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Relationships between the chemical composition, mineral profile and functional properties of sprouted corn and rice flours, as well as leaf extracts from taro (*Colocasia esculenta*) and sweet potato (*Ipomoea batatas*) grown in Côte d'Ivoire: A multivariate statistical approach

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Abstract

Child malnutrition remains a major problem in developing countries, partly due to the low nutritional density of cereal-based complementary foods. This study aimed to evaluate the relationships between the chemical composition, mineral composition, and functional properties of sprouted and unsprouted corn and rice flours, as well as leaf extracts from taro (*Colocasia esculenta*) and sweet potato (Ipomoea batatas), using a multivariate statistical approach. The raw materials were characterized based on their proximate composition, mineral profile, and functional properties. The results revealed significant differences ($p < 0.05$) among the samples. Cereal flours had the highest levels of available carbohydrates (78.00–80.48 % DM) and energy content (356.34–372.10 kcal/100 g DM). In contrast, the leaf extracts were distinguished by their high content of protein (26.34–28.76 % DM), ash, essential minerals, and bioactive compounds. The taro leaf extract had the highest levels of protein, magnesium, calcium, and iron, while the sweet potato leaf extract was particularly rich in potassium, phosphorus, zinc, and copper. Germination improved several nutritional and functional characteristics of the grains. Correlation analysis revealed strong relationships between proteins, minerals, and functional properties, while principal component analysis explained 87.83% of the total variability along the first two axes. These results confirm the complementary nature of sprouted grains and leaf extracts for the development of ingredients suitable for the formulation of enriched infant foods with high nutritional and technological value.

Keywords: Infant foods; Sprouting; Grains; Leaf extracts; Nutritional composition; Functional properties; PCA

1 Introduction

Child malnutrition remains one of the major global public health challenges, particularly in low- and middle-income countries, where it is a significant cause of morbidity, mortality, and stunting among children under five [1]. This situation is closely linked to the poor quality of complementary foods introduced after the period of exclusive breastfeeding. In many settings, these foods are primarily prepared from grains such as corn and rice, which are a significant source of energy due to their high carbohydrate content [2]. However, these raw materials generally have low nutritional density, characterized by limited levels of high-biological-value proteins, essential micronutrients, and bioactive compounds that are indispensable for the growth, cognitive development, and strengthening of the immune systems of young children [3]. In addition to these nutritional shortcomings, the products sometimes have technological properties that are ill-suited for infant nutrition, including high viscosity in porridges, poor digestibility, and reduced bioavailability of certain nutrients, which limits their consumption and nutritional effectiveness [4]. In this context, the

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development of infant cereals that offer both improved nutritional quality and suitable functional properties is a priority for nutrition and food security programs. Improving these formulations, particularly through the use of local food resources with high nutritional and functional value, thus represents a promising strategy for helping to prevent child malnutrition and improve the nutritional status of young children [5].

Among the strategies developed to improve the nutritional quality of complementary foods, cereal germination and the utilization of nutrient-rich local plant resources are among the most promising approaches [6]. Germination induces significant biochemical changes within the grains, promoting improved digestibility, nutrient bioavailability, protein quality, and certain technological properties essential for food processing [7]. At the same time, the leaves of taro (*Colocasia esculenta*) and sweet potato (Ipomoea batatas), which remain underutilized in many African countries, are plant resources with high nutritional potential. They contain significant amounts of protein, dietary fiber, minerals, vitamins, and bioactive compounds with antioxidant activity, which can increase the nutritional density of complementary foods intended for young children [8].

Beyond their nutritional value, the raw materials used in the formulation of infant foods must possess functional properties that are compatible with the technological requirements of infant cereals. Characteristics such as water absorption capacity, swelling capacity, solubility index, bulk density, and emulsifying properties determine the ease of processing, texture, viscosity, stability, and, consequently, the acceptability of the finished products [9, 10]. These properties depend largely on the biochemical composition of the raw materials, particularly their starch, protein, fat, fiber, and mineral content, as well as on structural changes induced by processing methods such as germination [11].

Although numerous studies have separately described the nutritional composition or functional properties of sprouted grains and leafy greens, few have sought to elucidate the relationships between these different characteristics. In particular, the interactions between chemical composition, mineral profile, and functional properties remain insufficiently explored using multivariate statistical approaches capable of identifying the most discriminating variables and the complex correlations among the various quality parameters. Such an approach would, however, provide a better understanding of the mechanisms underlying the technological performance of these ingredients and help guide their use more effectively in food formulations.

In this context, the present study aims to characterize the chemical composition, mineral composition, and functional properties of corn and rice flours, both sprouted and unsprouted, as well as leaf extracts from taro (*Colocasia esculenta*) and sweet potato (Ipomoea batatas). It also aims to explore, using multivariate statistical approaches, the relationships between these various characteristics in order to identify the main determinants of the raw materials' functional properties. The knowledge generated will contribute to a better selection of local ingredients with high nutritional and technological potential for the development of high-quality complementary foods intended to prevent childhood malnutrition.

2 Material and methods

2.1. Raw Materials and Preparation of Ingredients

The raw materials used in this study included taro leaves (*Colocasia esculenta* (L.) Schott), sweet potato leaves (Ipomoea batatas L.), corn kernels (*Zea mays* L., variety EV99-MRP), and rice grains (*Oryza sativa* L.). The taro and sweet potato leaves were harvested from an experimental plot located in Bécédi-Brignan (Adzopé, Côte d'Ivoire). The corn kernels and paddy rice were purchased at the Adjamé market (Abidjan) and the Bongouanou market (Ivory Coast), respectively. Before use, all raw materials were carefully sorted to remove impurities, plant debris, damaged kernels, and any other foreign matter.

Six ingredients were then prepared: ungerminated and germinated corn flours, ungerminated and germinated rice flours, taro leaf extract powder, and sweet potato leaf extract powder. The preparation methods for each of these ingredients are described in the following sections.

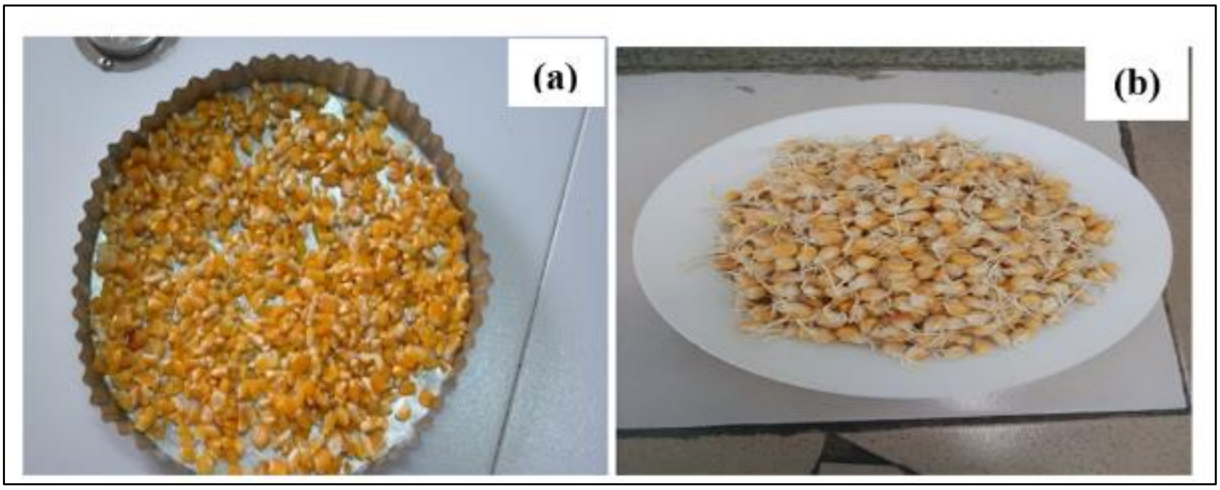


Figure 1 Ungerminated corn kernels (a); germinated corn kernels (b)

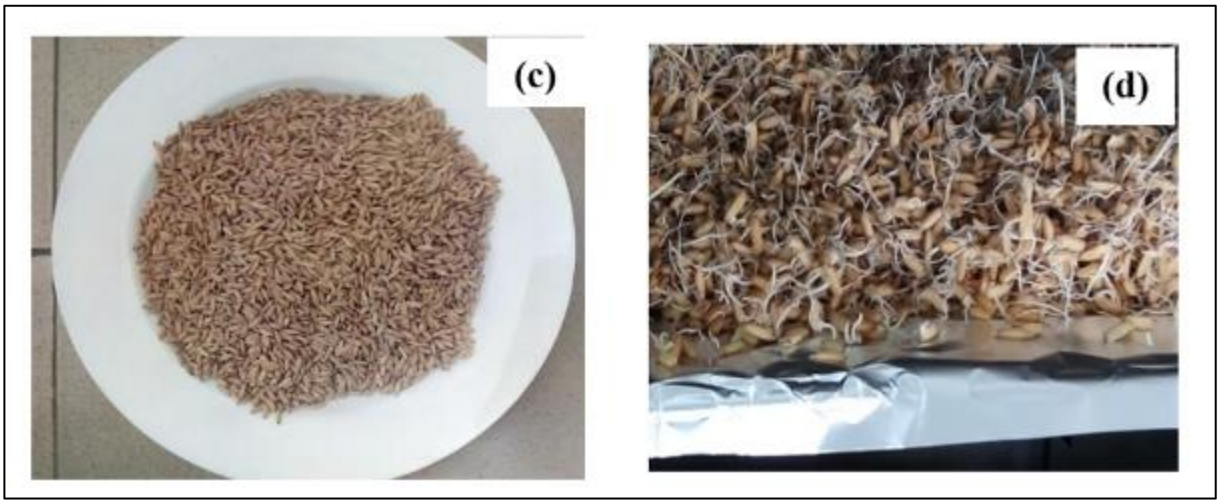


Figure 2 Rice seed (c); germinated rice seed (d)

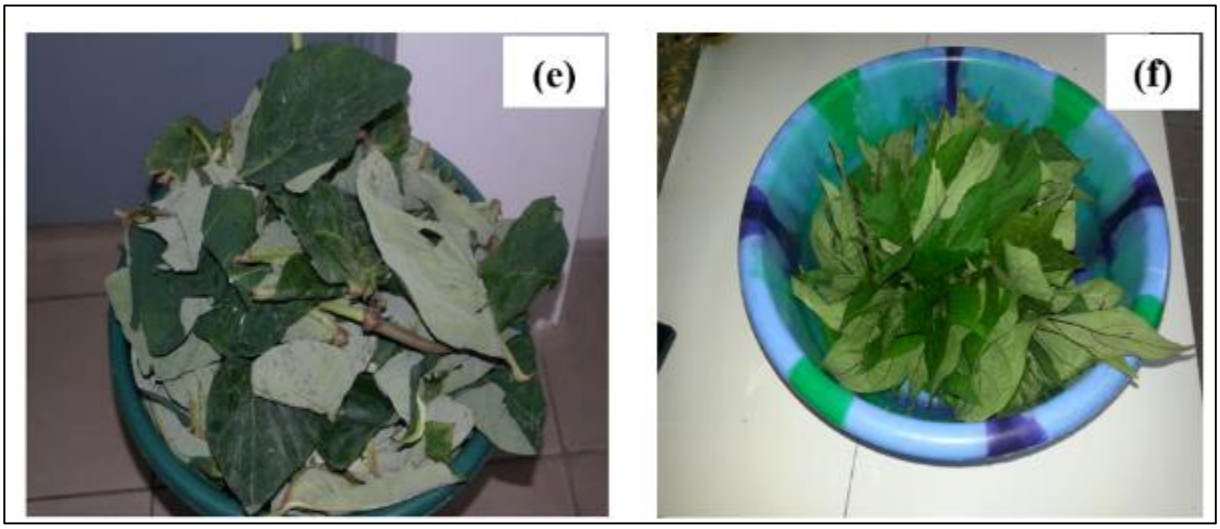


Figure 3 Taro leaf (e); sweet potato leaf (f)

2.2. Preparation of Cereal Flours

Corn and rice flours, whether germinated or not, were prepared using the methods described below.

2.2.1 Preparation of ungerminated corn flour

Corn kernels (*Zea mays L*., variety EV99-MRP) were sorted, winnowed, and washed with potable water to remove impurities. After drying at 50 °C for 48 hours until a constant weight was reached, the kernels were ground using an electric grinder (Ilux LX-176P, 220–240 V, 50 Hz, 350 W), then sieved through a 300 µm sieve. The resulting flour was packaged in hermetically sealed glass jars and stored at room temperature until analysis.

2.2.2 Preparation of Sprouted Corn Flour

Corn kernels (*Zea mays* L., variety EV99-MRP) were sorted, winnowed, and washed with drinking water, then soaked for 24 hours. After draining, they were germinated for 48 hours at room temperature on a moistened cotton cloth, which was kept damp by regular misting. The germinated kernels were then dried at 50 °C for 72 hours to constant weight, ground using an electric grinder (Ilux LX-176P, 220–240 V, 50 Hz, 350 W) and sieved through a 300 µm sieve. The resulting flour was packaged in hermetically sealed glass jars and stored at room temperature until analysis.

2.2.3 Preparation of Non-Germinated Rice Flour

Paddy rice grains (*Oryza sativa* L.) were sorted, winnowed, washed with drinking water, and then hulled. The husked grains were dried at 50 °C for 48 hours until constant weight was reached, ground using an electric grinder (Ilux LX-176P, 220–240 V, 50 Hz, 350 W), and sieved through a 300 µm sieve. The resulting flour was packaged in hermetically sealed glass jars and stored at room temperature until analysis.

2.2.4 Preparation of Sprouted Rice Flour

Paddy rice grains (*Oryza sativa* L.) were sorted, winnowed, washed with drinking water, and then hulled before being soaked for 24 hours. After draining, the grains were germinated for 48 hours at room temperature on a moistened cotton cloth, which was kept damp by regular misting. The germinated grains were then dried at 50 °C for 72 hours until a constant weight was reached, ground using an electric grinder (Ilux LX-176P, 220–240 V, 50 Hz, 350 W) and sieved through a 300 µm sieve. The resulting flour was packaged in hermetically sealed glass jars and stored at room temperature until analysis.

2.3. Preparation of Leaf Extract Powders

Leaf extract powders from taro (*Colocasia esculenta* (L.) Schott) and sweet potato (Ipomoea batatas L.) were prepared according to the method described by Domokos-Szabolcsy et al. [12], with slight modifications. Fresh, healthy leaves free of damage were washed with drinking water, drained, and then cut into small pieces. They were then ground with water at a leaf-to-water ratio of 1:2 (m/v) using an electric blender. The resulting pulp was filtered and pressed through a clean cloth to recover the leaf juice. This juice was brought to a boil (100 °C) for 30 min to induce protein coagulation. The coagulum was then recovered by centrifugation at 4,000 rpm for 15 minutes, then dried at 45 °C for 24 hours until a constant weight was reached. The dried product was ground and sieved through a 300 µm sieve to obtain a fine powder of leaf extract. The resulting powders were packaged in airtight containers and stored at 4 °C until analysis.

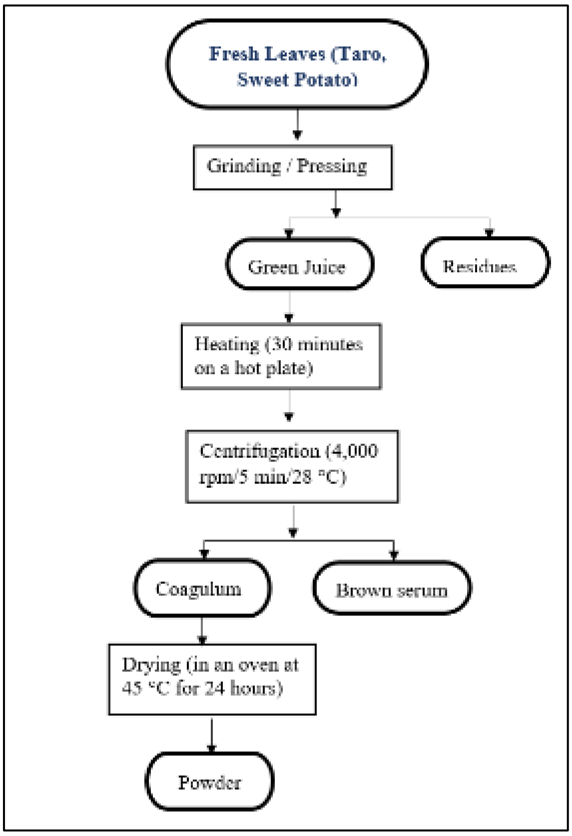


Figure 4 Production Flowchart for Leaf Extract (Taro, Sweet Potato)

2.4. Determination of Chemical Composition

The chemical composition of the samples was determined according to the official AOAC methods [13]. Moisture content was determined by drying 5 g of the sample at 105 °C to constant weight, while ash content was obtained by incinerating 5 g of the sample in a muffle furnace at 550 °C for 6 h. Crude fiber was determined according to the method described by [13], following successive acid and alkaline hydrolysis followed by calcination of the residue at 900 °C for 30 min. Crude protein was determined using the Kjeldahl method [13], applying a nitrogen conversion factor of 6.25, while lipids were extracted using the Soxhlet method with hexane for 6 h according to the AOAC method [13]. Available carbohydrates were calculated by subtraction [100 − (moisture + ash + protein + lipids + fiber)], and the energy value was estimated using the general Atwater and Rosa factors [14] according to the equation: Energy value (kcal/100 g) = (carbohydrates × 4) + (proteins × 4) + (fats × 9).

2.5. Determination of Mineral Composition

The mineral composition was determined by atomic absorption spectrophotometry following acid digestion of the ash. A 0.1 g sample of ash was treated with a mixture of hydrofluoric and sulfuric acids; the residue was then dissolved in hydrochloric acid and the volume was adjusted to 100 mL with distilled water. The concentrations of the mineral elements were subsequently determined by atomic absorption spectrophotometry.

2.6. Determination of Functional Properties

The functional properties of the samples were evaluated by determining bulk density (BD), water absorption capacity (WAC), water solubility index (WSI), emulsifying activity (EA), hydrophilic-lipophilic balance (HLB), and least gelation concentration (LGC). Bulk density (BD) was determined according to the method described by [15]. Water absorption capacity (WAC) and water solubility index (WSI) were measured following the methods of [15] and [16], respectively. Briefly, one gram of sample was mixed with 10 mL of distilled water, stirred for 30 min, and centrifuged at 4,500 rpm for 10 min. WAC was calculated from the weight of the hydrated sediment, whereas WSI was determined by drying the supernatant at 105 °C to constant weight. Emulsifying activity (EA) was determined according to the method of [19] using a distilled water/sunflower oil system. The hydrophilic-lipophilic balance (HLB) was calculated as the ratio of water absorption capacity (WAC) to oil absorption capacity (OAC), following the method of [20] (HLB = WAC/OAC), where OAC was determined according to the method of [17] by mixing 1 g of sample with 10 mL of sunflower oil, incubating the mixture at 37 °C for 30 min, and centrifuging at 4,500 rpm for 10 min. The least gelation concentration (LGC) was determined according to the method described by [21] as the minimum concentration required to form a stable gel after heating and cooling.

2.7. Statistical Analysis

All determinations were performed in triplicate, and the results are expressed as mean ± standard deviation. The data were subjected to an analysis of variance (ANOVA) using Statistica 7.1 software (StatSoft Inc., Tulsa, OK, United States). Differences between means were compared using Duncan's test at the 5 % significance level ($p < 0.05$).

Principal component analysis (PCA) and Pearson's correlation analysis were performed to explore the relationships between the chemical composition, mineral composition, and functional properties of the ingredients studied.

3 Results

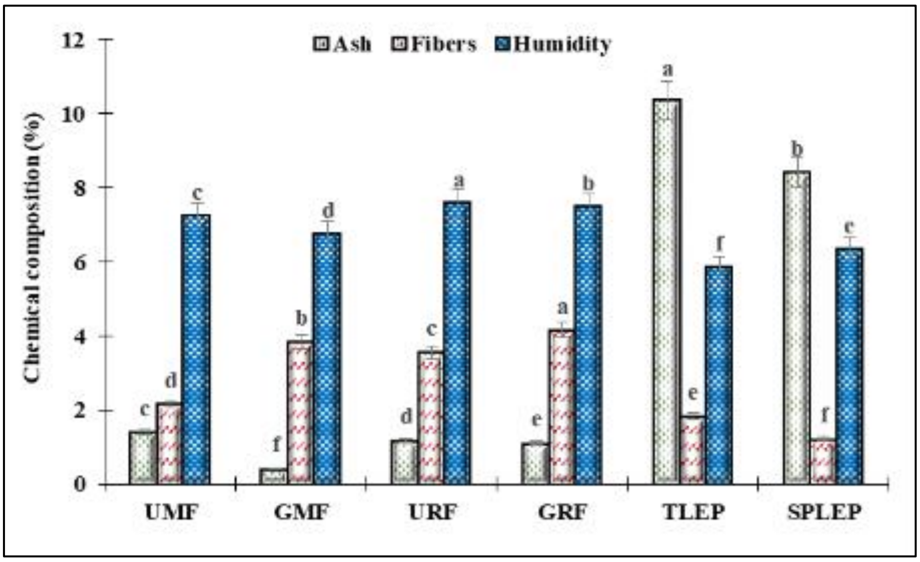
3.1. Proximate composition of cereal flours and leaf extracts

Figure 5 shows the moisture, ash, and dietary fiber contents of maize flours (UMF and GMF), rice flours (URF and GRF), and taro leaf extract (TLEP) and sweet potato leaf extract (SPLEP).

The moisture content differed significantly among the samples ($p < 0.05$). The highest values were recorded in URF (7.59 ± 0.02 %) and GRF (7.46 ± 0.04 %), followed by UMF (7.23 ± 0.06 %). The leaf extracts exhibited significantly lower moisture contents, with 6.33 ± 0.03 % for SPLEP and 5.86 ± 0.05 % for TLEP, the latter showing the lowest value.

Significant differences ($p < 0.05$) were also observed in the ash content. The leaf extracts exhibited the highest ash contents, reaching 10.35 ± 0.04 % for TLEP and 8.42 ± 0.02 % for SPLEP. In contrast, the cereal flours showed considerably lower ash contents, ranging from 0.42 ± 0.02 % in GMF to 1.41 ± 0.02 % in UMF.

The dietary fiber content also differed significantly among the samples ($p < 0.05$). The highest value was recorded in GRF (4.16 ± 0.03 %), followed by GMF (3.84 ± 0.09 %) and URF (3.56 ± 0.03 %). Lower dietary fiber contents were observed in the leaf extracts, with 1.85 ± 0.04 % for TLEP and 1.23 ± 0.03 % for SPLEP, the latter representing the lowest value.



Data are presented as mean ± standard deviation (n = 3). For a given parameter, bars labeled with the same letter are not significantly different according to Tukey's test ($p < 0.05$). UMF = ungerminated maize flour; GMF = germinated maize flour; URF = ungerminated rice flour; GRF = germinated rice flour; TLEP = taro leaf extract powder; SPLEP = sweet potato leaf extract powder.

Figure 5 Moisture, ash, and dietary fiber content

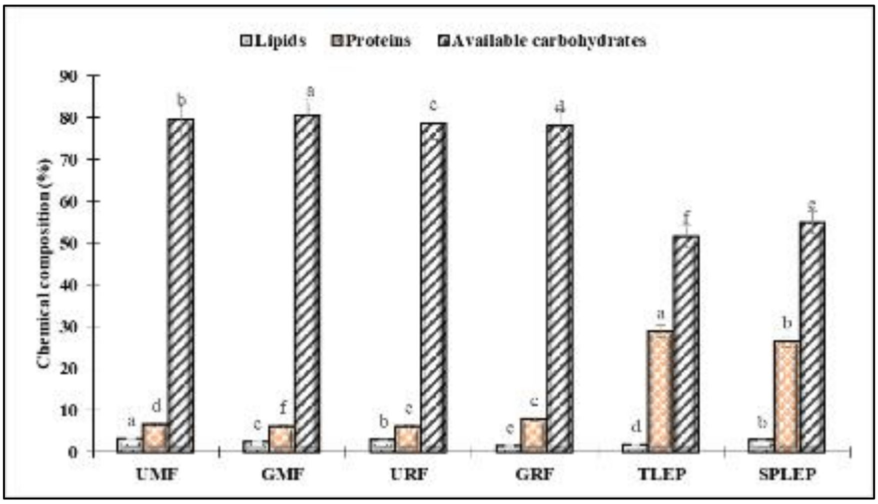
3.2. Macronutrient composition of cereal flours and leaf extracts

Figure 6 presents the contents of available carbohydrates, proteins, and lipids of maize flours (UMF and GMF), rice flours (URF and GRF), and taro leaf extract (TLEP) and sweet potato leaf extract (SPLEP).

The available carbohydrate contents differed significantly among the samples ($p < 0.05$). Cereal flours exhibited the highest values, ranging from 78.00 ± 0.03 % DM in GRF to 80.48 ± 0.07 % DM in GMF. In contrast, leaf extracts showed significantly lower carbohydrate contents, with 51.51 ± 0.05 % DM for TLEP and 55.00 ± 0.06 % DM for SPLEP, with TLEP exhibiting the lowest value.

Significant differences ($p < 0.05$) were also observed in protein contents. Leaf extracts showed the highest protein levels, reaching 28.76 ± 0.03 % DM in TLEP and 26.34 ± 0.05 % DM in SPLEP. Cereal flours exhibited lower protein contents, ranging from 6.10 ± 0.03 % DM in GMF to 7.83 ± 0.03 % DM in GRF.

Lipid contents also varied significantly ($p < 0.05$) among the samples. The highest lipid content was recorded in UMF (3.07 ± 0.03 % DM), followed by URF (2.72 ± 0.02 % DM) and SPLE (2.68 ± 0.02 % DM). Lower values were observed in GMF (2.39 ± 0.02 % DM) and TLEP (1.67 ± 0.03 % DM), whereas GRF (1.45 ± 0.04 % DM) exhibited the lowest lipid content.



Data are presented as mean ± standard deviation (n = 3). For a given parameter, bars labeled with the same letter are not significantly different according to Tukey's test ($p < 0.05$). UMF = ungerminated maize flour; GMF = germinated maize flour; URF = ungerminated rice flour; GRF = germinated rice flour; TLEP = taro leaf extract powder; SPLEP = sweet potato leaf extract powder.

Figure 6 Content of available carbohydrates, protein, and fat

3.3. Energy value of cereal flours and leaf extracts

Figure 7 presents the total energy value of maize flours (UMF and GMF), rice flours (URF and GRF), and taro leaf extract (TLEP) and sweet potato leaf extract (SPLEP).

The total energy value differed significantly among the samples ($p < 0.05$). Cereal flours exhibited the highest energy values, ranging from 356.34 ± 1.36 kcal/100 g DM to 372.10 ± 3.13 kcal/100 g DM. The ungerminated maize flour (UMF) showed the highest energy value (372.10 ± 3.13 kcal/100 g DM), followed by germinated maize flour (GMF, 367.83 ± 2.02 kcal/100 g DM) and ungerminated rice flour (URF, 364.28 ± 4.26 kcal/100 g DM). Germinated rice flour (GRF) exhibited a significantly lower energy value (356.34 ± 1.36 kcal/100 g DM) among the cereal flours.

The leaf extracts showed significantly lower energy values ($p < 0.05$) compared with cereal flours. Sweet potato leaf extract (SPLEP) presented an energy value of 349.48 ± 1.29 kcal/100 g DM, which was higher than that of taro leaf extract (TLEP, 336.11 ± 2.23 kcal/100 g DM), the latter representing the lowest value among all samples.

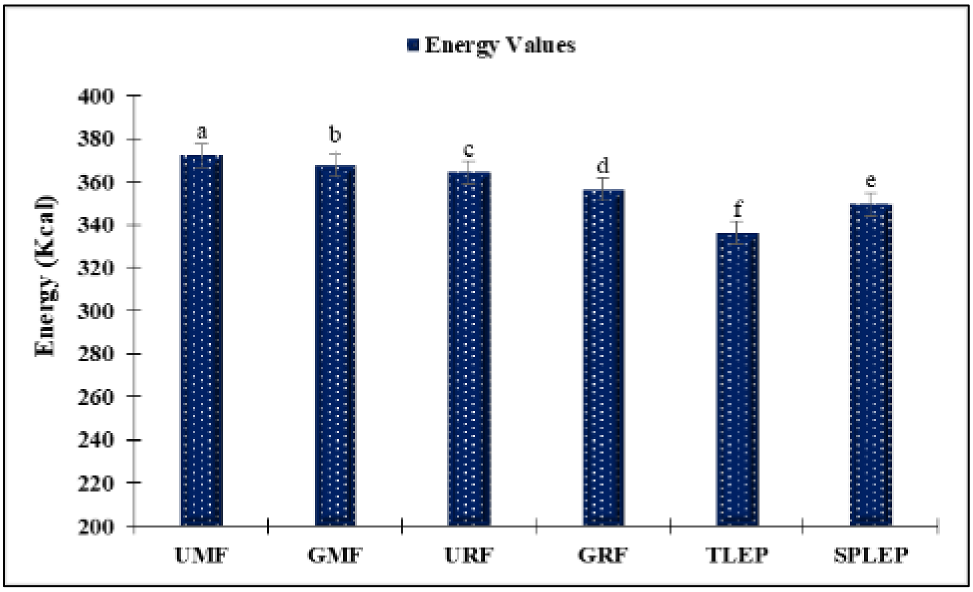


Figure 7 Total Energy Value

Data are presented as mean ± standard deviation (n = 3). For a given parameter, bars labeled with the same letter are not significantly different according to Tukey's test ($p < 0.05$). UMF = ungerminated maize flour; GMF = germinated maize flour; URF = ungerminated rice flour; GRF = germinated rice flour; TLEP = taro leaf extract powder; SPLEP = sweet potato leaf extract powder.

1.4. Mineral composition of cereal flours and leaf extracts

The mineral contents of the base flours and leaf extracts are presented in Table 1. Significant differences ($p < 0.05$) were observed among the samples for all macroelements and trace elements analyzed.

The potassium contents ranged from 105.45 ± 3.91 to 274.42 ± 2.00 mg/100 g DM. The highest concentration was recorded in sweet potato leaf extract powder (SPLEP, 274.42 ± 2.00 mg/100 g DM), followed by germinated maize flour (GMF, 259.97 ± 0.39 mg/100 g DM) and germinated rice flour (GRF, 247.73 ± 2.00 mg/100 g DM), whereas ungerminated rice flour (URF) showed the lowest value (105.45 ± 3.91 mg/100 g DM).

For magnesium, the values ranged from 105.10 ± 4.53 to 259.66 ± 4.56 mg/100 g DM. Taro leaf extract powder (TLEP) exhibited the highest concentration (259.66 ± 4.56 mg/100 g DM), followed by SPLEP (220.23 ± 0.89 mg/100 g DM). The cereal flours showed magnesium contents ranging from 105.10 ± 4.53 to 131.23 ± 2.05 mg/100 g DM.

The phosphorus contents varied significantly ($p < 0.05$) from 91.55 ± 6.97 to 127.81 ± 5.10 mg/100 g DM. The highest values were recorded in GMF (127.81 ± 5.10 mg/100 g DM) and SPLEP (124.04 ± 5.34 mg/100 g DM), whereas TLEP showed the lowest phosphorus content (91.55 ± 6.97 mg/100 g DM).

Regarding sodium, the contents ranged from 1.12 ± 0.08 to 14.85 ± 0.65 mg/100 g DM. The highest value was observed in GMF (14.85 ± 0.65 mg/100 g DM), followed by GRF (13.41 ± 0.45 mg/100 g DM). The leaf extracts exhibited the lowest sodium contents, with 1.12 ± 0.08 mg/100 g DM for TLEP and 4.33 ± 0.17 mg/100 g DM for SPLEP.

Calcium contents differed significantly among the samples ($p < 0.05$) and ranged from 99.26 ± 0.12 to 182.49 ± 3.07 mg/100 g DM. The highest calcium concentration was found in TLEP (182.49 ± 3.07 mg/100 g DM), whereas GRF presented the lowest value (99.26 ± 0.12 mg/100 g DM).

The iron concentrations ranged from 0.85 ± 0.04 to 2.16 ± 0.10 mg/100 g DM. The highest iron content was observed in TLEP (2.16 ± 0.10 mg/100 g DM), followed by SPLEP (1.91 ± 0.03 mg/100 g DM) and URF (1.77 ± 0.08 mg/100 g DM), while UMF showed the lowest value (0.85 ± 0.04 mg/100 g DM).

The zinc contents varied from 0.65 ± 0.04 to 1.64 ± 0.05 mg/100 g DM. Germinated maize flour (GMF) exhibited the highest zinc concentration (1.64 ± 0.05 mg/100 g DM), followed by SPLEP (1.27 ± 0.06 mg/100 g DM). The lowest values were recorded in UMF (0.66 ± 0.03 mg/100 g DM) and URF (0.65 ± 0.04 mg/100 g DM).

The copper contents ranged from 0.41 ± 0.05 to 0.76 ± 0.03 mg/100 g DM. The highest concentrations were observed in GMF (0.76 ± 0.03 mg/100 g DM) and SPLEP (0.75 ± 0.07 mg/100 g DM), whereas TLEP showed the lowest copper content (0.41 ± 0.05 mg/100 g DM).

Table 1 Mineral composition of the base flours and leaf extracts used in the formulation of fortified infant flours

Parameters	UMF	GMF	URF	GRF	TLEP	SPLEP
Potassium	197.19 ± 2.00 ^{d}	259.97 ± 0.39 ^{b}	105.45 ± 3.91 ^{f}	247.73 ± 2.00 ^{c}	176.77 ± 2.24 ^{e}	274.42 ± 2.00 ^{a}
Magnesium	131.23 ± 2.05 ^{c}	128.52 ± 1.03 ^{cd}	105.10 ± 4.53 ^{e}	124.77 ± 1.16 ^{d}	259.66 ± 4.56 ^{a}	220.23 ± 0.89 ^{b}
Phosphorus	111.84 ± 7.30 ^{b}	127.81 ± 5.10 ^{a}	98.49 ± 2.01 ^{c}	112.47 ± 1.61 ^{b}	91.55 ± 6.97 ^{c}	124.04 ± 5.34 ^{a}
Sodium	10.16 ± 0.03 ^{c}	14.85 ± 0.65 ^{a}	6.25 ± 0.08 ^{d}	13.41 ± 0.45 ^{b}	1.12 ± 0.08 ^{f}	4.33 ± 0,17 ^{e}
Calcium	105,59 ± 4,05 ^{cd}	124,15 ± 1,79 ^{b}	112,11 ± 3,29 ^{bc}	99,26 ± 0,12 ^{d}	182,49 ± 3,07 ^{a}	117,88 ± 14.56 ^{b}
Iron	0.85 ± 0.04 ^{f}	1.34 ± 0,05 ^{e}	1.77 ± 0.08 ^{c}	1.65 ± 0,05 ^{d}	2.16 ± 0.10 ^{a}	1.91 ± 0.03 ^{b}
Zinc	0.66 ± 0.03 ^{d}	1.64 ± 0.05 ^{a}	0.65 ± 0.04 ^{d}	0.94 ± 0.05 ^{c}	0.86 ± 0.04 ^{c}	1.27 ± 0.06 ^{b}
Copper	0.55 ± 0.04 ^{c}	0.76 ± 0.03 ^{a}	0.44 ± 0.05 ^{d}	0.65 ± 0.04 ^{b}	0.41 ± 0.05 ^{d}	0.75 ± 0.07 ^{a}

Values in the same row followed by the same superscript letter are not significantly different according to Tukey's test at the 5% significance level ($p < 0.05$). Results are expressed as mean ± standard deviation (n = 3). UMF = ungerminated maize flour; GMF = germinated maize flour; URF = ungerminated rice flour; GRF = germinated rice flour; TLEP = taro leaf extract powder; SPLEP = sweet potato leaf extract powder.

1.5. Functional Properties of Cereal Flours and Leaf Extracts

The functional properties of the base flours and leaf extracts are presented in Table 2. Significant differences ($p < 0.05$) were observed among the samples for all the functional properties evaluated.

The porosity ranged from 34.50 ± 0.23% to 58.60 ± 0.12%. The highest value was recorded for SPLEP (58.60 ± 0.12%), followed by TLEP (52.29 ± 0.14%), whereas UMF exhibited the lowest porosity (34.50 ± 0.23%).

The bulk density (BD) varied significantly ($p < 0.05$) between 0.50 ± 0.05 and 0.77 ± 0.08 g/mL. UMF presented the highest bulk density (0.77 ± 0.08 g/mL), while the lowest value was observed for SPLEP (0.50 ± 0.05 g/mL). The remaining samples displayed intermediate values ranging from 0.56 ± 0.03 to 0.74 ± 0.04 g/mL. The lightness (L*) values ranged from 12.38 ± 0.18 to 21.27 ± 0.73. SPLEP showed the highest lightness (21.27 ± 0.73), followed by TLEP (18.95 ± 0.23) and GRF (16.52 ± 0.14), whereas UMF exhibited the lowest value (12.38 ± 0.18).

The water absorption capacity (WAC) differed significantly among the samples ($p < 0.05$), varying from 124.35 ± 3.16 % to 210.52 ± 1.42%. The highest WAC was observed in SPLEP (210.52 ± 1.42 %), followed by TLE (185.09 ± 2.15%) and GRF (165.39 ± 1.65%), while UMF presented the lowest value (124.35 ± 3.16%). The water solubility index (WSI) ranged from 2.53 ± 0.10 to 4.79 ± 0.19 g/g. The highest values were recorded for SPLEP (4.79 ± 0.19 g/g) and TLEP (4.55 ± 0.36 g/g), whereas UMF (2.53 ± 0.10 g/g) and URF (2.70 ± 0.25 g/g) exhibited the lowest values.

Significant differences ($p < 0.05$) were also observed for emulsifying activity (EA). Values ranged from 43.00 ± 1.34 % in UMF to 72.14 ± 0.24 % in SPLEP. Intermediate values were recorded for URF (45.82 ± 1.20 %), GMF (50.41 ± 0.39%), GRF (58.82 ± 1.14 %), and TLEP (66.60 ± 2.56 %). The hydrophilic-lipophilic balance (HLB) varied from 2.21 ± 0.10 to 3.93 ± 0.05 g/g. The highest value was observed for SPLEP (3.93 ± 0.05 g/g), followed by TLEP (3.65 ± 0.25 g/g) and GRF (3.13 ± 0.23 g/g), whereas UMF (2.21 ± 0.10 g/g) and URF (2.24 ± 0.21 g/g) showed the lowest values.

The least gelation concentration (LGC) ranged from 86.19 ± 1.28 % to 134.42 ± 3.08 %. SPLE exhibited the highest value (134.42 ± 3.08 %), followed by TLEP (121.56 ± 1.53 %) and GRF (102.90 ± 1.53 %), while UMF recorded the lowest value (86.19 ± 1.28 %).

Table 2 Functional properties of the base flours and leaf extracts used for the formulation of enriched infant flours

Parameters	UMF	GMF	URF	GRF	TLEP	SPLEP
Porosity (%)	34.50 ± 0.23 f	44.16 ± 0.08 d	36.38 ± 0.29 e	47.48 ± 0.02 c	52.29 ± 0.14 b	58.60 ± 0.12 a
BD (g/mL)	0.77 ± 0.08 a	0.66 ± 0.03 bc	0.74 ± 0.04 ab	0.64 ± 0.03 c	0.56 ± 0.03 d	0.50 ± 0.05 d
Lightness (L*)	12.38 ± 0.18 f	14.92 ± 0.47 d	13.15 ± 0.14 e	16.52 ± 0.14 c	18.95 ± 0.23 b	21.27 ± 0.73 a
WAC (%)	124.35 ± 3.16 f	150.52 ± 1.50 d	133.70 ± 1.13 e	165.39 ± 1.65 c	185.09 ± 2.15 b	210.52 ± 1.42 a
WSI (g/g)	2.53 ± 0.10 c	3.90 ± 0.09 b	2.70 ± 0.25 c	3.52 ± 0.21 b	4.55 ± 0.36 a	4,79 ± 0.19 a
EA (%)	43.00 ± 1.34 f	50.41 ± 0.39 d	45.82 ± 1.20 e	58.82 ± 1.14 c	66.60 ± 2.56 b	72.14 ± 0.24 a
HLB (g/g)	2.21 ± 0,10 d	2.80 ± 0.13 c	2.24 ± 0.21 d	3.13 ± 0,23 b	3.65 ± 0.25 a	3,93 ± 0.05 a
LGC (%)	86.19 ± 1.28 f	95.48 ± 0.83 d	90.06 ± 1.22 e	102.90 ± 1.53 c	121.56 ± 1.53 b	134.42 ± 3.08 a

Values in the same row followed by the same superscript letter are not significantly different according to Tukey's test at the 5% significance level ($p < 0.05$). Values are expressed as mean ± standard deviation (n = 3 replicates). UMF = Ungerminated maize flour; GMF = Germinated maize flour; URF = Ungerminated rice flour; GRF = Germinated rice flour; TLE = Taro leaf extract; SPLE = Sweet potato leaf extract. BD = Bulk density; WAC = Water absorption capacity; WSI = Water solubility index; EA = Emulsifying activity; HLB = Hydrophilic-lipophilic balance; LGC = Least gelation concentration.

1.6. Correlation between chemical composition and functional properties of raw materials

Pearson's correlation analysis (Table 3) revealed strong relationships among the chemical composition, mineral composition, and functional properties of the raw materials used for the formulation of enriched complementary flours. Proteins exhibited very strong positive correlations with magnesium (r = 0.981), porosity (r = 0.826), lightness (r = 0.880), water absorption capacity (WAC; r = 0.861), water solubility index (WSI; r = 0.832), emulsifying activity (EA; r = 0.882), hydrophilic-lipophilic balance (HLB; r = 0.871), and least gelation concentration (LGC; r = 0.924). Conversely, proteins were strongly negatively correlated with available carbohydrates (r = −0.980), energy value (r = −0.901), moisture content (r = −0.885), and bulk density (r = −0.861). Moisture content showed positive correlations with available carbohydrates (r = 0.825), energy value (r = 0.754), and bulk density (r = 0.777), whereas it was negatively correlated with the major functional properties, including porosity (r = −0.735), WAC (r = −0.727), WSI (r = −0.856), EA (r = −0.732), HLB (r = −0.778), and LGC (r = −0.776). Functional properties were also strongly interrelated. Porosity displayed very high positive correlations with lightness (r = 0.991), WAC (r = 0.993), WSI (r = 0.961), EA (r = 0.984), HLB (r = 0.993), and LGC (r = 0.965), while exhibiting an almost perfect negative correlation with bulk density (r = −0.996). In addition, marked associations were observed among minerals, particularly between phosphorus and copper (r = 0.974), potassium (r = 0.821), and zinc (r = 0.774), as well as between potassium and copper (r = 0.897) and zinc (r = 0.755). Overall, the Pearson correlation matrix highlights the close relationships among the nutritional composition, mineral profile, and functional characteristics of the studied raw materials, providing a comprehensive overview of their physicochemical associations for the development of enriched complementary foods.

Table 3 Pearson correlation matrix between the chemical composition, mineral composition, and functional properties of sprouted corn and rice flours, as well as taro and sweet potato leaf extracts

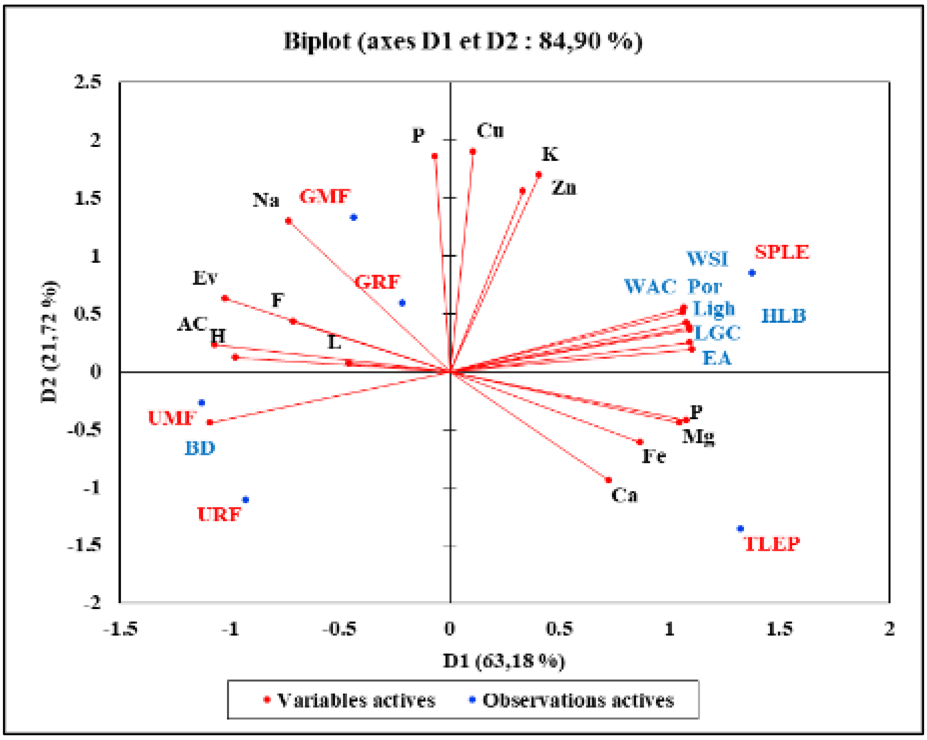
Variables	**H**	**L**	**P**	**F**	**AC**	**Ev**	**K**	**Mg**	**P**	**Na**	**Ca**	**Fe**	**Zn**	**Cu**	**Por**	**BD**	**Ligh**	**WAC**	**WSI**	**EA**	**HLB**	**LGC**
H	**1**	0,230	-0,885	0,685	0,825	0,754	-0,297	-0,939	0,061	0,595	-0,833	-0,522	-0,369	-0,020	-0,735	0,777	-0,749	-0,727	-0,856	-0,732	-0,778	-0,776
L	0,230	**1**	-0,261	-0,319	0,151	0,621	-0,177	-0,292	0,286	-0,010	-0,387	-0,548	-0,089	0,091	-0,455	0,426	-0,403	-0,395	-0,425	-0,476	-0,488	-0,315
P	-0,885	-0,261	**1**	-0,785	-0,980	-0,901	0,172	0,981	-0,231	-0,812	0,715	0,723	0,089	-0,112	0,826	-0,861	0,880	0,861	0,832	0,882	0,871	0,924
F	0,685	-0,319	-0,785	**1**	0,813	0,473	-0,098	-0,777	0,088	0,744	-0,423	-0,222	0,104	0,098	-0,461	0,500	-0,550	-0,528	-0,459	-0,523	-0,509	-0,646
AC	0,825	0,151	-0,980	0,813	**1**	0,835	-0,233	-0,931	0,110	0,791	-0,577	-0,700	-0,131	-0,004	-0,853	0,883	-0,910	-0,898	-0,830	-0,900	-0,879	-0,957
Ev	0,754	0,621	-0,901	0,473	0,835	**1**	-0,054	-0,884	0,438	0,728	-0,756	-0,876	0,007	0,263	-0,793	0,816	-0,828	-0,809	-0,780	-0,867	-0,846	-0,837
K	-0,297	-0,177	0,172	-0,098	-0,233	-0,054	**1**	0,189	0,821	0,406	-0,186	-0,122	0,755	0,897	0,584	-0,533	0,504	0,519	0,555	0,469	0,541	0,428
Mg	-0,939	-0,292	0,981	-0,777	-0,931	-0,884	0,189	**1**	-0,243	-0,763	0,795	0,642	0,110	-0,135	0,778	-0,815	0,824	0,799	0,820	0,829	0,837	0,865
P	0,061	0,286	-0,231	0,088	0,110	0,438	0,821	-0,243	**1**	0,616	-0,527	-0,427	0,774	0,974	0,191	-0,148	0,110	0,140	0,188	0,038	0,103	0,052
Na	0,595	-0,010	-0,812	0,744	0,791	0,728	0,406	-0,763	0,616	**1**	-0,656	-0,681	0,377	0,569	-0,408	0,469	-0,516	-0,493	-0,406	-0,528	-0,466	-0,613
Ca	-0,833	-0,387	0,715	-0,423	-0,577	-0,756	-0,186	0,795	-0,527	-0,656	**1**	0,593	0,037	-0,457	0,415	-0,475	0,441	0,409	0,575	0,460	0,489	0,475
Fe	-0,522	-0,548	0,723	-0,222	-0,700	-0,876	-0,122	0,642	-0,427	-0,681	0,593	**1**	0,035	-0,252	0,701	-0,731	0,731	0,728	0,679	0,759	0,712	0,734
Zn	-0,369	-0,089	0,089	0,104	-0,131	0,007	0,755	0,110	0,774	0,377	0,037	0,035	**1**	0,821	0,479	-0,468	0,380	0,401	0,591	0,315	0,406	0,307
Cu	-0,020	0,091	-0,112	0,098	-0,004	0,263	0,897	-0,135	0,974	0,569	-0,457	-0,252	0,821	**1**	0,367	-0,319	0,280	0,311	0,343	0,219	0,280	0,206

Por	-0,735	-0,455	0,826	-0,461	-0,853	-0,793	0,584	0,778	0,191	-0,408	0,415	0,701	0,479	0,367	**1**	-0,996	0,991	0,993	0,961	0,984	0,993	0,965
BD	0,777	0,426	-0,861	0,500	0,883	0,816	-0,533	-0,815	-0,148	0,469	-0,475	-0,731	-0,468	-0,319	-0,996	**1**	-0,993	-0,993	-0,973	-0,983	-0,991	-0,976
Ligh	-0,749	-0,403	0,880	-0,550	-0,910	-0,828	0,504	0,824	0,110	-0,516	0,441	0,731	0,380	0,280	0,991	-0,993	**1**	0,999	0,942	0,995	0,991	0,991
WAC	-0,727	-0,395	0,861	-0,528	-0,898	-0,809	0,519	0,799	0,140	-0,493	0,409	0,728	0,401	0,311	0,993	-0,993	0,999	**1**	0,940	0,992	0,987	0,987
WSI	-0,856	-0,425	0,832	-0,459	-0,830	-0,780	0,555	0,820	0,188	-0,406	0,575	0,679	0,591	0,343	0,961	-0,973	0,942	0,940	**1**	0,924	0,958	0,920
EA	-0,732	-0,476	0,882	-0,523	-0,900	-0,867	0,469	0,829	0,038	-0,528	0,460	0,759	0,315	0,219	0,984	-0,983	0,995	0,992	0,924	**1**	0,992	0,983
HLB	-0,778	-0,488	0,871	-0,509	-0,879	-0,846	0,541	0,837	0,103	-0,466	0,489	0,712	0,406	0,280	0,993	-0,991	0,991	0,987	0,958	0,992	**1**	0,971
LGC	-0,776	-0,315	0,924	-0,646	-0,957	-0,837	0,428	0,865	0,052	-0,613	0,475	0,734	0,307	0,206	0,965	-0,976	0,991	0,987	0,920	0,983	0,971	**1**

H = Moisture; L = Lipids; P = Proteins; F = Dietary fiber; AC = Available carbohydrates; Ev = Energy value; K = Potassium; Mg = Magnesium; P (mineral) = Phosphorus; Na = Sodium; Ca = Calcium; Fe = Iron; Zn = Zinc; Cu = Copper; Por = Porosity; BD = Bulk density; Ligh = Lightness (L*); WAC = Water absorption capacity; WSI = Water solubility index; EA = Emulsifying activity; HLB = Hydrophilic-lipophilic balance; LGC = Minimum gelation concentration.

1.7. Principal Component Analysis (PCA)

Principal component analysis (PCA) was used to summarize the variability of the data into two principal axes explaining 87.83% of the total variance, with 65.67% explained by axis F1 and 22.16% by axis F2. Axis F1 primarily grouped variables related to chemical composition (proteins, magnesium, calcium, iron) and functional properties (porosity, clarity, water absorption capacity, water solubility index, emulsifying activity, hydrophilic-lipophilic balance, and minimum gelation concentration), while moisture content, available carbohydrates, energy value, and bulk density were negatively correlated with it. The F2 axis was primarily defined by mineral elements, notably copper, phosphorus, potassium, and zinc, as well as sodium. The projection of the observations clearly distinguished leaf extracts from cereal flours, reflecting contrasting nutritional and functional profiles. This structuring highlights a clear differentiation among the raw materials studied based on their chemical, mineral, and technological characteristics.



H = Moisture; L = Lipids; P = Proteins; F = Dietary fiber; AC = Available carbohydrates; Ev = Energy value; K = Potassium; Mg = Magnesium; P (mineral) = Phosphorus; Na = Sodium; Ca = Calcium; Fe = Iron; Zn = Zinc; Cu = Copper; Por = Porosity; BD = Bulk density; Ligh = Lightness (L*); WAC = Water absorption capacity; WSI = Water solubility index; EA = Emulsifying activity; HLB = Hydrophilic-lipophilic balance; LGC = Minimum gelation concentration.

Figure 8 Biplot of the principal component analysis (PCA) illustrating the clustering of raw materials based on their chemical composition, mineral composition, and functional properties

4. Discussion

The present study investigated the relationships between the chemical composition, mineral profile, and functional properties of sprouted and non-sprouted maize and rice flours, as well as taro (*Colocasia esculenta*) and sweet potato (Ipomoea batatas) leaf extracts, using Pearson correlation analysis and principal component analysis (PCA). The multivariate approach clearly demonstrated that the chemical composition of the raw materials strongly influenced their technological behavior. The correlation matrix revealed that protein content was positively associated with most functional properties, including porosity, water absorption capacity (WAC), water solubility index (WSI), emulsifying activity (EA), hydrophilic-lipophilic balance (HLB), and minimum gelation concentration (LGC), whereas available carbohydrates and energy value exhibited strong negative correlations with these properties. Similarly, the PCA explained 87.83% of the total variability on the first two principal components, indicating that the variability among raw materials was mainly driven by their nutritional composition and technological characteristics. The first component was positively associated with proteins, magnesium, porosity, WAC, WSI, EA, HLB, and LGC, while moisture, available carbohydrates, energy value, and bulk density contributed negatively. These findings demonstrate that multivariate statistical analysis effectively discriminated the raw materials according to their nutritional and functional characteristics.

The close association between protein-rich samples and improved functional properties can be attributed to the physicochemical characteristics of proteins, which possess numerous hydrophilic and hydrophobic functional groups capable of interacting with water, lipids, and other food constituents. These interactions enhance water binding, emulsion formation, gelation, and structural stability, thereby improving the technological quality of flour blends intended for complementary foods [21]. In addition, germination induces hydrolysis of storage macromolecules and partial degradation of starch granules through endogenous enzymatic activity, increasing the exposure of polar sites and enhancing hydration properties [22]. These mechanisms explain the strong positive relationships observed between proteins, magnesium, porosity, WAC, WSI, and emulsifying activity. Similar observations have been reported by Kayisoglu et al. [23], who demonstrated that germination significantly improves the functional properties of cereal flours through structural modification of starch and proteins. Likewise, Jahan et al. [24] showed that germinated cereals exhibit enhanced hydration, solubility, and nutrient availability, characteristics particularly desirable for infant food formulations.

Conversely, the strong negative correlations observed between available carbohydrates, energy value, and most functional properties suggest that starch-rich raw materials tend to produce denser matrices with reduced hydration and emulsification capacities. Native starch granules possess a compact crystalline organization that limits water penetration and decreases the accessibility of hydrophilic sites. Consequently, flours containing higher proportions of available carbohydrates generally exhibit higher bulk density and lower porosity, resulting in less favorable technological characteristics for complementary foods. This observation agrees with the findings of Chuqui-Paulino et al. [25], who reported that starch-rich cereal flours generally produce more viscous porridges with limited water absorption capacity. Similar relationships were also described by Shaik et al. [26], who demonstrated that germination reduces starch content while improving hydration and functional performance through enzymatic degradation of reserve carbohydrates.

The mineral profile also contributed substantially to the discrimination of the raw materials. PCA showed that potassium, phosphorus, copper, and zinc were the principal variables defining the second principal component, while Pearson analysis revealed strong positive associations among these minerals. Such relationships probably reflect their common localization within plant tissues and similar mechanisms of mineral accumulation during plant development. The positive associations observed between magnesium, calcium, iron, and several functional properties further suggest that mineral-rich matrices may contribute indirectly to improved technological performance through interactions with proteins and cell wall polysaccharides. Similar associations between mineral composition and functional behavior have been reported by López-Calabozo et al. [27], who highlighted the influence of mineral distribution on protein functionality and water-binding capacity in cereal-legume systems. Furthermore, the remarkable clustering of leaf extracts apart from cereal flours confirms their distinct nutritional composition characterized by elevated protein and mineral concentrations.

Overall, the combined use of Pearson correlation and principal component analysis provided a comprehensive understanding of the complex interactions governing the quality of the studied raw materials. The clear separation of cereal flours and leaf extracts demonstrates that germination and leaf-derived ingredients complement each other by simultaneously improving nutritional composition and technological functionality. These findings support the use of sprouted cereals enriched with taro and sweet potato leaf extracts as promising ingredients for developing nutrient-dense complementary foods suitable for combating childhood malnutrition in Côte d'Ivoire. More importantly, the multivariate statistical approach identified proteins, magnesium, porosity, WAC, EA, and HLB as the principal determinants of functional performance, thereby providing valuable scientific evidence for selecting raw materials with superior nutritional and technological attributes for infant food formulation.

5. Conclusion

This study demonstrated the nutritional and technological potential of combining germinated cereals with taro and sweet potato leaf extracts to improve ingredients intended for complementary infant foods. The cereal flours primarily served as energy sources due to their high available carbohydrate content, whereas the leaf extracts enhanced the nutritional density of the plant-based matrices through their high levels of proteins, essential minerals, and bioactive compounds. Germination also improved several nutritional and functional characteristics of the cereals, thereby increasing their suitability for infant food formulations.

The multivariate approach made it possible to identify the main factors discriminating the raw materials and to highlight the close relationships between chemical composition, mineral profile, and functional properties. Parameters such as porosity, water absorption capacity, free hydration index, and emulsifying activity were strongly associated with protein- and mineral-rich matrices, particularly the leaf extracts.

Overall, the combined utilization of germinated cereals and taro and sweet potato leaves represents a promising strategy for developing nutritionally enhanced complementary foods that meet the dietary needs of young children while promoting the sustainable use of locally available plant resources in Côte d'Ivoire.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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