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Impact of agroecological conditions on the nutritional and biochemical quality of cashew nuts (*Anacardium occidentale* l.) in Côte d'Ivoire

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Abstract

Cashew (*Anacardium occidentale* L.) is a major export crop and source of income in Côte d'Ivoire, the world's leading producer since 2015. Beyond its economic importance, cashew kernels are valued for their nutritional and functional properties. However, limited information is available on how production environments affect kernel composition. This study aimed to evaluate the influence of agroecological conditions on the physico-chemical and mineral properties of cashew nuts produced in three key regions of Côte d'Ivoire : Bondoukou (Gontougo), Dabakala (Hambol), and Mankono (Béré).

Composite nut samples were collected in each production zone according to EU Regulation N°401/2006. Standard methods were applied to determine biochemical parameters (dry matter, protein, fat, fiber, sugars) and mineral components (Na, K, Ca, Mg, P, Fe, Zn, Cu).

Results revealed marked variability across zones. Nuts from Mankono showed the highest fat (50.14%) and dietary fiber contents (3.40 g/100 g). Dabakala samples were characterized by elevated dry matter (95.55 g/100 g) and protein levels (19.15 g/100 g). In contrast, Bondoukou nuts contained higher sugar concentrations (1.93 °Brix ; 17.20 g/100 g total sugars) and important copper levels (3.57 g/100 g).

These findings demonstrate that agroecological factors significantly affect cashew nut composition, leading to measurable differences in nutritional quality. Such variability highlights opportunities for the regional valorization of Ivorian cashew production, while providing baseline data for both industrial processing and nutrition-oriented utilization.

Keywords: Cashew Nuts; Biochemical Composition; Mineral Content; Agroecological Variability; Côte d'Ivoire

1. Introduction

Cashew (*Anacardium occidentale* L.) is a versatile tropical tree crop cultivated for its nuts and apples. It thrives under a wide range of climatic conditions and can grow on poor soils, making it particularly important in marginal agricultural systems [1,2]. At maturity, the tree produces kidney-shaped nuts attached to fleshy peduncles commonly called cashew apples [3]. In Côte d'Ivoire, cashew cultivation has rapidly expanded and has become a key driver of rural household income and national economic growth [4,5]. Cashew production is now established across almost all ecological regions of the country, and Côte d'Ivoire remains the world's leading producer, with raw cashew nut output reaching about 1.2 million tons in 2023, representing roughly 40% of global supply [6].

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Cashew kernels are not only of economic importance but also represent a valuable source of nutrition. They are rich in unsaturated fatty acids, proteins, vitamins, essential minerals, amino acids, and dietary fiber. Regular consumption of tree nuts, including cashew, has been linked to multiple health benefits such as reduced risks of cardiovascular disease, type 2 diabetes, obesity, and metabolic disorders, as well as improved antioxidant status and bone mineral density [7,8]. Recent reviews further highlight cashew as a functional food with potential roles in chronic disease prevention [7].

Despite being the third most produced tree nut worldwide, cashew remains comparatively under-researched. While its biochemical and mineral compositions have been studied [1,9], evidence suggests that nut quality varies significantly across ecological zones and production environments [2,10,11]. In Côte d'Ivoire, most research has focused on cashew apples [12,13] or pest management [14,15] with limited attention given to kernel quality. Apart from a few morphometric and genotypic studies [16–18], there is little information linking cashew nut composition to agroecological conditions.

Based on this knowledge gap, we hypothesize that agroecological conditions strongly influence the biochemical and mineral composition of cashew kernels in Côte d'Ivoire. The objective of this study was therefore to characterize the variability of key nutritional and physico-chemical traits of cashew nuts across three major production zones. This work provides baseline data essential for the nutritional valorization of cashew, supports strategies for regional product differentiation, and contributes to the sustainable development of the cashew value chain in Côte d'Ivoire.

2. Material and methods

2.1. Plant material

Cashew nuts from the three main production areas of Côte d'Ivoire were used for this study. These nuts were collected from randomly selected farmers in twenty-one [21] different localities in Bondoukou (Gontougo region), Dabakala (Hambol region), and Mankono (Béré region) (Table 1). The cashew nuts were collected between February and May 2018.

Table 1 Quantity of cashew nuts collected per locality

Zone	Localities	Quantity (kg)
Bondoukou	Pélégoudi, Nanfanbeni	53
	Séréoudé	47
	Taoudi	55
	Zépo	49
	Wakiala	43
Subtotal		247
Dabakala	Kotolo	54
	Sokala-Sobara	51
	Kafoudou-bambarasso	57
	Nassoulo	52
	Kokolo	49
Subtotal		263
Mankono	Bouandougou, Kamoro	51
	Bielou, Fisankoro	63
	Dialakoro, Mamouroudougou	67
	Béréda	58
	Gbaziasso	47

	Kankanazo, Dandougou	56
Subtotal		342
TOTAL		852

2.2. Sample preparation for analysis

The nuts collected from each locality were pooled together, forming three different batches of cashew nuts according to the agroecological production zones (Reg. 401/2006). A representative sample of 10 kg from each batch was taken following the international standard ISO 2859 (ISO 2859-1). The quartering method was then used to prepare laboratory samples intended for physico-chemical analyses. Two opposite fractions were combined to form two subsamples. The first was used for biochemical component analysis, and the second for mineral component analysis. Thus, three 1-kg samples from each subsample of each batch, according to cashew nut origin, were obtained, protected from light, and stored at room temperature.

Raw cashew nuts were cut along the shell intersection line using a “calao” clamp. The kernels obtained were ground in a porcelain mortar until a paste was formed. The resulting pastes were placed in plastic containers and stored at room temperature for subsequent analyses.

2.3. Biochemical composition analysis

2.3.1. Determination of hydrogen potential (pH)

The pH was determined according to ISO method [19] using a pH meter (pH meter, Hanna). The pH was measurement using an electronic pH meter by immersing the electrode in in 5 mL of suspension (kernel solution), and the pH value was read directly from the pH meter screen. Before pH measurement, the device was calibrated using two buffer solutions at pH 7.0 and 4.0.

2.3.2. Determination of the Refractometric Dry Extract (°Brix)

The refractometric dry extract (RDE) was determined using an ATR-W2 plus refractometer (2009/230, Germany) following the method used by Adou [13]. After cleaning and calibration with distilled water, a drop of the cashew kernel solution is placed on the refractometer prism. The device is then closed and the reading is taken directly from the screen. The reading is repeated three times.

2.3.3. Determination of Dry Matter (DM) content

Dry Matter Content was determined according to the method used by Adou et al. [20]. One gram of cashew flour was weighed into a pre-dried porcelain crucible of known mass and dried at 105 °C for 24 h. After cooling in a desiccator, the crucible was reweighed. Dry matter (%) was calculated as :

$$DM (\%) = [(Pi - P_0) / P_1] \times 100$$

Where :

Pi = the initial weight of the sample, P_0 = the mass of the empty crucible (g), P_1 = the mass of the crucible after drying (g).

2.3.4. Determination of Titratable Acidity (TA)

Three (3) g of cashew kernel grind were mixed with 28 mL distilled water and centrifuged at 3000 rpm for 10 min. Ten (10) ml of the filtrate were collected and mixed with 90 ml of distilled water, and 2 to 3 drops of phenolphthalein solution were added to the mixture. The titratable acidity was determined as the volume (in ml) of 0.1 N NaOH required to neutralize the mixture [21]. The results represent the average of three trials. The titratable acidity rate is calculated using the following formula :

$$TA (\%) = (N_{NaOH} \times V_{NaOH} \times 0.09 \times 100) / V$$

Where :

V = volume of the sample aliquot, N_{NaOH} = normality of the NaOH used (meq/L), V_{NaOH} = volume of NaOH used (ml), 0.09 = milliequivalent weight of lactic acid.

2.3.5. Determination of Fat Content (FC)

Lipids were extracted from 10 g of cashew kernel grind using a Soxhlet apparatus for 6 hours [22]. The dehydrated cashew kernel grind is introduced into an extraction cartridge (Wattman cartridge) and inserted into the extraction flask. Extraction was performed with 300 mL hexane at 70 °C. After evaporation of solvent and drying at 130 °C, fat content was calculated as :

$$FC\ (\%) = [(P2 - P1) / Pe] \times 100$$

Where :

P_1 = empty flask weight, P_2 = flask + fat weight, Pe = sample weight.

2.3.6. Determination of crude Ash Content (AC)

After lipid extraction, three (03) g of cashew kernel flour obtained after drying were used for the determination of the ash content according to the gravimetric method [23]. The incineration of the samples is carried out in a muffle furnace (Nabertherm GmbH, Germany) at 550°C for 6 hours. The crucible is then removed and cooled in a desiccator, then weighed again. The ash content (AC) obtained after incineration is calculated using the formula :

$$AC\ (\%) = [(m3 - m1) / (m2 - m1)] \times 100$$

Where :

m1 = weight of empty crucible, m2 = weight of crucible + sample before incineration, m3 = weight of crucible + ash.

2.3.7. Determination of Protein Content (P)

Protein was determined by the Kjeldahl method as described by Zhou et al. [24]. One (1) g of kernel flour was digested in concentrated H_2SO_4 with copper sulfate catalyst, distilled with NaOH, and titrated with 0.1 N H_2SO_4. The protein content was calculated by multiplying the total nitrogen content by a conversion factor of 6.25, using the following formulas :

$$TP\ (\%) = [(V_{H_2SO_4} \times 0.1 \times 0.014) / P_0] \times 6.25 \times 100$$

Where: $V_{H_2SO_4}$ = Volume of sulfuric acid used (mL), P_0 = Mass of the sample (g), 0.014 = Ratio of the molar mass of nitrogen per liter of titrant solution.

2.3.8. Determination of Total Sugars in cashew nuts (TS)

The determination of total sugars was carried out by the phenol-sulfuric method [25]. Prior to the determination, Ten (10) g of ground kernel were added to 90 ml of distilled water, then vortexed for 30 min. The suspension (kernel solution) was left to rest for 10 min. Ten (10) mL of 80°C ethanol was added to 1 mL of kernel solution and then centrifuged at 2500 rpm for 15 min. The supernatant was recovered and then 2 mL lead acetate was added and centrifuged at 2500 rpm for 15 min. The supernatant was collected again and 2 mL oxalic acid was added. Everything is centrifuged at 2500 rpm for 15 minutes. In addition, the supernatant is collected and brought to the water bath (80°C). After cooling, distilled water was added to the sample to the previous level. For the determination of total sugars, 2 mL phenol (5%) was added to 2 mL of the solution taken from a test tube. Then 8 mL concentrated sulfuric acid (H2SO4) (96%) was added rapidly and the mixture was stirred immediately. Everything is put in the dark for 30 min. A yellow coloration develops, stable for several hours. Absorbance is measured at 490 nm. The concentration of total sugars is determined with reference to a standard glucose range.

2.3.8. Determination of Crude Fiber (CF) content

Crude fiber content was estimated according to the methods described by Thiex [26]. One (1) g of of cashew kernel flour is boiled in 50 ml of H_2SO_4 (0.25 N) and then in 50 ml of NaOH (0.31 N) for 1h. The resulting residue is dried at 105°C for 8 h then incinerated at 550°C for 3 h.

2.4. Mineral Composition Analysis

Mineral composition was determined following the official methods used [27,28]. Briefly, 5 g of almond cake were oven-dried at 105 °C for 24 h, cooled in a desiccator, and 0.3 g of the dried material was ashed in a porcelain crucible at 600 °C for 5 h in a muffle furnace until white ash was obtained. After cooling to room temperature, the ash was treated with 5 ml of nitric acid (1 N) and evaporated to dryness on a hot plate, followed by the addition of 5 ml of hydrochloric acid (1 N) and heating at 400 °C for 30 min. The residue was dissolved in 10 ml of hydrochloric acid (0.1 N), transferred into a 50 ml volumetric flask, and supplemented with 5 ml of lanthanum chloride to suppress Ca and K interferences. Elemental concentrations were quantified using atomic absorption spectrophotometry (AAS) at the following wavelengths: Mg (285.2 nm), K (766.5 nm), Zn (213.9 nm), Fe (248.3 nm), Ca (424.7 nm), Cu (324.8 nm), and Na (589.0 nm). Calibration curves were established from standard solutions for each element, and blank solutions were run between successive samples.

Phosphorus (P) was analyzed colorimetrically after wet digestion following Abot (2017) [29]. The method is based on the molybdenum blue reaction, where the formation and reduction of the phosphomolybdic complex yields a blue coloration measured at 885 nm. Mineral contents (T, $mg \cdot kg^{-1}$) were calculated according to the equation :

$$T(mg \cdot kg^{-1}) = [(C_{sample} - C_{blank}) / m] \times V$$

Where :

C_{sample} = Sample concentration obtained by AAS, C_{blank} = blank concentration, V = volume (ml) of hydrochloric acid 0.1 N, m = mass (mg) of the calcined dry sample.

2.5. Reproducibility of Analyses

All determinations (pH, dry matter, fiber, total sugars, ash, fat, minerals) were carried out in triplicate. Results are expressed as mean values ± standard deviation.

2.6. Statistical Analysis

Data were analyzed using STATISTICA version 7.1. First, analysis of variance (ANOVA) at a 5% significance level was applied. When significant differences were detected, Tukey's post hoc test was used to identify differing variables. Secondly, principal component analysis (PCA) was performed to visualize parameter relationships and to assess the distribution of physico-chemical variables of cashew nuts according to production zones.

3. Results

3.1. Biochemical components of cashew nuts by production zones

3.1.1. pH, Titratable Acidity, RDE (°Brix), Dry Matter, and Ash content of cashew nuts

Significant differences were observed between production zones for pH, acidity, dry matter, °Brix, and ash content (Table 2). Dabakala cashew nuts recorded the highest dry matter content (95.65%), while Bondoukou nuts showed the highest °Brix value (1.93). Ash content was also significantly higher in Bondoukou cashew nuts (4.41%).

Table 2 pH, RDE (°Brix), titratable acidity, dry matter, and ash content of cashew nuts from different production zones

Parameter	Mankono	Dabakala	Bondoukou	Mean
pH	6.35 ± 0.05^a	6.36 ± 0.03^a	6.39 ± 0.03^b	6.37 ± 0.04
Titratable acidity (%)	0.06 ± 0.008^a	0.04 ± 0.01^b	0.06 ± 0.008^a	0.06 ± 0.01
RDE (°Brix)	1.08 ± 0.18^a	1.16 ± 0.26^a	1.93 ± 0.05^a	1.42 ± 0.44
Dry matter (%)	95.47 ± 0.17^a	95.65 ± 0.31^a	95.47 ± 0.31^a	95.53 ± 0.27
Ash (%)	4.08 ± 0.14^a	4.34 ± 0.12^b	4.41 ± 0.10^b	4.28 ± 0.18

Values in the same row followed by the same letter are not significantly different at the 5% level (Tukey test).

3.1.2. Total Total sugars, Protein, Fat, and Crude Fiber content of cashew nuts

The analysis results also show that the total sugars, protein, fat, and fiber content of nuts varies depending on the origin of the nuts. Indeed, Dabakala and Bondoukou cashew nuts contained significantly more protein (19.15 and 18.95 g/100g, respectively) than Mankono nuts (18.47 g/100g). Fiber content was highest in Mankono cashew nuts (3.40 g/100g). Fat content was slightly higher in Mankono (50.14%) and Dabakala (48.35%) compared to Bondoukou (46.36%) (Table 3).

Table 3 Total sugars, protein, fat, and crude fiber of cashew nuts from different production zones

Parameters	**Mankono**	**Dabakala**	**Bondoukou**	**Mean**
Total sugars (g/100g)	16.80 ± 0.14^a	17.17 ± 0.14^a	17.20 ± 0.17^a	17.06 ± 0.24
Protein (g/100g)	18.47 ± 0.06^a	19.15 ± 0.09^b	18.95 ± 0.28^b	18.86 ± 0.34
Fat (g/100g)	50.14 ± 1.92^a	48.35 ± 2.15^a	46.36 ± 3.68^a	48.28 ± 2.58
Fiber (g/100g)	3.40 ± 0.13^a	3.02 ± 0.31^b	3.02 ± 0.29^b	3.15 ± 0.30

Values in the same row followed by the same letter are not significantly different at the 5% level (Tukey test).

3.2. Mineral Components of Cashew Nuts by Production Zones

3.2.1. Macro-element composition of cashew nut minerals

The mineral composition of cashew nuts revealed five macro-elements (Na, Mg, Ca, P, K). Values ranged from 33.27–35.57 mg/100g (Na), 250.92–251.79 mg/100g (Mg), 465.20–466.15 mg/100g (P), 659.84–665.60 mg/100g (K), and 37.46 mg/100g (Ca). Zone of origin significantly influenced these levels ($p < 0.05$).

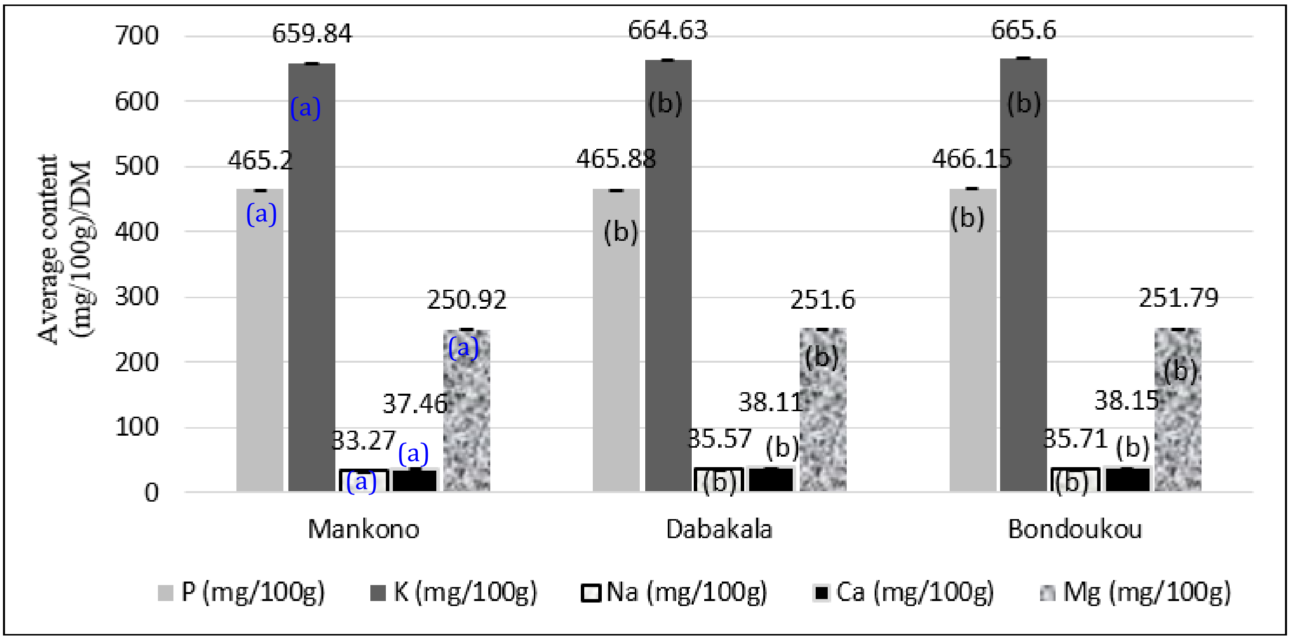

Figure 1 Macro-element concentrations in cashew nuts from different production zones

3.2.2. Micro-element composition of cashew nut minerals

Three micro-elements (Fe, Cu, Zn) were identified. Only iron showed significant differences between zones : 5.15 mg/100g (Bondoukou), 4.91 mg/100g (Dabakala), and 5.27 mg/100g (Mankono).

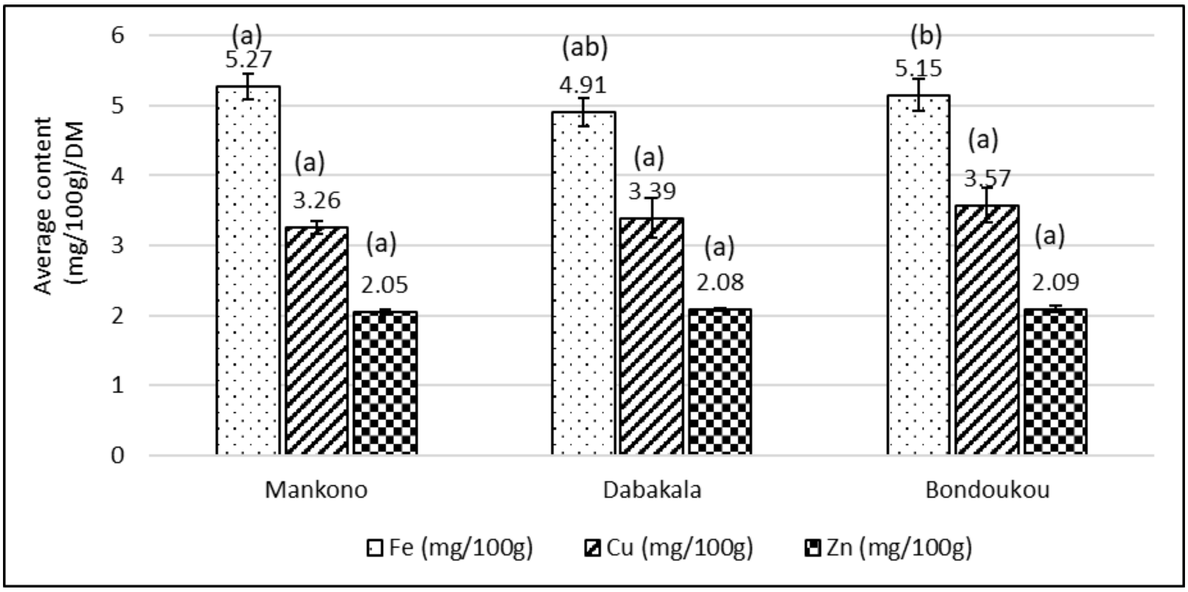

Figure 2 Micro-element concentrations in cashew nuts from different production zones

3.3. Effect of Agroecological Zones on Biochemical Components

Axes F1 and F2 explain 100% of the total variability (Figure 3A). Observation of the correlation circle reveals that all biochemical parameters studied are well represented. The distribution of production zones on the factorial plane (F1-F2) revealed the presence of three classes based on their similarity criteria (Figure 3B). The principal component analysis (PCA) grouped the zones into three classes: Bondoukou (class I: sweeter nuts), Mankono (class II: higher in fiber and fat), and Dabakala (class III: higher in protein and dry matter).

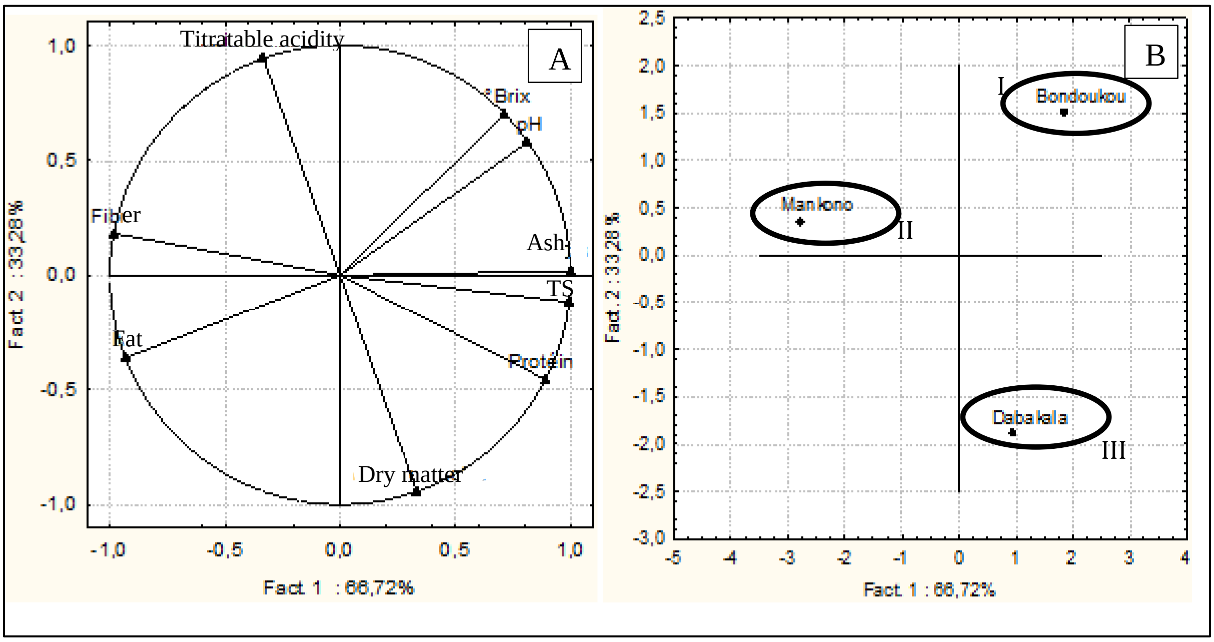

Figure 3 PCA projection of biochemical components and representation of production zones (F1–F2). (TS : total sugars)

3.4. Effect of Agroecological Zones on Mineral Components

The F1 and F2 axes of PCA explain all (100%) of the variances (Figure 4A). PCA also distinguished three groups according to their particularity (Figure 4B) : Bondoukou (higher in Cu), Mankono (higher in Fe), and Dabakala (higher in macro-elements such as P and K).

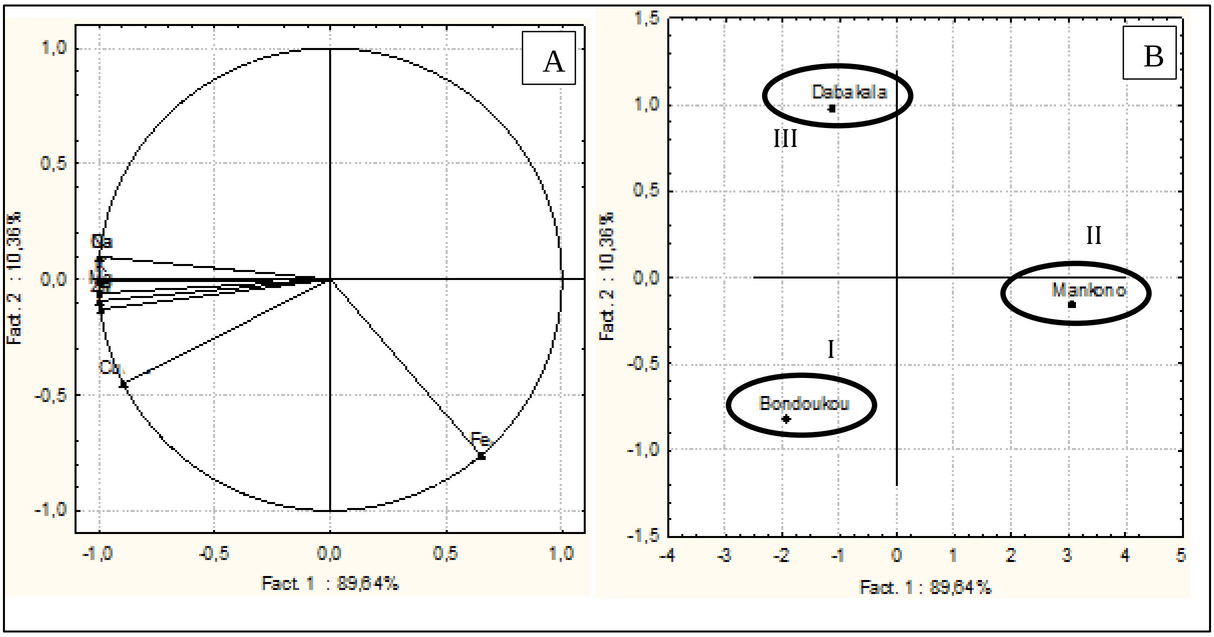

Figure 4 PCA projection of mineral components and representation of production zones (F1–F2). (Ca: calcium, K: potassium, Mg: magnesium, P: phosphorus, Zn: zinc, Na: sodium)

4. Discussion

This study demonstrates a marked variability in the physicochemical and mineral composition of cashew nuts across the agroecological zones of Bondoukou, Dabakala, and Mankono. This indicates that environmental and production conditions significantly influence nut quality. Moreover, similar results have been confirmed in recent studies such as that by [2] in: *Correlating the Morphology of Anacardium occidentale L. Fruits from 30 Orchards with their Physicochemical and Nutritional Properties*, which reported protein levels in cashew kernels varying from 19.7 to 24.0 g/100 g depending on the accession and location. Likewise, Characterization of Cashew Nut Germplasm for Kernel Quality Attributes [30] revealed substantial diversity in kernel quality traits—further supporting our finding that geographic origin plays a large role in shaping nutritional composition.

From the statistical analysis of our data, Dabakala nuts showed the highest protein concentrations; this is consistent with the results of the Burkina Faso study where protein in kernels ranged between 22 and 24% in some accessions [2]. Meanwhile, Bondoukou nuts stood out for sugar content (°Brix and total sugars); which parallels conclusions from global analyses of cashew kernels. Indeed, a study of fresh raw cashew kernels from various origins (including Côte d'Ivoire, India, Brazil, Vietnam) revealed that they are rich in sugar and protein with average contents of 20.5 and 21.3% respectively [9].

The elevated fat and fiber contents found in Mankono nuts also find support in the literature. The same study of diverse kernel origins indicated fat around 48.3% on average, with high proportions of unsaturated fatty acids, and a substantial dietary fiber content [9]. In addition, another study underscores that cashew kernels are rich in healthy lipids, bioactive compounds, fiber, and minerals, all modulated by genotype, environment, and cultivation practices [31].

Concerning mineral content, our observation that macroelements (P, K, Ca, Mg, Na) varied significantly by origin is consistent with agro-morphological and nutritional assessments in Burkina Faso [2], which identified differences in mineral profiles (e.g., potassium, phosphorus) across geographical and genetic accessions. Similarly, work characterizing physical properties and germplasm highlights that agroecological characteristics, associated with genotypic variation, affect kernel yield, grain size, and indirectly mineral accumulation [11,21].

Overall, these results reinforce the argument that agroecological zones significantly affect the composition of cashew nuts. Variables such as soil type, rainfall pattern, harvest interval, and post-harvest practices in cashew nut production interact with genotype to produce measurable differences in protein, fat, fiber, total sugars, and mineral concentrations. Our findings, viewed in light of these recent discoveries, support the potential for region-based valorization of cashew nuts adapted to local conditions.

5. Conclusion

This study revealed significant variability in the physico-chemical and mineral composition of cashew nuts (*Anacardium occidentale* L.) from three major production zones in Côte d'Ivoire. Nuts from Bondoukou were characterized by higher sugar and copper contents, those from Dabakala by elevated protein and dry matter, and those from Mankono by higher fat and fiber levels. These results confirm that agroecological conditions play a decisive role in shaping the nutritional and biochemical quality of cashew nuts.

These findings provide a scientific basis for the regional valorization of cashew nut production in Côte d'Ivoire. They highlight opportunities for developing differentiated products linked to specific production zones, while also informing breeding programs and quality improvement strategies. Furthermore, given the increasing global demand for nutritious and functional foods, promoting the distinct nutritional attributes of Ivorian cashew nuts could enhance their competitiveness in international markets.

Compliance with ethical standards

Disclosure of conflict of interest

There is no conflict of interest.

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