Impact of particle size and plantain variety on nutritional quality, physico-chemical properties, and functionalities of powders prepared from New Ivorian plantain hybrids

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Summary

The influence of particle size of powders from three plantain hybrids (Big Ebanga, FHIA 21 and PITA 3) and a traditional variety Corne 1 on nutritional quality, physico-chemical properties and functionalities was investigated. Corne 1 served as reference material. Plantain fingers were blanched for 15 min in boiling 5 g·l^{-1} citric acid, cooked at 100 °C in a buffer solution containing 3 g·l^{-1} sodium pyrophosphate, sliced into 10-mm cubes and dried in a convection air oven to reach 8–10 % moisture content. Dried slices were milled, resulting in a fine powder that was separated in two granulometric classes: < 180 μm (class 1) and 180–500 μm (class 2). Proximate composition, granulometry parameters, colour and functional properties were analysed. It appeared that variety and particle size significantly affected powder proximate composition, physical properties and functionalities. When the particle size was decreased, moisture and protein contents decreased, whereas the proportions of fat and ash increased. Powder lightness was significantly reduced for class 2 powders. Oil absorption index was significantly lowered for class 1 powders. Water absorption index was higher in class 2 powders. Corne 1 showed the highest nutrients content for the raw powder.

Keywords

powder flowability; sieving; granulometric fractions; plantain variety; chemical composition

Plantain (*Musa* spp.) is a climacteric fruit widely grown in tropical and subtropical regions of developing countries. The fruits resemble bananas but are approximately twice as large. They have a thicker skin and contain more starch and less sugar than bananas. Plantain is a staple crop for over 70 million people in sub-Saharan Africa and a good source of carbohydrates [1].

Plantain is one of the major food crops in Ivory Coast and more generally in the sub-region of West Africa. In Ivory Coast, it is the most consumed foodstuff with a distribution of 53.4 % in urban areas and 46.6 % in rural areas in 1998. Its annual production was estimated at 1 883 000 t in 2018. It is consumed at various maturity degrees from stage 2 (light green) to stage 9 (more black than yellow) of in the forest zone and represents half of the consumption of starchy foods in Abidjan, the largest city of Ivory Coast. Plantain fruits are most often used for preparation of traditional dishes such as, in vernacular names, foutou, alloco or claclo [2].

In spite of its importance, the plantain food sector is unfortunately experiencing many difficulties due to the seasonal nature of plantain production and the use of low-yielding varieties that are susceptible to diseases such as black sigatoka or those caused by *Fusarium* fungi. These factors are detrimental to production efficiency and regular market supply. In order to reduce the incidence of the black sigatoka, the International Institute of Tropical Agriculture (IITA, Nigeria), the Regional Center on Banana and Plantain Research (CRBP, Cameroon) and the Honduran Foundation of Agricultural Investigation (FHIA, Honduras) developed hybrids that resist to this phytopathology [3]. Thus, the National Center for Agronomic Research (CNRA) of Ivory Coast in collabora-

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tion with the West Africa Agricultural Productivity Program (WAAPP) allowed, through the funding of several research projects, the introduction in farming areas of these new hybrids presenting a high productivity, a relatively short production cycle and resistance to black sigatoka.

Many attempts have been made to set up easy-to-store products from plantain fruits. Indeed, Kouakou et al. [4] studied the biochemical and morphological variations during the conservation of the vivo plants of varieties Corne 1, FHIA 21 and PITA3. Plantain fruits are usually processed into flours or dried chips. Work performed upstream by the Laboratory of Biochemistry and Technology of Tropical Products (LBATPT, Abidjan, Ivory Coast) enabled the formulation of foufou and foutou powders with local varieties meeting these requirements [5]. Several studies evidenced that the particle size distribution influences chemical and physical properties of powders [6–8]. The separation of plantain powder into granulometric fractions, presumably varying in physical and chemical properties, has both commercial and academic significance to identify the variety or varieties as well as the fraction(s) suitable for domestic use. Indeed, powder sieving, rationally performed dependently from drying and grinding conditions, provides the possibility to produce specialty powders [7–9].

This study was undertaken to determine the effect of particle size and plantain variety on nutritional quality, physico-chemical properties (proximate composition, particle size distribution, particle shape, colour) and functionalities of powders prepared from new plantain hybrids (Big Ebanga, FHIA 21 and PITA 3) and a local variety (Corne 1) serving as control. For this purpose, the main functional properties of plantain powders were evaluated: water absorption index, swelling powe, and flowing properties (basic flowability energy, compressibility, fluidisability-aeration sensitivity). It is important to note that this study was carried out as part of a large project covering the production, conservation, processing and dissemination of these new varieties introduced in Ivory Coast.

MATERIALS AND METHODS

Fruits

Plantain powders were prepared from ripe plantain at stages 4 and 5 of ripening, i.e. more yellow than green and yellow with green necks, respectively [10]. Three hybrid varieties were used, namely, Big Ebanga, FHIA 21 and PITA 3, together with a traditional variety Corne 1. The methodology described by Gnagne et al. [5] was used. The fruits were supplied by the Research Station on Fruits and Citrus Fruits of National Center of Agronomic Research (CNRA, Azaguié, Ivory Coast), located 20 km east of Abidjan. They were all harvested at the stage of maximal maturity, when at least one ripe fruit appears on the bunch. Starting from the date of flowering, this stage corresponds to 82–90 days for the three hybrids. The control variety Corne 1 was harvested after 80 days. The fruits were artificially ripened (in the same conditions to minimize intra- and extra-variety disparities) up to stages 4 and 5 by using an aqueous solution of 20% (v/v) ethylene glycol (Sigma Aldrich, St. Louis, Missouri, USA) [5, 11].

Preparation of powders

Plantain fingers were blanched for 15 min in boiling deionised water (at 100 °C) containing 5 $g \cdot l^{-1}$ citric acid (Sigma Aldrich) to limit enzymatic browning. After that, pulps were cooked in a buffer solution containing 0.3 $g \cdot l^{-1}$ sodium pyrophosphate (Sigma Aldrich) at pH 4.5, sliced into 10-mm cubes using a stainless steel knife and dried in a convection air oven (Minergy, Atie Process, Pont-de-Larn, France) at 65 °C for 8 h to reach 8–10 % moisture content. After that, dried plantain slices were milled in a grinder with hammer (I2T, Abidjan, Ivory Coast) equipped with a 500 μm sieve and then in a grinder with hammer (Forplex, Béthune, France) to obtain a fine powder. Produced powders were packaged in airtight polyethylene bags and stored at 10 °C for a maximum of three months. They were referred to as instant powders in this study.

Processing of powders

Following the results obtained with the Mastersizer 3000 laser granulometer (Malvern Instruments, Malvern, United Kingdom), the powders were separated in two distinct granulometric classes. Class 1 corresponded to fine particles, as it gathered all particles passing through a 180 μm sieve. Class 2 corresponded to retained particles between 180 μm and 500 μm sieves. Sieving of 100 g batches during 10 min was performed at 1 mm amplitude with the Analysette 3 apparatus (Fritsch, Idar-Oberstein, Germany), operating by vertical vibration.

Proximate composition of plantain fruits and powders

In order to determine the proximate composition, fruits were washed in deionised water, peeled and cut in slices of 2 cm thickness. The slices were subsequently dried in a ventilated drying oven UF 55 (Memmert, Schwabach, Germany) at 45 °C during 48 h [5]. After being milled into fine powders with an ultracentrifugal mill ZM 200 (Retsch, Haan, Germany) equipped with a sieve with 1 mm trapezoidal holes, powdered dried fruits (called raw powders hereafter) were placed in airtight polyethylene bags and stored in the same conditions as instant powders for further analyses within three months.

The proximate composition of raw flours and powders made from the different hybrids and traditional variety was evaluated. Moisture and dry matter contents of powders were determined thermogravimetrically by drying 3 g sample at 103 °C until reaching constant weight according to AOAC method 925.10 [12] (Eq. 1).

$$DM = 100 - M \quad (1)$$

where DM is dry matter and M is moisture, expressed as weight percentages.

The content of minerals (ash) was determined according to AOAC method 923.03 [12] where 2–3 g powder was weighed in pre-heated ceramic crucibles. The crucibles were then placed overnight in a controlled muffle furnace heated at 550 °C. After that, the crucibles were placed in a desiccator and weighed. The ash content was determined as weight percentage on dry basis according to Eq. 2:

$$A = \frac{m_2 - m_0}{m_1 - m_0} \times 100 \quad (2)$$

where A is the ash content expressed as weight percentage, m_0 is the mass of empty crucible, m_1 is the mass of crucible and initial powder sample and m_2 is the mass of crucible and ash all expressed in grams.

Total protein was determined using Kjeldahl method (AOAC method 920.87) [12]. The crude protein content was obtained by multiplying the nitrogen content by the conventional factor of 6.25 according to Eq. 3:

$$P = N \times 6.25 \quad (3)$$

where P and N represent protein and nitrogen contents, respectively, expressed in weight percentage on dry basis.

Total fat content, expressed in weight percentage on dry basis, was determined by weight difference after Soxhlet extraction with hexane (Eq. 4):

$$F = \frac{m_c - m_b}{m_a} \times 100 \quad (4)$$

where F is the fat content expressed in percent, m_a is the sample mass, m_b is the mass of empty flask and m_c is the mass of flask with extracted fat, all expressed in grams.

Total carbohydrates were calculated by difference with other components according to AOAC method 995.13 [12] following Eq. 5:

$$C = 100 - (M + P + F + A) \quad (5)$$

where C is carbohydrates content expressed as weight percentage on dry basis.

Quantification of reducing sugars was carried out according to the method of Bernfeld [13], which is based on the reducing properties of soluble sugars. For the extraction of soluble sugars, 1 g sample was diluted in 10 ml distilled water at 60 °C and the mixture was then cooled down at 20 ± 1 °C. After that, the mixture was filtered and the filtrate was completed to 20 ml with deionised water. A volume of 100 μl of the solution was introduced into a test tube and supplemented with 100 μl deionised water and 200 μl 3,5-dinitrosalicylic acid (DNS, Sigma Aldrich). The mixture was heated in a boiling water bath for 5 min. After cooling, 3.6 ml deionised water was added and absorbance was read at 540 nm against a blank. A standard range (0.08, 0.11, 0.17, 0.25, and 0.5 g·l^{-1}) was established from a stock solution of 1 g·l^{-1} glucose and the amount of reducing sugars in each sample was calculated from the regression equation established using the standard range.

All chemical analyses were performed in triplicate.

Particle size distribution

The particle size distribution of powders, determined by laser granulometry, is their major characteristic. This parameter determines many physical and functional properties of powders, such as water and oil absorption index stability, basic flowability energy, compressibility, fluidisability or aeration sensitivity [14]. The particle size distribution of powders was measured at 20 ± 2 °C with a Mastersizer 3000 laser granulometer operating by static light scattering, supplied with the Aero S dry dispersion unit. Approximately 5 g sample was analysed after air dispersion at 1.0–1.5 Pa in the following conditions: 100 % air pressure, 40 % feed rate and 1.5 mm hopper length. Volume-based particle size distributions were characterised by classical granulometric parameters. The span, which describes the width of the particle size distribution, was also recorded (Eq. 6).

$$S = \frac{D_{90} - D_{10}}{D_{50}} \quad (6)$$

where S is the span and D_x (D_{10}, D_{50} and D_{90}) means that x percent of the volume of particle has a diameter lower than D_x.

Colour properties

Colour parameters (lightness L^*, redness a^* and yellowness b^*) of plantain powders were measured using a UV-Vis spectrophotometer Microflash 4.0 (Datacolor International, Lucerne, Switzerland) in CIE $L^*a^*b^*$ system. Approximately 10 g sample was homogenously distributed in a Petri dish. After calibration with black and white standards, the measurement cell was directly positioned below the Petri dish containing the powder sample. Five measurements were carried out per replicate and sample results were the mean of three analytical replicates. Chroma (C) representing colour saturation was calculated as follows (Eq. 7):

$$C = \sqrt{a^{*2} + b^{*2}} \quad (7)$$

where a^* is the redness, b^* is the yellowness.

Functional properties

Water absorption index (*WAI*), which allows to highlight the amount of water in grams retained per 100 g of powder after saturation and centrifugation, were determined at room temperature (20 ± 2 °C) according to the methods of Phillips et al. [15] with some modifications. A sample of 1 g was suspended in 10 ml deionised water and gently agitated on a Campsas mechanical shaker (Bioblock, Illkirch, France) for 30 min. The suspension was then centrifuged (SW12R, Firlabo, France) at 400 ×*g* for 15 min. The recovered sediment was dripped for 10 min and dried in an oven at 103 ± 2 °C until reaching a constant weight. *WAI* was calculated using the following Eq. 8:

$$WAI = \frac{m_f - m_e}{m_e} \quad (8)$$

where m_e is the mass of the sample after centrifugation expressed in grams and m_f is the mass of the sample after drying expressed in grams.

Oil absorption index (*OAI*) was determined following the method of Sosulski [16]. A volume of 10 ml of a commercial palm oil (Soata, Grand-Bassam, Ivory Coast) was added to 1 g dry sample (m_3) and stirred for 30 min. Samples were centrifuged at 4 400 ×*g* for 15 min. After centrifugation, the supernatant was removed, the tubes were inverted for 25 min to drain the oil and then they were weighed (m_4) (Eq. 9):

$$OAI = \frac{m_4 - m_3}{m_3} \quad (9)$$

where m_3 is the mass of a dry sample expressed in grams and m_4 is the mass of the sample after centrifugation expressed in grams.

Flowing properties

The study of powder flow properties consisted in performing stability, compressibility, aeration and shear cell tests using FT4 Powder Rheometer (Freeman Technology, Tewkesbury, United Kingdom) with 25 mm vessels. Every measurement was preceded by a step of powder bed conditioning, involving the downward and upward movement of a blade at 100 mm·s^{-1} through the powder bed, in order to remove excess stress or entrapped air.

The aeration test was carried out by measuring basic flowability energy (*BFE*) in aerated conditions at 100 mm·s^{-1} blade tipspeed. Here, air was circulated upwards through the powder bed at velocities from 0 mm·s^{-1} to 10 mm·s^{-1} at 2 mm·s^{-1} steps. Prior to the aeration test, three conditioning cycles were carried out. A complete test was then performed by measuring the flow energy of the powder bed and a conditioning cycle was carried out between each aeration test cycle to achieve a steady state of the aerated powder. The following fluidisation parameter, normalised aeration sensitivity (*NAS*) was determined as a measure of powder sensitivity to aeration and expressed in second per millimetres. Fluidisation occurred for class 1 and unsieved powders, so the minimum fluidisation velocity (*MFV*) was also recorded.

The compressibility test was carried out by applying increasing normal stresses with a vented piston to a conditioned powder bed and measuring the volume change. Powder sample was first placed in the measurement cell and submitted to three conditioning cycles. After that, the vessel was split to remove any excess powder and the dynamic blade was replaced with a 23.5 mm vented piston. Then, powder was slowly compressed by the vented piston moving vertically at 0.05 mm·s^{-1} and applying levels of normal stresses from 0.5 kPa to 15 kPa while measuring the volume change. Compressibility (*CPS*) was determined as the percentage change in volume after compression at an applied normal stress of 15 kPa.

For shear tests, the powder sample was first conditioned to achieve a homogenous initial state and slowly pre-compacted under a normal stress of 9 kPa with a vented piston. Then, the vented piston was replaced with a shear cell head and the powder sample was recompressed to remove any disturbances caused by the split and to ensure that the sample surface was properly consolidated. After this pre-consolidation step, the sample was pre-sheared at 9 kPa. Measurements consisted of recording the shear stress required to cause failure of the pre-compacted powder bed when applying five decreasing normal stresses from 7 kPa to 3 kPa in steps of 1 kPa. Powder cohesion (C_m, expressed in kilopascals), was evaluated as the shear stress at zero normal stress (i.e. intercept of the linear regression of the shear stress vs applied normal stress curve) and the flowability index, also called flow factor (*ff,* dimensionless), was calculated as the ratio between the major principal stress and the unconfined yield stress, using the yield locus approach. The classification of powders by JENIKE [17] according to the *ff* value was then applied.

Statistical analysis

All analyses of this study were carried out in triplicates and reported values were means ± standard deviations. Statistical analysis was performed using Sigma Stat 7.1 (Systat Software, Chicago, Illinois, USA). The presence of significant differences between sample results was investigated by one-way ANOVA and the means were separated by Tukey's honestly significant difference (HSD) test at $p \leq 0.05$. This work will only present the most salient results.

RESULTS AND DISCUSSION

Proximate composition and chemical characteristics

Tab. 1 summarises the proximate composition and the chemical characteristics of raw flours, powders of two granulometric classes and unsieved plantain powders. Moisture content was overall lower than 10 % for the powders. Moisture content of foods or processed products gives an indication of shelf life and nutritional quality. In fact, low moisture content is a requirement for long shelf life [4]. According to KAUR et al. [18], this low moisture content (lower than 12 %) is favourable for the long shelf life of these powders over six months.

There was a significant difference between the moisture, ash, lipids and reducing sugars contents for the Big Ebanga, FHIA 21 and PITA 3 varieties for all the powders compared to the reference variety (Corne 1, control powder). Carbohydrates contents were high with small differences between samples. These results reinforced previous studies showing a large proportion of carbohydrates in plantain [5]. According to LUZIA and JORGE [19], high amounts of carbohydrates are a good source of fibres in food and may constitute an important energy source once included in diet.

A significant difference ($p < 0.05$) existed between the raw flours in reducing sugars compared to the other powders. Reducing sugars contents were high (close to 4 $g \cdot kg^{-1}$ DM) and the plantain variety did not have a significant effect, except for the FHIA 21 hybrid for which the content of reducing sugars was enhanced in raw flours. This high reducing sugars content could be explained by the temporal decrease in the starch level as ripening progressed, owing to starch hydrolysis into sugars [20]. These authors also demonstrated that plantain consistently contained more starch than banana and the hydrolysis rate of banana starch was higher than of plantain starch. Reducing sugars content in granulometric classes and unsieved powders ranged from 0.7 $g \cdot kg^{-1}$ to 20.6 $g \cdot kg^{-1}$ DM. For class 1 powders, the maximum contents of moisture, crude protein and reducing sugars, as well as the minimum fat content were observed for the hybrid variety FHIA 21. The minimum contents of ash, protein and reducing sugars, as well as a lower pH were obtained for the hybrid variety Big Ebanga, whereas the traditional variety Corne 1 had the lowest moisture content.

For class 2 powders, the hybrid FHIA 21 showed the highest contents of moisture, ash, protein, and reducing sugars, whereas the control variety Corne 1 had the lowest ash and reducing sugars contents, as well as the highest fat content.

Overall, in samples where the mean particle size was higher (class 2 powders), contents of moisture, proteins and reducing sugars were higher, whereas ash, fat and carbohydrates contents were low. Similar results were obtained by NURA et al. [21] and BECKER et al. [8] for rice and *Hieracium pilosella* powders, respectively, and these studies related the differences of proximate composition between granulometric classes to the influence of the combined grinding and sieving procedure as well as the differences in proximate composition of different plant parts.

Apart from total carbohydrates, all other chemical parameters (contents of proteins, ash, fat and reducing sugars) were lower in powders than in raw flours. So, statistical analysis showed that water, protein and reducing sugar contents increased ($p < 0.05$) with particle size, while ash, lipid and total carbohydrates contents decreased.

Particle size distribution

Particle size distribution, granulometric characteristics and the weight proportions of granulometric classes measured after sieving of powders are presented in Tab. 2. These results are close to those reported by GNAGNE et al. [5] for plantain powders (foufou) of three varieties (Orishele,

Tab. 1. Proximate composition of raw flour and powders from plantain hybrids.

Type of powder	Plantain variety	Moisture [g·kg-1]	Ash [g·kg-1]	Protein [g·kg-1]	Fat [g·kg-1]	Total carbohydrates [g·kg-1]	Reducing sugars [g·kg-1]
Raw flour	Big Ebanga	7.74 ± 0.18 de	2.12 ± 0.12 cde	3.07 ± 0.71 cdef	1.46 ± 0.34 def	85.60 ± 0.65 gh	3.04 ± 0.03 g
	FHIA 21	10.33 ± 0.11 j	2.37 ± 0.08 ef	5.40 ± 0.33 ij	0.95 ± 0.05 abc	80.96 ± 0.48 a	4.64 ± 0.15 ib
	PITA 3	9.61 ± 0.01 ij	2.55 ± 0.01 f	3.84 ± 0.74 fgh	1.12 ± 0.02 bcd	82.88 ± 0.74 bcd	3.49 ± 0.31 h
	Corne 1	9.16 ± 0.42 hi	2.30 ± 0.04 def	5.53 ± 0.03 j	1.03 ± 0.07 abcd	81.98 ± 0.36 ab	3.23 ± 0.01 gh
Unsieved powder (< 500 μm)	Big Ebanga	6.13 ± 0.21 b	2.03 ± 0.25 cde	1.40 ± 0.11 a	0.66 ± 0.08 ab	89.78 ± 0.18 k	0.77 ± 0.02 bc
	FHIA 2	8.18 ± 0.01 efg	1.96 ± 0.04 cd	2.33 ± 0.08 bc	0.54 ± 0.07 a	86.98 ± 0.13 h	1.01 ± 0.02 cd
	PITA 3	6.72 ± 0.39 bc	2.11 ± 0.06 cde	1.86 ± 0.10 ab	0.91 ± 0.01 abc	88.39 ± 0.28 g	1.16 ± 0.08 d
	Corne 1	8.12 ± 0.06 efgh	2.03 ± 0.04 cde	4.50 ± 0.03 hi	1.28 ± 0.04 cde	84.07 ± 0.06 def	0.85 ± 0.01 bc
Class 1 powder (< 180 μm)	Big Ebanga	6.85 ± 0.51 bcd	1.54 ± 0.08 ab	2.64 ± 0.44 bcd	1.88 ± 0.07 f	87.08 ± 0.75 ij	0.47 ± 0.01 a
	FHIA 2	8.82 ± 0.37 fghi	1.86 ± 0.38 bc	4.25 ± 0.10 gh	1.65 ± 0.09 efg	83.43 ± 0.40 cde	1.77 ± 0.09 e
	PITA 3	7.82 ± 0.43 def	2.23 ± 0.03 cdef	3.18 ± 0.07 cdef	1.99 ± 0.12 g	84.78 ± 0.34 efg	0.78 ± 0.01 bc
	Corne 1	4.65 ± 0.75 a	1.88 ± 0.16 bc	3.57 ± 0.13 efg	2.94 ± 0.08 h	86.97 ± 0.72 h	0.67 ± 0.01 ab
Class 2 powder (180–500 μm)	Big Ebanga	7.56 ± 0.38 cde	1.51 ± 0.04 ab	2.77 ± 0.05 bcde	1.81 ± 0.15 fg	86.35 ± 0.53 e	0.73 ± 0.01 abc
	FHIA 2	9.62 ± 0.18 ij	2.06 ± 0.13 cde	4.64 ± 0.03 hij	1.52 ± 0.18 defg	82.31 ± 0.19 abc	2.06 ± 0.01 f
	PITA 3	7.97 ± 0.31 ef	2.01 ± 0,07 cde	3.98 ± 0.23 fgh	1.12 ± 0.07 bcd	84.92 ± 0.23 fg	1.59 ± 0.10 e
	Corne 1	9.09 ± 0.07 ghi	1.35 ± 0.06 a	3.49 ± 0.03 defg	2.56 ± 0.15 h	83.50 ± 0.23 cde	0.73 ± 0.05 abc

Means with different superscripted letters in the same column were significantly different according to Tukey's HSD test (p < 0.05).

Tab. 2. Physical properties of powders from plantain hybrids.

Type of powder	Plantain variety	D_{50} [μm]	Span	Lightness L^*	Chroma C	Sieved mass fractions [%]
Unsieved powder (< 500 μm)	Big Ebanga	90.67 ± 1.89 d	2.86 ± 0.02 i	84.45 ± 0.93 gh	19.52 ± 0.83 b	nd
	FHIA 21	173.67f± 1.15 b	1.97 ± 0.02 ef	80.54 ± 0.39 cd	22.46 ± 0.96 cd	nd
	PITA 3	93.27 ± 0.12 d	2.57 ± 0.02 h	81.95 ± 0.03 e	19.89 ± 1.25 b	nd
	Corne 1	75.60 ± 1.15 c	2.40 ± 0.04 g	83.24 ± 0.19 f	24.26 ± 0.77 d	nd
Class 1 powder (< 180 μm)	Big Ebanga	68.73 ± 0.46 b	1.51 ± 0.02 d	86.53 ± 0.31 j	23.81 ± 0.65 d	81.1
	FHIA 21	132.67 ± 1.15 e	1.59 ± 0.04 d	83.49 ± 0.10 fg	19.12 ± 0.53 b	74.3
	PITA 3	79.17 ± 2.12 c	1.89 ± 0.04 e	84.80 ± 0.26 hi	16.92 ± 0.52 a	92.6
	Corne 1	53.93 ± 0.15 a	2.04 ± 0.01 f	85.92 ± 0.02 ij	21.03 ± 0.67 bc	73.0
Class 2 powder (180–500 μm)	Big Ebanga	263.00 ± 1.00 g	0.73 ± 0.02 b	81.09 ± 0.26 de	23.41 ± 0.44 d	17.0
	FHIA 21	306.67 ± 3.79 j	0.75 ± 0.06 b	74.38 ± 0.31 b	27.91 ± 0.28 e	25.0
	PITA 3	284.33 ± 1.53 h	0.61 ± 0.01 a	72.86 ± 0.37 a	27.76 ± 0.14 e	6.5
	Corne 1	296.33 ± 5.51 i	0.86 ± 0.02 c	79.76 ± 0.56 c	32.43 ± 0.56 f	25.9

Means with different superscripted letters in the same column were signi cantly different according to Tukey's HSD test (p < 0.05).
D_{50} – median particle diameter, nd – not determined.

Corne 1 and French 2), which exhibited monomodal particle size distributions with D_{50} ranging between 75.6 μm and 131.3 μm. Mean particle size of investigated powders increased according to variety in the following order: Corne 1 < Big Ebanga < PITA 3 < FHIA 21.

It can be seen that a majority of particles of unsieved plantain powders was able to pass through a 180 μm sieve, as the sieved mass fraction of class 1 was approximately 76 % (except for the hybrid PITA 3). This shows that powder processing permitted to produce fine powders that were not sensitive to agglomeration upon vibrations occurring during sieving. The PITA 3 hybrid achieved the highest yield (92.6 %) for class 1 powders and, therefore, the lowest yield (6.5 %) for class 2 powders. This could be justified by the irregular shape (for instance, more elongated particles) of particles of this plantain variety, thus allowing their passage through a mesh sieve inferior to their mean size. The sum of classes 1 and 2 did not equal 100 % (Tab. 2) because there was a little powder loss during sieving with powder remaining stuck on the sieve walls or escaping sieves during recovery.

As expected from the action of the sieving process, class 1 had markedly lower D_{50} than class 2. D_{90} of class 1 powders was inferior to 180 μm, whereas D_{10} of class 2 powders were systematically superior to 180 μm. This confirmed the efficiency of the sieving process performed in the conditions of the study to discriminate unsieved plantain powders into two well-differentiated granulometric classes (Fig. 1), like in previous studies on other plant powders [7, 8]. Whatever the variety, both granulometric classes presented monomodal particle size distributions with low to very low span values (< 1 for class 1 and < 2 for class 2), showing that the grinding and sieving procedure permitted to obtain two narrow particle populations having different granulometric characteristics. The sieving efficiency decreased in the following order: Corne 1 > FHIA 21 > Big Ebanga > PITA 3.

Colour properties

Colour parameters of plantain powders are presented in Tab. 2. L*, which represents sample lightness, was between 72.86 and 85.92. L^* was significantly lowered when increasing the particle size. Chroma C was 16.92–32.40 and it could be noticed that C increased with particle size, indicating a higher colour saturation of class 2 powders. Thus, it can be suggested from these results that class 2 powders were less bright and more coloured. Generally, an increase in colour saturation of food powders is indicative of a higher content in coloured compounds, which are often antioxidant, such as anthocyanins [22]. It could be therefore speculated that class 2 powders may have more positive health effects. The major colours of class 1, class 2 and unsieved powders were orange-yellow, yellow-orange, and yellow, respectively. From visual observation, this particle size-driven difference between powder colours was obvious: in comparison with unsieved powder. Class 1 powders were lighter and less coloured, while the opposite was true for class 2 powders.

The obtained colourimetric parameters were close to those obtained by Anyasi et al. [23] for unripe banana powders of three varieties (Luvhele, Mabonde and M-red). However, they obtained lower values of b^* and C, which may be indicative of a positive effect of plantain ripening on colour saturation, i.e. unripe plantain may lead to less coloured powders than ripe plantain. L^* value of the hybrid Big Ebanga for all powders was significantly higher, and L^* value of the

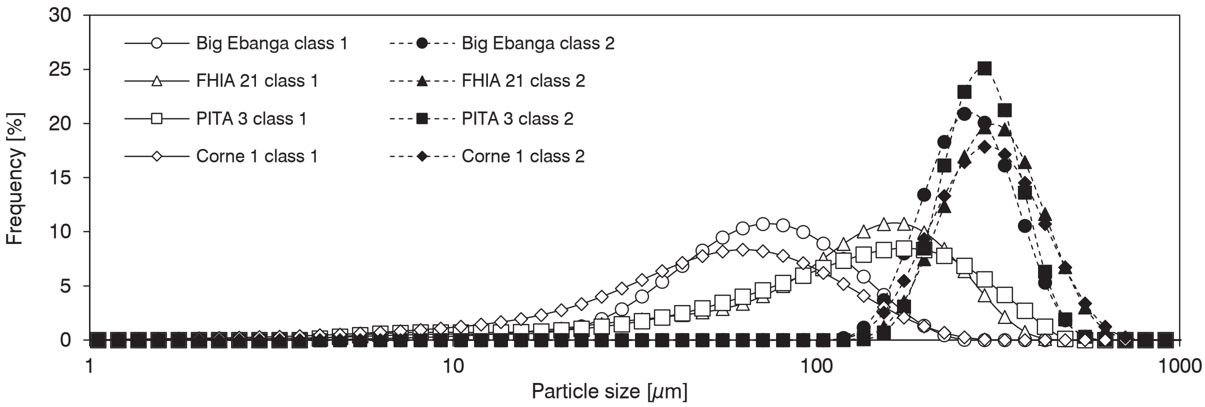

Fig. 1. Particle size distribution of powders from plantain hybrids.

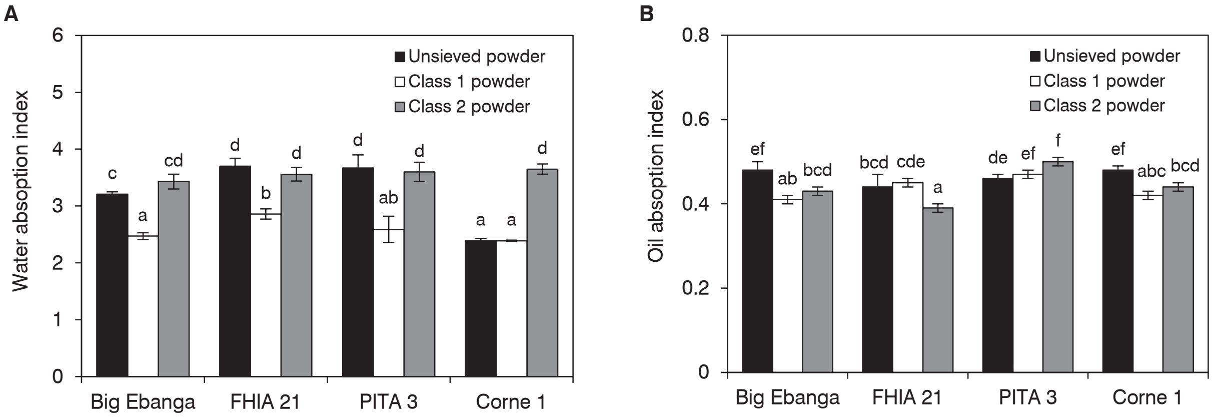

Fig. 2. Functional properties of powders from plantain hybrids.

A – water absorption index, B – oil absorption index.
Bars topped with different letters corresponded to significantly different results according to Tukey's HSD test ($p < 0.05$).

hybrid FHIA 21 for all powders was significantly lower. The rather high L^* values of unsieved powders for all varieties, but more specifically for Big Ebanga, could be attributed to the anti-browning effect of citric acid and sodium pyrophosphate pre-treatments [23]. The higher chroma C of class 2 powders may be due to a higher pigment content. According to Wrolstad and Smith [24], the chroma C of a food product increases when increasing pigment content and it undergoes a marked decrease as the sample becomes darker (i.e. at lower L^*). The high contents in proteins and reducing sugars of class 2 powders (Tab. 1) could have led to darker and browner colour than unsieved and class 1 powders. This darkness could result from the Maillard reaction between reducing sugars and proteins, leading to the formation of dark brown compounds.

Functional properties

The functional properties of unsieved plantain powders and of their granulometric fractions are presented in Fig. 2. The *WAI* of investigated powders was between 2.39 and 3.70 on dry basis. Comparable results were generally obtained for class 2 and unsieved powders, whereas the water-holding capacity of class 1 powders was often lower. This might be attributed to the lower amylose and dietary fibre contents of the latter [23]. Protein content (Tab. 2) was somewhat lower in class 1 powders, which could have contributed to the decrease in water absorption of these fractions. These results agree with the poor water absorption of finely milled cowpea powders [6]. *WAI* is greatly affected by the extent of disintegration of native starch granules and can be attributed to the physical state of starch, as well as amylose, dietary fibre and protein contents of the powder. Also, the small particles would have undergone more intense mechanical stresses and heating, in particular during grinding, which probably led to a higher degree of starch degradation.

The *OAI* range of unsieved powders was from 0.4 (for FHIA 21) to 0.5 (for Big Ebanga and Corne 1). In class 1 powders, the lowest value was recorded for the Big Ebanga hybrid (0.4) and the highest value for the PITA 3 hybrid (0.5). In class 2 powders, the PITA 3 hybrid showed the highest *OAI* value (0.5) and FHIA 21 the lowest value (0.4). For the Big Ebanga, PITA 3 and Corne 1 varieties, *OAI* slightly increased with particle size. However, for the FHIA 21 variety, *OAI* decreased from class 1 (0.5) to class 2 (0.4). All the powders displayed stronger affinity for water than for oil. Obtained *OAI* values were lower than those reported for unripe banana powder pre-treated with various contents of three organic acids (1.3–2.0) [24], but were close to those reported for ripe Cavendish banana pulp powder (0.7–0.8 at 40 °C) [25]. The low *OAI* observed in investigated samples could be explained by the low starch content of these powders produced from plantain at stages 4 and 5 of ripening, because ripening is known to induce hydrolysis of starch to sugars [18].

The calculation of Pearson correlation coefficients provided evidence that D_{50} and convexity positively correlated with *WAI* ($r = 0.98$ and $r = 0.94$, respectively). This indicated that large particles were more prone to interact with water, presumably owing to a more porous structure.

Flowing properties

Flowing properties of unsieved powders and their granulometric classes are listed in Tab. 3.

The range of *BFE* values between 112.75 mJ and 250.93 mJ was previously found to be typical for powders of medium to high flowability [26]. Significant differences were observed between samples. In fact, whatever the granulometric class, FHIA 21 variety had the highest *BFE* value. *BFE* seemed to increase with particle size, as previously reported in the literature. Thus, class 1 powders appeared to have a better dynamic flowability.

Unsieved and class 1 powders showed a fluidised state at the end of the aeration test and the *MFV* was between 1.07 mm·s^{-1} and 2.33 mm·s^{-1}. Sensitivity to small aeration rates (*NAS*) was between 0.37 s·mm^{-1} and 1.30 s·mm^{-1}, with significant differences among samples. The low *NAS* values obtained by class 2 powders may be explaine by their greater proportion of large particles, which are more difficult to suspend in the air than non-cohesive small particles. In fact, these powders had average sensitivity to aeration (aeration ratios *AR* between 2 and 6), whereas the other powders (unsieved and class 1) were very sensitive to aeration ($AR > 10$), which was a sign of low cohesion of the latter powders. Indeed, as a general rule, the larger the aeration ratio and the lower the aeration energy, the less cohesive the powder.

When increasing applied normal stress from 1 kPa to 15 kPa, compressibility *CPS* increased. No significant variety effect was observed for *CPS* of class 2 powders. Generally, highly compressible powders require more energy to flow. Compressibility of unsieved and class 1 powders was much greater than that of class 2 powders. This may be due to the lower mean particle size of unsieved and class 1 powders, as powders of low particle size tend to be cohesive and entrap large amounts of air, thus becoming sensitive to compression. Also, powders constituted by several particle populations and/or presenting a large dispersion of particle sizes around the mean value (i.e. having a high span) may likely be more compressible [27].

The shear cell test permitted to confirm the low cohesion of studied plantain powders, which ranged from 0.13 kPa to 0.47 kPa, similarly to results of Gnagne et al. [5]. All investigated samples were free-flowing powders, with *ff* values between 9.99 and 34.64. Also, it was noted that shear and compressibility test results were in good agreement as the higher the compressibility of the powder bed, the higher cohesion deduced from shear cell test and the lower the powder flowability. Both particle shape and particle size distribution significantly influenced the shear properties of the samples. D_{50} and convexity appeared to be negatively correlated with specific energy ($r = -0.70$), *NAS* ($r = -0.94$ and $r = -0.92$, respec-

Tab. 3. Bulk properties and flow parameters of powders from plantain hybrids.

Type of powder	Plantain variety	*BFE* [mJ]	*NAS* [s·mm^{-1}]	*MFV* [mm·s^{-1}]	*CPS* [%]	C_m [kPa]	*ff*
Unsieved powder (< 500 μm)	Big Ebanga	146.61 ± 6.94^{b}	1.01 ± 0.03^{bc}	1.60 ± 0.40^{a}	12.0 ± 0.9^{f}	0.35 ± 0.01^{cde}	12.41 ± 0.43^{abc}
	FHIA 21	180.33 ± 3.04^{cd}	0.92 ± 0.12^{b}	2.33 ± 0.58^{a}	5.6 ± 0.1^{c}	0.19 ± 0.01^{ab}	22.81 ± 1.27^{bcde}
	PITA 3	154.74 ± 5.48^{bc}	1.30 ± 0.04^{d}	1.20 ± 0.01^{a}	7.2 ± 0.4^{d}	0.33 ± 0.03^{bcde}	13.25 ± 0.92^{abcd}
	Corne 1	174.95 ± 4.15^{cd}	0.47 ± 0.01^{a}	1.47 ± 0.46^{a}	7.5 ± 0.4^{d}	0.28 ± 0.02^{abcd}	15.26 ± 1.30^{abcd}
Class 1 powder (< 180 μm)	Big Ebanga	164.36 ± 4.32^{bc}	1.19 ± 0.01^{bcd}	1.33 ± 0.23^{a}	8.9 ± 0.1^{e}	0.17 ± 0.01^{a}	24.38 ± 0.95^{def}
	FHIA 21	178.45 ± 5.12^{cd}	0.92 ± 0.06^{b}	1.60 ± 0.01^{a}	4.5 ± 0.2^{bc}	0.18 ± 0.03^{ab}	23.30 ± 3.12^{cdef}
	PITA 3	141.95 ± 4.80^{b}	1.25 ± 0.01^{cd}	1.20 ± 0.01^{a}	5.8 ± 0.2^{c}	0.21 ± 0.06^{abc}	21.90 ± 6.74^{bcde}
	Corne 1	112.75 ± 4.18^{a}	1.18 ± 0.22^{bcd}	1.07 ± 0.46^{a}	11.4 ± 1.0^{f}	0.37 ± 0.02^{de}	11.62 ± 0.46^{ab}
Class 2 powder (180–500 μm)	Big Ebanga	191.50 ± 11.91^{d}	0.42 ± 0.05^{a}	nd	3.0 ± 0.3^{a}	0.47 ± 0.09^{e}	9.99 ± 1.76^{a}
	FHIA 21	250.93 ± 19.29^{e}	0.53 ± 0.12^{a}	nd	3.6 ± 0.0^{ab}	0.46 ± 0.07^{e}	11.76 ± 4.50^{abc}
	PITA 3	143.77 ± 6.25^{b}	0.58 ± 0.06^{a}	nd	2.5 ± 0.1^{a}	0.15 ± 0.04^{a}	29.00 ± 8.23^{ef}
	Corne 1	167.42 ± 14.95^{bcd}	0.37 ± 0.12^{a}	nd	2.8 ± 0.4^{a}	0.13 ± 0.02^{a}	34.64 ± 6.88^{f}

Means with different superscripted letters in the same column were significantly different according to Tukey's HSD test ($p < 0.05$).
BFE – basic flowability energy, *NAS* – normalised aeration sensitivity, *MFV* – minimum fluidisation velocity, *CPS* – compressibility at 15.0 kPa, C_m – cohesion, *ff* – flowability index.
nd – not demined, i.e. minimal fluidisation velocity was not reached in conditions of FT4 standard aeration test.

tively) and *CPS* at 15 kPa (r = –0.85 and r = –0.73, respectively). Also, compressibility at 15 kPa was found to be positively correlated with specific energy (r = 0.84) and *NAS* (r = 0.80). This shows that large particles of instant plantain powders had better flowing properties and were less sensitive to aeration and compaction.

CONCLUSION

Physico-chemical properties as well as functionalities of plantain powders were mostly influenced by the particle size. *OAI* was significantly lower for fine powders. All powders displayed stronger affinity for water than for oil. Powder flow characteristics clearly showed that particle size significantly affected all flow properties. Except for the Big Ebanga variety, particle size distribution significantly influenced the flowing properties of powder samples.

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REFERENCES

1. Ahenkora, K. – Kye, A. – Marfo, K. – Banful, B.: Nutritional composition of false horn Apantu pa plantain during ripening and processing. African Crop Science Journal, *4*, 1996, pp. 243–248. ISSN: 1021-9730.
2. Lassois, L. – Busogoro, J. – Jijakli, H.: La banane : de son origine à sa commercialisation. (Banana: from its origin to its marketing.) Biotechnologie, Agronomie, Société et Environnement, *13*, 2009, pp. 575–586. ISSN: 1370-6233. In French.
3. Zakpaa, H. – Mak-Mensah, E. – Adubofour, J.: Production and characterization of flour produced from ripe "apem" plantain (*Musa sapientum* L. var. *paradisiaca*; French horn) grown in Ghana. Journal of Agricultural Biotechnology and Sustainable Developpement, *2*, 2010, pp. 92–99. ISSN: 2141-2340.
4. Kouakou, K. R. – Traore, S. – Kone, T. – Ouattara, H. D. – Kone, M. – Dogbo, D. O.: Variations biochimiques et morphologiques au cours de la conservation des vivo plants de trois varietes de bananier plantain [*Musa* x *Paradisiaca*, (*Musaceae*)]. (Biochemical and morphological variations during the conservation of the vivo plants of three varieties of plantain [*Musa* x *Paradisiaca*, (*Musaceae*)].) Agronomie Africaine, *31*, 2019, pp. 1–14. ISSN: 1015-2288. <https://www.ajol.info/index.php/aga/article/view/186713> In French.
5. Gnagne, E. – Petit, J. – Gaiani, C. – Scher, J. – Amani, G.: Characterisation of flow properties of *foutou* and *foufou* flours, staple foods in West Africa, using FT4 powder rheometer. Journal of Food Measurement and Characterization, *11*, 2017, pp. 1128–1136. DOI: 10.1007/s11694-017-9489-2.
6. Kerr, W. L. – Ward, C. D. W. – McWatters, K. H. – Resurreccion, A. V. A.: Effect of milling and particle size on functionality and physicochemical properties of cowpea flour. Cereal Chemistry Journal, *77*, 2000, pp. 213–219. DOI: 10.1094/CCHEM.2000.77.2.213.
7. Zaiter, A. – Becker, L. – Petit, J. – Zimmer, D. – Karam, M.-C. – Baudelaire, É. – Scher, J. – Dicko, A.: Antioxidant and antiacetylcholinesterase activities of different granulometric classes of *Salix alba* (L.) bark powders. Powder Technology, *301*, 2016, pp. 649–656. DOI: 10.1016/j.powtec.2016.07.014.
8. Becker, L. – Zaiter, A. – Petit, J. – Karam, M.-C. – Sudol, M. – Baudelaire, E. – Scher, J. – Dicko, A.: How do grinding and sieving impact on physicochemical properties, polyphenol content, and antioxidant activity of *Hieracium pilosella* L. powders? Journal of Functional Foods, *35*, 2017, pp. 666–672. DOI: 10.1016/j.jff.2017.06.043.
9. Irie, K. R. – Petit, J. – Gnagne, E. H. – Kouadio, O. K. – Gaiani, C. – Scher, J. – Amani, G. N.: Effect of particle size on flow behaviour and physical properties of semiripe plantain (*AAB Musa* spp.) powders. International Journal of Food Science and Technology, *56*, 2020, pp. 205–214. DOI: 10.1111/ijfs.14620.
10. Lii, C.-Y. – Chang, S.-M. – Young, Y.-L.: Investigation of the physical and chemical properties of banana starches. Journal of Food Science, *47*, 1982, pp. 1493–1497. DOI: 10.1111/j.1365-2621.1982.tb04968.x.
11. Goonatilake, R.: Effects of diluted ethylene glycol as a fruit-ripening agent. Global Journal of Biotechnology and Biochemistry, *3*, 2008, pp. 8–13. ISSN: 2078-466X. <https://idosi.org/gjbb/gjbb3(1)08/2.pdf>
12. Helrich, K. (Ed.): Official methods of analysis of AOAC International. 15th edition. Arlington: AOAC International, 1990. ISBN: 0-935584-42-0.
13. Bernfeld, P.: Amylase, α and β. Methods in Enzymology, *1*, 1955, pp. 149–158. DOI: 10.1016/0076-6879(55)01021-5.
14. Schuck P.: Modifications des propriétés fonctionnelles des poudres de protéines laitières: Impact de la concentration et du séchage. (Modification of the functional properties of dairy protein powders: impact of concentration and drying.) Innovations Agronomiques, *13*, 2011, pp. 71–99. ISSN: 1958-5853. In French.

15. Phillips, R. D. – Chinnan, M. S. – Branch, A. L. – Miller, J. – McWatters, K. H.: Effects of pretreatment on functional and nutritional properties of cowpea meal. Journal of Food Science, *53*, 1988, pp. 805–809. DOI: 10.1111/j.1365-2621.1988.tb08959.x.
16. Sosulski, F. W.: The centrifuge methods for determining flour absorption in hard red spring wheat. Cereal Chemistry, *39*, 1962, pp. 344–350. ISSN: 0009-0352.
17. Jenike, A. W.: Storage and flow of solids. Bulletin of the University of Utah : Bulletin No. 123 of the Utah Engineering Experiment Station, volume *53*. 6th revised edition. Salt Lake City : University of Utah, 1970.
18. Kaur, H. – Datt, M. – Ekka, M. K. – Mittal, M. – Singh, A. K. – Kumaran, S.: Cys-Gly specific dipeptidase Dug1p from *S. cerevisiae* binds promiscuously to di-, tri-, and tetra-pepetides: Peptide-protein interaction, homology modeling, and activity studies reveal a latent promiscuity in substrate recognition. Biochimie, *93*, 2011, pp. 175–186. DOI: 10.1016/j.biochi.2010.09.008.
19. Luzia, D. M. – Jorge, N.: Study of antioxidant activity of non-conventional Brazilian fruits. Journal of Food Science and Technology, *51*, 2014, pp. 1167–1172. DOI: 10.1007/s13197-011-0603-x.
20. Offem, J. O. – Thomas, O. O.: Chemical changes in relation to mode and degree of maturation of plantain (*Musa paradisiaca*) and banana (*Musa sapientum*) fruits. Food Research International, *26*, 1993, pp. 187–193. DOI: 10.1016/0963-9969(93)90052-k.
21. Nura, M. – Kharidah, M. – Jamilah, B. – Roselina, K.: Textural properties of laksa noodle as affected by rice flour particle size. International Food Research Journal, *18*, 2011, pp. 1309–1312. ISSN: 2231-7546. <http://www.ifrj.upm.edu.my/18%20(04)%202011/(15)IFRJ-2011-100.pdf>
22. Malela, K. E. – Petit, J. – Nzikou, J. M. – Scher, J.: Physicochemical characterisation and phytochemical study of *Grewia coriacea* Mast powders: focus on polyphenols. International Journal of Innovative Science, Engineering and Technology, *3*, 2016, pp. 512–525. ISSN: 2348–7968. <https://ijiset.com/vol3/v3s3/IJISET_V3_I3_63.pdf>
23. Anyasi, T. A. – Jideani, A. I. O. – Mchau, G. R. A.: Effect of organic acid pretreatment on some physical, functional and antioxidant properties of flour obtained from three unripe banana cultivars. Food Chemistry, *172*, 2015, pp. 515–522. DOI: 10.1016/j.foodchem.2014.09.120.
24. Wrolstad, R. E. – Smith, D. E.: Color analysis. In: Nielsen, S. S. (Ed.): Food analysis. Cham : Springer, 2017, pp. 545–555. ISBN: 978-3-319-45776-5. DOI: 10.1007/978-3-319-45776-5_31.
25. Aremu, M. O. – Olaofe, O. – Akintayo, E. T.: Functional properties of some Nigerian varieties of legume seed flours and flour concentration effect on foaming and gelation properties. Journal of Food Technology, *5*, 2007, pp. 109–115. ISSN: 1684-8462.
26. Jan, S. – Ghoroi, C. – Saxena, D. C.: Characterization of bulk and shear properties of basmati and non-basmati rice flour. Journal of the Science of Food and Agriculture, *98*, 2017, pp. 667–673. DOI: 10.1002/jsfa.8512.
27. Salameh, C. – Banon, S. – Hosri, C. – Scher, J.: An overview of recent studies on the main traditional fermented milks and white cheeses in the Mediterranean region. Food Reviews International, *32*, 2016, pp. 256–279. DOI: 10.1080/87559129.2015.1075210.

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