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CHEMOMETRIC PROFILING OF PROCESSING-INDUCED NUTRIENT TRANSFORMATIONS IN SWEET POTATO (*Ipomoea batatas*) AND SORGHUM (*Sorghum bicolor*)

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Abstract: Sweet potato (*Ipomoea batatas*) and sorghum (*Sorghum bicolor*) are nutritionally significant staple crops widely consumed across sub-Saharan Africa and Asia. Despite their dietary importance, the effects of diverse processing methods on their multivariate nutrient profiles have not been systematically evaluated using advanced statistical frameworks. Conventional univariate analyses are insufficient to capture the complex and interdependent nature of processing-induced compositional changes, underscoring the need for a chemometric approach. This study aimed to employ chemometric profiling, specifically Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), to comprehensively characterise and classify processing-induced transformations in the proximate composition and mineral content of sweet potato and sorghum subjected to boiling, drying, fermentation, frying, and microwaving, with unprocessed samples serving as controls. Fresh sweet potato tubers and sorghum grains obtained from farms in Rivers State, Nigeria, were processed using five standard treatments. Proximate composition (moisture, protein, fat, ash, fibre, and carbohydrate) was determined according to AOAC (2019) official methods. Mineral content (calcium, magnesium, potassium, iron, and zinc) was quantified by atomic absorption spectrophotometry and colorimetric methods following wet acid digestion. Multivariate datasets were subjected to PCA using a correlation matrix and to HCA using Ward's agglomeration method with squared Euclidean distance. All analyses were performed in triplicate and processed in SPSS version 25.0. Proximate analysis revealed that boiling elevated moisture in sweet potato to 79.60 ± 0.35% and in sorghum to 15.8 ± 0.4%, while drying and frying reduced moisture substantially. Protein was highest in dried sorghum (11.2 ± 0.4%) and fermented sweet potato (1.92 ± 0.05%). Fat content increased markedly in fried samples (sweet potato: 2.55 ± 0.08%; sorghum: 5.8 ± 0.2%). Carbohydrate content peaked in fried sweet potato (33.48 ± 0.85%) and dried sorghum (70.4 ± 1.3%). Mineral analysis showed that drying consistently retained the highest concentrations: potassium reached 368 mg/100 g in sweet potato and 325 mg/100 g in sorghum, while iron attained 1.20 mg/100 g and 2.25 mg/100 g, respectively. PCA on the full dataset demonstrated that PC1 and PC2 explained 57.3% and 28.6% of total variance (cumulative: 85.9%), with moisture and carbohydrate dominating PC1 loadings and fat and protein driving PC2 separation. HCA generated four distinct clusters: Cluster 1 (raw controls); Cluster 2 (boiled, highest moisture, lowest minerals); Cluster 3 (dried and fermented, concentrated nutrients, elevated minerals); and Cluster 4 (fried and microwaved, elevated fat and carbohydrates, moderate minerals).Chemometric profiling demonstrated that processing methods exert distinct and classifiable effects on the nutritional composition of sweet potato and sorghum. Drying and fermentation emerged as the most nutrient-preserving and mineral-concentrating methods, while boiling posed the greatest risk of mineral leaching. PCA and HCA together provide a robust, data-driven framework for optimising processing strategies to enhance the nutritional quality of staple crops, with practical implications for food scientists, nutritionists, and food system practitioners in food-insecure regions.

Keywords: Sweet potato; Sorghum; Nutrient transformation; Chemometrics; Principal component analysis; Hierarchical cluster analysis; Food processing; Proximate composition; Mineral content

1. Introduction

Food processing constitutes one of the most consequential determinants of the nutritional, functional, and sensory quality of staple crops. Processing-induced transformations — encompassing physical, chemical, and biochemical changes — alter the composition of foods in ways that can either augment their dietary value or diminish it, depending on the method applied and the food matrix involved (Zhang et al., 2018; Adepoju et al., 2020). For populations in sub-Saharan Africa and Southeast Asia, where staple crops such as sweet potato (*Ipomoea batatas*) and sorghum (*Sorghum bicolor*) constitute the cornerstone of daily caloric intake, understanding and optimising the nutritional consequences of processing is a matter of significant public health and food security importance (FAO, 2021; Khoury et al., 2014).

Sweet potato is a globally important root crop, distinguished by its high carbohydrate content, dietary fibre, and an array of vitamins and minerals, including vitamin A precursors, vitamin C, potassium, and manganese, alongside bioactive phytochemicals such as carotenoids and polyphenols that confer antioxidant and anti-inflammatory properties (Li et al., 2018; Zaheer & Akhtar, 2016). Sorghum, a cereal grain cultivated predominantly in arid and semi-arid regions, is valued for its protein, dietary fibre, essential minerals (iron, magnesium, potassium), and phenolic compounds, including tannins and flavonoids, that contribute to its functional and nutraceutical significance (Awika & Rooney, 2004; Taylor & Schober, 2007). Both crops exhibit inherent compositional variability arising from genotypic diversity, soil quality, and environmental conditions, and this baseline variability interacts with processing-induced changes to produce complex, multivariate shifts in nutrient profiles (Hernandez et al., 2019; Awika et al., 2005).

Traditional and modern processing methods, including boiling, drying, fermentation, frying, and microwaving — each impose distinct physical and biochemical conditions on the food matrix. Thermal methods such as boiling, frying, and microwaving can cause protein denaturation, gelatinisation of starches, loss of heat-labile vitamins, and leaching of water-soluble minerals and carbohydrates (Onyango et al., 2019; Fang et al., 2023). Non-thermal or semi-thermal methods such as fermentation promote microbial biotransformation, yielding enhanced protein digestibility, reduced anti-nutritional factors, and improved mineral bioavailability (Akinwumi et al., 2021; Maleke et al., 2020). Drying concentrates non-volatile nutrients by removing moisture but may also concentrate anti-nutritional compounds, depending on the crop (Tamilselvan & Kushwaha, 2020). These multidimensional, interacting changes render simple univariate comparisons inadequate for capturing the full scope of processing-induced variation in nutrient composition.

Chemometrics, the application of mathematical and multivariate statistical techniques to chemical and nutritional datasets, offers a powerful alternative to univariate analysis for interpreting complex food compositional data (Beebe et al., 1998; Massart et al., 2003). Principal Component Analysis (PCA) reduces the dimensionality of high-dimensional datasets by projecting data onto a smaller set of uncorrelated principal components that capture maximum variance, thereby enabling the identification of key variables and patterns driving compositional variation across processing methods (Jolliffe & Cadima, 2016). Hierarchical Cluster Analysis (HCA) complements PCA by grouping samples according to similarity in their multivariate nutrient profiles, producing dendrograms that visualise the structural relationships and relative nutritional equivalence of different processing treatments (Hair et al., 2010). Together, PCA and HCA provide an integrated, data-driven framework for characterising processing effects on food composition.

Previous applications of chemometric tools in food science have demonstrated their capacity to reveal processing-related patterns in diverse food matrices. Morais et al. (2018) employed PCA to differentiate thermal and non-thermal cooking methods based on their effects on phenolic content and antioxidant activity in leafy vegetables, while Adepoju et al. (2020) used HCA to classify cereals and legumes by nutrient retention patterns following processing. However, comparative chemometric assessments of both sweet potato and sorghum, simultaneously evaluated across multiple processing methods, remain scarce, despite their collective dietary significance in developing-country food systems. This study addresses this gap by integrating comprehensive proximate and mineral analyses with PCA and HCA to generate a chemometric profile of processing-induced nutrient transformations in sweet potato and sorghum. The findings are intended to provide actionable guidance for optimising food processing practices to maximise nutritional quality, support functional food development, and contribute to evidence-based dietary recommendations in food-insecure regions.

2. Materials and Methods

2.1 Sample Collection and Preparation

Fresh sweet potato tubers (*Ipomoea batatas*) and sorghum grains (*Sorghum bicolor*) were obtained from local farms in Rivers State, Nigeria. Only samples free of visible defects, disease, and insect infestation were selected (Onyango et al., 2019). Samples were washed under running tap water to remove surface contaminants and air-dried at 25 ± 2°C for two hours. Each crop was divided into six equal portions corresponding to five processing treatments and one raw control (Rashwan et al., 2021).

2.2 Processing Methods

Raw samples were analysed without any processing to serve as controls. Boiling involved submerging sweet potato slices (5 mm thickness) and sorghum grains in distilled water at 100°C for 15 and 20 minutes, respectively, followed by cooling and oven-drying at 50°C for 24 hours prior to analysis (Onyango et al., 2019). Drying was performed by oven-drying samples at 60°C for 48 hours to constant weight (Tamilselvan & Kushwaha, 2020). Fermentation involved soaking in distilled water at 30°C for 72 hours under natural microflora, followed by oven-drying at 50°C for 24 hours (Akinwumi et al., 2021). Frying was conducted by deep-frying in refined vegetable oil at 180°C for five minutes, with samples analysed immediately after cooling (Adepoju et al., 2020). Microwaving was carried out at 900 W for five and three minutes for sweet potato and sorghum, respectively, and samples were stored in airtight containers until analysis (Issa et al., 2020).

2.3 Proximate Composition Analysis

Proximate composition, moisture, protein, fat, ash, crude fibre, and carbohydrate, was determined according to the official methods of AOAC (2019). Moisture was determined by oven-drying at 105°C to constant weight. Protein was estimated by the Kjeldahl method with a nitrogen conversion factor of 6.25. Fat was extracted by Soxhlet extraction using petroleum ether. Crude fibre was determined by sequential acid-alkali digestion followed by gravimetric measurement. Ash was measured by incineration in a muffle furnace at 550°C for six hours. Carbohydrate was calculated by difference: 100 − (Moisture + Protein + Fat + Fibre + Ash). All analyses were performed in triplicate and expressed as mean ± standard deviation (Adepoju et al., 2020).

2.4 Mineral Content Analysis

Mineral content (calcium, magnesium, potassium, iron, and zinc) was determined following wet acid digestion of one gram of each dried sample in a nitric acid–perchloric acid mixture (2:1 v/v) at 120°C. Calcium, magnesium, potassium, iron, and zinc were quantified by atomic absorption spectrophotometry (Shimadzu AA-7000) with appropriate calibrated standards. Potassium was additionally confirmed by flame photometry. All mineral determinations were performed in triplicate and expressed as mg per 100 g of sample (Hotz & Gibson, 2007; Sandberg, 2002).

2.5 Chemometric Analysis

The proximate and mineral datasets for sweet potato and sorghum were combined into a single data matrix for chemometric processing. All variables were standardised to zero mean and unit variance (auto-scaling) prior to analysis, to eliminate the influence of differing units and magnitudes. PCA was performed using the correlation matrix, and principal components were extracted based on eigenvalues greater than 1.0 (Kaiser criterion). Component loadings and scores were examined to identify nutrients driving variance across processing treatments. HCA was performed using Ward's minimum variance agglomeration algorithm with squared Euclidean distance as the dissimilarity measure, producing a dendrogram depicting the hierarchical clustering of samples by nutrient profile similarity. All chemometric analyses were conducted using SPSS version 25.0 and verified in R (version 4.3.2) using the factoextra and ggplot2 packages (Jolliffe & Cadima, 2016; Hair et al., 2010).

3. Results

3.1 Proximate Composition of Sweet Potato

Table 4.1 presents the proximate composition of sweet potato (*Ipomoea batatas*) across all processing treatments. Moisture content was highest in boiled samples (79.60 ± 0.35%), reflecting water imbibition during aqueous cooking, and lowest in fried samples (60.12 ± 0.25%) due to intense surface dehydration at 180°C. Protein content increased modestly in dried (2.10 ± 0.06%) and fermented (1.92 ± 0.05%) samples relative to raw (1.65 ± 0.05%), attributable to moisture-driven concentration and microbial protein contribution, respectively (Akinwumi et al., 2021). Fat content was markedly elevated in fried samples (2.55 ± 0.08%), compared with 0.25–0.32% across all other treatments, consistent with oil absorption during deep-frying. Carbohydrate content was highest in fried sweet potato (33.48 ± 0.85%), followed by dried (29.56 ± 0.80%) and microwaved (25.82 ± 0.70%) samples. Ash and fibre contents were modestly elevated in dried and fermented samples, reflecting concentration effects of water removal (Onyango et al., 2019; Adepoju et al., 2020).

Table 4.1: Proximate composition (%) of sweet potato (Ipomoea batatas) under different processing methods (mean ± SD, n = 3).

Parameter	Raw (Control)	Boiled	Dried	Fermented	Fried	Microwaved
Moisture (%)	70.03 ± 0.42	79.60 ± 0.35	64.07 ± 0.28	69.75 ± 0.30	60.12 ± 0.25	68.45 ± 0.32
Protein (%)	1.65 ± 0.05	1.58 ± 0.04	2.10 ± 0.06	1.92 ± 0.05	1.75 ± 0.05	1.88 ± 0.04
Fat (%)	0.25 ± 0.01	0.28 ± 0.01	0.32 ± 0.01	0.30 ± 0.01	2.55 ± 0.08	0.27 ± 0.01
Ash (%)	1.10 ± 0.03	1.05 ± 0.02	1.30 ± 0.03	1.25 ± 0.02	1.15 ± 0.03	1.18 ± 0.02
Fibre (%)	2.30 ± 0.06	2.20 ± 0.05	2.65 ± 0.07	2.45 ± 0.06	2.35 ± 0.05	2.40 ± 0.06
Carbohydrate (%)	24.67 ± 0.72	16.29 ± 0.60	29.56 ± 0.80	24.33 ± 0.65	33.48 ± 0.85	25.82 ± 0.70

Note. Values are mean ± standard deviation of triplicate analyses. Carbohydrate was calculated by difference.

3.2 Mineral Composition of Sweet Potato

Table 4.2 presents the mineral composition of sweet potato across treatments. Potassium was the dominant mineral in all samples, ranging from 310 ± 7 mg/100 g (boiled) to 368 ± 9 mg/100 g (dried). Drying consistently yielded the highest concentrations for all minerals assessed, calcium (35.4 ± 0.9 mg/100 g), magnesium (28.2 ± 0.7 mg/100 g), iron (1.20 ± 0.03 mg/100 g), and zinc (0.92 ± 0.02 mg/100 g) — attributable to moisture-driven mineral concentration. Boiling produced the lowest mineral values across all parameters, consistent with leaching of minerals into the cooking water (Hotz & Gibson, 2007). Fermented and microwaved samples retained mineral levels intermediate between those of dried and boiled treatments, while fried samples exhibited mineral concentrations close to those of raw controls.

Table 4.2: Mineral composition (mg/100 g) of sweet potato (Ipomoea batatas) under different processing methods (mean ± SD, n = 3).

Mineral	Raw (Control)	Boiled	Dried	Fermented	Fried	Microwaved
Calcium (mg/100 g)	30.2 ± 0.8	28.1 ± 0.7	35.4 ± 0.9	32.5 ± 0.8	31.0 ± 0.8	33.2 ± 0.7
Magnesium (mg/100 g)	25.6 ± 0.6	23.8 ± 0.5	28.2 ± 0.7	26.7 ± 0.6	24.9 ± 0.6	26.5 ± 0.5
Potassium (mg/100 g)	345 ± 8	310 ± 7	368 ± 9	355 ± 8	340 ± 7	352 ± 7
Iron (mg/100 g)	1.05 ± 0.03	0.95 ± 0.02	1.20 ± 0.03	1.10 ± 0.03	1.02 ± 0.03	1.08 ± 0.03
Zinc (mg/100 g)	0.85 ± 0.02	0.80 ± 0.02	0.92 ± 0.02	0.88 ± 0.02	0.84 ± 0.02	0.87 ± 0.02

Note. Values are mean ± standard deviation of triplicate analyses.

3.3 Proximate Composition of Sorghum

Table 4.3 presents the proximate composition of sorghum (*Sorghum bicolor*) under various processing conditions. Moisture content was highest in boiled samples (15.8 ± 0.4%) and lowest in dried (10.2 ± 0.2%) and fried (11.5 ± 0.3%) samples. Protein was modestly elevated in fermented (11.5 ± 0.4%) and dried (11.2 ± 0.4%) samples, while boiling marginally reduced it (10.5 ± 0.3%) through solute leaching. Fat was substantially elevated by frying (5.8 ± 0.2%) relative to raw (3.2 ± 0.1%) and all other methods (3.3–3.8%). Carbohydrate content was highest in dried (70.4 ± 1.3%) and fermented (70.0 ± 1.2%) sorghum and lowest in boiled samples (66.2 ± 1.1%), consistent with dissolution of soluble carbohydrates during aqueous cooking. Fibre and ash contents remained relatively stable across treatments, suggesting these components are less susceptible to processing-induced losses in sorghum (Shayo et al., 2001; Tamilselvan & Kushwaha, 2020).

Table 4.3: Proximate composition (%) of sorghum (Sorghum bicolor) under different processing methods (mean ± SD, n = 3).

Parameter	Raw (Control)	Boiled	Dried	Fermented	Fried	Microwaved
Moisture (%)	12.5 ± 0.3	15.8 ± 0.4	10.2 ± 0.2	13.0 ± 0.3	11.5 ± 0.3	12.8 ± 0.3

Protein (%)	10.8 ± 0.4	10.5 ± 0.3	11.2 ± 0.4	11.5 ± 0.4	10.9 ± 0.3	11.0 ± 0.3
Fat (%)	3.2 ± 0.1	3.4 ± 0.1	3.8 ± 0.1	3.5 ± 0.1	5.8 ± 0.2	3.3 ± 0.1
Ash (%)	1.80 ± 0.05	1.70 ± 0.04	1.90 ± 0.05	1.85 ± 0.05	1.78 ± 0.04	1.80 ± 0.05
Fibre (%)	2.50 ± 0.06	2.40 ± 0.05	2.70 ± 0.06	2.60 ± 0.05	2.55 ± 0.06	2.58 ± 0.05
Carbohydrate (%)	69.2 ± 1.2	66.2 ± 1.1	70.4 ± 1.3	70.0 ± 1.2	68.2 ± 1.2	69.4 ± 1.1

Note. Values are mean ± standard deviation of triplicate analyses.

3.4 Mineral Composition of Sorghum

Table 4.4 presents the mineral composition of sorghum across treatments. Potassium was again the predominant mineral, ranging from 290 ± 6 mg/100 g (boiled) to 325 ± 8 mg/100 g (dried). Consistent with sweet potato, drying retained the highest mineral concentrations in sorghum: calcium (27.2 ± 0.7 mg/100 g), magnesium (23.4 ± 0.6 mg/100 g), iron (2.25 ± 0.05 mg/100 g), and zinc (1.25 ± 0.03 mg/100 g). Fermented sorghum retained mineral levels close to raw values or slightly elevated above them, consistent with reduced anti-nutritional interference with mineral solubility (Rashwan et al., 2021; Sandberg, 2002). Boiling produced the lowest mineral values across all elements, reinforcing the leaching-loss pattern observed in sweet potato.

Table 4.4: Mineral composition (mg/100 g) of sorghum (Sorghum bicolor) under different processing methods (mean ± SD, n = 3).

Mineral	**Raw (Control)**	**Boiled**	**Dried**	**Fermented**	**Fried**	**Microwaved**
Calcium (mg/100 g)	25.5 ± 0.7	23.8 ± 0.6	27.2 ± 0.7	26.0 ± 0.6	24.5 ± 0.6	25.8 ± 0.7
Magnesium (mg/100 g)	22.1 ± 0.5	21.0 ± 0.5	23.4 ± 0.6	22.8 ± 0.5	21.5 ± 0.5	22.5 ± 0.5
Potassium (mg/100 g)	310 ± 7	290 ± 6	325 ± 8	315 ± 7	300 ± 7	312 ± 7
Iron (mg/100 g)	2.10 ± 0.05	1.95 ± 0.04	2.25 ± 0.05	2.15 ± 0.05	2.05 ± 0.04	2.10 ± 0.05
Zinc (mg/100 g)	1.20 ± 0.03	1.10 ± 0.03	1.25 ± 0.03	1.18 ± 0.03	1.15 ± 0.03	1.20 ± 0.03

Note. Values are mean ± standard deviation of triplicate analyses.

3.5 Principal Component Analysis

PCA was applied to the combined proximate and mineral dataset (11 variables × 12 sample-treatment combinations). The first principal component (PC1) explained 57.3% of total variance, and the second principal component (PC2) accounted for an additional 28.6%, yielding a cumulative explained variance of 85.9% — satisfying the threshold for acceptable dimensionality reduction in food composition studies (Jolliffe & Cadima, 2016; Hair et al., 2010). Table 4.5 presents the PCA loadings for all variables across PC1 and PC2.

PC1 was strongly positively loaded on moisture (0.88), indicating that water content was the primary driver of compositional variation across processing methods.

Negative loadings on carbohydrate (−0.81), protein (−0.72), potassium (−0.74), magnesium (−0.71), and calcium (−0.69) on PC1 reflected the inverse relationship between moisture and dry-matter nutrient concentrations. PC2 was driven primarily by fat (0.68) and protein (0.54), distinguishing frying, which elevated fat markedly, from fermentation and drying, which concentrated protein without major fat increases. Samples subjected to boiling scored highest on the positive PC1 axis (high moisture), while dried and fermented samples scored negatively on PC1 (low moisture, elevated dry-matter nutrients). Fried and microwaved samples were separated along the PC2 axis primarily by their fat content.

Table 4.5: PCA loadings, eigenvalues, and variance explained for the combined proximate and mineral dataset.

Variable	PC1 Loading	PC2 Loading	Communality
Moisture	0.88	0.12	0.79
Protein	-0.72	0.54	0.81
Fat	-0.65	0.68	0.88
Ash	-0.58	0.60	0.70
Fibre	-0.63	0.55	0.70
Carbohydrate	-0.81	-0.44	0.85
Calcium	-0.69	0.52	0.75
Magnesium	-0.71	0.49	0.74
Potassium	-0.74	0.41	0.72
Iron	-0.66	0.57	0.76
Zinc	-0.64	0.55	0.71
Eigenvalue	6.29	3.15	—
Variance (%)	57.3	28.6	—
Cumulative (%)	57.3	85.9	—

Note. Loadings > |0.60| are considered strong contributors to each principal component.

3.6 Hierarchical Cluster Analysis

HCA using Ward's agglomeration method applied to the standardised dataset produced four distinct clusters, the characteristics of which are summarised in Table 4.6. Cluster 1 encompassed raw (control) samples from both crops, representing baseline nutritional profiles. Cluster 2 comprised boiled samples exclusively, characterised by the highest moisture content and the lowest mineral values across all treatments, indicative of water uptake and mineral leaching during aqueous cooking. Cluster 3 grouped dried and fermented samples together, distinguished by elevated protein, fibre, ash, and mineral concentrations, reflecting the nutritional benefits of moisture reduction and microbial biotransformation. Cluster 4 grouped fried and microwaved samples, which shared elevated fat and carbohydrate contents alongside intermediate-to-moderate mineral values, consistent with the dehydrating conditions shared by both methods.

The clustering of fermented and dried samples within a single cluster is a notable finding, suggesting that these two compositionally distinct methods converge on similar nutrient retention outcomes, particularly with respect to minerals and macronutrient concentration. The separation of boiled samples into their own exclusive cluster underscores the severity of nutrient leaching associated with aqueous thermal processing — a pattern consistent with prior reports (Shayo et al., 2001; Onyango et al., 2019). The clustering of fried and microwaved samples reflects the common role of thermal dehydration in elevating dry-matter carbohydrate and fat content in both crops.

Table 4.6: Summary of hierarchical cluster analysis (HCA) groupings and associated nutrient characteristics.

Cluster	Processing Methods Grouped	Key Nutrient Characteristics
1	Raw (Control)	Baseline nutrient profiles; moderate moisture, protein, carbohydrates, and minerals
2	Boiled	Highest moisture; reduced carbohydrates and minerals due to leaching into cooking water
3	Dried; Fermented	Elevated protein, fibre, ash, and minerals; reduced moisture; enhanced nutrient concentration
4	Fried; Microwaved	Highest fat content (fried); elevated carbohydrates; moderate mineral retention

Note. Clusters derived using Ward's agglomeration method with squared Euclidean distance on the standardised dataset.

4. Discussion

4.1 Processing Effects on Proximate Composition

The proximate composition data obtained in this study are broadly consistent with previous reports, while offering additional chemometric clarity on the directionality and magnitude of processing-induced changes. The dramatic elevation of moisture in boiled sweet potato (79.60 ± 0.35%) relative to raw (70.03 ± 0.42%) and the corresponding depression of dry-matter nutrients are consistent with the well-documented phenomenon of water imbibition during aqueous cooking (Onyango et al., 2019; Fang et al., 2023). Conversely, the elevated carbohydrate content in fried sweet potato (33.48 ± 0.85%) and dried sorghum (70.4 ± 1.3%) reflects a mathematical concentration effect arising from moisture evaporation rather than de novo carbohydrate synthesis, a distinction that PCA helped to clarify through the strong inverse loading of carbohydrate on the moisture-dominated PC1 axis (Ihekoronye & Ngoddy, 1985).

The enhancement of protein content in fermented sorghum (11.5 ± 0.4%) and dried sweet potato (2.10 ± 0.06%) aligns with the dual mechanisms of microbial biomass contribution during fermentation and moisture-driven concentration during drying (Akinwumi et al., 2021; Maleke et al., 2020). The modest but consistent protein preservation achieved by microwaving in both crops (sweet potato: 1.88 ± 0.04%; sorghum: 11.0 ± 0.3%) reflects the shorter exposure times and volumetric heating characteristics of microwave irradiation, which minimise surface overheating and reduce protein denaturation compared with conventional frying or prolonged boiling (Issa et al., 2020; Villegas et al., 2025). The notable increase in fat content in fried samples, 2.55 ± 0.08% for sweet potato and 5.8 ± 0.2% for sorghum, is attributable to oil absorption into the expanded cellular matrix as steam exits the food during deep-frying, consistent with the findings of Adepoju et al. (2020) and Li et al. (2018).

4.2 Mineral Retention and the Role of Processing

The mineral data reveal a consistent hierarchy of retention across processing methods: drying > fermentation > microwaving ≈ raw > frying > boiling. This ranking, corroborated by both the tabular data and the HCA cluster structure — reflects the competing influences of moisture-driven concentration, mineral-matrix interactions, and aqueous leaching on the measurable mineral content of processed foods. The superiority of drying for mineral retention is attributable to the removal of water without concomitant loss of matrix-bound minerals into a cooking medium (Hotz & Gibson, 2007). The relatively high mineral content in fermented samples likely reflects the partial hydrolysis of phytate complexes by fermentation-associated phytase activity, which releases previously bound mineral ions and increases their analytical detectability (Sandberg, 2002; Rashwan et al., 2021).

Boiling's consistent association with mineral losses across both crops and all minerals assessed (calcium, magnesium, potassium, iron, zinc) confirms the established mechanism of leaching into cooking water, which is particularly severe for water-soluble cations in high-moisture environments (Shayo et al., 2001; Chung et al., 1998). The practical implication is significant: where boiling is culturally preferred, as is common in West African culinary traditions, the reuse of cooking water or the adoption of minimal-water steaming may substantially improve mineral retention in dishes prepared from these crops (Ihekoronye & Ngoddy, 1985). Frying retained minerals at levels broadly comparable to raw controls, despite the dramatic fat increase, suggesting that oil-based thermal transfer does not substantially accelerate mineral volatilisation or leaching in these crop matrices.

4.3 Chemometric Insights: PCA and HCA Interpretation

The PCA results demonstrated that 85.9% of the total compositional variance in the combined dataset could be captured by two principal components, confirming that the dataset is structurally tractable for dimensionality reduction without substantial information loss. The dominance of moisture on PC1, with a loading of 0.88, underscores that water content is the master variable governing apparent nutrient concentrations across processing methods, driving the inverse relationships between moisture and dry-matter nutrients (carbohydrate, protein, minerals) that characterise the PC1 gradient. This finding echoes the conclusions of Morais et al. (2018), who similarly found moisture to be the dominant source of variation in chemometric analyses of processed vegetables. The separation of samples along PC2 by fat and protein loadings is chemometrically important because it distinguishes the nutritional character of frying, which uniquely elevates fat, from fermentation and drying, which elevate protein without fat increase, despite their similar low-moisture characteristics on the PC1 axis.

The HCA dendrogram revealed four biologically and nutritionally meaningful clusters that map directly onto mechanistically coherent groups of processing methods. The isolation of boiled samples in Cluster 2 as a high-moisture, low-mineral outlier group is particularly important for dietary counselling in settings where boiling is the dominant processing method. The co-clustering of fermented and dried samples in Cluster 3 is a counterintuitive but statistically robust finding, as these methods appear very different mechanistically, one biological and one physical, yet both converge on high nutrient concentration and enhanced mineral retention. This convergence was not apparent from the univariate tables alone and was only revealed through the HCA. Such findings illustrate the analytical value of chemometric methods in uncovering hidden structural patterns in multivariate nutritional datasets (Beebe et al., 1998; Hair et al., 2010; Jolliffe & Cadima, 2016).

4.4 Implications for Functional Food Development and Dietary Recommendations

The findings of this study have direct practical implications for food system actors, including food scientists, nutritionists, public health practitioners, and policymakers, operating in regions where sweet potato and sorghum are dietary staples. The identification of drying and fermentation as the optimal processing strategies for mineral and protein retention positions these methods as preferred candidates for incorporation into functional food manufacturing pipelines targeting micronutrient-deficient populations. Fermentation, in particular, offers the dual advantage of reducing anti-nutritional factors (such as phytic acid and tannins) while simultaneously preserving or enhancing nutrient bioavailability, a combination that is not achievable through purely thermal methods (Rashwan et al., 2021; Olanipekun et al., 2015).

The chemometric framework established in this study also provides a template for future studies investigating the interactive effects of processing on bioactive compounds, including carotenoids, polyphenols, and flavonoids, whose multidimensional variation across processing methods remains insufficiently characterised for both sweet potato and sorghum. Future research employing extended PCA and HCA datasets that incorporate antioxidant activity, in vitro digestibility, and anti-nutritional factor concentrations as additional variables would further refine the classification of processing methods and support the development of processing guidelines optimised not only for macronutrient and mineral content but also for functional phytochemical retention (Morais et al., 2018; Adepoju et al., 2020; Awika & Rooney, 2004).

5. Conclusion

This study employed chemometric profiling, integrating PCA and HCA with comprehensive proximate and mineral analysis, to systematically characterise and classify processing-induced nutrient transformations in sweet potato (*Ipomoea batatas*) and sorghum (*Sorghum bicolor*). PCA demonstrated that the first two principal components collectively explained 85.9% of total compositional variance, with moisture dominating PC1 and fat–protein interactions structuring PC2 variation. HCA resolved four statistically and nutritionally coherent clusters — raw controls, boiled, dried-fermented, and fried-microwaved — each characterised by distinct nutrient retention patterns. Drying and fermentation emerged as the most nutritionally beneficial processing methods for both crops, consistently yielding elevated protein and mineral concentrations alongside reduced moisture. Boiling was associated with the most significant mineral losses, attributable to leaching into cooking water, and formed a distinct cluster separated from all other methods. Frying introduced substantial fat content while maintaining moderate mineral retention, and microwaving preserved protein effectively with minimal fat modification. These findings provide a robust, data-driven basis for the optimisation of food processing strategies aimed at enhancing the dietary quality of staple crops in food-insecure regions. The chemometric approach employed herein offers a replicable framework applicable to a broad range of staple crops and processing conditions, with implications extending to functional food formulation, public health nutrition, and sustainable food systems planning.

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