



Nutraceutical Potential of *Amaranthus* Seeds: A Comparative Analysis of Nutrient and Phytochemical Constituents

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Abstract

This study presents a comprehensive comparative analysis of the nutritional, phytochemical, and anti-nutritional profiles of seeds from six *Amaranthus* species, *A. viridis*, *A. blitum*, *A. hybridus*, *A. caudatus*, and green and red variants of *A. spinosus*. Results revealed significant interspecific variation ($P < 0.05$) in vitamin composition, with the red and green variants of *A. spinosus* exhibiting superior concentrations of vitamins A (19.22 and 18.20 mg/100g, respectively) and C (24.60 and 20.11 mg/100g, respectively), suggesting high antioxidant potential. *Amaranthus hybridus* stood out with the highest protein (21.08%) and calcium (1012.4 mg/100g) content, while *A. viridis* was notably rich in iron (877.4 mg/100g) and zinc (44.2 mg/100g), indicating a promising source of micronutrients for dietary interventions. Phytochemical screening showed *A. hybridus* also had the highest levels of tannins (307.0 mg/100g), phenols, and alkaloids, while anti-nutritional factors such as oxalates and phytates remained within acceptable limits. The findings underscore the potential of *Amaranthus* species seeds particularly *A. hybridus* and *A. spinosus*—as functional food ingredients and nutraceuticals in addressing protein-energy malnutrition and micronutrient deficiencies.

Keywords: *Amaranthus*, nutritional composition, phytochemicals, functional foods, anti-nutritional factors, food security.

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Introduction

Global demand for functional foods and nutraceuticals has heightened interest in underutilized crops with health-promoting properties. *Amaranthus* species, long valued for their nutritional and therapeutic potential, are traditionally cultivated in tropical and subtropical regions and consumed mainly as leafy vegetables, grains, or pseudo-cereals (Das, 2016; Rastogi & Shukla, 2013). While the leaves are widely used, the seeds remain underexploited despite evidence of exceptional nutrient and phytochemical richness.

Amaranthus seeds provide high-quality proteins, unsaturated fatty acids, vitamins (A, C, and B-complex), and essential minerals such as calcium, iron, and magnesium

(Kauffman & Weber, 1990; Nascimento et al., 2013). They also contain diverse bioactive compounds—including flavonoids, tannins, alkaloids, and phenolics that confer antioxidant, antimicrobial, and anti-inflammatory properties (Rastogi & Shukla, 2013; Barba de la Rosa et al., 2009). Their unusually high lysine content further enhances their value in protein-deficient diets (Mlakar et al., 2010). Despite this profile, comparative studies of *Amaranthus* seeds are scarce, particularly in sub-Saharan Africa where multiple species coexist. Such evaluations are essential for identifying nutritionally superior species, guiding food fortification, and supporting crop diversification (Bressani, 1994; Adebooye & Opabode, 2004).

This study therefore investigates six species—*A. blitum*, *A. viridis*, *A. hybridus*, *A. caudatus*, and the red and green variants of *A. spinosus*—to compare their proximate, mineral, vitamin, and phytochemical compositions. The findings aim to highlight candidates for nutraceutical development and dietary inclusion, particularly in regions facing malnutrition and micronutrient deficiencies.

Malnutrition and micronutrient deficiencies remain major public health challenges in sub-Saharan Africa, where access to nutrient-dense foods is limited (FAO, 2017). Although *Amaranthus* leaves are widely consumed, the seeds—rich in protein, minerals, vitamins, and bioactive phytochemicals—are largely neglected (Rastogi & Shukla, 2013; Barba de la Rosa et al., 2009). Existing studies focus on individual species, but comprehensive comparative analyses are lacking (Nascimento et al., 2013; Mlakar et al., 2010). This gap hinders evidence-based dietary diversification and limits the integration of *Amaranthus* seeds into functional food formulations and nutrition programs.

Diversifying affordable, nutrient-rich food sources is critical to addressing food insecurity and diet-related diseases. *Amaranthus* seeds, with their favorable amino acid profile, mineral density, and phytochemical abundance, represent a promising but

underutilized resource (Kauffman & Weber, 1990; Bressani, 1994). By evaluating six species, this study seeks to identify those with superior nutraceutical profiles for food fortification, dietary diversification, and functional food development. The results will inform nutrition-sensitive agricultural policies, encourage utilization of indigenous crops, and contribute to sustainable food systems (Adebooye & Opabode, 2004).

This research also fills a critical knowledge gap in seed-based nutritional data and aligns with global initiatives promoting traditional crops for food and nutrition security (FAO, 2017; WHO, 2014). Therefore, this study is to evaluate and compare the nutraceutical potential of seeds from selected *Amaranthus* species and identify those with superior nutritional and health-promoting qualities.

Materials and Methods

Selection of Study Specimens

Species Selection and Collection: Seeds were collected from four *Amaranthus* species: *A. hybridus*, *A. viridis*, *A. caudatus*, *A. blitum*, alongside two varieties of *A. spinosus*—one red (reddish petiole, stem, fruit) and one green (greenish stem, petiole, leaf) (Fig. 1). These samples were sourced from wild populations in their natural habitats (Table 1). The selection of these species was guided by their known agricultural and medicinal significance (Sarker & Oba, 2020).



Amaranthus blitum



Amaranthus caudatus



Amaranthus hybridus



Amaranthus spinosus (green variant)



Amaranthus spinosus (red variant)



Amaranthus viridis

Fig. 1: Photographs of some *Amaranthus* species used in this study

Table 1: Nigerian species of *Amaranthus* studied

S/No.	Species	Common names
1	<i>Amaranthus hybridus</i> L.	Smooth Pigweed
2	<i>Amaranthus viridis</i> L.	Green Amaranth, Slender Amaranth
3	<i>Amaranthus caudatus</i> L.	Purple Amaranth, a grain/leaf type
4	<i>Amaranthus blitum</i> L.	Purple Amaranth or Guernsey Pigweed
5	<i>Amaranthus spinosus</i> L. (Red variant)	Spiny Amaranth
6	<i>Amaranthus spinosus</i> L. (Green variant)	Spiny Amaranth

Seed Planting and Cultivation

Experimental plots were established at the Botanical Garden, Department of Plant Biology, University of Ilorin. The land was cleared, tilled, and arranged into twelve vegetable beds (two per species). Plots were fenced to prevent herbivory. Seeds of six *Amaranthus* species (*A. blitum*, *A. viridis*, *A. hybridus*, *A. caudatus*, and red and green variants of *A. spinosus*) were sown by broadcasting and watered daily.

Collection of Plant Specimens

Upon maturation, seeds were harvested from distinct populations within each bed during the same growing season to minimize variability. For each sample, species identity, plot code, collection date, and morphological features were recorded.

Sample Preparation

Seeds were washed with distilled water, oven-dried at 60 °C to constant weight, and ground

into fine powder. Powdered samples were stored in airtight containers until analysis.

Nutritional Assessment

Proximate Composition

Moisture, ash, crude protein, crude fat, crude fiber, and carbohydrate contents were determined following AOAC (1990) procedures. Protein was estimated by the Kjeldahl method ($N \times 6.25$), fat by Soxhlet extraction, and carbohydrate by difference.

Mineral Analysis

Samples were digested using a HNO_3 –HCl mixture (3:1) and analyzed for mineral content via Atomic Absorption Spectroscopy (Sahrawat et al., 2002; AOAC, 1990).

Vitamin Analysis

Vitamins A, B₁, B₂, B₃, B₆, C, E, and K were quantified spectrophotometrically following the method of Pkwu (2005), with minor modifications. Standard calibration curves were used for quantification.

Phytochemical Profiling

Sample Preparation

Seeds from six *Amaranthus* taxa (*A. hybridus*, *A. viridis*, *A. cruentus*, *A. blitum*, and red and green variants of *A. spinosus*) were cleaned, air-dried (25–30 °C), and ground into fine powder. Extracts were prepared using aqueous, ethanol, and methanol solvents via Soxhlet extraction for non-volatile compounds and hydrodistillation for essential oils (Nada et al., 2023). Solvent systems of varying polarity were employed to maximize compound recovery.

Qualitative Screening

Preliminary phytochemical screening was conducted following established procedures for the qualitative detection of secondary metabolites in plant materials (Harborne, 1998; Sofowora, 1993; Evans, 2009). Standard chemical tests were employed to detect the major classes of bioactive compounds. Phenolic compounds and tannins were screened using ferric chloride and gelatin tests, respectively, while flavonoids were detected using the alkaline reagent test. Saponins were identified by the froth test, and alkaloids were detected using Dragendorff's reagent. Betalains were assessed by thin-layer chromatography (TLC) using a butanol:acetic acid:water solvent system in a ratio of 4:1:5. Terpenoids were screened using the Salkowski test, whereas cardiac glycosides were detected using the Keller–Killiani test. These conventional qualitative procedures are widely employed in preliminary phytochemical investigations for establishing the presence or absence of major classes of secondary metabolites in plant extracts (Harborne, 1998; Sofowora, 1993; Evans, 2009).

Quantitative Analysis

Quantitative determination of selected phytochemicals was subsequently carried out using standardized analytical procedures. Total phenolic content (TPC) was determined using the Folin–Ciocalteu colorimetric assay and expressed as milligrams of gallic acid equivalents per gram (mg GAE/g) of sample. Total flavonoid content (TFC) was determined using the aluminium chloride colorimetric method and expressed as milligrams of

quercetin equivalents per gram (mg QE/g). Betalain content was quantified using high-performance liquid chromatography (HPLC) equipped with a C18 column, with betanin and indicaxanthin used as reference standards. Saponin content was determined gravimetrically and expressed as a percentage of the extract, whereas alkaloids were quantified following acid–base extraction and subsequent gravimetric or titrimetric determination. The use of chromatographic and spectrophotometric techniques for the characterization and quantification of plant secondary metabolites is consistent with established phytochemical analytical approaches (Harborne, 1998; Evans, 2009).

Statistical Analysis

All analyses were performed in triplicate ($n = 3$), and the results were expressed as mean $\pm$ standard deviation (SD). The data were initially assessed for conformity to the assumptions of parametric statistical analysis. Normality was evaluated using the Shapiro–Wilk test, while homogeneity of variance was assessed using Levene's test. One-way analysis of variance (ANOVA) was subsequently performed to determine whether significant differences existed among the species for the measured variables. Where significant differences were detected, Tukey's honestly significant difference (HSD) post hoc test was used for pairwise comparisons. Statistical significance was established at $p < 0.05$.

The variables subjected to statistical analysis included proximate composition parameters, namely moisture, ash, protein, fat, fibre, and carbohydrate contents; mineral elements, including calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), iron (Fe), zinc (Zn), phosphorus (P), copper (Cu), and manganese (Mn); and vitamins A, B₁, B₂, B₃, B₆, C, and E. Phytochemical variables included saponins, tannins, alkaloids, phenols, and flavonoids, while the anti-nutritional factors analysed were phytates and oxalates. Descriptive bar charts incorporating error bars were generated to facilitate visual comparison of the measured parameters among the studied species. Principal Component Analysis (PCA) was also performed to identify the variables

that contributed most substantially to interspecific variation and to examine patterns of association among the species and the measured biochemical characteristics. All statistical analyses were performed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA) and R version 4.3.1, with the level of statistical significance set at $\alpha = 0.05$.

Results

The comparative nutritional evaluation of six *Amaranthus* species seeds reveals a diverse and nutrient-rich profile, marked by significant interspecies variations in vitamin, mineral, proximate, and phytochemical composition.

Vitamin Composition

Among the vitamins assessed (Table 2), the red and green variants of *Amaranthus spinosus*

emerged as the richest sources of both vitamin A (19.22 and 18.20 mg/100g, respectively) and vitamin C (24.60 and 20.11 mg/100g), significantly surpassing other species ($P < 0.001$). These two variants also contained the highest levels of vitamin B₁ (4.01 and 3.62 mg/100g) and B₂ (2.63 and 2.14 mg/100g), underscoring their superior B-vitamin content. Although *A. caudatus* had a moderate vitamin profile overall, it showed exceptional vitamin E content (6.15 mg/100g), significantly higher than all other species. Vitamin B₃ (niacin) and B₆ (pyridoxine) levels showed less dramatic variation across species, though *A. caudatus* and *A. hybridus* had marginally higher B₃ content. Vitamin K levels were generally low across all species, with *A. hybridus* exhibiting the highest concentration (0.20 mg/100g).

Table 2: Vitamin composition of *Amaranthus* species seeds (mg/100g dry weight)^a

Vitamin	<i>A. viridis</i>	<i>A. blitum</i>	<i>A. hybridus</i>	<i>A. caudatus</i>	<i>A. spinosus</i> (green)	<i>A. spinosus</i> (red)	P-value ^b	LSD ^c
Vitamin A	2.01 ^d	6.38 ^c	1.62 ^d	9.04 ^b	18.20 ^a	19.22 ^a	<0.001	1.23
Vitamin C	12.40 ^c	11.21 ^c	6.21 ^d	2.11 ^e	20.11 ^b	24.60 ^a	<0.001	2.45
Vitamin B ₁ (Thiamine)	1.10 ^d	2.46 ^c	1.09 ^d	0.85 ^e	3.62 ^b	4.01 ^a	<0.001	0.34
Vitamin B ₂ (Riboflavin)	1.89 ^b	1.19 ^c	1.08 ^c	1.18 ^c	2.14 ^b	2.63 ^a	<0.001	0.28
Vitamin B ₃ (Niacin)	0.63 ^c	0.89 ^b	1.00 ^{ab}	1.10 ^a	1.02 ^{ab}	1.01 ^{ab}	0.042	0.22
Vitamin B ₆ (Pyridoxine)	1.02 ^a	0.72 ^{bc}	0.90 ^{ab}	1.01 ^a	0.74 ^{bc}	0.68 ^c	0.018	0.19
Vitamin E (α -tocopherol)	0.20 ^c	1.06 ^b	0.26 ^c	6.15 ^a	0.42 ^c	0.46 ^c	<0.001	0.45
Vitamin K	0.09 ^b	0.07 ^b	0.20 ^a	0.11 ^b	0.09 ^b	0.07 ^b	0.025	0.06

Mineral Composition

Mineral profiling further distinguishes *A. hybridus* as a calcium-dense species, with a remarkable 1012.4 mg/100g, an order of magnitude higher than others (Table 3). *A. viridis* stood out for its extraordinarily high iron (877.4 mg/100g) and zinc (44.2 mg/100g) levels, suggesting its potential as a biofortification candidate for addressing

micronutrient deficiencies. The same species also had the highest manganese content (10.4 mg/100g), while *A. hybridus* exhibited the highest copper concentration (20.6 mg/100g). Potassium and magnesium values varied more modestly, with *A. caudatus* having the highest potassium (82.9 mg/100g) and *A. hybridus* the highest magnesium (121.3 mg/100g).

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Table 3: Mineral composition of *Amaranthus* species seeds (mg/100g dry weight)

Element	<i>A. blitum</i>	<i>A. viridis</i>	<i>A. hybridus</i>	<i>A. caudatus</i>	<i>A. spinosus</i> (green)	<i>A. spinosus</i> (red)	CV% ^a
Macroelements							
Ca	82.4±2.1 ^c	43.6±1.8 ^d	1012.4±12.3 ^a	86.5±3.2 ^c	61.7±2.4 ^{cd}	58.4±2.1 ^{cd}	8.2
Mg	31.6±1.2 ^c	51.0±2.3 ^b	121.3±4.1 ^a	28.3±1.1 ^c	38.5±1.8 ^c	28.6±1.3 ^c	12.4
K	40.9±1.8 ^c	68.1±2.9 ^b	57.9±2.4 ^b	82.9±3.1 ^a	41.3±1.9 ^c	42.8±2.0 ^c	15.3
Microelements							
Cu	11.68±0.34 ^b	6.8±0.22 ^c	20.6±0.67 ^a	0.20±0.01 ^d	0.22±0.01 ^d	0.32±0.02 ^d	22.1
Mn	3.70±0.12 ^b	10.4±0.41 ^a	4.3±0.18 ^b	0.97±0.04 ^c	1.21±0.06 ^c	1.06±0.05 ^c	28.6
Zn	2.91±0.11 ^b	44.2±1.82 ^a	3.2±0.14 ^b	1.02±0.05 ^c	0.31±0.02 ^c	0.30±0.02 ^c	35.4
Fe	48.3±2.1 ^c	877.4±23.4 ^a	68.5±3.2 ^c	30.1±1.4 ^d	16.2±0.8 ^d	14.8±0.7 ^d	41.2

Proximate Composition

In terms of macronutrients, *A. hybridus* contained the highest crude protein content (21.08%), closely followed by the green (20.15%) and red (19.05%) variants of *A. spinosus*. These three species also exhibited higher crude fat levels, particularly the green variant (4.75%). Moisture content was highest in *A. viridis* (17.84%), while *A. caudatus* had the lowest (8.62%), making it potentially more

shelf-stable. Crude fiber was highest in *A. caudatus* (6.10%) and *A. spinosus* (green) (5.43%), highlighting their possible role in dietary fiber enhancement. Carbohydrate content was inversely related to protein, with *A. blitum* having the highest carbohydrate content (63.01%), while *A. spinosus* (green) had the lowest (37.19%) as obtained in Table 4.

Table 4: Proximate composition of seed of *Amaranthus* species seeds (% dry weight basis)

Parameter	<i>A. blitum</i>	<i>A. viridis</i>	<i>A. hybridus</i>	<i>A. caudatus</i>	<i>A. spinosus</i> (green)	<i>A. spinosus</i> (red)	F-ratio ^a
Ash	14.62±0.01 ^c	19.22±0.02 ^a	15.34±0.00 ^c	12.15±0.01 ^d	18.40±0.01 ^b	18.22±0.01 ^b	2847.6***
Moisture	9.23±0.02 ^c	17.84±0.02 ^a	14.25±0.01 ^c	8.62±0.02 ^c	13.59±0.01 ^d	14.08±0.02 ^c	3921.4***
Crude fat	1.25±0.05 ^d	3.22±0.02 ^c	3.11±0.01 ^c	2.45±0.02 ^c	4.75±0.05 ^a	4.25±0.05 ^b	486.7***
Crude protein	9.25±0.05 ^d	9.85±0.01 ^d	21.08±0.02 ^a	15.21±0.01 ^c	20.15±0.01 ^b	19.05±0.03 ^b	6234.8***
Crude fiber	2.65±0.05 ^d	1.96±0.02 ^c	4.63±0.03 ^c	6.10±0.10 ^a	5.43±0.01 ^b	4.16±0.00 ^c	1876.3***
Carbohydrate ^b	63.01±0.06 ^a	48.92±1.03 ^b	41.60±0.02 ^c	55.49±0.10 ^b	37.19±0.46 ^c	40.25±0.11 ^c	489.2***

Phytochemical Composition

The phytochemical analysis revealed *A. hybridus* as the most phytochemically dense species, recording the highest values of total tannins (307.0 mg/100g), total phenols (0.125 mg/100g), and alkaloids (26.05 mg/100g). *A. blitum* exhibited the highest flavonoid content (2.41 mg/100g), while *A. caudatus* and *A. spinosus* variants showed

elevated alkaloid levels. Interestingly, *A. caudatus* had the highest oxalate content (0.205 mg/100g), an anti-nutrient, although still within acceptable dietary limits. Phytate content was highest in *A. hybridus* (4.11 mg/100g), which may affect mineral bioavailability but also contributes antioxidant potential (Table 5).

Table 5: Phytochemical composition of *Amaranthus* species seeds (mg/100g dry weight)

Compound	<i>A. blitum</i>	<i>A. viridis</i>	<i>A. hybridus</i>	<i>A. caudatus</i>	<i>A. spinosus</i> (green)	<i>A. spinosus</i> (red)	Significance ^a
Phenolic compounds							
Total tannins	163.0±3.0 ^c	205.5±2.5 ^b	307.0±1.0 ^a	165.0±3.0 ^c	145.0±3.0 ^d	144.5±1.5 ^d	***
Flavonoids	2.41±0.01 ^a	1.43±0.03 ^c	1.86±0.02 ^b	1.64±0.01 ^{bc}	1.07±0.01 ^d	1.10±0.01 ^d	***
Total phenols	0.085±0.005 ^c	0.110±0.010 ^b	0.125±0.005 ^a	0.110±0.010 ^b	0.045±0.005 ^d	0.055±0.005 ^d	***
Alkaloids and glycosides							
Alkaloids	18.8±0.1 ^c	14.85±0.05 ^d	26.05±0.05 ^a	22.3±0.1 ^b	21.2±0.4 ^b	22.0±0.4 ^b	***
Anti-nutritional factors							
Oxalates	0.115±0.005 ^b	0.060±0.000 ^c	0.075±0.005 ^c	0.205±0.005 ^a	0.105±0.005 ^b	0.095±0.005 ^b	***
Phytates	2.41±0.01 ^c	2.45±0.35 ^c	4.11±0.01 ^a	3.63±0.01 ^b	2.41±0.01 ^c	3.08±0.02 ^b	***

Among the *Amaranthus* species analyzed, *A. hybridus* and both variants of *A. spinosus* (green and red) emerged as nutritionally and phytochemically superior, based on their high protein, vitamin, mineral, and phytochemical contents. *Amaranthus viridis*, notable for its iron and zinc richness, also presents significant haematopoietic and nutritional potential. These findings support the inclusion of *Amaranthus* seeds in human and animal diets as functional food ingredients with health-promoting benefits.

ANOVA Results

One-way analysis of variance (ANOVA) revealed statistically significant differences among the six *Amaranthus* species with respect to moisture, protein, and carbohydrate contents. Moisture content differed significantly among the species, with an F-value of 96.86 ($F(5, 12) = 96.86, p < 0.001$). Similarly, protein content showed a significant interspecific difference ($F(5, 12) = 10.24, p < 0.001$), while carbohydrate content also varied significantly among the species ($F(5, 12) = 44.23, p < 0.001$). In contrast, no statistically significant differences were observed among the species in ash, fat, and fibre contents ($p > 0.05$), suggesting a relatively uniform distribution of these proximate components across the species examined.

Post-hoc Tukey HSD Test

To identify the specific species responsible for the significant differences observed in the ANOVA, Tukey's honestly significant difference (HSD) post-hoc test was performed. For moisture content, *Amaranthus viridis* and *A. caudatus* recorded significantly

higher moisture levels than *A. hybridus* and *A. spinosus* (Red) ($p < 0.05$). With respect to protein content, *A. spinosus* (Green) exhibited significantly higher protein levels than *A. viridis* and *A. blitum* ($p < 0.05$). For carbohydrate content, *A. hybridus* and *A. spinosus* (Red) had significantly higher carbohydrate concentrations than *A. caudatus* and *A. blitum* ($p < 0.01$).

The observed interspecific differences in proximate composition demonstrate considerable nutritional variability within the genus *Amaranthus*. Such differences may be important for nutritional evaluation and species selection for food and feed applications. In addition, the consistent variation observed in particular nutritional attributes may provide useful complementary characters for species discrimination and potentially contribute to chemotaxonomic assessment when considered alongside morphological, anatomical, and other biochemical characteristics.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) provided a multivariate representation of the variation in proximate composition among the *Amaranthus* species (Fig. 2). The first two principal components (PC1 and PC2) accounted for the largest proportion of the total variation in the dataset, thereby providing the most informative dimensions for visualizing relationships among the species based on their nutritional profiles. The PCA ordination showed discernible separation of some species, particularly *A. caudatus* and *A. viridis*, indicating differences in their overall

proximate composition. This separation suggests that these species possess distinctive nutritional profiles relative to the other taxa examined. Overall, the PCA findings

complement the univariate ANOVA results by demonstrating that the combined variation in proximate parameters contributes to the differentiation of the *Amaranthus* species.

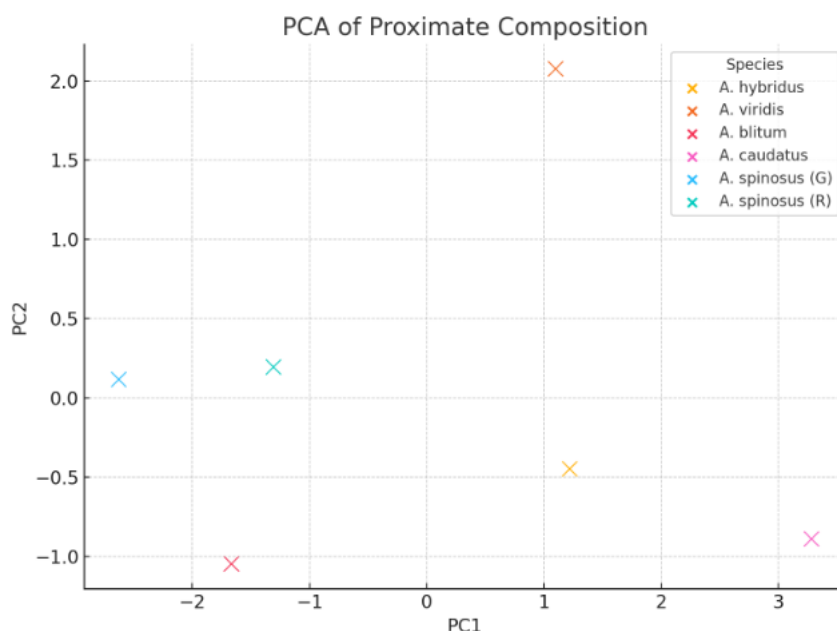


Fig. 2: Principal component analysis (PCA) based on the proximate composition

Comparative Nutritional Value and Recommendation

A heat map matrix summarizing the overall nutrient density highlights the red and green variants of *A. spinosus* as exceptional for vitamin A, C, and protein content, albeit with modest mineral and phytochemical values. *A. hybridus* stands out as the most nutritionally balanced, combining superior protein and calcium with rich phytochemical content. *A. viridis* excels in iron and zinc, which are critical for addressing micronutrient malnutrition, although it is comparatively poor in protein and vitamin A.

Species-Specific Nutritional and Phytochemical Potential

The results demonstrated distinct nutritional and phytochemical profiles among the *Amaranthus* species, highlighting their potential for different food and nutraceutical applications. *Amaranthus hybridus* exhibited a favourable profile for high-protein diets, calcium fortification, and antioxidant-rich food formulations, suggesting its potential as a valuable source of protein, minerals, and bioactive phytochemicals. The red and green

variants of *A. spinosus* showed promising vitamin profiles, particularly with respect to vitamins A and C, indicating their potential usefulness in vitamin-rich dietary formulations and in addressing deficiencies of these micronutrients.

Amaranthus viridis demonstrated appreciable levels of iron and zinc, highlighting its potential as a natural dietary source of these essential trace elements, particularly in populations vulnerable to micronutrient deficiencies. *Amaranthus caudatus* was characterized by relatively high vitamin E and dietary fibre contributions, suggesting its potential application in formulations aimed at enhancing antioxidant intake and improving dietary fibre consumption. *Amaranthus blitum*, on the other hand, exhibited comparatively high carbohydrate and flavonoid contents, indicating its potential suitability for energy-rich and flavonoid-enriched food products.

Overall, the observed interspecific variation in nutritional and phytochemical composition indicates that the different *Amaranthus* species possess distinct functional attributes that could be exploited for functional food development,

dietary diversification, nutritional supplementation, and nutraceutical applications. The species-specific differences observed in this study therefore provide a basis for selecting particular *Amaranthus* taxa according to their nutritional and phytochemical characteristics and intended end use.

Discussion

The present study provides compelling evidence for the nutritional and nutraceutical potential of seeds from six *Amaranthus* species namely *A. viridis*, *A. blitum*, *A. hybridus*, *A. caudatus*, and both green and red variants of *A. spinosus*. Our findings reinforce previous reports on the underutilized value of *Amaranthus* seeds as sources of essential nutrients and bioactive compounds with significant relevance to food security and public health. The observed interspecific variations in vitamin, mineral, proximate, and phytochemical profiles align with previous findings that attribute considerable biochemical heterogeneity to genetic and environmental factors influencing *Amaranthus* growth and metabolism (Shukla *et al.*, 2010; Nascimento *et al.*, 2014).

Vitamin Composition and Antioxidant Potency

The high levels of vitamins A and C in *Amaranthus spinosus*, particularly the red variant (vitamin A: 19.22 mg/100g; vitamin C: 24.60 mg/100g), suggest a strong antioxidant capacity, consistent with previous reports linking these vitamins to free radical scavenging and immune support (Okonya & Maass, 2014; Ribaya-Mercado & Blumberg, 2004). The superior antioxidant vitamin content in both red and green variants of *A. spinosus* (green variant: vitamin A: 18.20 mg/100g; vitamin C: 20.11 mg/100g) suggests cultivar-specific phytochemical plasticity, likely influenced by genotype and environmental conditions (Nankar *et al.*, 2020). Vitamin A, essential for vision and epithelial integrity, was significantly elevated in *A. spinosus*, while vitamin C, critical for collagen synthesis and antioxidant defense, and was also prominent.

Although *A. caudatus* exhibited lower vitamin C content, its high vitamin E concentration

underscores its potential role in lipid peroxidation prevention, as vitamin E is a lipophilic antioxidant vital for cellular membrane integrity (Písařiková & Zralý, 2009). B-complex vitamins were variably distributed, with *A. spinosus* (red) displaying elevated B1 and B2 levels. These vitamins are pivotal in energy metabolism, nervous system function, and erythropoiesis (Watanabe, 2007). The low or undetectable levels of vitamins D and K across all species reflect typical plant-based limitations, as these vitamins are generally sourced from animal products or microbial synthesis (Yuan *et al.*, 2022).

Mineral Composition and Micronutrient Richness

Among the species analyzed, *A. hybridus* demonstrated exceptional mineral content, with the highest calcium (1012.4 mg/100g) and magnesium concentrations. The high calcium content exceeds values reported for many commonly consumed cereals and vegetables, supporting its dietary importance for bone health and metabolic regulation (NRC, 2005). These minerals are essential for skeletal development, neuromuscular transmission, and enzymatic activity (Soetan *et al.*, 2010).

Micronutrient analysis revealed significant interspecific variability, with *A. viridis* demonstrating the most remarkable profile. The extraordinary iron content recorded in *A. viridis* (877.4 mg/100g) far exceeds conventional plant sources and aligns with findings by Alvarez-Jubete *et al.* (2010), who reported comparable mineral richness in pseudocereal grains including *Amaranthus*. This reinforces its suitability for combating iron-deficiency anemia in vulnerable populations (Iqbal *et al.*, 2006). Additionally, the significant zinc content in *A. viridis* (44.2 mg/100g) and manganese levels enhance its therapeutic appeal due to the roles of these trace elements in immune modulation, hematopoiesis, and oxidative stress regulation (Prasad, 2008; WHO, 2011). Given the global burden of iron and zinc deficiencies, especially among women and children in sub-Saharan Africa, the inclusion of *A. viridis* in diet diversification strategies could have far-reaching implications. The absence of heavy metals such as lead and chromium in all seed samples is particularly

noteworthy, supporting the safety of these species for dietary applications. This finding aligns with prior studies indicating the phytoremediation efficiency and soil-dependent mineral uptake profiles of *Amaranthus* (Jain *et al.*, 2014).

Proximate Composition and Macronutrient Value

The seeds of *A. hybridus* exhibited exceptionally high protein levels (21.08%), corroborating their potential as sustainable plant-based protein alternatives and aligning with earlier reports by Shukla *et al.* (2010). This positions *A. hybridus* as a viable candidate for addressing protein-energy malnutrition, particularly in low-income regions where animal protein is less accessible. Such protein content is comparable to that found in traditional legumes, suggesting the utility of *Amaranthus* in addressing protein-energy malnutrition (Mlakar *et al.*, 2010). *Amaranthus caudatus* emerged as the richest source of dietary fiber, which supports gut health, glycemic regulation, and lipid metabolism (Anderson *et al.*, 2009).

Although fat levels were modest across species, the green variant of *A. spinosus* showed slightly elevated lipid content, which, in combination with high protein, enhances its energy value. The high ash content in *A. viridis* reflects its mineral abundance, whereas *A. blitum* was the most carbohydrate-dense species, making it a potential energy source, especially in carbohydrate-based diets.

Phytochemical Profile and Functional Bioactivity

Phytochemical analyses revealed significant interspecific variation in bioactive compounds. *Amaranthus hybridus* possessed the highest concentrations of tannins (307.0 mg/100g), alkaloids, and phenolic compounds, consistent with its ethnomedicinal use in anti-inflammatory and antimicrobial therapies (Kumar *et al.*, 2013). These compounds are well-documented for their antioxidant, anti-inflammatory, and antimicrobial activities (Kaur & Kapoor, 2001). Tannins possess metal-chelating, antimicrobial, and antioxidant properties, while alkaloids may exert pharmacological effects such as antihypertensive and analgesic actions.

The abundant flavonoids in *A. blitum* suggest a high polyphenolic index, correlating with antioxidative and anti-carcinogenic properties (Panche *et al.*, 2016). While anti-nutritional factors such as phytates and oxalates were detected in varying concentrations, with *A. hybridus* showing the highest phytate levels, their concentrations remained within the range deemed safe for human consumption (Umata *et al.*, 2005). Although these compounds can reduce mineral bioavailability by chelating divalent ions, they also confer health benefits, including anti-cancer properties and lipid-lowering effects when consumed in moderation (Sandberg, 2002; Weaver & Plawecki, 1994; Gupta *et al.*, 2015). The absence of saponins across all species may enhance palatability, as these compounds are often associated with bitter taste and anti-nutritional effects at high concentrations.

Nutraceutical Implications

The collective nutrient and phytochemical richness observed in *A. hybridus*, *A. spinosus*, and *A. viridis* underscores their high nutraceutical potential. The nutritional superiority of these seeds reinforces their relevance as functional foods and dietary supplements. Their seed compositions suggest applications not only in traditional diets but also in the formulation of functional foods, dietary supplements, and therapeutic food products. Given their favorable nutrient profiles, particularly in protein, iron, and antioxidants, these species could be integrated into interventions targeting malnutrition, oxidative stress-related disorders, and anemia. Their incorporation into food systems—either as flour, additives, or ingredients in fortified products—could provide sustainable solutions to malnutrition and contribute to achieving global nutrition targets.

Conclusion

This study highlights the remarkable nutritional and nutraceutical potential of seeds from six *Amaranthus* species, revealing significant interspecific variation in vitamins, minerals, proximate composition, and phytochemicals. Notably, *A. viridis* emerged as a rich source of iron and zinc, *A. hybridus* demonstrated superior protein and tannin content, while *A. spinosus* (red and green variants) exhibited

elevated antioxidant vitamins. These findings underscore the capacity of *Amaranthus* seeds to serve as sustainable, plant-based sources of essential nutrients and bioactive compounds with relevance to food security, public health, and functional food development. The absence of heavy metals further supports their safety for dietary applications, while the presence of beneficial phytochemicals affirms their therapeutic potential. Collectively, the results position *Amaranthus* seeds as promising candidates for dietary diversification, fortification, and nutraceutical innovation, particularly in regions burdened by malnutrition and micronutrient deficiencies. Future research should focus on bioavailability studies, product development, and large-scale cultivation strategies to fully harness the value of these underutilized crops in achieving global nutrition and health targets.

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