Enhancing the quality of overripe plantain powder by adding superfine fractions of *Adansonia digitata* L. pulp and *Hibiscus sabdariffa* L. calyces: characterization and antioxidant activity assessment

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Abstract

In this study, the overripe plantain has been used to produce high-antioxidant powders, using *Adansonia digitata* L. pulp and *Hibiscus sabdariffa* L. calyces as antioxidant supplements. The constrained mixture design (ranged between 0.9–1.0 for plantain and 0–0.1 for supplements) was used to generate ten powder formulations. The obtained powders were evaluated for physicochemical properties and antioxidant activities. Generally, significant differences ($p < 0.05$) were found between moisture, proteins, ash, fibers, carbohydrates and fat contents of different raw material powders. The increase in the proportions of *A. digitata* L. and *H. sabdariffa* L. significantly increased ($p < 0.05$) the levels of polyphenols (40.19–583.46 mg GAE/100 g DM), flavonoids (18.27–103.46 mg RE/100 g DM), condensed tannins (28.73–276.47 mg CE/100 g DM), carotenoids (8.41–9.48 mg/100 g DM) and vitamin C (31.55–77.30 mg/100 g DM) in the formulated powders. The antioxidant properties of the powder formulations revealed higher radical-scavenging activities DPPH (IC₅₀ of 0.80 mg/mL) and ABTS (IC₅₀ of 1.51 mg/mL) for M10 formulation consists of 91.67% overripe plantain, 1.67% *A. digitata* L. and 6.66% *Hibiscus sabdariffa* L. The best reducing powers were found in M5, M6 and M10 formulations which improved by more than 2 to 3 times the value of M1 (2.66 mg AAE/g DM) not containing antioxidant supplements. M10 was the powder formulation that exhibited the best antioxidant activities despite its low hydration capacity. *A. digitata* L. pulp and *H. sabdariffa* L. calyces revealed the potential for an efficient improve of antioxidant activity of overripe plantain powder. High-antioxidant powders from the mixtures showed promise in helping to combat oxidative stress in Africa and other countries where chronic diseases pose a threat.

Keywords Overripe plantain · Supplement · Powder formulation · Physicochemical characterization · Antioxidant activity

1 Introduction

Plantain (*Musa paradisiaca* L.) is one of the most important food crops widely produced and consumed in sub-Saharan Africa [1]. In Cameroon where production is about

3 million tons per year [2], plantain occupy a prominent place in households and plays an important role in food security of the population [3]. In this respect, plantain consumption has been evaluated at 150 kg/inhabitant/year in Cameroon [4]. Regarding the nutrient contents, it

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has been reported that 100 g of plantain contain about 35.5 g of carbohydrates, 1.3 g of protein, 0.3 g of fat and 5.8 g of fiber and provide 122 kcal [5]. In addition, ripe plantain contains many bioactive molecules, including carotenoids (4680 µg/100 g), vitamin C (11.7 mg/100 g), minerals and phenolic compounds. Thus, its regular consumption can be an effective way to fight against oxidative stress [6, 7] which may cause many chronic diseases, like some cancers, diabetes, cardiovascular diseases, renal, neurological and chronic respiratory diseases [8]. Despite this nutritional importance and the bioactive potentials of plantain, its use is limited by post-harvest losses of more than 20–40% in Cameroon [2]. In fact, after harvest, mature green fruits undergo rapid ripening leading to the appearance of black spots on the surface of their peels 10–12 days later (overripe plantain). Beyond this stage of ripening, the nutritional content of the fruit decreases and it loses its technological properties (due to excessive softening of its pulp), even its market value [9].

To cope with the losses associated with excessive fruit ripening, studies have proposed the powder processing technologies on ripe fruits such as mangoes [10] and dates [11, 12]. Others have produced enriched date powders by incorporating plants with interesting antioxidant activity, such as spirulina [13] and olive leaves [12]. Thus, such technology could be applied for the valorization of overripe plantain pulp, using tropical antioxidant-containing plants. Among these plants, two of the most representative used in our previous studies are *A. digitata* L. and *H. sabdariffa* L. These plants are very attractive in food and medicinal usages of their fruits and calyces respectively. According to their biological properties reported in previous studies, fine powder fractions from these plant parts can be indicated as good sources of natural antioxidants that can be used as functional food ingredients and nutraceuticals [14]. *A. digitata* L. fruit pulp is a valuable source of vitamin C, almost ten times that of oranges [15]. It contains sugars but no starch and is rich in pectin. Since it can be dissolved in water or milk, the liquid is then used as a drink and sauce for food, a fermenting agent in local brewing, or as a substitute for cream of tartar in baking. Nutritional importance of the calyces of *H. sabdariffa* L. is mainly due to high content anthocyanins and others bioactive compounds [14, 16]. Calyces are used for food coloring and the preparation of a soft drink widely consumed for varied health benefits. These health properties include anti-hypertensive, anti-inflammatory, anti-diabetic, hepatoprotective, anti-bacterial and anti-oxidant activities [14, 17, 18]. Thus, *A. digitata* L. fruits and *H. sabdariffa* L. calyces could be used to increase the nutraceutical potential of overripe plantain powder. This powder could serve as a

raw material for the production of foods with high nutritional quality as well as beneficial health effects.

Therefore, this work seeks to valorise the overripe plantain pulp by producing powders with high antioxidant activity, using *A. digitata* L. fruit and *H. sabdariffa* L. calyces as bioactive supplements.

2 Materials and methods

2.1 Plant material

In this study, a basic raw material: plantain (*M. paradisiaca* L.) and two tropical plants: *A. digitata* L. fruits and *H. sabdariffa* L. calyces were used. These plant materials were purchased from Ngaoundere market in the Adamawa Region of Cameroon and transported to the laboratory. The plantain was fresh and matured to the extent where its ripening process had been initiated. It was placed at room temperature (25 ± 2 °C) for it to fully ripe at maturity stage 7 (overripe plantain: appearance of black spots on the surfaces of their peels). The fruits and calyces were bought in the dried form.

2.2 Pre-treatment and production of overripe plantain powder

The powder of overripe plantain (*M. paradisiaca* L.) was produced according to the protocol described by Surendranatha [19] with a slight modifications. The overripe plantain heads were cut into clusters and then separated from each other. The fruits were washed to remove dust particles, blanched at 75 °C for 15 min, peeled and cut into slices. Blanched plantain slices were crushed in a robot blender mill (MOULINEX model, Paris, France) and then centrifuged (Thermo Scientific, Heraeus Megafuge 8R Centrifuge, Osterode am Harz, Germany) at 3500 rpm for 20 min and the supernatant discarded. This treatment reduces the water and sugar content to facilitate the drying process. The residue was collected and dried at 40 °C in an air convection electric dehydrator (Riviera & Bar QD 100 A, Paris, France) to a brittle touch (moisture content at about 10%). The dried mats were crushed for 30 s using a knife mill (GRINDOMIX, GM 200, Retsch, Germany). The powder obtained was sieved on 500 µm with the laboratory vibrating sieve (Fritsch, Idar-Oberstein, Germany) for 15 min and then weighed and stored in high-density polyethylene bags (61 µm).

2.3 Production of *Adansonia digitata* L. and *Hibiscus sabdariffa* L. powder fractions

The dried fruits of *A. digitata* L. and calyces of *H. sabdariffa* L. were sorted to remove impurities and other foreign materials. The dried plant materials were ground separately in the robot blender mill (MOULINEX model, Paris, France). The obtained powders were then sieved through a superimposition of two sieves of mesh sizes of 180 µm and 212 µm respectively. The powder fractions with a particle size between 180 and 212 µm were obtained. The particle size selected for these plants was that with the best antioxidant activity in our previous studies [14]. The resulting powders were packaged, sealed in polyethylene bags and stored at 25 °C/65% air humidity until analysis.

2.4 Formulation of supplemented plantain powders

A “constrained mixture design” was used to evaluate the effect of powder proportions (overripe plantain, *A. digitata* L. and *H. sabdariffa* L.) on the properties of powder formulations. For plantain powder, minimum and maximum levels were established on the objective of using it at a proportion > 90% for its better valorization. Nevertheless, the proportions of *A. digitata* L. and *H. sabdariffa* L. powders of < 10% were established in relation to their antioxidant capacity. Table 1 presents the experimental matrix for this constrained mixture design. The different powder proportions in the formulation resulting from the experimental design ranged between 0.9–1.0 for plantain and 0–0.1 for *A. digitata* L. and *H. sabdariffa* L.

Table 1 Experimental matrix of the formulation of powders

*Formulation codes (Mx)	Overripe plantain powder (%)	Antioxidant supplements (%)	
		<i>Adansonia digitata</i>	<i>Hibiscus sabdariffa</i>
M1 (100-0-0)	100	0	0
M2 (95-5-0)	95	5	0
M3 (95-0-5)	95	0	5
M4 (90-10-0)	90	10	0
M5 (90-0-10)	90	0	10
M6 (90-5-5)	90	5	5
M7 (93.33-3.33-3.34)	93.33	3.33	3.34
M8 (96.66-1.67-1.67)	96.66	1.67	1.67
M9 (91.66-6.67-1.67)	91.66	6.67	1.67
M10 (91.67-1.67-6.66)	91.67	1.67	6.66

*Mx (overripe plantain–*Adansonia digitata*–*Hibiscus sabdariffa*)

The powders were thoroughly mixed to obtain homogeneous powder mixtures coded as Mx. The samples were stored in polyethylene bags at 25 °C/65% air humidity until ready for use.

2.5 Proximate composition analysis of raw material powders

Protein, ash, moisture, crude fat, crude fiber and carbohydrate contents of the different powders from overripe plantain, *A. digitata* L. and *H. sabdariffa* L. were determined according to the official method of analysis described by the Association of Official and Analytical Chemist [20]. Analyses were performed in triplicates.

2.6 Physicochemical characterization of formulated powders

2.6.1 Water activity measurement

Water activity determination was performed with a dew point hygrometer (HygroLab HW4-Series 2, rotronic Devices Inc., USA) at 22 ± 1 °C. This machine was primarily designed for measuring the water activity (a_w) of foods, pharmaceuticals and cosmetics. For each sample, measurements were performed in triplicate.

2.6.2 Porosity measurement

The volume displacement method described by Samejima et al. [21] was used to determine true density (TD), bulk density (BD) and porosity of each sample. A portion of mixture powder (M1) was added to a volumetric cylinder, and the volume was recorded as V1. After the same volume (V1) of displacement fluid (isobutyl alcohol/phthalic acid diethyl ester 1:1) was added to the cylinder, the total volume of the powder plus solvent in the cylinder was recorded as V2. TD, BD, and porosity were calculated according to the following equations:

$$\text{True density (TD)} = \frac{M1}{V1 - V2}$$

$$\text{Bulk density (TD)} = \frac{M1}{V1}$$

$$\text{Porosity (TD)} = 1 - \frac{BD}{TD}$$

2.6.3 Water and oil absorption capacity and water solubility index measurements

Water absorption capacity (WAC) and water solubility index (WSI) were evaluated according to Phillips et al. [22] and Anderson et al. [23] methods, respectively. A portion (M1) of each formulation was mixed with 10 mL of distilled water in centrifuge tube of 50 mL, incubated in a water-bath at 30 °C for 30 min, centrifuged (Thermo Scientific, Heraeus Megafuge 8R Centrifuge, Osterode am Harz, Germany) at 3500 rpm for 20 min, the supernatant decanted and the wet pellet weighed (M2). The excess water absorbed by the powder was expressed as the percentage water bound by 100 g of powder using the formula:

$$\text{WAC (\%)} = \frac{M2 - M1}{M1} \times 100$$

For the determination of water solubility index, the supernatant was dried in an air convection electric dehydrator (Riviera & Bar QD 100 A, Paris, France) at 105 °C for 24 h to constant weight (M3). The soluble matter was expressed per 100 g of powder as follows:

$$\text{WSI (\%)} = \frac{M3}{M1} \times 100$$

The oil absorption capacity (OAC) of the samples was determined as described by Beuchat [24]. A portion of each sample (M1) was mixed with 10 mL of oil in a centrifuge tube of 50 mL for 1 min. The samples were then allowed to stand at 25 °C for 30 min and centrifuged (Thermo Scientific, Heraeus Megafuge 8R Centrifuge, Osterode am Harz, Germany) at 3500 rpm for 30 min. The supernatant was discarded and the pellet weighed (M4). The weight of oil absorbed by 100 g of powder was calculated and expressed as oil absorption capacity using the formula:

$$\text{OAC (\%)} = \frac{M4 - M1}{M1} \times 100$$

2.7 Bioactive compounds and antioxidant activity evaluation of formulated powders

2.7.1 Extraction and determination of carotenoid and ascorbic acid contents

Carotenoid content in each powder formulation was determined according to the method described by Alasalvar et al. [25]. In brief, 0.5 g of powder sample was mixed with 5 mL of hexane/acetone (30/70; v/v) using a rotary shaker for 2 h and centrifuged (Thermo Scientific, Heraeus

Megafuge 8R Centrifuge, Osterode am Harz, Germany) at 3500 rpm for 10 min at 4 °C. The extraction was repeated for five times with 3 mL of hexane/acetone until no color was extracted, and volume was made to 25 mL (V). The quantification of total carotenoid was carried out as described by Fu et al. [26] at 450 nm using UV-spectrophotometer (Shimadzu UV-VIS 1605, Tokyo, Japan). A standard curve made of beta-carotene ($R^2 = 0.995$) was established and the concentration of total carotenoid expressed in milligram per 100 g of dry weight were calculated using follow formula:

$$\begin{aligned} \text{Total carotenoid content (mg/100g DW)} \\ = \frac{(\text{Abs} \times V \times 1000)}{A_{1\text{cm}}^{1\%} m} \times 100 \end{aligned}$$

where Abs absorbance at 450 nm, V sample's final volume (mL), m sample mass (g), and $A_{1\text{cm}}^{1\%} = 2592$ (beta-carotene extinction coefficient in petroleum ether).

Ascorbic acid content was determined using the method described by Baldesten et al. [27] with some modifications. The sample (5 g) was digested with 25 mL of acetic/water solution (1/4). The aliquot was analysed by iodometry in the presence of a known amount of excess diode. In a beaker, 5 mL of each extract were mixed with 10 mL of a diode solution of known concentration and a few drops of starch and titrated with a solution of sodium thiosulfate (5.0×10^{-3} mol/L) until equivalence (clear solution). Ascorbic acid was used as standard and the results were expressed in milligram of ascorbic acid per 100 g of dry matter.

2.7.2 Preparation of methanolic/water extracts

Extraction of phenolic compounds from formulated powders were carried out according to the method of Kim et al. [28] with some modifications. 500 mg of each powder formulation was macerated during 24 h under stirring in 20 mL of methanol/water (70/30, v/v). Then, the methanol/water extract was centrifuged (Thermo Scientific, Heraeus Megafuge 8R Centrifuge, Osterode am Harz, Germany) at 3500 rpm for 15 min. The supernatant was filtered and the resulting extract (25 mg/mL) was stored at 4 °C prior to analysis.

2.7.3 Determination of total phenolic content

Total phenolic compounds (TPC) in powder extracts were determined according to the protocol described by Wafa et al. [29]. 40 µL of extract solution was added in test tubes containing 2980 µL of distilled water,

500 μL of Folin–Ciocalteu (1 N) and 400 μL of sodium carbonate (Na_2CO_3 , 20%). The mixture was thoroughly mixed with vortex. After 20 min of incubation at room temperature, the absorbance was recorded at 760 nm using UV-spectrophotometer (Shimadzu UV–VIS 1605, Tokyo, Japan). For the calibration curves calibration ($R^2=0.983$), gallic acid solution (0.2 g/L) was used and total phenolic content was expressed as milligram of gallic acid equivalent per 100 g of dry matter (mg GAE/100 g DM).

2.7.4 Determination of total flavonoid and condensed tannins contents

Total flavonoid content (TFC) was assayed by a colorimetric method described by Dewanto et al. [30]. Extract solution (100 μL) was added in a volumetric flask containing 2.4 mL of distilled water and 150 μL of sodium nitrite (Na_2NO_2 , 5%). After 5 min, 300 μL of aluminum chloride ($\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$, 10%) was added. After 5 min, 500 μL of sodium hydroxide (NaOH , 1 N) was added to the mixture and vortex. The samples were stored at room temperature for 5 min and the absorbance recorded at 510 nm. Solution of rutin (0.1 g/L) was used as standard and the total flavonoid contents was expressed as milligram of rutin equivalent per 100 g of dry matter (mg RE/100 g DM).

The condensed tannins content was determined according the protocol of Sun et al. [31]. 50 μL of extract solution was mixed with 3 mL of vanillin 4% and 1.5 mL of concentrate H_2SO_4 and the mixture was incubated at room temperature for 30 min. Absorbance was measured at 500 nm and the solution of catechin (0–0.600 mg/mL) used as standard. The condensed tannins content was expressed as milligram of catechin equivalent per 100 g of dry matter (mg CE/100 g DM).

2.7.5 Measurement of DPPH radical scavenging capacity

The DPPH radical scavenging activity of the methanolic/water extracts was measured in accordance with the method of Zhang and Hamazu [32] with slight modifications. For this determination, the extract sample (25 mg/mL) was first diluted in methanol/water (70/30, v/v) to obtain solutions of concentration 0.025–5 mg/mL. Then, each solution (0.5 mL) was added to 2.0 mL of 0.2 g/L DPPH methanolic. The reaction mixture was incubated in the dark for 60 min at room temperature ($25 \pm 2^\circ\text{C}$) and the optical density recorded at 517 nm using the solvent of extraction for the control tube. The percentage of DPPH free radical scavenging effect was calculated as follows:

$$\text{DPPH scavenging effect(\%)} = \frac{\text{DO}_{\text{control}} - \text{DO}_{\text{sample}}}{\text{DO}_{\text{control}}} \times 100$$

The IC_{50} (mg sample/mL) is the effective concentration of antioxidants at which free radicals were scavenged by 50%. IC_{50} values were obtained by plotting the graph of DPPH scavenging effect (%) as a function of the concentration followed by extrapolation. Ascorbic acid was used for comparison.

2.7.6 Measurement of ABTS radical scavenging capacity

The ABTS radical-scavenging activity of the methanolic/water extracts was determined according to the method described by Re et al. [33]. ABTS radical was produced with the mixture of 7 mM ABTS and 2.45 mM potassium persulfate and incubated at room temperature in the dark for 16 h before use. After incubation, the absorbance of the solution at 734 nm was adjusted to 0.70 ± 0.02 by dilution with 95% ethanol. To 2 mL of diluted ABTS radical solution, 150 μL of sample solutions (0.025–5 mg/mL) were added and mixed thoroughly, incubated at room temperature for 6 min and the absorbance recorded at 734 nm using the solvent of extraction for the control tube. The percentage of free radical scavenging effect was calculated as follows:

$$\text{ABTS scavenging effect(\%)} = \frac{\text{DO}_{\text{control}} - \text{DO}_{\text{sample}}}{\text{DO}_{\text{control}}} \times 100$$

The IC_{50} which refers to the effective concentration of antioxidants at which free ABTS^+ radical was scavenged by 50% was obtained as described above (in the case of DPPH). Ascorbic acid was used as standard.

2.7.7 Measurement of the total reducing power

The total reducing power of the methanolic/water extracts was investigated using the method developed by Oyaizu [34]. A volume of the extract (2.5 mL) of each sample was mixed with 2.5 mL of phosphate buffer (200 mM, pH 6.6) and 2.5 mL of 1% potassium ferricyanide solution. The mixture was incubated in a water bath at 50°C for 30 min, cooled, mixed with 2.5 mL of 10% trichloroacetic acid solution and centrifuged (Thermo Scientific, Heraeus Megafuge 8R Centrifuge, Osterode am Harz, Germany) at 3,000 rpm for 10 min. The supernatant (2.5 mL) was mixed with 2.5 mL of distilled water and 0.5 mL FeCl_3 (1.0%), allowed to react for 10 min at room temperature and the absorbance was measured at 700 nm. Ascorbic acid solution was used as standard. The reducing power were expressed in terms of milligram ascorbic acid equivalent per g of dry matter (mg AAE/g DM).

2.8 Statistical analysis

All analyses were performed in triplicate and the results presented as mean $\pm$ SD. Statistical significance of differences between sample means was determined using analysis of variance (ANOVA) followed by a Duncan's test at 95% confidence level using statgraphics 15.1. Principal component analysis (PCA) has been used to classify and correlate the factors whose define antioxidant activity and physicochemical properties and was realized by XL-STAT 2019.

3 Results and discussion

3.1 Proximate composition of overripe plantain, *Adansonia digitata* L. and *Hibiscus sabdariffa* L. powders

The proximate composition of powders from overripe plantain pulp, *A. digitata* L. fruit and *H. sabdariffa* L. calyces is given in Table 2. The moisture content of the powder samples was low and varied from 8.01% (*H. sabdariffa* L. powder) to 10.01% (overripe plantain powder) on wet basis. This low moisture content of different plant powders makes them less prone to microbial attack than fresh materials and would have a longer shelf life. Indeed, as reported by Devi et al. [35] moisture content lower than 10%, which means a minimum of 85.5% of total solid content, ensures powder stability during storage and packaging. Therefore, the formulation of a composite powder from these powder samples could fulfil this legal requirement.

Regarding the nutrient contents, significant differences ($p < 0.05$) were found between protein, ash, fiber, carbohydrate and fat depending on the nature of the plant. the protein content of the powders ranged from 1.74% (*A. digitata* L. powder) to 3.21% (overripe plantain powder) on dry basis. The protein content of overripe plantain was comparable to that of 3.5% reported by

Adegboyega [36] on ripe plantain. Similarly, the value obtained for *A. digitata* L. powder was compared with 1.86% obtained by Muthai et al. [37]. However, the protein content of *H. sabdariffa* L. powder (2.44% on dry basis) was lower than 4.71% reported by Adanlawo and Ajibade [38] on fresh calyces. The ash content of plant powders ranged from 1.30% (overripe plantain powder) to 2.01% (*H. sabdariffa* L. powder) on dry basis. These values were low but comparable to the value of 1.33% reported for ripe plantain powder by Adegunwa et al. [39]. High-content of ash in plant materials is an indicator for a good source of mineral elements. Thus, formulating powders from these raw materials could be a good approach to record this mineral potential. The crude fiber content of powders ranged from 3.02% (*H. sabdariffa* L. powder) to 5.58% (overripe plantain powder) on dry basis. The crude fiber content of overripe plantain powder is similar to 5.6% value reported by Adegboyega [36] for ripe plantain. Whereas, those of *H. sabdariffa* L. of 3.02% and *A. digitata* L. of 3.24% (on dry basis) were low compared to the value of 12.0% obtained by Mahadevan and Kamboj [40] for *H. sabdariffa* L. and the value of 6.69–8.83% obtained by Muthai et al. [37] for *A. digitata* L. This could be explained by the fact that during the finer sieving in this study, the stiffer fibers do not pass easily through the sieve and are found less in small particles obtained [41].

In general, these plant materials are poor in fat and rich in carbohydrates. The carbohydrate content of the powder samples ranges from 35.88% (*A. digitata* L. powder) to 56.55% (overripe plantain powder) on dry basis. Overripe plantain powder had the highest value in concordance with published data on fruits. The carbohydrate content of *H. sabdariffa* L. (40.80%) was lower than that obtained by Nnam and Onyeke [42] (79.25%). Similarly, the value 35.88% (on dry basis) of carbohydrates for *A. digitata* L. powder was as low as 76.2% reported by Osman [43]. The carbohydrate contents of these plant powders are low compared to the reported values. However, their mixture would boost the energy potential of the powder

Table 2 Proximate composition (expressed as percentage on dry basis) of powders from overripe plantain pulp, *Adansonia digitata* L. fruits and *Hibiscus sabdariffa* L. calyces

Characteristics	Plant powders		
	Overripe plantain pulp	<i>Adansonia digitata</i>	<i>Hibiscus sabdariffa</i>
Moisture*	10.01 $\pm$ 1.01 ^c	9.10 $\pm$ 0.71 ^b	8.01 $\pm$ 1.01 ^a
Protein	3.21 $\pm$ 0.04 ^c	1.74 $\pm$ 0.02 ^a	2.44 $\pm$ 0.05 ^b
Ash	1.30 $\pm$ 0.05 ^a	1.82 $\pm$ 0.02 ^b	2.01 $\pm$ 0.14 ^b
Fiber	5.58 $\pm$ 0.04 ^b	3.24 $\pm$ 0.08 ^a	3.02 $\pm$ 0.19 ^a
Carbohydrates	56.55 $\pm$ 0.02 ^c	35.8 $\pm$ 0.01 ^a	40.80 $\pm$ 0.01 ^b
Fat	0.58 $\pm$ 0.03 ^b	0.48 $\pm$ 0.04 ^a	0.75 $\pm$ 0.01 ^c

*Expressed as percentages on wet weight. Means $\pm$ standard deviations with different superscripted letters within the same row differed significantly ($p < 0.05$) according to Duncan's multiple range test ($n = 3$)

formulations. The fat content in powders was low and ranged from 0.48% for *A. digitata* L. powder to 0.75% (on dry basis) for *H. sabdariffa* L. powder. This low-fat content limits the oxidation of these raw material powders, showing that the proposed valorization of overripe plantain by mixing the three plant powders can be technically feasible.

3.2 Water activity, porosity and functional properties of formulated powders

Water activity (a_w) is one among the factors that determine quality and safety of foods. High value of a_w indicates more free water available for biochemical reactions or to microbial growth and chemical or physical properties, and hence shorter shelf life. In this study, a_w values were not statistically different ($p > 0.05$) and ranged from 0.40 (M10 formulation) to 0.48 (M2 formulation) (Table 3). These values were under the lower limit ($a_w < 0.6$) for the growth of most microorganisms (molds, yeasts and bacteria) [44]. Thus, all the formulated powders can be considered biochemically or microbiologically quite stable.

Bulk and true densities are used to determine the porosity which indicates the powder expansion as well as the volume of packaging material [45]. The values of porosity of the ten powder formulations were significantly ($p < 0.05$) different and ranged from 0.40 (M9 formulation) to 0.65 (M2 formulation). Generally, there is a decrease in the porosity of the powder formulations when the incorporation levels of *A. digitata* L. and *H. sabdariffa* L. increase. The highest porosities were seen for the formulations M1, M2, M6, M7 and M8 which contain less than 5% supplements. This result could be explicated by a tendency to compaction when the finer powders of *A. digitata* L. and

H. sabdariffa L. are incorporated into the plantain powder. In fact, the inter-particle voids decrease by adding the finer powder, this would offer a larger contact surface with the surroundings, leading to a more compact structure and this would result in a decrease in porosity. The same trend was reported by Zhao et al. [46] and Deli et al. [47] respectively on red grape pomace and three tropical plants powders. According to Hu et al. [48], the quality of powder in food industry could be controlled by porosity (which depends on bulk and true densities), and have been fundamentally exploited. Thus, powders with high porosity would have a higher solubility and dispersibility, which would be beneficial to filling in preparing tablets or capsule products [46].

The use of formulated powders in the preparation of food products such as beverages or pastries depends on their interaction with water during the hydration process. The obtained results showed a decrease ($p < 0.05$) in water absorption capacity (WAC) and water solubility index (WSI) when *A. digitata* L. and *H. sabdariffa* L. are incorporated. The WAC values ranged from 267.1% for M1 to 125.2% for M2 while those of WSI ranged from 51.7% for M1 to 28.7% for M6 (Table 3). The observed reduction can be associated to the reduction in the porosity due to incorporation of finer powders. This result could also be explained by a dilution effect on the hydrophilic compounds (proteins, carbohydrates and fibers) of plantain after incorporation of the supplements, which showed lower contents (Table 2). In fact, as reported by Deli et al. [47], powders with high WAC and WSI contained more hydrophilic compounds such as carbohydrates and fibres. Also, protein has both hydrophilic and hydrophobic nature and therefore they can interact with water in foods. Since solubility of powders is

Table 3 Changes in water activity, porosity and functional properties of powder formulations prepared with overripe plantain pulp, *Adansonia digitata* L. fruits and *Hibiscus sabdariffa* L. calyces

*Powder formulations	a_w (-)	Porosity (-)	Functional properties (%)		
			WAC	OAC	WSI
M1 (100-0-0)	0.45 ± 0.01 ^{bc}	0.57 ± 0.03 ^{bc}	267.1 ± 8.01 ^d	63.1 ± 2.81 ^c	51.7 ± 3.31 ^c
M2 (95-5-0)	0.48 ± 0.01 ^c	0.65 ± 0.04 ^c	125.2 ± 8.12 ^a	65.1 ± 3.43 ^c	32.1 ± 3.91 ^b
M3 (95-0-5)	0.41 ± 0.02 ^{ab}	0.52 ± 0.03 ^b	149.1 ± 9.25 ^b	40.5 ± 3.32 ^a	39.9 ± 3.97 ^{ab}
M4 (90-10-0)	0.42 ± 0.02 ^b	0.53 ± 0.03 ^b	173.2 ± 15.1 ^c	47.1 ± 1.56 ^b	39.3 ± 2.95 ^{ab}
M5 (90-0-10)	0.41 ± 0.03 ^{ab}	0.49 ± 0.04 ^{ab}	134.1 ± 8.01 ^a	93.2 ± 7.51 ^e	35.4 ± 2.01 ^{ab}
M6 (90-5-5)	0.40 ± 0.03 ^a	0.51 ± 0.06 ^b	130.1 ± 6.11 ^a	78.1 ± 4.24 ^d	28.7 ± 3.74 ^a
M7 (93.33-3.33-3.34)	0.41 ± 0.02 ^{ab}	0.59 ± 0.01 ^{bc}	147.2 ± 8.21 ^b	73.2 ± 2.12 ^d	39.3 ± 3.18 ^{ab}
M8 (96.66-1.67-1.67)	0.42 ± 0.01 ^b	0.62 ± 0.06 ^c	153.1 ± 4.01 ^b	78.1 ± 2.69 ^d	43.3 ± 2.74 ^b
M9 (91.66-6.67-1.67)	0.41 ± 0.03 ^{ab}	0.40 ± 0.04 ^a	148.2 ± 5.03 ^b	73.5 ± 3.04 ^d	47.8 ± 2.38 ^b
M10 (91.67-1.67-6.66)	0.40 ± 0.01 ^a	0.48 ± 0.07 ^{ab}	134.1 ± 3.18 ^a	65.3 ± 2.13 ^c	38.7 ± 2.79 ^{ab}

*Mx (overripe plantain–*Adansonia digitata*–*Hibiscus sabdariffa*)

a_w : water activity, WAC: water absorption capacity, OAC: oil absorption capacity, WSI: water solubility index

Means ± standard deviations with different superscripted letters within the same column differed significantly ($p < 0.05$) according to Duncan's multiple range test ($n = 3$)

the main parameter that determines their utility in beverages preparation and others, maltodextrins and protein isolates are commonly used as ingredients [49] due to their higher water solubility. This can be considered for low WAC and WSI formulations. Another functional characteristic important for the use of powders is their ability to bind oil. In this study, the oil absorption capacity (OAC) of the formulated powders ranged from 40.5% for M3 to 93.2% for M5 (Table 3). The higher OAC suggests the lipophilic nature of powder constituents [50]. In contrast, a larger proportion of hydrophilic groups or polar amino acids on the surface of protein molecules tend to cause a decrease in OAC of powders in this study. However, powders with high OAC (93.2%, 78.1% and 78.1%, respectively for M5, M6 and M8 formulations) are potentially useful in structural interaction in food especially in flavour retention and improvement of palatability, particularly in the bakery where fat absorption is desired.

3.3 Biochemical composition of formulated powders

The biochemical composition of powder formulations is reported in Table 4. Globally, the results showed a significant difference ($p < 0.05$) between the contents of bioactive compounds of powder formulations. Polyphenols, flavonoids, condensed tannins and vitamin C contents increased as incorporation levels of *A. digitata* L. and *H. sabdariffa* L. powders increase, while total carotenoid increased as per the increase in overripe plantain powder in the powder formulation. The powder formulations

that showed the higher contents of total phenolic compounds (TPC) were M5 (659.66 mg GAE/100 g DM) and M10 (583.46 mg GAE/100 g DM), fifteen times higher than the M1 formulation (40.19 mg GAE/100 g DM), which possessed the lowest level. The phenolic content of the powder formulations studied were higher than those of some plant sources such as dried citrus (166.0 mg/100 g DM) [51]. The high contents of phenolic compounds in M5 and M10 formulations were attributed to their high levels of *H. sabdariffa* L. incorporation (10% and 6.66% respectively) and the granulometry in which it was used. In fact, as indicated by Deli et al. [14], finer powder (size particles 180–212 μm) of *H. sabdariffa* L. calyces has reported to be richer in phenolic compounds and antioxidants.

The total flavonoid content of the powder formulations exhibited similar behaviors. Similar increase ($p < 0.05$) in flavonoid content was found in the formulations with high levels of *A. digitata* L. and *H. sabdariffa* L. The highest content of flavonoids was obtained with the M6 (103.46 mg RE/100 g DM), M5 (90.12 mg RE/100 g DM), M7 (75.80 mg RE/100 g DM) and M10 (66.91 mg RE/100 g DM). The high incorporation of *H. sabdariffa* L. (in M5 and M10 formulations) or the moderate incorporation *A. digitata* L. and *H. sabdariffa* L. (in M6 and M7 formulations), increased the total flavonoid content in the powder formulations by 4–6 times compared to the M1 powder (100% overripe plantain). The formulated powders in this study has been regarded a potential source of flavonoids with higher contents than those reported by Bhat and Riar [52] in pigmented aromatic rice cultivars (24.0 mg RE/100 g DM) and those of Konstantinos et al. [51] in dried citrus (43.0 mg

Table 4 Changes in contents of bioactive compounds (polyphenols, flavonoids, condensed tannins, carotenoids and vitamin C) of powder formulations prepared with overripe plantain pulp, *Adansonia digitata* L. fruit and *Hibiscus sabdariffa* L. calyces

*Powder formulation	Phytochemicals				
	Total polyphenols (mg GAE/100 g DM)	Total flavonoids (mg RE/100 g DM)	Condensed tannins (mg CE/100 g DM)	Total carotenoids (mg/100 g DM)	Vitamin C (mg/100 g DM)
M1 (100-0-0)	40.19 $\pm$ 5.32 ^a	18.27 $\pm$ 0.01 ^a	28.73 $\pm$ 1.52 ^a	9.48 $\pm$ 0.03 ^d	31.55 $\pm$ 2.90 ^a
M2 (95-5-0)	64.77 $\pm$ 1.30 ^b	43.70 $\pm$ 0.01 ^c	51.53 $\pm$ 0.01 ^b	9.36 $\pm$ 0.03 ^{cd}	54.33 $\pm$ 2.68 ^c
M3 (95-0-5)	305.06 $\pm$ 23.42 ^g	36.05 $\pm$ 0.52 ^b	55.40 $\pm$ 0.61 ^b	8.82 $\pm$ 0.08 ^b	48.22 $\pm$ 3.00 ^b
M4 (90-10-0)	138.52 $\pm$ 7.82 ^d	35.80 $\pm$ 1.05 ^b	54.54 $\pm$ 0.61 ^b	9.46 $\pm$ 0.05 ^d	77.30 $\pm$ 2.46 ^f
M5 (90-0-10)	659.66 $\pm$ 28.68 ^j	90.12 $\pm$ 3.14 ^g	276.47 $\pm$ 5.47 ^g	8.96 $\pm$ 0.11 ^b	65.09 $\pm$ 3.10 ^d
M6 (90-5-5)	369.59 $\pm$ 10.43 ^h	103.46 $\pm$ 3.14 ^h	133.25 $\pm$ 2.43 ^e	8.74 $\pm$ 0.07 ^{ab}	71.20 $\pm$ 2.78 ^e
M7 (93.33-3.33-3.34)	207.96 $\pm$ 3.91 ^f	75.80 $\pm$ 1.05 ^f	117.33 $\pm$ 0.61 ^d	8.77 $\pm$ 0.09 ^{ab}	57.91 $\pm$ 2.82 ^c
M8 (96.66-1.67-1.67)	103.49 $\pm$ 13.04 ^c	32.35 $\pm$ 7.33 ^b	75.61 $\pm$ 1.22 ^c	8.41 $\pm$ 0.56 ^a	44.64 $\pm$ 2.86 ^b
M9 (91.66-6.67-1.67)	181.54 $\pm$ 1.30 ^e	59.51 $\pm$ 4.71 ^d	110.02 $\pm$ 6.08 ^d	8.99 $\pm$ 0.27 ^{bc}	67.62 $\pm$ 2.64 ^{de}
M10 (91.67-1.67-6.66)	583.46 $\pm$ 0.01 ⁱ	66.91 $\pm$ 2.10 ^e	168.95 $\pm$ 11.56 ^f	8.94 $\pm$ 0.35 ^b	61.49 $\pm$ 2.96 ^d

*Mx (overripe plantain–*Adansonia digitata*–*Hibiscus sabdariffa*)

GAE: gallic acid equivalent, RE: rutin equivalent, CE: catechin equivalent

Means $\pm$ standard deviations with different superscripted letters within the same column differed significantly ($p < 0.05$) according to Duncan's multiple range test ($n = 3$)

RE/100 g DM). Flavonoids have been suggested to protect the lipids against oxidative damage by various mechanisms [53]. The condensed tannin content of the powder formulations ranged between 28.73 and 276.47 mg/100 g DM. Likely, the total polyphenols and total flavonoids, increased substitution with plant powders significantly increases ($p < 0.05$) the condensed tannins content of the powder formulations. The highest content of condensed tannins was recorded in M5 (276.47 mg CE/100 g DM) followed by M10 (168.95 mg CE/100 g DM), M6 (133.25 mg CE/100 g DM) and M7 (117.33 mg CE/100 g DM). Generally, *H. sabdariffa* L. powder may be considered a good ingredient to boost phenolic compounds contents in overripe plantain powder. However, the combination of the two plants: *A. digitata* L. and *H. sabdariffa* L. seems to have a synergistic effect.

Regarding the vitamins, some powder formulations were higher in the carotenoid (provitamin A) content with the fractions M1, M4, M2 and M9 having the highest contents with respective values of 9.48 mg/100 g DM, 9.46 mg/100 g DM, 9.36 mg/100 g DM and 8.99 mg/100 g DM (Table 4). Unlike phenolic compounds, the total carotenoid content decreased with increasing levels of *A. digitata* L. and *H. sabdariffa* L. incorporation. This suggests that the overripe plantain was richer in total carotenoid than the two plants. Although, the difference in carotenoid content was not great enough from one powder formulation to another. We observed that the vitamin C content was higher for the M4 (77.30 mg/100 g DM) and M6 (71.20 mg/100 g DM) formulations, which have 10% and 5% *A. digitata* L., respectively plus 5% *H. sabdariffa* L. This suggests that *A. digitata* L. had a huge effect on enhancing the vitamin C content in powder formulations, a three-fold increase. However, the fact remains that the incorporation of the two plants, in varying proportions, also helped to double the vitamin C content (M5: 65.09 mg/100 g DM; M9: 67.62 mg/100 g DM; M10: 61.49 mg/100 g DM), compared to the M1 formulation (31.55 mg/100 g DM). The same trend was observed by Adegunwa et al. [39] who reported that increased substitution of tiger nut in the plantain flour increased vitamin C content in the flour blends. The increase in the total phenolic compounds, flavonoids, carotenoids, condensed tannins and vitamin C, with moderate incorporation ($< 10\%$) of *A. digitata* L. and *H. sabdariffa* L. powders may also have a consequence on the antioxidant capacities of powders from overripe plantain pulp.

3.4 Antioxidant activity of formulated powders

3.4.1 Free-radical scavenging activities

Fruits and vegetables have been shown to possess antioxidant activities in different in vitro models, ability to scavenge free-radicals and to protect against cardiovascular disease. These properties were attributed to specific sulfur-containing compounds and flavonoids [54, 55]. One of the antioxidant mechanisms is to provide hydrogen atoms to free-radicals and to stop the chain reaction. The DPPH method has been extensively used to measure the free radical scavenging ability of various antioxidant substances. In Fig. 1a is reported the antioxidant activity of the powder formulations assessed by DPPH test. The results revealed that, increased incorporation of *A. digitata* L. and *H. sabdariffa* L. powders significantly ($p < 0.05$) increased the DPPH radical scavenging activity of powder formulations. IC_{50} DPPH values for various samples ranges from 0.80 mg/mL to 17.11 mg/mL. The high antioxidant activity that corresponds to the smallest IC_{50} was recorded by the M10 (0.80 mg/mL), M7 (1.38 mg/mL), M6 (1.71 mg/mL) and M5 (2.58 mg/mL) formulations. Especially, M10 formulation has improved sixteen times the IC_{50} DPPH radical scavenging activity of 100% overripe plantain powder (M1 formulation). The highest activity in M10, M7, M6 and M5 formulations was due to the high total polyphenols, flavonoids, and tannins in these formulations as we can see in Table 4. Indeed, it is possible because of their structure rich in hydroxyl groups which is capable to fix and neutralize free radicals by giving up their protons or their electrons [14, 45]. This high activity may be also due to the synergistic effect of phenolic compounds and vitamins contained in these powders as reported by Allane and Benamara [56].

ABTS radical scavenging assay can also be applied to test food and natural water-soluble bioactive compounds. This is why in this study the free radical scavenging activity of powder formulations was also assessed by ABTS method (Fig. 1b). Generally, results were consistent with those of the DPPH method. Increased substitution of overripe plantain powder with *A. digitata* L. and *H. sabdariffa* L. powders significantly ($p < 0.05$) increases the ABTS radical scavenging activity of the powder formulations. In this respect, the powder samples exhibited IC_{50} ABTS values of 1.54–18.36 mg/mL. Similar to DPPH activity, the best ABTS antioxidant activity was obtained for the M10 (IC_{50} 1.54 mg/mL), M7 (IC_{50} 2.29 mg/mL), M6 (IC_{50} 2.46 mg/mL) and M5 (IC_{50} 2.69 mg/mL) formulations. This trend was confirmed by Pearson's correlation coefficients: 0.82 for IC_{50} values, indicating positive correlations of strong intensity between the two methods. Generally, the results indicated that the powders made by adding a greater amount of *H. sabdariffa* L. (M5 and M10) or equal amounts of *A. digitata*

Fig. 1 DPPH radical (a) and ABTS radical (b) scavenging activities (IC_{50} in mg/mL) of powder formulations prepared with overripe plantain pulp, *Adansonia digitata* L. fruit and *Hibiscus sabdariffa* L. calyces. Powder formulations (overripe plantain–*Adansonia digitata*–*Hibiscus sabdariffa*): M1 (100-0-0); M2 (95-5-0); M3 (95-0-5); M4 (90-10-0); M5 (90-0-10); M6 (90-5-5); M7 (93.33-3.33-3.34); M8 (96.66-1.67-1.67); M9 (91.66-6.67-1.67); M10 (91.67-1.67-6.66). Bars topped by different superscripted letters differed significantly ($p < 0.05$) according to Duncan's multiple range test ($n = 3$)

L. and *H. sabdariffa* L. (M6 and M7), possess a powerful free radical (DPPH and ABTS) scavenging activities compared to other powder formulations, although less than vitamin C activity (IC_{50} 0.04 mg/mL). The M10 formulation being particularly the most interesting.

3.4.2 Total reducing activity

Reducing power has been used as one of the antioxidant capability indicators of powder fractions of *Moringa oleifera* leaves by Verma et al. [57]. Also, Djiogue et al.

Fig. 2 Reducing power (mg AAE/g DM) of powder formulations prepared with overripe plantain pulp, *Adansonia digitata* L. fruit and *Hibiscus sabdariffa* L. calyces. Powder formulations (overripe plantain–*Adansonia digitata*–*Hibiscus sabdariffa*): M1 (100-0-0); M2 (95-5-0); M3 (95-0-5); M4 (90-10-0); M5 (90-0-10); M6 (90-5-5); M7 (93.33-3.33-3.34); M8 (96.66-1.67-1.67); M9 (91.66-6.67-1.67); M10 (91.67-1.67-6.66). Bars topped by different superscripted letters differed significantly ($p < 0.05$) according to Duncan's multiple range test ($n = 3$)

[58] have shown that the antioxidation effect exponentially increased as a function of the development of the reducing power of onion powder. In Fig. 2 is presented the reducing power of the powder formulations based on overripe plantain, *A. digitata* L. fruits and *H. sabdariffa* L. calyces. The reducing power of the powder samples varied significantly ($p < 0.05$), with values ranging from 2.66 to 9.58 mg AAE/100 g DM. Likewise with DPPH and ABTS radical scavenging activities, increased substitution of overripe plantain with *A. digitata* L. and *H. sabdariffa* L. increased the reducing power activity of the powder formulations. The best reducing power activities were obtained with the M5 (9.58 mg AAE/100 g DM), M6 (8.60 AAE/100 g DM), M10 (7.05 mg AAE/100 g DM) and M7 (6.55 mg AAE/100 g DM) formulations, respectively. As mentioned above (Table 4), total phenolic compounds and vitamin C content analysis showed that M10, M6, M7 and M5 formulations had higher contents of these active molecules. Phenolic compounds such as flavonoids and tannins are shown to be the main secondary metabolites found in plants and are potential antioxidants [51, 52]. Thus, reducing power recorded in these powder formulations may be associated with their higher secondary metabolite contents and higher vitamin C content. It has been well established that these bioactive molecules inhibit lipid peroxidation in biological and food systems [57]. Inhibition could be caused by absence of fer-ryl–perferryl complex or by scavenging the free radicals or by changing the $\text{Fe}^{3+}/\text{Fe}^{2+}$ or by reducing the rate of conversion of ferrous to ferric or by chelating the iron itself

[59]. In this study, the additive effect (high amount of *H. sabdariffa* L. in M5 and M10) and synergistic effect (equal amount of *A. digitata* L. and *H. sabdariffa* L. in M6 and M7) in powder formulations would be linked to high contents of phenolic compounds and vitamins of *H. sabdariffa* L. and *A. digitata* L., respectively.

3.5 Principal components analysis

Principal components analysis (PCA) was conducted to analyze the correlation between bioactive compounds, antioxidant activities and physicochemical properties of powder formulations from overripe plantain and plants. It may be seen from Fig. 3 that the two axis F1 and F2, based on the correlation with the variables, explained 72.98% variation among the powder properties. F1 was responsible for 61.74% while F2 explained only 11.24% of variation. It is observed that the total phenolic compounds and vitamin C are highly positively correlated with the radical scavenging activities ($r = 0.64$ for DPPH; $r = 0.78$ for ABTS), while a medium correlation was observed with reducing power ($r = 0.55$). Total flavonoids, condensed tannins and carotenoids explained a medium correlation ($r = 0.56$) with radical scavenging activities and was mostly correlated with reducing power ($r = 0.94$ for flavonoids; $r = 0.93$ for tannins). Also, it can be seen from the Fig. 3 that the bioactive compounds in the powder formulations were in the opposite of WAC and WSI, reflecting a perfect negative correlation. The structure and lipophilicity of

Fig. 3 Principal Components Analysis of antioxidant activities and physicochemical properties of powder formulations prepared with overripe plantain pulp, *Adansonia digitata* L. fruit and *Hibiscus sabdariffa* L. calyces. a_w : Water activity; WSI: Water solubility index; WAC: Water absorption capacity; OAC: Oil absorption capacity; CT: Condensed tannins; TF: Total flavonoid; TPC: Total phenolics content; RP: Reducing power; Vit C: Vitamin C. Powder formulations

(overripe plantain–*Adansonia digitata*–*Hibiscus sabdariffa*): M1 (100-0-0); M2 (95-5-0); M3 (95-0-5); M4 (90-10-0); M5 (90-0-10); M6 (90-5-5); M7 (93.33-3.33-3.34); M8 (96.66-1.67-1.67); M9 (91.66-6.67-1.67); M10 (91.67-1.67-6.66). Bars topped by different superscripted letters differed significantly ($p < 0.05$) according to Duncan's multiple range test ($n = 3$)

phenolic compounds have been shown to be important factors from which their low water-solubility derives [60]. Since the lipophilicity affect the depth of the incorporation of these compounds into the lipid phase of the cell membranes, it has been shown to be important for their antioxidant activity [60, 61]. This justifies that the powder formulations richest in phenolics are classified among the powder samples having the highest DPPH and ABTS radical scavenging activities and reducing power. In this respect, it appears that M5, M6, M7 and M10 formulations are very close each other and opposite to M1 powder used here as negative standard of high-antioxydant powder formulation. These powders exhibited characteristics in between high antioxidant capacity and high level of phenolic compounds and vitamins. They were also in the opposite of the M2, M3, M4, M8 and M9 formulations (r ranged -0.67 to -0.83) which exhibited the low level of bioactive compounds and low antioxidant activities, but the high hydration properties. The M5, M6 and M7 formulations which were revealed as richer in active compounds failed in enhancing the antioxidant activity as compared to the M10 formulation, which has proven to be the best.

4 Conclusion

High-antioxidant powder can be produced from overripe plantain by adding in moderate quantity fine powder fractions of *A. digitata* L. fruits and *H. sabdariffa* L. calyces. However, the water absorption capacity and the solubility have decreased in the formulated powders, due to their low porosity and the dilution effect on the hydrophilic nutrients. The incorporation of *A. digitata* L. fruit and *H. sabdariffa* L. calyces had successfully to improve the total phenolic compounds, total flavonoids, condensed tannins, total carotenoids and vitamin C contents of powder formulations. Nevertheless, the powder formulations differ, depending on whether they contain a higher proportion of *A. digitata* L. or *H. sabdariffa* L. On the other hand, the incorporation of plant powders in equal proportion gives high activities due to the synergistic effect between these compounds. Strong correlation has been observed between phenolic compounds and the antioxidant activity in powder formulations. M10 formulation consists of 91.67% of overripe plantain, 1.67% of *A. digitata* L. fruit and 6.66% of *H. sabdariffa* L. calyces

was the powder which exhibited the best antioxidant activities. The incorporation of fine powder fractions of *A. digitata* L. fruit and *H. sabdariffa* L. calyces is helpful for improving the antioxidant properties in low-value plantain. This approach makes it possible to valorise the overripe plantain, with a potential to contribute to the management of oxidative stress and certain pathologies.

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Compliance with ethical standards

Conflict of interest All authors declare no conflict of interest.

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