 L water) for 5 min in a blender (model Royalty Line, Switzerland). The slurry obtained was mixed with tap water, mashed with a spatula, and filtered thrice successively through sieves (mesh sizes 200, 125, and 50 μm). This operation was repeated several times until the filtrate became clear. The filtrate was allowed to stand for 24 h at room temperature for the starch to settle, and the supernatant was discarded. The sediment (fresh starch) was dried at 40 °C in an oven until a constant weight was obtained. The dried starch sample obtained was milled, sieved (mesh size = 200 μm) weighed, and packaged in polythene bags for subsequent analyses. The starch yield was determined using the formula

$$Y = \frac{M_1}{M_2} \times 100 \quad (1)$$

where Y = starch yield, M_1 = mass of dried starch, and M_2 = mass of fresh pulp used.

Starch characterization

Size and shape of starch granules

Size and shape were observed and determined by optical microscopy in visible light using a LEICA DM6000 (model 3557, Wetzlar, Germany) optical microscope equipped with a micrometer. 80 μL potassium iodide (2%) was measured and deposited onto a glass slide; 2 mg of each banana starch sample was then added, homogenized, and covered with a coverslip. Observation was carried out with 40× magnification and the images were taken using a Sony camera (Optical SteadyShot DSC-W360, Tokyo, Japan) with zoom adapted to one of the eyepieces equipped with an optical micrometer, which allowed the measurement of the average granule diameter. The shapes of the granules were assessed by simple observation.

Physicochemical characteristics – total titratable acidity (TTA), pH, dry matter content (DMC) and ash content of the extracted starch – were evaluated using standard methods.[17]

Amylose and amylopectin contents

Amylose and amylopectin were determined using a modified colorimetric method.[18] A standard curve for amylose was previously constructed using different concentrations ranging from 0 to 70 mg pure amylose (amylose from potato, A0512-250MG, Sigma-Aldrich, St Louis, MO, USA). These were weighed separately into 50 mL volumetric flasks, into which 0.5 mL of 80% ethanol, 5 mL distilled water and 1 mL of 10% sodium hydroxide were added. The mixture was heated in a water bath until the solution became clear and then cooled to room temperature. The volume was made up to the mark with distilled water. 5 mL of the solution obtained above was measured and introduced into a 250 mL volumetric flask, then 100 mL distilled water was added and immediately acidified with a few drops of 1 mol L^{-1} hydrochloric acid. After mixing the contents, 5 mL of a 5% iodine solution was added and the volume adjusted to 250 mL with distilled water.

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The absorbance of the resulting solution was read at 640 nm on a spectrophotometer (ultraviolet–visible mini, model 1240, Shimadzu, Kyoto, Japan). 100 mg starch was weighed and the above procedure was repeated. The concentration of amylose was calculated from the standard curve and that of amylopectin was deduced by subtraction (% amylopectin = 100 − % amylose).

Functional properties of starch

The percentage solubility and swelling power were determined according to a modified protocol.[19] Water and oil retention capacities were respectively determined according to modified methods.[20,21] A modified method described by Singh *et al*. was used to study syneresis.[22] Syneresis was determined on 2% starch gels over 21 days after storage at 4° C. A 2% (w/v) starch suspension was prepared with distilled water, introduced into test tubes, and heated for 30 min in a water bath at 90° C with stirring every 5 min. The syneresis, expressed as the proportion of water released after centrifugation at 1980 × *g* for 10 min, was calculated according to the following formula:

$$\text{Syneresis}(\%) = \frac{\text{Separated liquid}}{\text{gel weight}} \times 100 \quad (2)$$

In vitro *starch digestibility*

A modified protocol was used to study starch *in vitro* digestibility.[4] A bacterial α-amylase (from *Bacillus* sp. ≥1500 units mg^{-1} protein; Sigma-Aldrich, Burlington, MA, USA) was used to follow up on the kinetics of starch hydrolysis as a function of time. Reducing sugars released were quantified according to the colorimetric method with 3,5-dinitrosalicylic acid. 0.33 g banana starch powder was mixed with 10 mL phosphate buffer (0.2 mol L^{-1}, pH 6.9) in a 15 mL test tube. After heating in a water bath (Polytest 30, Fisher Scientific, Germany) at 95° C for 30 min and cooling to 25° C, 1 mL of 0.1 mg mL^{-1} α-amylase enzyme suspension was added before incubation. The incubation lasted for 120 min at 20° C in the water bath with constant stirring. The hydrolysis was stopped by the addition of 1.7 mL of 1% (v/v) sulfuric acid solution. For each sample, a blank consisting of a tube without enzyme was made. A reducing sugar (glucose) was used to prepare a standard curve. Starch digestibility was expressed as the percentage of damaged starch after enzymatic digestion with α-amylase after 2 h. The percentage of digested starch at digestion time t was determined from the following formula:

$$D = \frac{\text{DO} \times V_t \times M \times 0.9 \times 100}{m \times V_i \times 0.009} \quad (3)$$

where D is digested starch at digestion time t (%), DO is read optical density, V_t is total volume (12.2 mL), M is molar mass of glucose (180 g mol^{-1}), 0.9 is the starch–glucose conversion factor, V_i is the volume of the test sample (0.5 mL), and 0.009 is the slope of the calibration curve constructed for this purpose.

Predicted glycemic index (pGI)

pGI was determined by applying the following mathematical formula:[9]

$$\text{pGI} = 39.21 + 0.803 H_{90} \quad (4)$$

where H_{90} is the amount of reducing sugar produced after 90 min of incubation.

Rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS) fractions were determined as the digested fractions respectively after 30, 60 and 120 min, while the kinetic constant k and the equilibrium concentration C_∞ were determined from the equation below:[9]

$$C = C_\infty \left(1 - e^{-kt}\right) \quad (5)$$

where C_∞ = equilibrium concentration and k = kinetic constant.

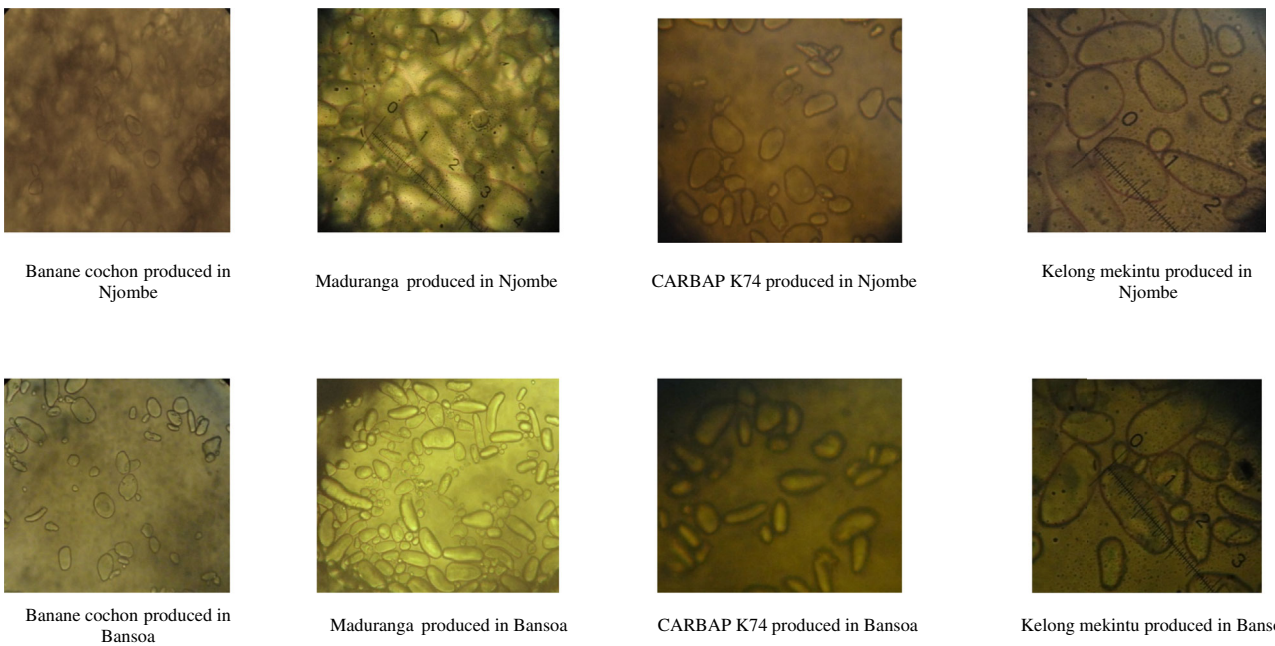

Figure 1. Photographs of starch granules of different cultivars from two agro-ecological zones seen under optical microscope in normal light (40× magnification).

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Table 2. Average size and shape of banana starch granules from different cultivars grown at low and high altitudes

Cultivar	Locality	Size (μm)	Shape
K74	Bansoa	19.0a (1.3)	Spherical and cylindrical
	Njombe	27.2b (0.1)	
MAD	Bansoa	21.7a (0.0)	Cylindrical
	Njombe	22.5b (0.2)	
KLM	Bansoa	21.5a (0.2)	Oval cylindrical
	Njombe	24.9b (0.1)	
BC	Bansoa	20.8a (0.1)	Spherical
	Njombe	23.9b (0.1)	

Abbreviation: K74, CARBAP K74; MAD, Maduranga; KLM, Kelong mekintu; BC, Banane cochon. The results are based on the mean of three trials; means ± standard deviations bearing the same letters for each cultivar are not significantly different at the 5% threshold using Tukey's test. Standard deviation is in parentheses.

Statistical analyses

All the experiments were performed in triplicate and results were expressed as mean ± standard deviation. Analyses of variance (ANOVA), multiple means comparisons using Tukey's test, and correlation of starch parameters using Pearson correlation coefficient at a 5% threshold were done using XLSTAT 2014 software.

RESULTS

Granulometry of different starches

Figure 1 shows the microscopic observations of starch granules and Table 2 presents their shapes. The starch granules from the studied *Musa* species were uniformly irregular in shape irrespective of the genotype, with sizes ranging between 19.5 and 27.2 μm that significantly decreased ($P < 0.05$) with altitude of production of the source.

Chemical characteristics of the four genotypes are presented in Table 3. Assessment of pH and TTA of banana starches can be important for their choice as food auxiliaries. TTA significantly differed within the genotype, while only Maduranga and Kelong mekintu significantly decreased with altitude. A reverse trend was, however, observed for pH (except for Maduranga). With a single exception, starch moisture and ash content increased and DMC decreased with altitude in all cultivars (significantly for Kelong mekintu and Banane cochon). Regarding genotype, no significant difference was noticed between Kelong mekintu and Maduranga. Amylose and amylopectin contents ranged from 15.5% to 45.2% and from 54.8% to 84.5%, respectively, irrespective of the genotype. Amylose content significantly differed for the four genotypes, while a significant increase was noted in amylose content with altitude for plantain and plantain-like hybrid (Kelong mekintu and CARBAP K74); a reverse trend was rather observed for cooking and dessert bananas (Maduranga and Banane cochon).

Functional properties

Tables 4 and 5 present banana starch's functional properties. Solubility reflects the extent of intermolecular cross-bonding within the granule, while the swelling index indicates the strength of the hydrogen bonding between the granules. Swelling index increased significantly in every genotype with altitude, whereas solubility remained constant. The oil absorption capacity (OAC) ranged from 1690 to 2140 g kg^{-1}, respectively, for Kelong mekintu and CARBAP K74 with significant increments observed with altitude. Knowing that native starch does not contain polar groups, its OAC essentially could be due to the entrapment of oil molecules in its structure. Water absorption capacity (WAC) is the ability of starches to retain their native water as well as added water. In general, WAC tended to increase with altitude (often reaching statistical significance). However, WAC70 and WAC90 were reduced with altitude in Maduranga and CARBAP K74, respectively.

Results of syneresis are presented in Table 5. Generally, the rate of syneresis was higher at Njombe than at Bansoa. After 21 days of syneresis study a significant difference was observed, with lowland banana starches exhibiting the highest values for all cultivars.

Digestive properties of starches

Unripe plantain is considered to be a natural source of resistant starch. Figure 2 shows the kinetics of starch *in vitro* digestion in the two locations. The various starches exhibited low digestibility ranging between 13.4% and 37.9%, with the patterns of CARBAP K74 and Maduranga contrasting markedly with those from Banane cochon and Kelong mekintu (Table 6). A significant difference was recorded in terms of substrate consumption, also known as RDS, SDS and RS fractions between the two altitudes

Table 3. Chemical characteristics of starches of different banana cultivars grown at low and high altitudes

Cultivar	Locality	TTA (mEq/L/100 g)	pH	Moisture (g kg^{-1})	DMC (g kg^{-1})	Amylose (g kg^{-1})	Amylopectin (g kg^{-1})	Ash content (g kg^{-1})
K74	Bansoa	211.8 ± 70.6a	6.2 ± 0.0a	83.0 ± 17.0a	927.0 ± 17.0a	460.0 ± 30.0a	540.0 ± 30.0b	2.7 ± 0.9a
	Njombe	258.8 ± 40.8a	5.4 ± 0.3b	58.0 ± 8.0a	946.0 ± 8.0a	377.0 ± 12.0b	623.0 ± 12.0a	1.8 ± 0.8a
MAD	Bansoa	141.2 ± 0.0b	5.9 ± 0.0b	86.0 ± 18.0a	924.0 ± 18.0a	155.0 ± 5.0b	845.0 ± 5.0a	12.9 ± 9.0a
	Njombe	211.8 ± 0.0a	6.0 ± 0.0a	54.0 ± 4.0a	946.0 ± 4.0a	187.0 ± 15.0a	813.0 ± 15.0b	7.6 ± 1.5a
KLM	Bansoa	141.2 ± 0.0b	6.3 ± 0.0a	103.0 ± 3.0a	897.0 ± 3.0b	328.0 ± 3.0a	672.0 ± 3.0b	11.0 ± 4.8a
	Njombe	329.4 ± 40.8a	4.9 ± 0.0b	72.0 ± 10.0b	928.0 ± 10.0a	260.0 ± 0.0b	740.0 ± 0.0a	10.2 ± 4.4a
BC	Bansoa	141.2 ± 0.0a	6.9 ± 0.0a	103.0 ± 3.0a	897.0 ± 3.0b	287.0 ± 29.0b	713.0 ± 29.0a	12.2 ± 3.0a
	Njombe	141.2 ± 0.0a	6.6 ± 0.0b	55.0 ± 12.0b	945.0 ± 12.0a	452.0 ± 8.0a	548.0 ± 8.0b	16.3 ± 8.1a

Abbreviation: K74, CARBAP K74; MAD, Maduranga; KLM, Kelong mekintu; BC, Banane cochon; TTA, total titrable acidity; DMC, dry matter content. The results are based on the mean of three trials; means ± standard deviations bearing the same letters for each cultivar are not significantly different at the 5% threshold using Tukey's test.

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Table 4. Functional properties of starches from different cultivars grown at low and high altitudes

Cultivar	Locality	Swelling index (g g^{-1})	Solubility (g g^{-1})	OAC (g kg^{-1})	WAC60 (g kg^{-1})	WAC70 (g kg^{-1})	WAC80 (g kg^{-1})	WAC90 (g kg^{-1})
K74	Bansoa	2.33 ± 0.02a	0.03 ± 0.0a	2140.0 ± 60.0a	2467.0 ± 12.0a	2960.0 ± 20.0a	6420.0 ± 89.0a	12 030.0 ± 70.0b
	Njombe	1.54 ± 0.19b	0.03 ± 0.00a	1993.0 ± 12.0b	1600.0 ± 20.0b	1080.0 ± 20.0b	3260.0 ± 40.0b	12 490.0 ± 150.0a
MAD	Bansoa	1.68 ± 0.02a	0.03 ± 0.0a	1930.0 ± 10.0a	1750.0 ± 50.0a	1055.0 ± 15.0b	5900.0 ± 60.0a	13 770.0 ± 130.0a
	Njombe	1.56 ± 0.03b	0.03 ± 0.0a	1920.0 ± 20.0b	1767.0 ± 23.0a	1550.0 ± 10.0a	4800.0 ± 40.0b	11 113.0 ± 35.0b
KLM	Bansoa	1.57 ± 0.05a	0.06 ± 0.03a	1940.0 ± 0.0a	1360.0 ± 20.0a	4770.0 ± 110.0a	9210.0 ± 590.0a	12 650.0 ± 170.0a
	Njombe	1.32 ± 0.03b	0.03 ± 0.0a	1690.0 ± 50.0b	1430.0 ± 50.0a	3320.0 ± 20.0b	4681.0 ± 50.0b	11 680.0 ± 40.0b
BC	Bansoa	2.04 ± 0.05a	0.03 ± 0.0a	2047.0 ± 110.0a	2100.0 ± 0.0a	2153.0 ± 70.0a	6180.0 ± 20.0a	12 040.0 ± 140.0a
	Njombe	1.66 ± 0.06b	0.03 ± 0.0a	2020.0 ± 80.0b	1940.0 ± 80.0b	1755.0 ± 25.0b	2330.0 ± 10.0b	10 680.0 ± 0.0b

Abbreviation: K74, CARBAP K74; MAD, Maduranga; KLM, Kelong mekintu; BC, Banane cochon; OAC, oil absorption capacity; WAC60, WAC70, WAC80 and WAC90, water absorption capacities at 60, 70, 80 and 90 °C.
Note: The results are based on the mean of three trials; means ± standard deviations bearing the same letters for each cultivar are not significantly different at the 5% threshold using Tukey's test.

(Table 6). However, no clear pattern could be observed among the four genoytpes.

The pGI of the different starches ranged from 49.30% to 69.61% for Maduranga and Kelong mekintu, respectively, and these values varied significantly ($P < 0.05$) with altitude (Table 6). However, it can be noted that Kelong mekintu and CARBAP K74 presented significantly higher pGI at low altitudes, while Maduranga and Banane cochon showed an inverse relation.

Some kinetics parameters of banana starch were also measured (Table 7). H_{90}, the amount of reducing sugar produced after 90 min, significantly differed in the two localities regardless of the variety. The same trend was noted for starch concentration at equilibrium ($C\alpha$), where values were significantly higher at high altitude for plantain and plantain-like hybrid. However, no significant difference was noted for kinetic constants even though they were very low.

DISCUSSION

The starch granule size is an important parameter that affects its physicochemical properties and applications, while the shape and crystalline structure play a major role in enzymatic susceptibility.[23] Significant differences in starch granule size and shape were found among the four genotypes evaluated in the current study. Moreover, starch granules were significantly smaller when gentoypes were grown in the high-altitude environment. Results from this study agree with the average particle sizes from 22.5 to 25.8 µm.[3,24] The physicochemical composition of starch can differ within the same botanical species because of different geographical origins and agronomic techniques. However, the non-uniformity in the size of the granules observed could be explained by the presence of granules still in full growth or even denatured granules during the extraction process, the latter being very important because it can affect its original form.[25] There was a remarkable variation in the shape of starch granules among the four genotypes evaluated in the current work (Table 2).

Oviri obtained pH values ranging between 4.5 and 5.5 for good-quality plantain starch in Nigeria.[6] A similar range of variation in pH was observed herein, with the exception of Banane cochon grown at high altitude with a pH of 6.9. This finding is in line with that of Bugaud *et al.*, who found that pH values of bananas (from flowering to harvest time) did not follow a specific trend with respect to altitude.[26]

Many authors have recorded different amylose values for *Musa* starches, but with no information on the altitude of starch extraction. Dufour *et al.*[27] registered values ranging between 15.4% and 29.9%, with dessert bananas presenting the lowest values and cooking bananas the highest. Amylose content of 42.07% in Nigeria,[7] a range from 19.3% to 26.4% for four cultivars in Mexico[28] and a 38–42% range in different Thai bananas[29] have

Table 5. Syneresis (%) of starches from different cultivars grown at low and high altitudes

Cultivar	Locality	D0	D1	D7	D14	D21
K74	Bansoa	36.1 ± 0.1b	39.6 ± 0.56b	39.7 ± 1.8b	41.2 ± 1.9b	41.4 ± 1.0b
	Njombe	42.6 ± 0.8a	54.3 ± 0.67a	55.4 ± 0.3a	55.9 ± 0.9a	56.2 ± 0.5a
MAD	Bansoa	33.5 ± 0.2b	44.3 ± 0.51b	35.5 ± 1.4b	40.4 ± 9.7a	43.4 ± 0.1b
	Njombe	42.3 ± 1.6a	46.6 ± 0.75a	48.8 ± 0.2a	51.9 ± 1.3a	52.0 ± 0.5a
KLM	Bansoa	42.6 ± 0.8a	52.2 ± 1.86a	53.6 ± 0.37b	54.2 ± 0.3b	56.5 ± 0.1b
	Njombe	43.0 ± 1.0a	50.6 ± 0.44a	54.4 ± 0.2a	57.1 ± 0.7a	57.5 ± 0.6a
BC	Bansoa	40.5 ± 0.7b	53.0 ± 0.6a	53.6 ± 0.2a	55.7 ± 1.1a	55.7 ± 0.2b
	Njombe	45.3 ± 1.0a	53.2 ± 1.3a	53.3 ± 0.4a	54.0 ± 1.0a	57.4 ± 0.9a

Abbreviation: K74, CARBAP K74; MAD, Maduranga; KLM, Kelong mekintu; BC, Banane cochon; D0, D1, D7, D14 and D21, 0, 1, 7, 14 and 21 days of storage. The results are based on the mean of three trials; means ± standard deviations bearing the same letters for each cultivar are not significantly different at the 5% threshold using Tukey's test.

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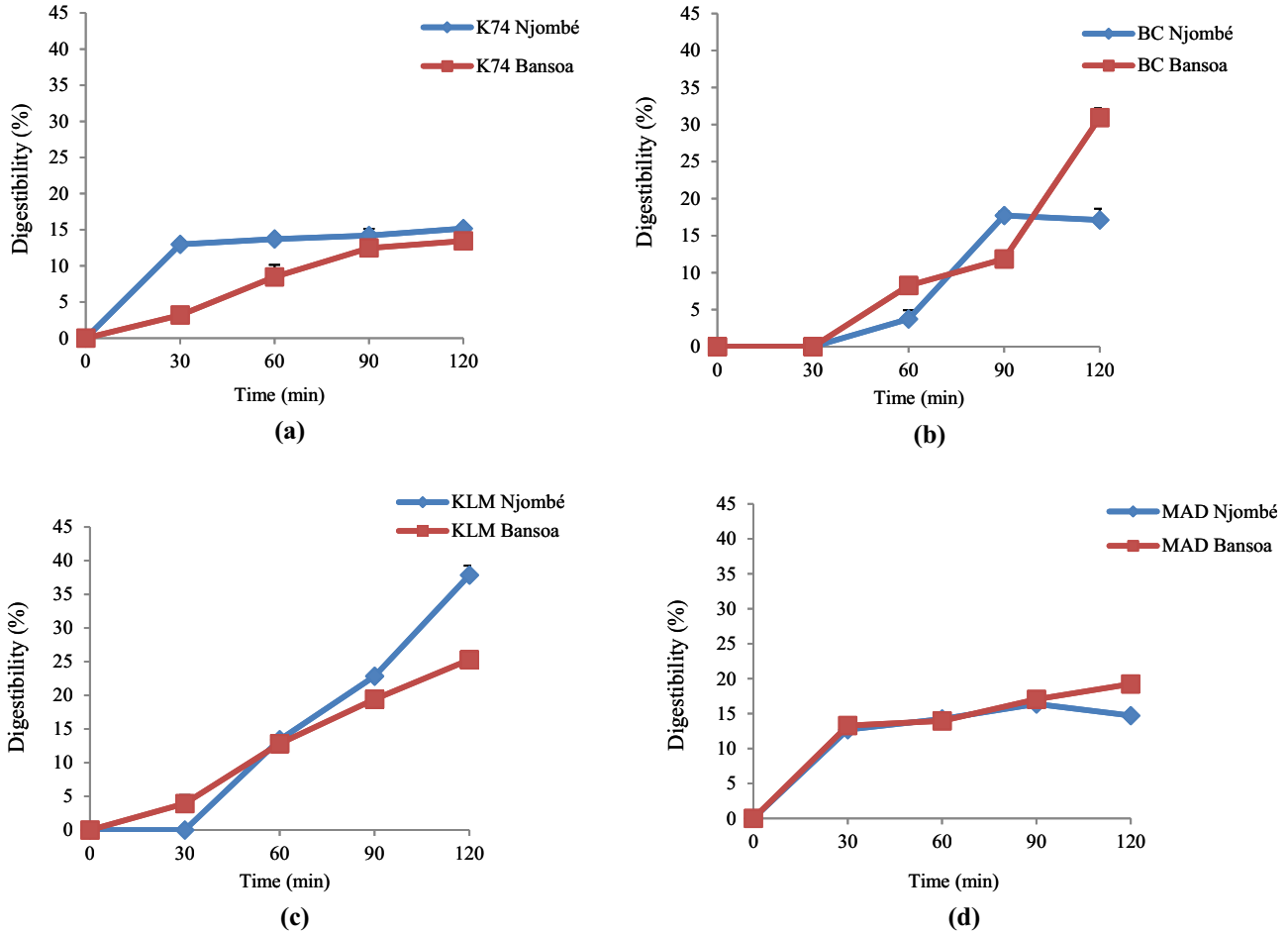

Figure 2. Kinetics of starch *in vitro* digestion; (a) CARBAP K74; (b) Banane cochon; (c) Kelong mekintu; (d) Maduranga after 2 h of incubation.

been reported. Similarly, amylose levels of 38.8% (Nigeria), 30.9% (Nigeria), and 35.0% (Mexico) for different plantain cultivars in Nigeria as well as in Mexico have been reported.[5,8,30] The present study measured a large and significant variation for amylose content among the four genotypes evaluated (from 16.5% to 41.9% for Maduranga and CARBAP K74, respectively). Moreover, the high-altitude growing environment reduced amylose content significantly in all genotypes, except Maduranga (which had the lowest levels of amylose content, as stated above).

Starch characteristics and final properties can be influenced to a large extent by their amylose/amylopectin ratio. The significant amylose content differences obtained for our *Musa* cultivars in two contrasted altitudes, as well as the divergences observed in the literature, can testify to the influence of the environmental conditions.

Interactions between starch chains within the amorphous and crystalline domains are responsible for the swelling power and solubility of starch.[4] Also the different amylose content, molecular

Table 6. Starch digestive parameters from different banana cultivars grown at low and high altitudes

Cultivars	Locality	RDS (%)	SDS (%)	RS (%)	pGI (%)
K74	Bansoa	9.4 ± 0.1b	4.2 ± 0.5a	86.6 ± 0.4a	50.0 ± 0.3b
	Njombe	13.0 ± 0.5a	2.4 ± 0.1b	84.8 ± 0.1b	51.4 ± 0.1a
MAD	Bansoa	13.9 ± 1.8a	5.4 ± 1.8a	80.8 ± 0.5b	54.7 ± 0.4a
	Njombe	12.7 ± 0.1a	2.0 ± 1.5b	87.7 ± 0.9a	49.3 ± 0.6b
KLM	Bansoa	3.9 ± 1.3a	22.4 ± 3.0b	74.7 ± 0.7a	59.5 ± 0.5b
	Njombe	0.0 ± 0.0b	38.2 ± 1.6a	62.1 ± 1.4b	69.6 ± 1.1a
BC	Bansoa	0.0 ± 0.0a	31.7 ± 0.8a	69.1 ± 1.3b	64.1 ± 1.0a
	Njombe	0.0 ± 0.0a	16.4 ± 0.6b	82.9 ± 1.5a	51.5 ± 2.8b

Abbreviation: K74, CARBAP K74; MAD, Maduranga; KLM, Kelong mekintu; BC, Banane cochon; RDS, rapidly digestible starch; SDS, slowly digestible starch; RS, resistant starch; pGI, predicted glycemic index. The results are based on the mean of three trials; means ± standard deviations bearing the same letters for each cultivar are not significantly different at the 5% threshold using Tukey's test.

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Table 7. Kinetic parameters of starches from different cultivars grown at low and high altitudes

Cultivar	Locality	H_{90} (%)	C_α [a] (%)	k [a] (min^{-1})
K74	Bansoa	13.4 ± 0.4b	13.4 ± 0.4b	0.010a
	Njombe	15.2 ± 0.1a	15.2 ± 0.1a	0.018a
MAD	Bansoa	19.3 ± 0.5a	19.2 ± 0.5a	0.015a
	Njombe	12.6 ± 0.8b	16.4 ± 1.3b	0.018a
KLM	Bansoa	25.3 ± 0.7b	25.3 ± 0.7a	0.008a
	Njombe	37.9 ± 1.4a	37.9 ± 9.0a	0.007a
BC	Bansoa	30.9 ± 1.3a	30.9 ± 1.3a	0.006a
	Njombe	15.3 ± 3.5b	17.1 ± 2.2b	0.007a

Abbreviation: K74, CARBAP K74; MAD, Maduranga; KLM, Kelong mekintu; BC, Banane cochon; H_{90}, amount of reducing sugar produced after 90 min of incubation.
[a] Parameters of the equation model $C = C_\infty(1 - e^{-kt})$, where C_∞ is the concentration at equilibrium and k is the kinetic constant. The results are based on the mean of three trials; means ± standard deviations bearing the same letters for each cultivar are not significantly different at the 5% threshold using Tukey's test.

weight distribution, degree of branching, length of branches and conformation of the molecules affected the swelling power and solubility of starch.[4] Solubility reflects the extent of intermolecular cross-bonding within the granule, while the swelling index indicates the strength of hydrogen bonding between the granules. Like the observation made on Vietnamese banana starches,[31] no significant difference ($P > 0.05$) was recorded for the solubility indices of the four banana clones produced at the two studied altitudes in Cameroon. However, swelling indices significantly increased with altitude, with CARBAP K74 exhibiting the highest value (2.3 g g^{-1}). Swelling changes with increasing temperature until the scattering and dispersion of the granule occur around 90° C after an average swelling, which can attain 36 g g^{-1} for plantain starch against 24.8 g g^{-1} for cassava starch at this same temperature.[32]

WAC is an essential parameter to control the consistency of the paste in pastification and others. WAC at 1300 m was higher than at 80 m above sea level (Table 4). This aligns with studies by Alcázar-Alay and Meireles,[33] whose hypothesis stipulates that water absorption and swelling of starch granules at temperatures close to gelatinization temperature are strongly and negatively correlated with their amylose content. Furthermore, after 21 days, only Maduranga and CARBAP K74 starches showed a significant difference ($P < 0.05$) in terms of syneresis between the two altitudes.

The resistant nature of the starch digestive properties in this study was related to the relatively low kinetic constant (k = 0.004 to 0.016 min^{-1}) recorded, irrespective of the variety and altitude (Table 7) and described by a nonlinear model.[16] These results are consistent with those reported earlier.[4,34] An *in vitro* digestibility of 11–31% for banana starch (without genotypic distinction) under the sole action of α-amylase was reported after 2 h.[34] In addition, banana starches were very resistant to enzymatic hydrolysis after 30, 60 and 90 min due to their physicochemical composition and crystalline structure.[4]

The differences observed during hydrolysis of the different starches in the present study can be explained, once again, by their structure and intrinsic composition such as their respective amylose content and granule size. Low pGI, i.e. 44.9–51.4% for three plantains and two dessert bananas, have been reported in Nigeria.[7] These values classify our starches as low or moderate glycemic index foods.[35] The differences recorded in terms of pGI for the various starches (50.0–69.9%, Table 6) can be explained by their different RS levels but also by their different amylose content levels. It can be stated, therefore, that the more amylose in

Table 8. Pearson correlation coefficients of starch-related parameters

Variable	Pulp firmness	Pulp DMC	Amylose content	Amylopectin content	pGi
Starch yield	0.20	0.20	−0.15	0.15	−0.21
Amylose content	**0.45**	-0.23	**1.00**	**−1.00**	−0.27
Amylopectin content	**−0.45**	0.23	**−1.00**	**1.00**	0.27
Swelling index 100 g^{-1}	0.21	**−0.42**	**0.41**	**−0.41**	−0.29
Solubility	**0.47**	**0.50**	0.04	−0.04	0.15
OAC	0.12	**−0.54**	**0.53**	**−0.53**	**−0.58**
WAC25	0.02	−0.35	0.37	−0.37	−0.26
WAC60	−0.06	**−0.66**	**0.42**	**−0.42**	−0.40
WAC70	**0.67**	**0.68**	0.22	−0.22	**0.48**
WAC80	**0.57**	**0.60**	−0.20	0.20	0.27
WAC90	0.35	**0.43**	−0.38	0.38	0.10
RDS	−0.02	0.06	−0.30	0.30	**−0.66**
SDS	0.05	0.23	−0.05	0.05	**0.93**
RS	−0.08	−0.37	0.23	−0.23	**−0.99**
SYN0	−0.12	−0.04	0.29	−0.29	0.17
SYN1	−0.11	−0.03	0.11	−0.11	0.36
SYN7	0.01	0.05	0.24	−0.24	0.38
SYN14	−0.10	0.06	0.08	−0.08	**0.42**
SYN21	−0.13	0.06	0.10	−0.10	**0.45**

Note: Values in bold are significant at $P < 0.05$. DMC, dry matter content; OAC, oil absorption capacity;WAC60, WAC70, WAC80 and WAC90, water absorption capacities at 60, 70, 80 and 90 °C; RDS, rapidly digestible starch; SDS, slowly digestible starch; RS, resistant starch; pGI, predicted glycemic index; SYN0, SYN1, SYN7, SYN14 and SYN21, syneresis after 0, 1, 7, 14 and 21 days of storage.

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starch, the more resistant to hydrolysis the starch is, and the lowest may be its impact on blood sugar. Finally, correlations between pGI and RDS ($r = -0.66$), SDS ($r = 0.93$) and RS ($r = -0.99$) show that these fractions are important parameters in the effective control of blood glucose as well as for the production of low-glycemic foods (Table 8).

This study shows that most banana starch physicochemical and functional parameters were influenced by the growing conditions, particularly altitude above sea level. Similar results have been reported for cassava starch.[36] For some traits the response to altitude was genotype dependent. The higher the altitude, the lower were the dry matter content, the size of starch granules and the TTA. The OAC, swelling index, WAC and starch pH, on the other hand, presented higher values at high altitudes. Starch solubility and ash content were not influenced by altitude. The influence of altitude on starch digestive parameters was cultivar dependent, with local plantain and plantain-like hybrid exhibiting high amylose content, and were resistant to hydrolysis. The low digestibility recorded was inversely proportional to the amylose content and differed significantly with altitude. The good water absorption capacity and oil absorption capacity, low digestibility, and high resistant starch content recorded for CARBAP K74 and Kelong mekintu predispose these banana starches from high altitude to be used as good thickeners and gelling agents as well as good ingredients for the formulation of low-calorie foods.

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CONFLICT OF INTEREST

The authors declare that they have no conflicting interests.

DATA AVAILABILITY STATEMENT

The data are avalable at CARBAP and can be shared at any moment.

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