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Variation in biochemical composition of baobab (*Adansonia digitata*) pulp, leaves and seeds in relation to soil types and tree provenances

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ABSTRACT

The present study was conducted in Benin to understand the effects of provenance, genetic variation and the effects of soil physicochemical characteristics on nutrient concentration of baobab pulp, leaves and seeds. Baobab parts were sampled from genetically different populations and soils in different climatic zones of Benin. Biochemical composition of baobab pulp, leaves and seeds was matched to different provenance and physicochemical characteristics of the soil. Results showed that the physicochemical characteristics of the soil seem to influence the nutritive value of baobab parts. Specifically, highly basic soils, rich in carbon, clay, fine silt and organic matter seem to positively relate with the concentration of iron, potassium, vitamin C, carbohydrates, zinc, proteins and lipids. However, for those same soils, the observed relationship between the soils and baobab parts concentration in magnesium, calcium, vitamin A and fibers was negative. Soils rich in gross silt and sand were found to have an opposite effect on these same parameters.

1. Introduction

Adansonia digitata (baobab) is a multipurpose tree whose leaves, seeds and pulp are consumed mostly by rural population in Africa (Assogbadjo et al., 2008). The leaves are commonly eaten fresh (leaf vegetable) or in the form of dried powder (for seasoning) in the savanna areas of West Africa, Kenya, Tanzania, Malawi and Zimbabwe. The dried pulp is commonly used to prepare fruit juice or mixed with porridge or gruels in parts of East Africa to benefit from generally higher levels of vitamin C than oranges and calcium than cow's milk. The nutrient-rich parts of Baobab plant have recently attracted the interest of the consumer products industry which seeks to use its materials. The species grows naturally in dry areas of Africa mainly in Sahelian, Sudano-Sahelian and Sudanian zones (Wickens, 1982; Sidibe and Williams, 2002). It grows not only on lateritic and stony soils but also on clayey, sandy and silty soils (Sidibe and Williams, 2002; Assogbadjo et al., 2005). Studies on the genetic diversity of natural baobab populations in Benin revealed genetic differentiations between populations originating from different climatic zones (Assogbadjo et al., 2006; Kyndt et al., 2009). The results of previous studies pointed to a certain level of physical isolation between baobab populations from the three climatic zones of Benin, presuming a genetic structuring between them (Assogbadjo et al., 2006; Kyndt et al., 2009). As a consequence, we hypothesized that variation in baobab part chemical component may depend on the intra specific genetic variation related to the species. Numerous studies have been conducted on the nutritional concentration of baobab parts (Yazzie et al., 1994; Nordeide et al., 1996; Sidibe et al., 1996; Delisle et al., 1997; Barminas et al., 1998; Sena et al., 1998; Codjia et al., 2001; Sidibe and Williams, 2002; Chadare et al., 2008). Chadare et al. (2009) have also reviewed various biochemical analyses which revealed that baobab parts (pulp, leaves, seeds) are rich in several nutrients. Micronutrients (iron, vitamins C, A, E and F) in baobab are high when compared to the daily recommended dose for human (Codjia et al., 2001; Sidibe and Williams, 2002; Chadare et al., 2009). However, there is a huge variation in the reported values for a given chemical element in the species. Chadare et al. (2009) posited that this variation might be due to several parameters including the composition of the soils and the provenance of the samples. However, no study has scientifically investigated the probable causes of variation. The goal

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of the research reported in this paper is to contribute to filling this gap in knowledge on baobab. The specific aims of the study are to: (i) assess the nutritive characteristics of different organs of baobab (pulps, leaves, seeds) from different provenances; (ii) assess how these nutritional variables can be associated with their provenances and (iii) match soil properties with the nutritional quality of the different organs of baobab.

2. Materials and methods

2.1. Study areas and baobab parts sampling for biochemical analyses

The baobab grows on varied types of soil and agroecological zones. In Benin, Baobab trees occur on soils to sandy texture in the Sudanian and Guinean zone, and on sandy – clayey soils in the Sudano – Guinean zone. In the Guineo-Congolian zone, the baobabs grow on basic soils while in the Sudanian zone, they are found on soils with acidic to neutral pH (Assogbadjo et al., 2005).

Based on the finding of genetic differentiation between the populations from different climatic zones (Assogbadjo et al., 2006), sampling was done randomly regardless of their age, size and stand density to select three individuals of baobab in each climatic zone of Benin: the Sudanian zone, located between 9°45′ and 12°25′N; the Sudano-Guinean zone, located between 7°30′ and 9°45′N; and the sub-humid Guineo-Congolian zone, located between 6°25′ and 7°30′N. To capture variability in soil, at least 1 km has been considered between two sample trees in a climatic zone. In the Sudanian zone, the rainfall is unimodal and is often less than 1000 mm per year. The relative humidity varies from 18% to 99% whereas the temperature varies from 24 °C to 31 °C. Following French classification of 1999, Sudanian zone has hydromorphic soils, well-drained soils, and lithosols. The vegetation of this zone is mainly composed of savannas with trees of smaller size. The rainfall is also unimodal in the Sudano-Guinean zone and the mean annual rainfall varies between 900 mm and 1110 mm. The relative humidity ranges from 31% to 98% and the annual temperature from 25 °C to 29 °C. The soils in this zone are ferruginous with variable fertility. The vegetation of the Sudano-Guinean transition zone is characterized by a mosaic of woodland, dry dense forests, tree and shrub savannas and gallery forests. In the Guineo-Congolian zone, the rainfall is bimodal with a mean annual rainfall of 1200 mm. The relative humidity varies between 69% and 97% and the mean annual temperature varies between 25 °C and 29 °C. The soils are either deep ferrallitic or rich in clay, humus and minerals. The primal vegetation consists of dense semi-deciduous forests and Guinean savannas.

Leaves (dried with silica gel after harvest), seeds and pulp were collected on each sampled tree for biochemical analyses regardless of level in the canopy and the light condition. Soil samples were collected around the selected baobab trees at a mean depth of 40 cm in order to establish relationships between the nutritive concentration of plant organs and the physico-chemical composition of the soils.

2.2. Biochemical characterization of baobab pulp, leaves and seeds

For each plant organ collected from the selected baobab individuals, the concentration in terms of selected minerals (Fe, Zn, Ca, K, Mg), vitamins (vitamin A and C) and macronutrients (dry matter, proteins, lipids, carbohydrates, crude fiber) were assessed. The macronutrient composition was measured using the methods of AOAC (A.O.A.C., 1984). Dry matter was measured by drying samples at 105 °C until constant weight. Nitrogen concentration was analyzed by the Kjeldahl method and protein concentration estimated using 6.25 as conversion factor. Lipids concentration was measured by the Weibull method using Soxhlet extractor. Crude fiber was measured by filtration. Carbohydrates concentration was calculated using the following difference method: % Carbohydrates = 100 − (% protein + % fat + % ash + % moisture).

Atomic absorption was used to determine the calcium, magnesium, potassium, sodium, iron and zinc concentration. Vitamin C concentration was determined using the method of dichloricindofenol.

Vitamin A concentration was measured by alkaline saponification in the presence of hydroquinone and extraction was done with diethyl ether-petroleum ether (1 + 1, v/v). Separation method involved reversed-phase liquid chromatography, with a mobile phase of methanol–water (92 + 8, v/v) and detection at 330 nm. The various analyses were conducted in triplicates and the mean values were recorded.

2.3. Physico-chemical characterization of soils

Soil samples were analyzed for the following parameters: particle size (%clay, %sand, %silt); nitrogen concentration; and the carbon/nitrogen (C/N) ratio. For the letter, total N concentration and soil organic C were analyzed and from these C/N ratio calculated. The C/N ratio informs on the degree of evolution of the organic matter and the biological activity (FAO, 2005). When C/N ratio is less than 10, the organic matter is not molded; for 10 < C/N < 15, the organic matter is well decomposed; for 15 < C/N < 25, the organic matter is weakly decomposed and not decomposed for C/N > 25. The particle size analysis was conducted using the international method for organic matter digestion in soil with oxygenated water (H_2O_2). The pH was measured using a pH meter in a ratio soil/water of 1/2.5. The nitrogen concentration was measured using the Kjedahl method. The organic carbon of the soil was measured using the calorimetric method which consists in oxidation of the organic matter using 1 N potassium dichromate in the presence of hot concentrated sulfuric acid; the determination of the remaining dichromate after oxidation of the organic matter is read in a colorimeter. The obtained value is used in a regression equation to determine the organic carbon.

2.4. Statistical analysis

To investigate the relationships between the climatic zones, the biochemical composition of the baobab organs and the physico-chemical composition of the soil, a 3-way analysis of variance (ANOVA) was conducted, using the partial nested model. In the model, “zones” and “baobab parts” were considered as fixed with three levels each (Sudanian, Sudano-Guinean, Guineo-Congolian for the zones; leaves, pulp, seeds for baobab parts). The baobab trees were considered as the nested factor (within the zones). The nutritive concentration of baobab parts, for trees from different zones (inter zone) and for trees from the same zone (intra zone), were compared. Principal Component Analysis (PCA) was conducted on the least square means of the biochemical concentration of the baobab parts to describe the relationship between them and to link them to the type of baobab parts in a specified climatic zone. Pearson correlation was then computed between the principal components defined by the biochemical concentration of the baobab organs and the physico-chemical composition of the soil.

3. Results and discussion

3.1. Biochemical composition of baobab pulp, leaves and seeds according to their provenance

Table 1 shows a summary of the nutritive concentration of leaves, pulp and seeds according to their provenance.

3.1.1. Macronutrients and dry matter concentration of baobab parts

The macronutrients and dry matter concentration of baobab parts are compared according to the different climatic zones (see Table 1). For proteins and lipids, there is no statistical significant difference between the Sudanian, the Sudano-Guinean zone and the Guineo-Congolian zone for the leaves, pulp and seeds concentration of baobab trees. The same conclusion can be drawn for the carbohydrates and fibers concentration of the baobab parts (Table 1). Therefore proteins and lipids concentration as well as the carbohydrates and fibers concentration of the baobab parts do not vary between the three climatic zones (Sudanian, Sudano-Guinean, and Guineo-Congolian zones). Among the three baobab parts investigated, the seeds had the highest levels of proteins and lipids but the lowest levels of carbohydrates and fibers. Indeed, the seeds contained eleven times and two times more proteins respectively than the pulp and leaves. For carbohydrates concentration, seeds are approximately three times lower than pulp and leaves.

As far as the dry matter is concerned, no statistical significant difference was noted between the three climatic zones, whatever the baobab part considered.

Studies conducted on baobab organs showed that crude protein, crude lipids and carbohydrates concentration ranged from 2.5 to 17 g 100 g^{-1} dw, 0.2 to 15.5 g 100 g^{-1} dw, 46.6 to 87.7 g 100 g^{-1} dm, respectively for baobab pulp (Wehmeyer, 1966; Saka and Msonthi, 1994; Lockett et al., 2000; Murray et al., 2001; Osman, 2004); 10.1 to 15 mg 100 g^{-1} dw, 4.0 to 6.3 g 100 g^{-1} dw, 40.2 to 69.0 g 100 g^{-1} dw respectively for baobab leaves (Becker, 1983; Yazzie et al., 1994; Nordeide et al., 1996; Lockett et al., 2000) and from 14.4 to 36.7 g 100 g^{-1} dw, 11.6 to 33.3 g 100 g^{-1} dw, 5.2 to 56.8 g 100 g^{-1} dw respectively for baobab seeds (Arnold et al., 1985; Glew et al., 1997; Proll et al., 1998). Most of the reported findings are similar to data generated from the analyses of baobab samples from Benin. Specifically, fiber and ash concentration of seeds and pulp from our study were found to be similar to the ones reported by Sidibe and Williams (2002) in Mali. However, notable exceptions documented in our study are as follows: crude protein concentration of leaves from Benin is slightly higher than the maximum reported value; and the lipid concentration is twice lower than the minimum reported value. The high value of carbohydrate concentration of the pulp and the leaves from Benin, compared to reported values in the literature, was also noted.

3.1.2. Micronutrients concentration of baobab parts

Baobab pulp, leaves and seeds contain minerals such as calcium, magnesium, potassium, zinc, iron, vitamin C and Vitamin A in variable proportions (Table 1). From the results of the analysis of variance performed (Table 1), it can be noted that whatever the baobab part, there is no statistical significant difference between the climatic zones for micronutrients concentration such as calcium (Ca), magnesium (Mg), potassium (K), and vitamin A. But a statistical significant difference was noted between the climatic zones for iron (Fe), zinc (Zn) and Vitamin C concentration. Whereas the significant difference of the iron concentration was noted only for leaves and, only for pulp for zinc concentration, it included all the three baobab parts for the vitamin C. Thus, the iron concentration of the leaves, the zinc concentration of pulp and all the three baobab parts concentration of vitamin C vary between the climatic zones while

Table 1
Means (m) and standard deviation (s) of biochemical parameters of baobab parts, according to the different climatic zones.

Organs	Provenance		Micronutrients							Macronutrients				DM (%)
			Fe (µg g^{-1})	Ca (µg g^{-1})	Mg (µg g^{-1})	K (mg g^{-1})	Zn (µg g^{-1})	Vit C (mg g^{-1})	Vit A (ng g^{-1})	Proteins (%)	Lipids (%)	Carbohydrates (%)	Fibers (%)	
Leaves	SZ	m	139b	1040a	3235a	16.8a	11.9a	4.87c	56.78a	14.10b	1.70b	75.10b	13.30a	84.30b
		s	10.0	400.0	200.0	2.6	0.5	0.12	0.04	0.03	0.01	0.01	0.06	0.03
	SGZ	m	139 b	1125a	3275a	17.8a	15.9a	55.79a	55.79a	14.10b	1.69b	75.24b	13.27a	82.80b
		s	10.0	100.0	0.00	5.7	6.2	0.03	0.05	0.03	0.01	0.15	0.06	0.74
	GCZ	m	177a	910a	3120a	22.7a	15.2a	55.79a	55.79a	14.10b	1.70b	75.55b	13.23a	84.30b
		s	40.0	300.0	200.0	0.1	0.0	0.05	0.02	0.03	0.03	0.69	0.01	0.03
Pulp	SZ	m	187a	725b	2060b	24.5a	9.3a	2.23c	29.20c	3.21c	0.40c	88.60a	11.10b	91.94a
		s	2.0	0.00	100.0	9.7	0.0	0.01	0.14	0.10	0.01	0.01	0.01	0.01
	SGZ	m	187a	690b	2470b	24.8a	15.0	29.15b	29.16c	3.21c	0.42c	88.80a	11.07b	90.94a
		s	2.0	100.0	100.0	3.4	3.0	0.07	0.06	0.10	0.02	0.23	0.01	0.01
	GCZ	m	187a	600b	1940b	22.4a	10.8b	29.15b	29.10c	3.21c	0.43c	89.15a	11.02b	90.94a
		s	0.0	100.0	600.0	2.2	0.0	0.07	0.14	0.10	0.03	0.69	0.01	1.40
Seeds	SZ	m	110b	255c	3260a	13.7b	31.7c	3.45c	30.70b	33.80a	28.32a	29.60c	8.70c	91.26a
		s	20.0	100.0	100.0	0.7	2.6	0.01	0.06	0.10	0.03	0.01	0.03	0.04
	SGZ	m	139 b	365c	3270a	13.8b	33.5c	30.72b	30.76b	33.89a	28.30a	29.10c	8.74c	91.26a
		s	10.0	0.00	0.00	2.1	2.1	0.01	0.06	0.06	0.03	0.70	0.03	0.04
	GCZ	m	139b	305c	3245a	14.3b	31.7c	30.60b	30.71b	33.87a	27.78a	29.60c	8.59c	90.76a
		s	10.0	0.00	0.00	2.5	0.5	0.14	0.01	0.08	0.65	0.01	0.20	0.67

SZ: Sudanian zone; SGZ: Sudano-Guinean zone; GCZ: Guineo-Congolian zone; Vit: Vitamin; DM: Dry Matter.
For the same organ, data with the same letter are not significantly different for the variables considered
m: mean; s: standard deviation.

Table 2
Results of analysis of variance, partial nested model on the biochemical parameters of the baobab organs: *F* values and significance.

Source	Zone	Trees (zone)	Baobab parts	Zone × Baobab parts	Trees × Baobab parts
DF	2	2	2	4	2
Fe	1.8	1.4	82.3*	6.3	0.2
Ca	108.6**	0.01	11.3	0.1	4.9
Mg	0.6	2.3	58.0*	0.4	1.2
K	0.3	1.7	2.9	0.2	5.2
Zn	11.9	0.2	93.4*	0.4	1.0
Vitamin C	341,970***	4	49,420***	9675***	8.0*
Vitamin A	0.8	4.8	55243.3***	0.1	5.6
Proteins	0.2	1	114,644***	0.1	7
Lipids	1.1	0.9	40119.2***	1.8	0.7
Carbohydrates	0.7	6.2	28112.6	0.4	3.2
Fibers	11.8	0.2	4686.7***	0.4	1.4
Dry matter	1.5	5.2	271.9**	1.6	2.9

DF: degree of freedom.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

the calcium, magnesium, potassium, and vitamin A concentration of three baobab parts do not vary between climatic zones.

Among the three baobab parts investigated, the pulp had the highest levels of iron. The seeds contained three times more zinc than the pulp but had a lower concentration of calcium compared to pulp and leaves. The leaves had the highest levels of vitamin A and vitamin C. Even if in general, for a given baobab organ, micronutrients concentration did not vary very much between zones, some specificities were however noted. For instance, whatever the baobab part considered, the lowest value of vitamin C was obtained in Sudanian zone.

In the literature, the micronutrients composition of baobab pulp and the reported values vary greatly from one author to another, whatever the baobab parts considered (Chadare et al., 2009). Reported Ca concentration of baobab pulp ranged from 3.0 mg 100 g^{-1} dw (Obizoba and Anyika, 1994) to 701 mg 100 g^{-1} dw (Nour et al., 1980). Reported Fe concentration in baobab leaves vary from 1.1 mg 100 g^{-1} dw (Smith et al., 1996) to 254 mg 100 g^{-1} dw (Yazzie et al., 1994). Calcium, magnesium, and zinc (9.3–33.5 $\mu g\, g^{-1}$) concentration of baobab part are reported in the literature to be similar to the one of parts of spontaneous plants reported by Glew et al. (1997) and Cook et al. (1998). In general, the results obtained in our study were within the range of reported values for most of the micronutrients. However, discrepancies were noted. For example, the iron concentration of baobab pulp and seeds from our study in Benin was found to be two times higher than the maximum reported value. The calcium concentration of the leaves was found to be 2–3 times lower than the minimum reported value (Chadare et al., 2009). Vitamin C concentration of baobab pulp is reported in the literature to vary from 209 to 360 mg 100 g^{-1} (Chadare et al., 2009), similar to what we found for pulp from the Sudanian zone in Benin. For the two other climatic zones, the vitamin C concentration was 10–15 times higher. However, until very recently, there were no reports on the vitamin C concentration of baobab leaves. Our study found that baobab leaves contain more vitamin C than baobab pulp from the same climatic zone. These findings require further investigations.

Simulations showed that consumption of 100 g of pulp from Guineo-Congolian and Sudano-Guinean zones may cover up to 34 times the Recommended Daily Intake (RDI) for pregnant women (19–30 y) and more than 100 times the RDI for children (4–8 y). In the other hand consumption of 100 g of leaves may cover less than 1/10 of the RDI for pregnant women (19–30 y) and children (4–8 y) (Chadare et al., 2009). It is important to note that such calculations are usually done considering the digestibility and bioavailability of the nutrients. The above mentioned data should be considered as maximum and are in reality probably lower. Food combination is necessary to cover RDI for all nutrients.

3.1.3. Link between provenance and nutritive value of baobab parts

The results from our research revealed that the vitamin C and Calcium concentrations vary significantly from one agro-climatic zone to another, in each of the baobab organs studied. The leaves, the pulp and the seeds from the Sudanian zone contained less vitamin C than the ones from the Sudano-Guinean and the Guineo-Congolian zones.

Results from the analysis of variance revealed relatively little variation in biochemical concentration of baobab organs among baobab individuals from the same agro-climatic zone. No statistical significant difference ($p > 0.05$) was noticed for the biochemical parameters of the baobab organs considered in the study (Table 2). This suggests that phenotypic and genetic variations between trees do not affect the biochemical properties of the baobab parts. Moreover, among the biochemical properties of baobab parts, only the calcium (Ca) and the vitamin C showed significant difference due to the provenance/agro-climatic zones. As expected, there was a significant difference between the leaves, seeds and pulp of baobab in terms of their nutritive concentration, regardless to the climatic zones. However, for Ca^{2+}, K^+ and carbohydrates no statistically significant differences were observed. Interactions between the agro-climatic zones and baobab organs were not significant for almost all the parameters analyzed except for Vitamin C. Other nutritive concentration of baobab organs do not vary significantly ($p > 0.05$), across agro-climatic zones. The proteins, lipids, carbohydrates, fibers, vitamin A, iron, zinc, calcium, potassium concentration of the pulp, the leaves and the seeds could therefore be linked neither to the agro-climatic zone of provenance nor to the genetic provenance of the trees.

3.2. Soils physico-chemical properties

Results from the physico-chemical analysis of the soils are summarized in Table 3. They revealed that parameters such as pH water, soils concentration in carbon (C), fine silt (Lf), gross silt (Lg), organic matter (OM) and the C/N ratio, were significantly different across agro-climatic zones. Soils sampled from the Sudano-Guinean (zone 2) and the Guineo-Congolian zones (zone 3) had high values for C/N ratio (C/N > 25) and the fine silt concentration. This high value for C/N ratio indicates that the organic matter is not well decomposed. Soils from the Guineo-Congolian zone exhibited the highest values of pH and carbon concentration, followed

Table 3
Physico-chemical parameters [means (m) and standard deviation (s)] of the soils on which trees were established.

	Sudanian zone (zone 1)		Sudano-guinean zone (zone 2)		Guineo-Congolian zone (zone 3)	
	m	s	m	s	m	s
pH water	6.59c	0.16	6.88b	0.01	7.50a	0.08
C (%)	1.87c	0.07	2.41b	0	2.91a	0.09
N (%)	0.07a	0	0.07a	0	0.07a	0.03
C/N	26.64b	1.02	34.43a	0	36.08a	4.67
Clay (%)	11.34a	0.36	11.87a	0.84	12.43a	0.88
Fine silt (%)	3.38b	0.67	9.73a	0.24	12.53a	2.81
Gross silt (%)	13.70a	0.11	5.27b	0.32	5.64b	3.48
Sand (%)	71.59a	0.42	72.07a	0.18	69.51a	7.26
Organic matter (%)	3.11b	0.22	4.15b	0	69.51a	7.26

On each row, values with the same letter are not significantly different.

by soils from the Sudano-Guinean and the Sudanian zones. Soils from the Guineo-Congolian zone had the highest concentration in organic matter while for the concentration in gross silt, soils from the Sudanian zone had the highest value.

3.3. Biochemical composition of baobab parts and the physico-chemical properties of the soil

Principal component analysis was conducted to describe the biochemical characteristics of the different baobab parts on each type of soil. The first two components extracted from the analysis explained 81.3% of the overall information of the biochemical concentration of the baobab parts. Table 4 presents the coefficient of correlation between the principal component and the biochemical parameters and also between them and the soil properties. Except for the vitamins (A and C) and the dry matter of the baobab parts, all the others biochemical parameters are significantly correlated with the first axis. On the first axis, iron (Fe), calcium (Ca), potassium (K), carbohydrates and fibers showed positive correlations whereas magnesium (Mg), zinc (Zn), protein and lipid showed negative correlation with the axis. These two groups of variables have opposite trends. Nutrients concentrations might be variably affected by soil composition and environmental factors and hence have variable/opposite sensitivity to these factors. Correlation between the first axis (Axis 1) and the physico-chemical parameters of the soil helped to link biochemical concentration of the baobab parts to the soils properties. We notice from Table 4 that high values of the pH water, carbon/nitrogen ratio (C/N), gross slits and organic matter of the soils seem to positively influence the concentration of iron, calcium, potassium and carbohydrates of baobab parts but negatively influence their concentration in magnesium, zinc, proteins and lipids.

Axis 2 revealed that high concentration in iron was often associated with low concentration in magnesium, vitamin A and dry matter. This axis had no significant correlation with the physico-chemical parameters of the soils.

Links between baobab parts in different agro-climatic zones and their biochemical properties were described by projecting the different parts in the axis system defined by the two above-mentioned principal components (Fig. 1). Fig. 1 indicates that the baobab pulp (ZP3) and the leaves (ZL3) from the Guineo-Congolian zone (zone 3) exhibited relatively higher concentration in iron, potassium, vitamin C, carbohydrates and lower concentration in magnesium, compared to the other zones. These pulp and leaves were taken from baobab trees that are usually established on soils rich in carbon, clay, fine silt, organic matter, with a high pH water and C/N ratio but with a low concentration in gross silt. The baobab seeds from the Sudanian zone (ZS1) showed opposite characteristics compared to the pulp and the leaves from the Guineo-Congolian zone. The leaves (ZL1) and the pulp (ZP1) of the baobabs from the

Table 4
Correlations between principal components related to the biochemical characteristics of baobab parts and the physico-chemical characteristics of the soil.

Parameters	Axis 1	Axis 2
Fe	0.68	−0.52
Ca	0.80	0.49
Mg	−0.50	0.80
K	0.71	−0.42
Zn	−0.94	0.12
VitC	0.24	0.47
VitA	0.45	0.87
Prot	−0.93	0.34
Lipid	−0.99	0.04
Carbohydrates	0.97	−0.21
Fibers	0.87	0.48
DM	−0.47	−0.87
Correlation between the 2 axes and the soil parameters		
pH water	0.77***	−0.06
C	0.90***	−0.01
N	−0.04	0.26
C/N	0.85***	0.17
Clay	0.50*	0.25
Fine silt	0.90***	0.08
Gross silt	−0.90	0.05
Sand	−0.10	−0.16
Organic matter	0.56*	−0.08

* $p < 0.05$.
*** $p < 0.001$.

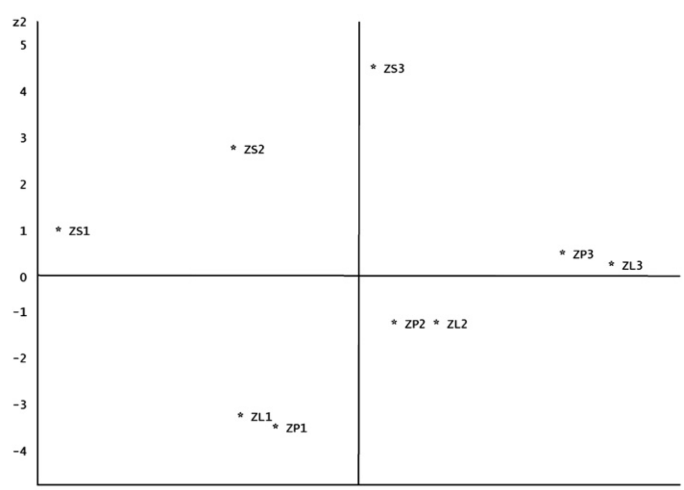

Fig. 1. Projection of the different baobab parts in the 3 climatic zones in the system axis defined by the biochemical concentration of baobab. [1ZL] = leaves from Sudanian zone; ZP1 = pulp from Sudanian zone; ZS1 = seeds from Sudanian zone; ZL2 = leaves from Sudano-Guinean zone; ZP2 = pulp from Sudano-Guinean zone; ZS2 = seeds from Sudano-Guinean zone; ZL3 = leaves from Guineo-Congolian zone; ZP3 = pulp from Guineo-Congolian zone; ZS2 = seeds from Guineo-Congolian zone.

Sudanian zone and to a lower extent the ones from the Sudano-Guinean zone (ZL2 and ZP2) exhibited relatively low concentration in zinc, proteins, lipids, but, higher concentration in calcium and vitamin A. They were taken from baobab trees growing on soils with high levels of gross silt but poor in carbon, clay, fine silt, with low pH water and C/N ratio. The seeds from the Sudano-Guinean and the Guineo-Congolian zones (ZS2 and ZS3) showed opposite characteristics compared to the leaves and pulp of baobabs from the Sudanian zone (ZL1 and ZP1).

The diversity of the soils on which baobab trees sampled are growing and especially the physico-chemical characteristics of these different types of soils could partially explain the variability in the biochemical composition of baobab parts. Such a link between the soil composition and biochemical composition of baobab parts is however rare and therefore the findings of this research adds significant knowledge.

4. Conclusions

Baobab is of high nutritive and economic importance to poor farmers in Africa. Its high nutritive concentration is gaining increased importance in the food industry and as additives to improve nutritional value of foods. The significance of findings from this study is that it fills important gaps in knowledge in Africa about the existence of such linkages. Specifically, the findings from this study provide concrete evidence which allow scientists to move from the realm of hypothesis to specific knowledge that should guide research and development on the conservation and use of baobab individuals across climatic zones. Our findings show that the biochemical composition of baobab parts did not vary according to the genetic and ecological provenance of the trees. This suggests that ecological provenance of baobab does not induce variability in the nutritional concentration of its parts. Rather, we have shown in our study that the physico-chemical characteristics of the soil have an influence on the nutritive value of baobab organs. The significance of the findings linking physico-chemical characteristics of soils with the nutritive concentration of baobab organs is that research and development should first assess soil characteristics and use the information to determine types and levels of fertilizer application to improve the nutritional value of baobab parts through targeted applications. Further to the findings of our study, we recommend more investigations on the bioavailability of nutrients from the different baobab parts and foods prepared from them as well as any anti-nutritional factors associated with soils characteristics. Beside, this work has provided insight into how far nutrient composition of baobab parts may be linked to soil characteristics of host habitats and provenance. However some other factors not considered in this study (including, light conditions, age and size of trees, stand density, leaves' age, leaves exposure to sun, etc.) may have also influenced the observed variations. Hence, exploring effect of these factors may also yield insightful input.

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