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Nutrient density and antioxidant capacity together with cyanide safety of cassava roots and leaves and ugali flour from smallholder households in Kamonyi District of Rwanda

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Abstract

Background

Cassava is a staple food for smallholder households in Rwanda, but root-based diets are low in protein and micronutrients, and inadequately processed cassava can contain hazardous levels of cyanide. This study compared the nutrient composition, cyanide content, and antioxidant capacity of cassava roots, leaves, and ugali flour from smallholder households and estimated their contribution to the nutrient requirements of adult women.

Methods

In a cross-sectional study (May–August 2026), fresh roots, leaves, and ugali flour (36 samples each) were collected from three sampling units in each of the 12 sectors of Kamonyi District. Samples were analysed for proximate composition (AOAC methods), iron, zinc, calcium, and potassium (atomic absorption spectrophotometry), β-carotene (HPLC), vitamin C (2,6-dichlorophenolindophenol titration), hydrogen cyanide (alkaline titration), total phenolics, phytate, and antioxidant capacity (DPPH assay). Products were compared using Welch's analysis of variance with Games–Howell post hoc tests.

Results

All parameters differed significantly among the three products ($p < 0.001$). On a dry-weight basis, leaves contained about 12 times more protein (24.7 ± 1.3 vs 2.1 ± 0.3 g/100 g) and 15 times more iron (18.6 ± 1.4 vs 1.2 ± 0.2 mg/100 g) than roots, with much higher zinc, calcium, β-carotene, vitamin C, and phenolics, and the strongest antioxidant activity. Fresh roots contained 47.3 ± 5.8 mg hydrogen cyanide/kg fresh weight, close to the Codex maximum of 50 mg/kg for sweet cassava, whereas ugali flour contained 6.2 ± 1.1 mg/kg, within the 10 mg/kg limit for cassava flour; the flour, however, contained over 90% less vitamin C than fresh roots. On a fresh-weight basis, 100 g of raw leaves could supply about 23% of the iron, 10% of the vitamin A, and 57% of the vitamin C requirements of adult women, compared with 12% or less from fresh roots.

Conclusions

Cassava leaves are a nutrient-dense, under-used food for cassava-reliant households, and locally processed ugali flour met the cyanide limit but retained little vitamin C. Promoting safe preparation and greater consumption of leaves, and refining flour processing to conserve vitamins, could improve diet quality; intervention studies are needed to confirm effects on nutrient intake and status.

Introduction

Cassava (*Manihot esculenta* Crantz) is one of the most important staple crops in the tropics. It provides dietary energy to an estimated 800 million people worldwide and serves as a food-security crop for smallholder farmers across sub-Saharan Africa because it tolerates drought and poor soils and can be harvested over a long period (Borku, 2025; Sakadzo et al., 2025). In Rwanda, cassava is one of the principal staples, particularly in the Southern Province, where districts such as Kamonyi combine extensive cassava cultivation with a large population of smallholder farming households (Kilwinger et al., 2021; Nyirakanani et al., 2021). The roots are mostly consumed after peeling, drying, and milling into flour, which is cooked in boiling water into a stiff dough known locally as ugali (ubugali), while the young leaves are pounded and cooked into a vegetable relish (isombe) that is eaten with starchy staples.

The two edible parts of the plant differ markedly in nutritional value. Cassava roots are rich in starch but poor in protein, fat, minerals, and most vitamins, so diets dominated by roots can meet energy needs while leaving micronutrient requirements unmet (Montagnac et al., 2009a), a limitation also emphasised in recent reviews (Borku, 2025; Forkum et al., 2025). Cassava leaves, by contrast, have been reported to contain substantial amounts of protein, iron, zinc, calcium, β-carotene, and vitamin C, and they are rich in phenolic compounds with antioxidant activity (Latif & Müller, 2015). They have therefore been described as an under-exploited food resource that could complement root-based diets. At the same time, the polyphenols and phytate in leaves can bind iron and zinc and reduce their absorption (Borku, 2025; Samtiya et al., 2020), so the nutritional benefit of leaves cannot be judged from their total mineral content alone. Despite this potential, the contribution of cassava leaves to household diets is rarely quantified, and data on their composition as consumed in East African households remain scarce.

Beyond their nutrient content, cassava leaves are a rich source of phenolic compounds, including flavonoids, which give them considerable antioxidant capacity (Latif & Müller, 2015). Dietary antioxidants may help to limit oxidative stress, although the health relevance of in vitro assays such as the DPPH test is limited, and such measurements are best interpreted as indicators of phenolic quality rather than of a health benefit. Measuring antioxidant capacity alongside phenolic content nevertheless allows the effects of drying and milling on these heat- and oxygen-sensitive compounds to be compared across products. Moreover, much of the published composition data for cassava leaves comes from West Africa, South America, and Asia, where varieties, soils, and preparation practices differ from those in Rwanda, so these values may not apply directly to Rwandan households (Latif & Müller, 2015; Montagnac et al., 2009a).

Micronutrient deficiencies, often termed hidden hunger, remain a major public-health problem in sub-Saharan Africa, where anaemia and deficiencies of iron, zinc, and vitamin A persist among young children and women of reproductive age (Wegmüller et al., 2020). In Rwanda, the 2019–20 Demographic and Health Survey reported that 33% of children under five years of age were stunted and that anaemia affected more than one-third of children aged 6–59 months (National Institute of Statistics of Rwanda et al., 2021). Low dietary diversity is a key underlying cause: studies in rural Rwanda have shown that many women consume few food groups and that dietary diversity is associated with homestead production and access to markets (Dusingizimana et al., 2025; Uwase et al., 2024). Locally available and indigenous

foods have been proposed as an affordable route to more diverse and nutrient-dense diets (Akinola et al., 2020; Rampa et al., 2020), and cassava leaves, which grow on the same plants as the roots, are an obvious candidate.

The nutritional value of cassava must, however, be balanced against its toxicological risks. All cassava tissues contain the cyanogenic glycosides linamarin and lotaustralin, which release hydrogen cyanide (HCN) when the tissue is damaged and the glycosides are hydrolysed by the endogenous enzyme linamarase (Panghal et al., 2021; Terefe et al., 2022). Inadequately processed cassava has been linked to acute cyanide poisoning and, where diets are monotonous and low in protein, to chronic neurological disorders such as konzo and tropical ataxic neuropathy (Nhassico et al., 2008). To protect consumers, the Codex Alimentarius sets a maximum total HCN content of 50 mg/kg for fresh sweet cassava and 10 mg/kg for edible cassava flour (Codex Alimentarius Commission, 1989, 2003). Cassava products therefore need to be assessed for both their nutrient content and their residual cyanide.

Processing is central to both the safety and the nutritional quality of cassava foods. Peeling, soaking, fermentation, grating, sun-drying, and boiling reduce the cyanogen content to varying degrees, but their effectiveness depends on the method, its duration, and the care with which it is carried out (Cardoso et al., 2005; Montagnac et al., 2009b). The same operations can also cause large losses of water-soluble and heat- or oxygen-sensitive nutrients, particularly vitamin C and carotenoids, so a process that is optimal for detoxification may not be optimal for nutrition (Montagnac et al., 2009b). For cassava leaves, mild processing methods that remove most cyanogens while conserving key nutrients have been described (Bradbury & Denton, 2011). In Rwanda, however, the dominant household route from root to food—peeling, sun-drying for several days, and milling into ugali flour—has not been evaluated simultaneously for its residual cyanide and its nutrient content.

Agricultural approaches that link on-farm production to household nutrition provide a further rationale for this work. Farm production diversity has been associated with household dietary diversity in sub-Saharan Africa (Fremmpong et al., 2023; Sekabira et al., 2022), both through home consumption and through income and market channels (Muthini et al., 2020; Ogutu et al., 2020). Because cassava is already grown by most smallholder households in the region (Borku, 2025; Sakadzo et al., 2025), greater use of its leaves requires little additional land or cash. Reliable local composition data are, however, a prerequisite for nutrition-sensitive recommendations, for national food-composition tables, and for the design of food-to-food fortified products such as composite flours containing leaf powder.

Despite the importance of cassava in Rwandan diets, few published studies have characterised the nutrient composition, cyanogenic potential, and antioxidant capacity of the cassava products that are actually available to smallholder households, and, to our knowledge, none has compared roots, leaves, and locally processed ugali flour within a single sampling frame. Such data are needed to judge whether cassava leaves can make a meaningful contribution to micronutrient intakes, and whether locally processed flour is both safe and nutritionally adequate.

This study therefore aimed to (1) characterise the proximate, mineral, vitamin, anti-nutritional, and antioxidant profiles of fresh cassava roots, cassava leaves, and ugali flour sampled across all 12 sectors of Kamonyi District, Rwanda; (2) assess the HCN content of these products against Codex Alimentarius limits; (3) compare the composition of the raw materials with that of the principal locally processed product as an indicator of the nutrient differences associated with processing; and (4) estimate the potential contribution of each product to the daily nutrient requirements of adult women.

Methods

Study design and setting

The analytical study was conducted as a cross-sectional sampling study in Kamonyi District, Rwanda (approximately 2°00' S, 29°46' E) during the period from May to August 2026. Located in the Southern Province of Rwanda, Kamonyi District comprises 12 administrative sectors, with agriculture being the primary economic activity. The district was intentionally selected due to its significant cassava production and the presence of a representative population of smallholder farming households.

Sample collection and preparation

Three categories of cassava products were examined: (1) fresh cassava roots, including three local varieties: TMS 30572, NASE 14, and a local landrace; (2) cassava leaves, specifically the young, tender leaves located at the third to fifth position from the apex; and (3) ugali flour, which involves traditional processing methods such as peeling, sun-drying for 3–4 days, and manual grinding. Fresh cassava roots were directly purchased from cassava-growing households across all 12 sectors in the Kamonyi District. The maturity (10–12 months post-planting) and disease-free criteria were applied to control for maturity-related compositional variation among roots. Cassava leaves were collected from local markets and household gardens within these 12 sectors and were analyzed fresh, without blanching or cooking. Ugali flour samples were obtained from both commercially produced and home-produced sources available in local markets and domestic manufacturers, reflecting the flour that is actually available to and consumed by local households, not all of which is home-milled; this mixed sourcing is a scope limitation relative to a strictly household-processed sample and is noted in Section 4.4.

Sampling design and sample size

Stratified sampling was used to cover Kamonyi District, with its 12 administrative sectors as strata. In each sector, three sampling units were selected at random for each product type (households for fresh roots; household gardens or local markets for leaves; local markets or domestic producers for ugali flour, as described in Section 2.2), giving 36 samples per product type and 108 samples in total. Because the aim was to compare the composition of three product types rather than to estimate a population prevalence, no prevalence-based sample-size formula was applied; with 36 independent samples per

product type, a one-way ANOVA has more than 95% power (α = 0.05) to detect a large between-group difference (Cohen's f = 0.40).

Each sample was analyzed in triplicate. Fresh samples were transported to the Rwanda Standards Board (RSB) Laboratory in Kigali in insulated coolers with ice packs (2–4°C); the maximum transport time was 6 h. On arrival, samples were assigned identification codes and stored under appropriate conditions (fresh roots and leaves refrigerated at 4°C; ugali flour, the only sun-dried product, stored at room temperature in sealed containers) until analysis, which began within 24 h of collection.

Chemicals and reagents

The chemicals and reagents utilized were of analytical grade. The solvents employed included absolute ethanol (≥ 99.5%; Merck, Darmstadt, Germany), hydrochloric acid (HCl, 37%, Merck), sulfuric acid (H_2SO_4, 98%, Merck), nitric acid (HNO_3, 65%, Merck), perchloric acid ($HClO_4$, 70%, Merck), and sodium hydroxide (NaOH, 98%, Merck). Ultrapure water with a resistivity of 18.2 MΩ·cm was obtained using the Milli-Q water purification system. Certified reference standards from Sigma-Aldrich (St. Louis, MO, USA) were used for mineral elements, including iron (Fe), zinc (Zn), calcium (Ca), and potassium (K) (1000 mg/L, TraceCERT®). Vitamin standards comprised all-trans-retinol (vitamin A, ≥ 95% purity), β-carotene (≥ 97% purity), and L-ascorbic acid (vitamin C, ≥ 99% purity), all sourced from Sigma-Aldrich. For antioxidant assays, 2,2-diphenyl-1-picrylhydrazyl (DPPH, ≥ 95% purity, Sigma-Aldrich) was used. The analysis of phenolic compounds was conducted using the Folin-Ciocalteu reagent (2N, Sigma-Aldrich) and anhydrous sodium carbonate (Na_2CO_3, ≥ 99.5%, Merck). Potassium hydroxide, n-hexane, acetone, methanol and acetonitrile (HPLC grade), petroleum ether (40–60°C), metaphosphoric acid, glacial acetic acid, 2,6-dichlorophenolindophenol sodium salt, silver nitrate, potassium iodide, ammonium hydroxide, Trolox, sodium phytate, ferric chloride, and sulfosalicylic acid were of analytical or HPLC grade and were obtained from Sigma-Aldrich or Merck. All reagents were stored as per the manufacturer's instructions.

Analytical methods

Proximate composition

The proximate analysis was conducted following the official methods of AOAC International (AOAC International, 2000). Moisture content was determined by air-oven drying at 105°C to constant weight. The estimated crude protein was measured using the Kjeldahl method (AOAC Method 984.13) with a nitrogen conversion factor of 6.25. Total lipid content was assessed through Soxhlet extraction in petroleum ether, following AOAC Method 920.39. Ash content was measured by incinerating the sample in a muffle furnace at 550°C for 6 hours, according to AOAC Method 942.05. Crude fiber was determined by sequential digestion with 1.25% H_2SO_4 and 1.25% NaOH, followed by drying and incineration of the residue, with fiber calculated as the loss in weight on ignition (AOAC Method 962.09). Moisture content is reported separately, on a fresh-weight basis. Carbohydrate content (dry-weight basis) was calculated

by difference from the dry-weight protein, fat, ash, and fiber percentages: Carbohydrate (%) = 100 – (%protein + %fat + %ash + %fiber). The energy value was calculated using the Atwater system: Energy (kcal/100g) = (Protein x 4) + (Fat x 9) + (Carbohydrate x 4); fiber was not included in the energy calculation. Carbohydrate and energy were calculated from the mean composition of each product, and their standard deviations were estimated by error propagation (see Statistical analysis).

Mineral elements

To evaluate the mineral composition, particularly iron, zinc, calcium, and potassium, Atomic Absorption Spectrophotometry (AAS) was utilized. Samples weighing 1.0 ± 0.001 g were digested in a concentrated acid mixture of HNO_3 and $HClO_4$ in a 4:1 volume ratio on a heating block until they were fully dissolved, resulting in clear solutions. After digestion, the samples were cooled and diluted to 50 mL with deionized water, then filtered using Whatman No. 42 filter paper. The Thermo Scientific iCE 3000 Series AAS was employed for elemental analysis, with each element being measured at its specific wavelength: 248.3 nm for Fe, 213.9 nm for Zn, 422.7 nm for Ca, and 766.5 nm for K, using an air-acetylene flame. Calibration curves were created using serial dilutions of certified reference standards in the 0.5-5.0 mg/L range. Quality control measures included analyzing certified reference material (NIST SRM 1570a Spinach Leaves), with an acceptable recovery range of 95–105 percent and a relative standard deviation (RSD) not exceeding 5 percent.

Vitamins

High-Performance Liquid Chromatography (HPLC) was employed to extract and quantify vitamin A, specifically retinol and β-carotene, through UV detection. A 5 g sample underwent saponification with a 10% w/v alcoholic KOH solution at 80°C for 30 minutes in the absence of light. The extraction utilized a hexane: acetone mixture (9:1 v/v), followed by drying under a nitrogen stream and reconstitution in the mobile phase. Chromatographic separation was achieved using a C18 reversed-phase column (250 x 4.6 mm, 5 µm particle size) with a flow rate of 1.0 mL/min, employing a methanol: acetonitrile (85:15 v/v) mobile phase. Measurements for β-carotene and retinol were taken at wavelengths of 450 nm and 325 nm, respectively. Vitamin C (ascorbic acid) was determined by the 2,6-dichlorophenolindophenol (DCIP) titrimetric method (AOAC Method 967.21). Samples were homogenised in a 3% metaphosphoric acid–8% acetic acid extracting solution and filtered, and an aliquot of the filtrate was titrated with standardised DCIP solution to a light rose-pink end point persisting for at least 5 s. The DCIP solution was standardised daily against an L-ascorbic acid standard solution (1 mg/mL), and results were expressed as mg ascorbic acid per 100 g DW.

Hydrogen cyanide, total phenolics, and phytate

Total hydrogen cyanide (HCN) was determined by the alkaline titration method (AOAC Method 915.03). Briefly, 20 g of finely ground sample was macerated with 200 mL of distilled water in a distillation flask

and left to autolyse at room temperature for 2 h to allow enzymatic release of HCN. The mixture was then steam-distilled, and approximately 150 mL of distillate was collected in 20 mL of 2.5% NaOH and made up to 250 mL with distilled water. To 100 mL of this solution, 8 mL of 6 M NH_4OH and 2 mL of 5% KI were added, and the solution was titrated with 0.02 M $AgNO_3$ to a faint but permanent turbidity. HCN content was calculated on the basis that 1 mL of 0.02 M $AgNO_3$ is equivalent to 1.08 mg HCN. The total phenol content was assessed using the Folin-Ciocalteu reagent method. A mixture of 2.5 mL Folin-Ciocalteu reagent and 0.5 mL methanol extracts was prepared, and after 5 minutes, 2.0 mL of a 7.5% w/v Na_2CO_3 solution was added. The absorbance at 760 nm was recorded after 90 minutes in the dark, with results expressed as mg gallic acid equivalents (GAE) per 100 g dry weight. Phytate levels were evaluated using the Wade reagent (0.03% $FeCl_3 \cdot 6H_2O$ and 0.3% sulfosalicylic acid) colorimetric test, with absorbance measured at 500 nm against a sodium phytate standard curve, and results reported as mg phytic acid per 100 g dry weight.

Antioxidant activity

The DPPH free radical scavenging assay was employed to assess the total antioxidant capacity. A sample extract of 0.1 mL was combined with a freshly prepared DPPH solution (2.9 mL, 0.1 mM in methanol), then vortexed and left to mix in the dark at room temperature for 30 minutes. Absorbance was measured at 517 nm against a methanol blank. The DPPH radical scavenging activity was calculated using the formula: Scavenging activity (percentage) = [(A0 - A1)/A0] × 100, where A0 represents the control absorbance and A1 the sample absorbance. Results were expressed as IC50 values (the concentration required to scavenge 50% of DPPH radicals) and Trolox equivalent antioxidant capacity (TEAC), calculated from a Trolox calibration curve (0–500 μM) prepared under the same assay conditions and expressed as μmol Trolox equivalents (TE) per g DW. Quality assurance and quality control. All analytical procedures adhered to Good Laboratory Practice (GLP). Quality assurance measures included: (1) calibration of all analytical instruments prior to analysis; (2) analysis of certified reference materials (CRM) with each sample batch; (3) duplicate or triplicate analysis of 10% of samples to evaluate precision; (4) method blanks to detect contamination; and (5) inter-laboratory proficiency testing. Method accuracy was verified through recovery studies using standard addition, yielding an acceptable recovery range of 90–110%. Precision was expressed as the relative standard deviation (RSD), with all parameters required to have an RSD below 10%. Glassware: Glassware was pre-treated with acid (10% HNO_3 overnight) and rinsed with ultrapure water to remove contaminants, then dried in a clean environment.

Contribution to nutrient requirements. The contribution of each product to the daily nutrient requirements of adult women (19–50 years) was calculated per 100 g of product on a fresh-weight (as-sampled) basis. Dry-weight results were first converted to fresh weight using the mean moisture content of each product [nutrient (FW) = nutrient (DW) × (100 − moisture %)/100], and the contribution was calculated as: % requirement = (nutrient per 100 g FW ÷ reference value) × 100. Reference values were the Dietary Reference Intakes for women aged 19–50 years: Recommended Dietary Allowances of 18 mg iron, 8 mg zinc, 1000 mg calcium, 700 μg retinol activity equivalents (RAE) vitamin A, and 75 mg vitamin C, and an

Adequate Intake of 2600 mg potassium (Institute of Medicine, 2000, 2001, 2011; National Academies of Sciences, Engineering, and Medicine, 2019). Vitamin A was expressed as RAE using a conversion factor of 12 µg dietary β-carotene = 1 µg RAE (Institute of Medicine, 2001). To indicate the likely bioavailability of minerals, phytate:zinc, phytate:iron, and phytate:calcium molar ratios were calculated from the mean phytate and mineral contents of each product (molecular weights: phytic acid 660, zinc 65.4, iron 55.8, calcium 40.1 g/mol) and compared with the critical values of 15, 1, and 0.24, respectively (Gibson et al., 2010). Because cassava leaves were analyzed raw and are normally cooked before consumption, which reduces heat-labile nutrients such as vitamin C, the values for leaves represent upper-bound estimates.

Statistical analysis

Each of the 36 samples per product was analysed in triplicate, and the mean of the triplicate determinations was used as the value for that sample; results are expressed as mean ± standard deviation (SD) of the 36 samples. Because the variances differed markedly among products (the ratio of the largest to the smallest variance was at least 2.9 for every parameter), differences among the three products were tested by Welch's one-way analysis of variance, followed by Games–Howell post hoc comparisons, neither of which assumes equal variances; with 36 samples per group, Welch's test is also robust to moderate departures from normality. For carbohydrate and energy, which were calculated rather than measured, SDs were estimated by first-order error propagation from the SDs of the measured components, assuming that these were independent [carbohydrate: $SD = \sqrt{(SD^2protein + SD^2fat + SD^2fiber + SD^2ash)}$; energy, which simplifies to 400 + 5 × fat − 4 × fiber − 4 × ash: $SD = \sqrt{(25\ SD^2fat + 16\ SD^2fiber + 16\ SD^2ash)}$], and the same tests were applied. Pearson's correlation coefficient was used to assess the relationship between total phenolic content and DPPH radical-scavenging activity across all 108 samples. Statistical significance was set at $p < 0.05$. To summarise differences between products, the ratio of each mean in leaves and in ugali flour to the corresponding mean in fresh roots was calculated on a dry-weight basis (HCN was converted to dry weight using the mean moisture content) and displayed on a $\log_2$ scale. Data management was performed in IBM SPSS Statistics version 27.0 (IBM Corp., Armonk, NY, USA) and GraphPad Prism version 9.0 (GraphPad Software, San Diego, CA, USA); Welch's analysis of variance and Games–Howell tests were computed in Python 3 with SciPy version 1.17.

Results

Proximate composition

All measured and calculated parameters differed significantly among the three products (Welch's analysis of variance, $p < 0.001$), and Games–Howell comparisons showed that each product differed significantly from the other two for every parameter (Tables 1–5). To summarise these differences, the composition of leaves and ugali flour was expressed relative to that of fresh roots on a dry-weight basis (Fig. 1). Leaves contained between 1.4 (potassium) and 458 (β-carotene) times more of each nutrient than roots, but less carbohydrate and HCN. Ugali flour contained 12–94% less of every nutrient than

fresh roots except fat (50% more) and carbohydrate (similar), with the largest differences for vitamin C (− 94%), HCN (− 94%), and β-carotene (− 75%). There was a notable variation in moisture content across different products, ranging from 12.3 ± 0.6% in ugali flour to 78.2 ± 1.8% in cassava leaves (fresh cassava roots: 63.4 ± 2.1%) ($p < 0.001$). Cassava leaves contained a higher amount of crude protein (24.7 ± 1.3 g/100g DW) compared to fresh roots (2.1 ± 0.3 g/100g DW) and ugali flour (1.8 ± 0.2 g/100g DW), representing approximately 12-fold and 14-fold increases, respectively. Crude fiber was highest in cassava leaves (10.4 ± 0.8 g/100g DW), compared with fresh roots (3.2 ± 0.4 g/100g DW) and ugali flour (2.8 ± 0.3 g/100g DW) ($p < 0.001$). Carbohydrate calculated by difference showed the opposite pattern: ugali flour (92.7 ± 0.4 g/100g DW), fresh roots (91.9 ± 0.6 g/100g DW), and cassava leaves (56.2 ± 1.6 g/100g DW). All samples exhibited relatively low lipid content (0.4–0.9 g/100g DW). The total mineral content (ash) was significantly higher in cassava leaves (7.8 ± 0.5 g/100g DW) compared to fresh roots (2.4 ± 0.3 g/100g DW) and ugali flour (2.1 ± 0.2 g/100g DW) ($p < 0.001$). Calculated energy values were 383 ± 2, 380 ± 2, and 332 ± 4 kcal/100g DW for ugali flour, fresh roots, and cassava leaves, respectively.

Table 1
Proximate composition and energy value of cassava roots, leaves, and ugali flour

Parameter	Fresh roots	Leaves	Ugali flour	Welch's F
Moisture (g/100 g FW)	63.4 ± 2.1^{b}	78.2 ± 1.8^{a}	12.3 ± 0.6^{c}	28893^{***}
Crude protein (g/100 g DW)	2.1 ± 0.3^{b}	24.7 ± 1.3^{a}	1.8 ± 0.2^{c}	5404^{***}
Crude fat (g/100 g DW)	0.4 ± 0.1^{c}	0.9 ± 0.2^{a}	0.6 ± 0.1^{b}	99.0^{***}
Crude fiber (g/100 g DW)	3.2 ± 0.4^{b}	10.4 ± 0.8^{a}	2.8 ± 0.3^{c}	1431^{***}
Ash (g/100 g DW)	2.4 ± 0.3^{b}	7.8 ± 0.5^{a}	2.1 ± 0.2^{c}	2029^{***}
Carbohydrate (g/100 g DW)†	91.9 ± 0.6^{b}	56.2 ± 1.6^{c}	92.7 ± 0.4^{a}	8555^{***}
Energy (kcal/100 g DW)†	380 ± 2^{b}	332 ± 4^{c}	383 ± 2^{a}	2737^{***}

Values are mean ± SD (n = 36 per product). Within a row, means with different superscript letters differ significantly (Games–Howell test, $p < 0.05$); a denotes the highest mean. Welch's F has 2 numerator degrees of freedom; ***$p < 0.001$. †Calculated values: carbohydrate = 100 − (protein + fat + fiber + ash); energy from Atwater factors (4, 9, and 4 kcal/g for protein, fat, and carbohydrate); SDs estimated by error propagation assuming independent components. DW dry weight, FW fresh weight

Mineral composition

Analysis using atomic absorption spectrophotometry revealed a significant difference in the mineral element composition (Table 2). Cassava leaves contained a much higher iron content (18.6 ± 1.4 mg/100g DW) than fresh roots (1.2 ± 0.2 mg/100g DW) and ugali flour (0.9 ± 0.1 mg/100g DW), with increases of 15-fold and 21-fold, respectively. Considering the widespread issue of iron deficiency anemia among women and children in Rwanda, this suggests that cassava leaves could be a valuable

dietary source of iron, although iron bioavailability is likely to be limited by phytate and polyphenols (Section 4.4). Zinc content was also greater in cassava leaves (3.8 ± 0.3 mg/100g DW) compared to fresh roots (0.7 ± 0.1 mg/100g DW) and ugali flour (0.5 ± 0.08 mg/100g DW) ($p < 0.001$). The most pronounced difference was in calcium levels: cassava leaves (456 ± 28 mg/100g DW), fresh roots (124 ± 15 mg/100g DW), and ugali flour (98 ± 12 mg/100g DW) ($p < 0.001$). Potassium levels were measured as follows: cassava leaves (1247 ± 82 mg/100g DW), fresh roots (876 ± 54 mg/100g DW), and ugali flour (723 ± 48 mg/100g DW) (all pairs comparison $p < 0.001$). The Fe: Zn ratio was 4.9:1 in cassava leaves, 1.7:1 in fresh roots, and 1.8:1 in ugali flour.

Table 2
Mineral composition of cassava roots, leaves, and ugali flour

Parameter	Fresh roots	Leaves	Ugali flour	Welch's F
Iron (mg/100 g DW)	1.2 ± 0.2^{b}	18.6 ± 1.4^{a}	0.9 ± 0.1^{c}	2844^{***}
Zinc (mg/100 g DW)	0.7 ± 0.1^{b}	3.8 ± 0.3^{a}	0.5 ± 0.08^{c}	2013^{***}
Calcium (mg/100 g DW)	124 ± 15^{b}	456 ± 28^{a}	98 ± 12^{c}	2506^{***}
Potassium (mg/100 g DW)	876 ± 54^{b}	1247 ± 82^{a}	723 ± 48^{c}	544^{***}
Fe:Zn mass ratio‡	1.7	4.9	1.8	–

Values are mean ± SD (n = 36 per product), determined by atomic absorption spectrophotometry. Within a row, means with different superscript letters differ significantly (Games–Howell test, $p < 0.05$); a denotes the highest mean. Welch's F has 2 numerator degrees of freedom; ***$p < 0.001$. ‡Calculated from mean values and not tested statistically. DW dry weight

Vitamin content

Vitamin content differed significantly among products (Table 3). Cassava leaves contained 3847 ± 246 µg β-carotene/100 g DW (equivalent to 321 µg RAE/100 g DW), whereas fresh roots and ugali flour contained less than 10 µg/100 g DW ($p < 0.001$), a difference of more than 400-fold. Vitamin C was also much higher in leaves (197 ± 14 mg/100 g DW) than in fresh roots (24 ± 3 mg/100 g DW), while ugali flour contained only 1.4 ± 0.3 mg/100 g DW. The more than 90% lower vitamin C content of ugali flour relative to fresh roots is consistent with the known sensitivity of ascorbic acid to heat, light, and oxygen during sun-drying.

Table 3
Vitamin content of cassava roots, leaves, and ugali flour

Parameter	Fresh roots	Leaves	Ugali flour	Welch's F
β-Carotene (µg/100 g DW)	8.4 ± 1.2^{b}	3847 ± 246^{a}	2.1 ± 0.4^{c}	4780^{***}
Vitamin A (µg RAE/100 g DW)§	0.7 ± 0.1^{b}	321 ± 21^{a}	0.2 ± 0.03^{c}	4781^{***}
Vitamin C (mg/100 g DW)	24 ± 3^{b}	197 ± 14^{a}	1.4 ± 0.3^{c}	4452^{***}

Values are mean ± SD (n = 36 per product). Within a row, means with different superscript letters differ significantly (Games–Howell test, $p < 0.05$); a denotes the highest mean. Welch's F has 2 numerator degrees of freedom; ***$p < 0.001$. §Calculated from β-carotene using a conversion factor of 12 µg β-carotene = 1 µg RAE (Institute of Medicine, 2001). DW dry weight, RAE retinol activity equivalents

Hydrogen cyanide and anti-nutritional factors

Table 4 illustrates that anti-nutritional factors were measured to highlight important food safety issues. Fresh cassava roots were found to contain an average of 47.3 ± 5.8 mg HCN/kg of fresh weight, which is close to the Codex Alimentarius maximum of 50 mg HCN/kg fresh weight for sweet cassava (Codex Alimentarius Commission, 2003); the lower limit of 10 mg/kg applies to cassava flour rather than to fresh roots (Codex Alimentarius Commission, 1989). Such roots therefore require adequate processing before consumption(Borku et al., 2025; Forkum et al., 2025). Ugali flour contained 6.2 ± 1.1 mg HCN/kg, below the Codex limit of 10 mg/kg for edible cassava flour (Codex Alimentarius Commission, 1989; Fig. 2). Because roots and flour differ greatly in moisture content, the difference is better expressed on a dry-weight basis: calculated from the mean values, HCN was approximately 129 mg/kg DW in fresh roots and 7.1 mg/kg DW in ugali flour, a difference of about 94% (87% when the as-sampled values are compared directly). Because the flour samples were not produced from the sampled roots, this figure describes the difference between the two products rather than a measured processing loss. Cassava leaves contained 12.4 ± 2.3 mg HCN/kg FW. The cassava leaves had the highest total phenolic content (876 ± 54 mg GAE/100g DW), followed by the fresh roots (234 ± 18 mg GAE/100g DW), and lastly, ugali flour (187 ± 15 mg GAE/100g DW) ($p < 0.001$). Phytate levels were recorded as follows: cassava leaves (543 ± 42 mg/100g DW), fresh roots (186 ± 14 mg/100g DW), and ugali flour (124 ± 11 mg/100g DW) ($p < 0.001$). The 33% lower phytate content of ugali flour relative to fresh roots is consistent with partial degradation during processing. Phytate:mineral molar ratios calculated from the mean values were 14.2 (zinc), 2.5 (iron), and 0.07 (calcium) for cassava leaves, 26.3, 13.1, and 0.09 for fresh roots, and 24.6, 11.7, and 0.08 for ugali flour. All three products therefore exceeded the critical phytate:iron ratio of 1, roots and flour exceeded the critical phytate:zinc ratio of 15, and none exceeded the critical phytate:calcium ratio of 0.24 (Fig. 3).

Table 4
Hydrogen cyanide, total phenolics, and phytate in cassava roots, leaves, and ugali flour

Parameter	Fresh roots	Leaves	Ugali flour	Welch's F
Hydrogen cyanide (mg/kg, as sampled)¶	47.3 ± 5.8[a]	12.4 ± 2.3[b]	6.2 ± 1.1[c]	925***
Total phenolics (mg GAE/100 g DW)	234 ± 18[b]	876 ± 54[a]	187 ± 15[c]	2692***
Phytate (mg/100 g DW)	186 ± 14[b]	543 ± 42[a]	124 ± 11[c]	1730***

Values are mean ± SD (n = 36 per product). Within a row, means with different superscript letters differ significantly (Games–Howell test, $p < 0.05$); a denotes the highest mean. Welch's F has 2 numerator degrees of freedom; ***$p < 0.001$. ¶Fresh weight for roots and leaves and as sold for ugali flour; Codex Alimentarius maximum levels are 50 mg/kg fresh weight for sweet cassava (Codex Alimentarius Commission, 2003) and 10 mg/kg for edible cassava flour (Codex Alimentarius Commission, 1989). DW dry weight, GAE gallic acid equivalents

Antioxidant capacity

DPPH radical-scavenging assays showed significant differences in antioxidant capacity among products (Table 5). Cassava leaves had the highest antioxidant activity (IC50 = 147 ± 12 µg/mL; TEAC = 428 ± 32 µmol TE/g DW), fresh roots were intermediate (IC50 = 386 ± 28 µg/mL; TEAC = 156 ± 14 µmol TE/g DW), and ugali flour had the lowest activity (IC50 = 512 ± 45 µg/mL; TEAC = 98 ± 11 µmol TE/g DW) ($p < 0.001$). Total phenolic content correlated strongly with DPPH radical-scavenging activity (Pearson $r = 0.923$, $n = 108$, $p < 0.001$), suggesting that phenolic compounds are major contributors to antioxidant activity.

Table 5
Antioxidant capacity of cassava roots, leaves, and ugali flour

Parameter	Fresh roots	Leaves	Ugali flour	Welch's F
DPPH IC_{50} (µg/mL)	386 ± 28[b]	147 ± 12[c]	512 ± 45[a]	1986***
TEAC (µmol TE/g DW)	156 ± 14[b]	428 ± 32[a]	98 ± 11[c]	1726***

Values are mean ± SD (n = 36 per product). Within a row, means with different superscript letters differ significantly (Games–Howell test, $p < 0.05$); a denotes the highest mean. Lower IC_{50} values indicate stronger radical-scavenging activity. Welch's F has 2 numerator degrees of freedom; ***$p < 0.001$. DPPH 2,2-diphenyl-1-picrylhydrazyl, DW dry weight, IC_{50} concentration giving 50% radical scavenging, TE Trolox equivalents, TEAC Trolox equivalent antioxidant capacity

Contribution to nutrient requirements

The estimated contributions to the daily requirements of adult women differed markedly among products (Fig. 4). On a fresh-weight basis, 100 g of raw cassava leaves would supply approximately 23% of the iron, 10% of the zinc and calcium, 11% of the potassium, 10% of the vitamin A, and 57% of the vitamin C requirements of adult women. In contrast, 100 g of fresh roots would supply 2–12% of each requirement and less than 1% of vitamin A, and 100 g of ugali flour less than 1–9% of each requirement

except potassium (24%). Because cassava leaves are cooked before consumption, their actual contribution, particularly of vitamin C, is likely to be lower than these raw-leaf estimates.

Discussion

Nutritional differences among cassava products

This study shows that the three cassava products available to smallholder households in Kamonyi District differ markedly in nutritional value, with every measured parameter differing significantly among roots, leaves, and ugali flour. Cassava leaves were by far the most nutrient-dense product, providing more protein, minerals, vitamins, phenolics, and antioxidant capacity than either fresh roots or flour. These findings are consistent with earlier reports of the nutritional superiority of cassava leaves (da Silva Santos et al., 2020; Lambebo et al., 2025) and extend them to products sampled directly from Rwandan smallholder households. The leaf protein content observed here (24.7 g/100 g DW) falls within the range reported in reviews of cassava leaf composition (Latif & Müller, 2015; Montagnac et al., 2009a) and is about 12 times that of the roots. Because diets based on starchy staples are typically low in protein, greater use of cassava leaves could improve household protein intake, although leaf protein is limited in sulphur-containing amino acids and is best complemented with legumes or animal-source foods (Latif & Müller, 2015).

The high mineral density of the leaves makes them a plausible low-cost source of iron, zinc, and calcium, but total mineral content overstates the amount that is absorbed. The leaves also contained the highest phytate and phenolic concentrations, and both compounds inhibit non-haem iron and zinc absorption (Borku, 2025; Samtiya et al., 2020). The phytate:mineral molar ratios calculated in this study illustrate this point. All three products exceeded the critical phytate:iron ratio of 1, indicating that iron absorption from cassava foods is likely to be poor, whereas only the leaves had a phytate:zinc ratio below the critical value of 15 (Gibson et al., 2010). In relative terms, therefore, the zinc in cassava leaves is likely to be more available than that in roots or flour. Because these ratios were calculated from product means, they should be confirmed with paired measurements and, ideally, with in vitro digestion or absorption studies.

Effects of processing on cyanide safety and nutrient content

The mean HCN concentration in fresh roots (47.3 mg/kg FW) was close to the Codex maximum of 50 mg/kg for sweet cassava (Codex Alimentarius Commission, 2003), and, given the standard deviation of 5.8 mg/kg, a substantial proportion of individual root samples is likely to have exceeded this limit. On a dry-weight basis, the mean root value corresponds to about 129 mg/kg, so flour produced from such roots without adequate detoxification would far exceed the 10 mg/kg limit for cassava flour (Codex Alimentarius Commission, 1989). Thorough processing is therefore essential, because acute cyanide poisoning can cause serious neurological effects, and chronic dietary exposure, particularly when

combined with low protein intake, has been linked to tropical ataxic neuropathy and konzo (Nhassico et al., 2008), as summarised in recent reviews (Bayode et al., 2025; Howard et al., 2024). The HCN content measured in fresh leaves (12.4 mg/kg FW) is lower than many values reported for cassava leaves, which are usually richer in cyanogens than the roots (Latif & Müller, 2015), and it should be interpreted with caution. Because leaves are pounded and boiled before they are eaten, residual cyanide in prepared leaf dishes is expected to be lower still (Bradbury & Denton, 2011).

Ugali flour contained 6.2 mg HCN/kg, within the Codex limit, indicating that the peeling, sun-drying, and milling practised locally generally achieved adequate detoxification (Forkum et al., 2025). This is consistent with the established mechanism: disruption of the tissue brings the cyanogenic glycosides into contact with linamarase, and the released HCN volatilises during drying (Cardoso et al., 2005; Montagnac et al., 2009b). Residual cyanogen levels in traditionally processed cassava flours vary considerably across Africa and depend on the duration and conditions of each processing step (Cardoso et al., 2005), so routine monitoring of household and market flours remains advisable. The flour, however, contained more than 90% less vitamin C and about 75% less β-carotene than fresh roots on a dry-weight basis. Because the flour and root samples were not paired, these differences reflect both processing losses and variation in the raw material, but they are consistent with the known instability of ascorbic acid and carotenoids during sun-drying and storage (Montagnac et al., 2009b). Processing methods that achieve adequate detoxification while limiting exposure to heat, light, and oxygen, such as shorter drying in shaded or solar dryers, deserve evaluation in this setting.

Implications for dietary diversification

The large nutritional differences between cassava leaves and roots offer a practical opportunity for diet diversification in cassava-dependent households (Borku, 2025; Borku et al., 2025). Our estimates indicate that 100 g of raw cassava leaves could supply about 23% of the daily iron, 10% of the vitamin A, and 57% of the vitamin C requirements of adult women, nutrients that are typically lacking in cassava-based diets. Even allowing for losses during cooking and for limited mineral bioavailability, regular consumption of leaf dishes such as isombe alongside ugali would add meaningful amounts of micronutrients at little extra cost, because the leaves are harvested from plants that the household already grows. This is in line with growing evidence that crop diversification and the use of on-farm biodiversity can strengthen nutrition security (Gawdiya et al., 2025; Mihrete & Mihretu, 2025). Food-to-food fortification, for example composite flours in which part of the cassava flour is replaced by dried leaf powder, offers a further route to improving the nutrient density of ugali, provided that the leaf material is adequately detoxified. Mild processing methods for cassava leaves that remove most cyanogens while conserving key nutrients have been described (Bradbury & Denton, 2011), and the choice of processing method strongly influences nutrient retention in cassava products more generally (Montagnac et al., 2009b). The acceptability, safety, and nutritional benefit of such products for Rwandan consumers should now be tested.

Limitations and future research

There are a number of limitations that should be considered in this study. First, only one processed product (ugali flour) was analyzed against its raw materials; comparably processed, more directly comparable local preparations (e.g., boiled or pounded cassava, cassava bread, cooked leaf relish) were not sampled, so the compositional comparison across roots, leaves, and flour should be read as a raw-material-to-processed-product comparison rather than a comparison of interchangeable, equally consumed foods. Second, hydrogen cyanide was measured in fresh roots and in dry ugali flour, not in a cooked, ready-to-eat form; cyanide levels at the point of consumption may differ from both of these. Third, we could not determine the mineral bioavailability, although we determined the total mineral content, which might be highly affected by anti-nutritional components like phytates and polyphenols. In the future, models of in vitro digestion or in vivo bioavailability should be used as a way of establishing the real mineral absorption of cassava products. Fourth, only vitamins A and C were analyzed; a more detailed characterization of B-complex vitamins, vitamin E, and other micronutrients would be a comprehensive nutritional characterization. Fifth, seasonal variation in nutrient composition was not investigated. Sixth, the ugali flour samples were not produced from the sampled roots, so differences between roots and flour reflect both processing and raw-material variation rather than paired measurements of processing losses. Seventh, three root varieties (TMS 30572, NASE 14, and a local landrace) were pooled within the root category, and variety was not analyzed as a factor; varietal differences, particularly in cyanogenic potential, may have contributed to the variability observed. Finally, the SDs of the calculated carbohydrate and energy values and the phytate:mineral molar ratios were derived from product means rather than from individual samples. Further research is warranted to explore: (1) the most effective processing techniques that would maximize cyanide removal with little vitamin loss; (2) the acceptability and suitability of cassava leaf incorporation techniques to consumers; (3) long-term intervention research into the effects of cassava leaf intake on biomarkers of micronutrient status; and (4) economical feasibility analysis of cassava leaf production and marketing systems to smallholder farmers.

Conclusions

This nutritional and food-safety analysis highlights significant variation in the composition of cassava roots, leaves, and processed ugali flour sampled in Kamonyi District, Rwanda. Cassava leaves show a substantially better nutritional profile than cassava roots and processed ugali flour, particularly in protein, minerals (iron, zinc, and calcium), vitamins (A and C), and antioxidant capacity. Fresh roots contained hydrogen cyanide close to the Codex maximum for sweet cassava and therefore require thorough processing before consumption. Locally processed ugali flour met the Codex cyanide limit for cassava flour but contained much less vitamin C than fresh roots. On a fresh-weight basis, 100 g of raw leaves could supply about one-quarter of an adult woman's daily iron requirement and over half of her vitamin C requirement, although cooking will reduce the latter. These compositional findings suggest that greater incorporation of cassava leaves, together with optimized processing and food-to-food fortification strategies, is a promising approach to improving dietary quality in cassava-reliant households; confirming an actual improvement in dietary diversity, micronutrient adequacy, or nutritional

security would require follow-up intervention research, as these outcomes were not measured in this study.

Abbreviations

AAS
Atomic Absorption Spectrophotometry
ANOVA
Analysis of Variance
AOAC
Association of Official Analytical Chemists
CRM
Certified Reference Material
DCIP
2, 6-Dichlorophenolindophenol
DPPH
2, 2 -Diphenyl- 1-picrylhydrazyl
DW
Dry Weight
FW
Fresh Weight
GAE
Gallic Acid Equivalents
GLP
Good Laboratory Practice
HCN
Hydrogen Cyanide
NaOH
Sodium Hydroxide
TE
Trolox Equivalents
HPLC
High-Performance Liquid Chromatography
IC50
half-maximal inhibitory concentration
RAE
Retinol Activity Equivalents
RSB
Rwanda Standards Board
TEAC

Trolox Equivalent Antioxidant Capacity

Declarations

Ethics approval and consent to participate

Ethical approval for this study was granted in January 2026 by the Catholic University of Rwanda Research Committee, the institutional ethics review board operating under the National Council for Science and Technology (NCST) of Rwanda (approval number CUR/097/2026). The study was conducted in accordance with the relevant guidelines and regulations of the Catholic University of Rwanda Research Committee and the National Council for Science and Technology, and with the ethical principles of the Declaration of Helsinki. Sampling was conducted with the permission of the Kamonyi District Administration and the Sector Executive Secretaries. Written informed consent was obtained from all household representatives who provided samples, after they had been informed of the purpose of the study and of their right to withdraw at any time without penalty. No personal health data were collected. All plant material was obtained from cultivated household gardens and local markets; no wild plant material was collected, and no collection permit was required under Rwandan regulations because cassava is a widely cultivated crop.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

GF conceptualised and designed the study, conducted the fieldwork, performed the laboratory and statistical analyses, and drafted the manuscript. JCD and JN supervised the study, contributed to the methodology, and critically revised the manuscript. EH contributed to data interpretation and critically

revised the manuscript. BM contributed to the food-safety interpretation and data validation and revised the manuscript. All authors read and approved the final manuscript.

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Figures

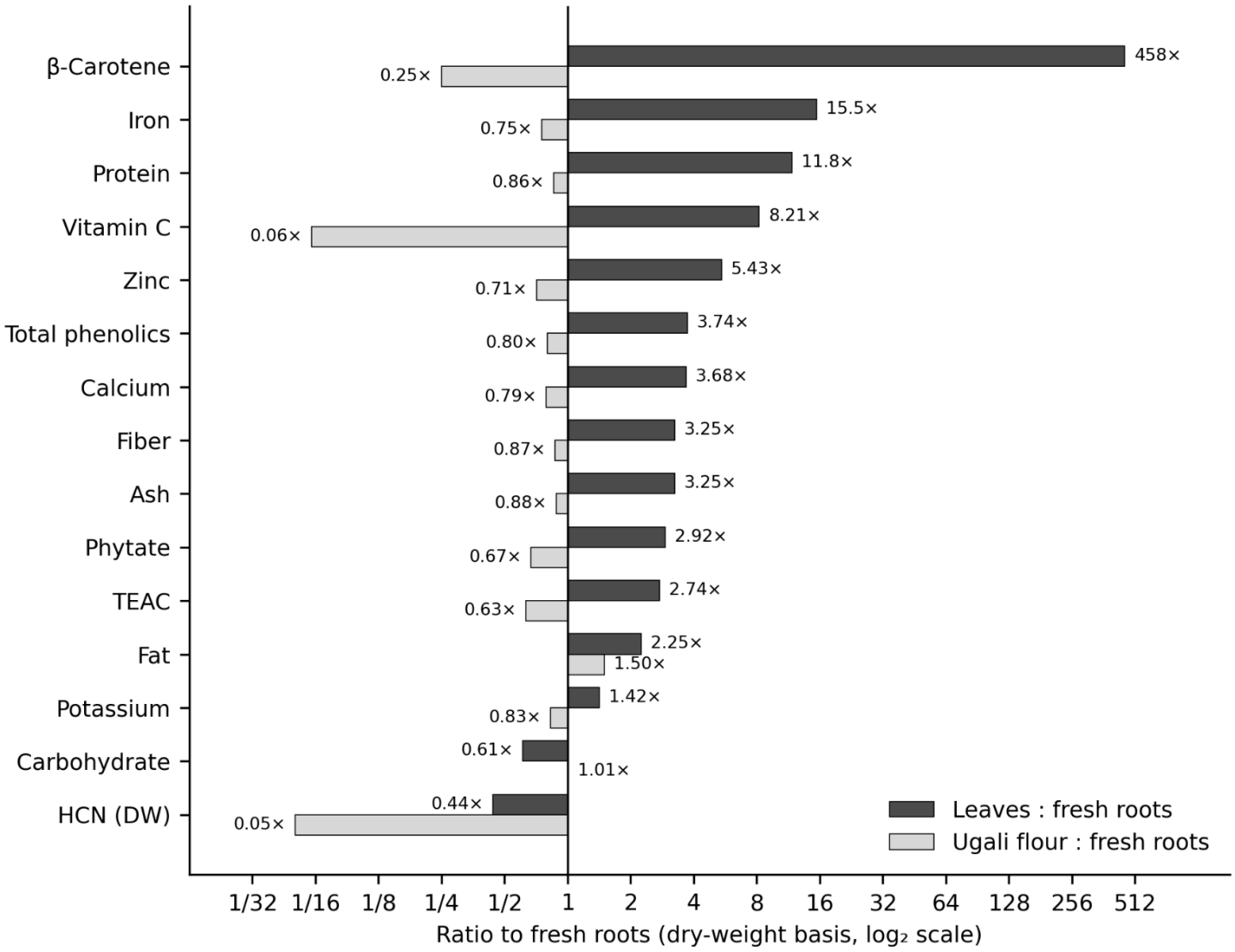


Figure 1

Composition of cassava leaves and ugali flour relative to fresh roots. Bars show the ratio of each product mean to the fresh-root mean on a dry-weight basis (log_2 scale); values greater than 1 indicate a higher content than in fresh roots. HCN values were converted to dry weight using mean moisture contents. HCN hydrogen cyanide, TEAC Trolox equivalent antioxidant capacity

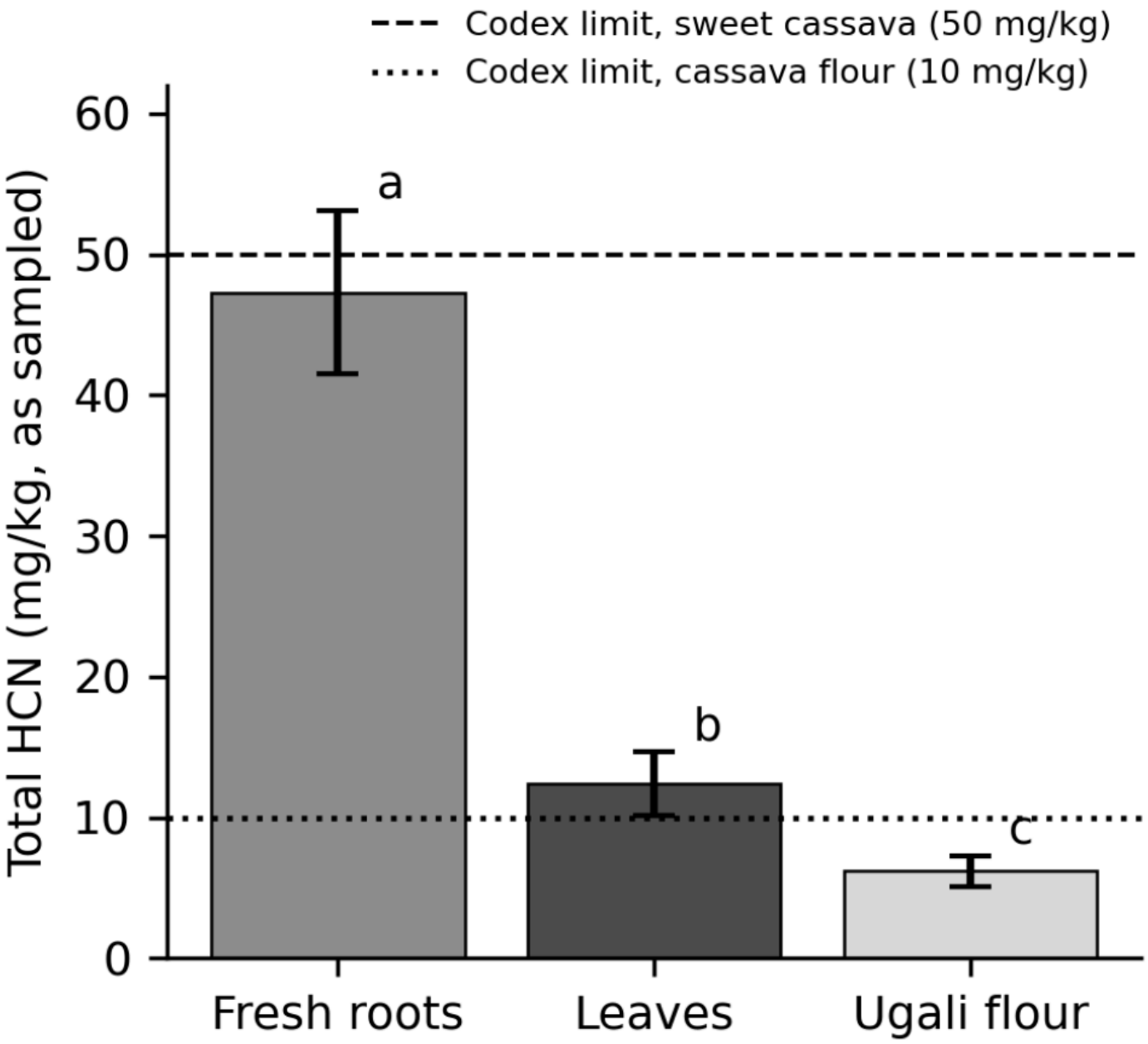


Figure 2

Hydrogen cyanide content of cassava roots, leaves, and ugali flour compared with Codex limits. Bars show mean ± SD (n = 36) on an as-sampled basis. The dashed line marks the Codex maximum for sweet cassava (50 mg/kg fresh weight) and the dotted line the maximum for edible cassava flour (10 mg/kg). Bars with different letters differ significantly (Games–Howell test, $p < 0.05$).

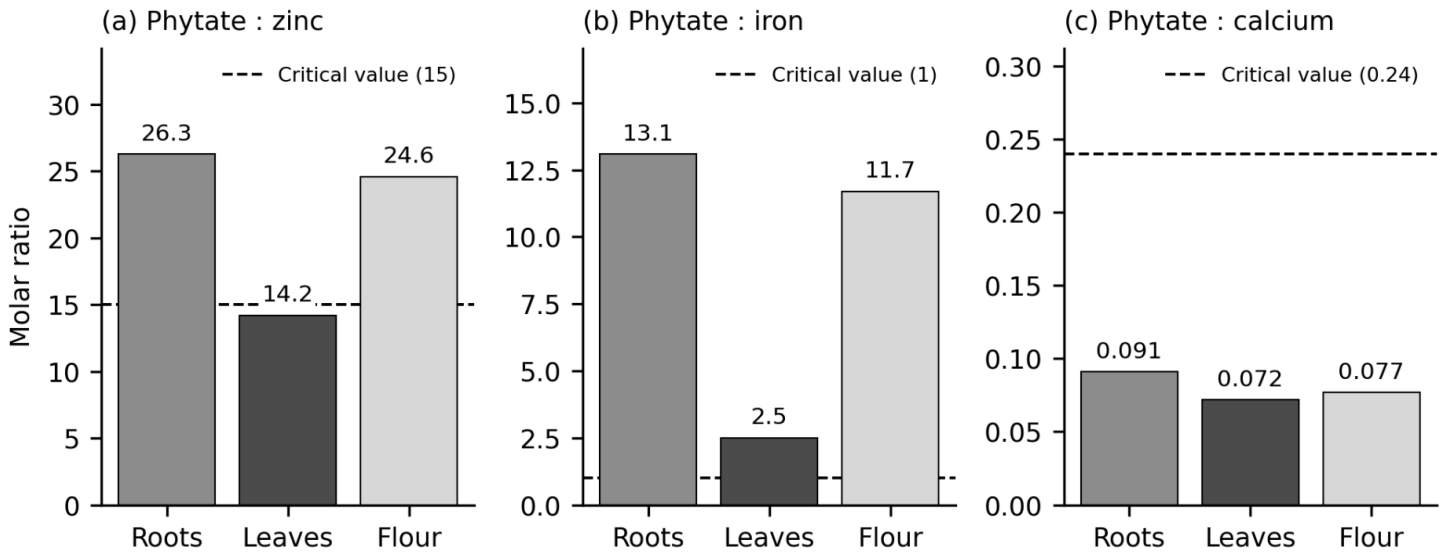


Figure 3

Phytate:mineral molar ratios of cassava roots, leaves, and ugali flour: (a) phytate:zinc, (b) phytate:iron, and (c) phytate:calcium. Ratios were calculated from mean contents (Tables 2 and 4). Dashed lines show the critical values above which mineral absorption is likely to be impaired (15, 1, and 0.24, respectively; Gibson et al., 2010)

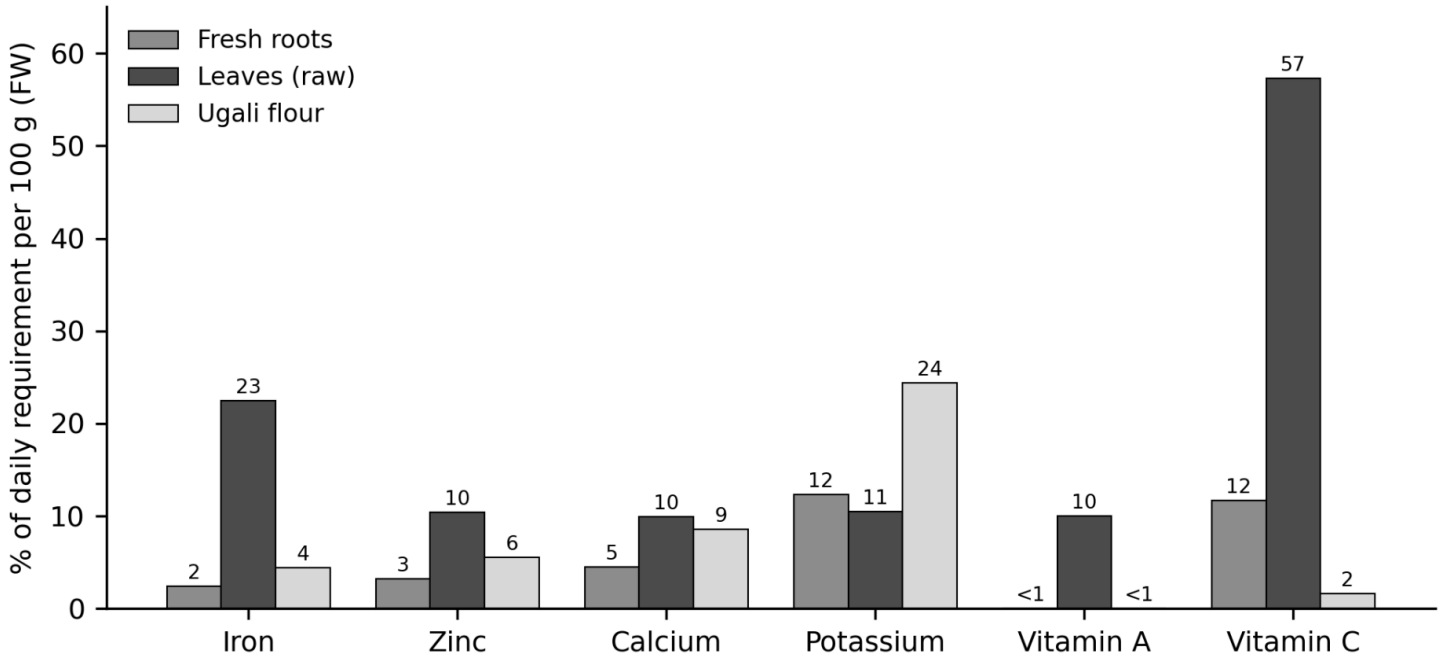


Figure 4

Estimated contribution of 100 g of each cassava product (fresh-weight basis) to the daily nutrient requirements of adult women aged 19–50 years. Values were calculated from mean nutrient and

moisture contents (Tables 1–3) and Dietary Reference Intakes (iron 18 mg, zinc 8 mg, calcium 1000 mg, potassium 2600 mg, vitamin A 700 µg RAE, vitamin C 75 mg). Leaf values refer to raw leaves and are upper-bound estimates.