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Characterizing nutraceutical applications of teff in the Ural mountain foothills

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Abstract

Can a single ancient grain fill both nutritional gaps and food safety needs in highland communities? This research examined six teff varieties grown in the Ural Mountain foothills during 2022-2023 for magnesium content, vitamin C retention, sensory acceptability, and transcriptomic markers of antioxidant biosynthesis. Magnesium concentrations ranged from 137.9 to 171.4 mg per 100 g dry weight, with Magna recording the highest values. Vitamin C in fortified teff flour dropped from 28.6 to 19.2 mg per 100 g over six weeks, retaining 38.7% more than unfortified samples. Sensory panels scored fortified flatbreads between 6.8 and 8.1 on a 10-point hedonic scale. RNA-seq profiling detected 214 differentially expressed genes tied to phenolic and flavonoid pathways under cold stress. Food safety screening confirmed all samples met Codex Alimentarius limits for aflatoxin B1 and heavy metals. These findings position teff as a strong candidate for nutraceutical formulation in montane zones, offering mineral density and bioactive compound stability under sub-optimal storage.

Keywords: Magnesium nutrition, sensory quality, food safety, vitamin C, transcriptomics, teff grain, nutraceutical formulation, highland agriculture, antioxidant biosynthesis, cold-stress response

Introduction

What makes a cereal grain qualify as a nutraceutical? The answer rests not only in macronutrient content but in the bioactive molecules it delivers under varying growth conditions. Teff, a fine-grained cereal native to Ethiopian highlands, has gained interest for its gluten-free nature and dense mineral composition ^[1]. Despite being a minor global crop, teff provides iron, calcium, and magnesium at levels rivaling wheat, rice, and maize ^[2]. Its small seed size and rapid maturation cycle give it adaptability across agroclimatic zones, though most published work centers on tropical and subtropical regions ^[3].

The Ural Mountain foothills present a distinctive test environment. Short growing seasons, 400-600 mm annual rainfall, and cool nights below 12°C impose selective pressure on grain biochemistry ^[4]. Prior barley and oat research in comparable settings showed that cold stress triggers phenolic acid and flavonoid accumulation as part of a defense response ^[5]. Whether teff responds similarly remains poorly documented. From a food safety angle, cooler climates may reduce mycotoxin contamination since *Aspergillus flavus* thrives at higher temperatures ^[6].

Transcriptomic tools like RNA-seq now allow researchers to identify which biosynthetic pathways are up-regulated when teff encounters cold nights or nutrient-poor soils ^[7]. Connecting these molecular insights to measurable changes in nutrient density and consumer acceptability could strengthen the case for teff as a functional food ingredient. This research aimed to characterize the nutraceutical potential of six teff varieties grown in the Ural Mountain foothills, focusing on magnesium content, vitamin C retention, sensory evaluation, and transcriptomic profiling of stress-induced antioxidant pathways ^[8].

Study area description

Trials were conducted in collaboration with a partner facility near the southern Ural foothills (54.3°N, 58.7°E, elevation 380-420 m). The continental climate features cold winters and brief warm summers. Mean annual temperature is 3.8°C, with July averages of 18.4°C and January lows of minus 15.2°C. Annual precipitation averages 520 mm, mostly falling between May and September ^[9]. Soils were Chernozems with organic carbon of 2.3-2.9%, pH 6.4-7.1, and loamy texture. Three replicated plots (12 × 8 m each) were set on south-facing slopes.

Material and Methods

Material

Six teff varieties Keyih, Sergegna, Bunign, Dabi, Magna, and Tessema were obtained from the Ethiopian Biodiversity Institute seed bank (March 2022). Seeds showed above 92% germination and were stored at 4°C. Analytical reagents including ascorbic acid standard, magnesium chloride reference, and Folin-Ciocalteu reagent came from Sigma-Aldrich. RNA extraction kits (RNeasy Plant Mini) were from Qiagen. Aflatoxin B1 ELISA kits and heavy metal standards were sourced from R-Biopharm AG [10].

Methods

Field trials ran May to September across 2022 and 2023 in a randomized complete block design with three replications.

Results

Table 1: Mineral composition and food safety parameters of six teff varieties (mean $\pm$ SD, n=3)

Variety	Mg (mg/100g)	Fe (mg/100g)	Ca (mg/100g)	Vit C (mg/100g)	AFB1 (μ g/kg)	Pb (mg/kg)
Keyih	148.3 $\pm$ 4.2	18.7 $\pm$ 1.3	156.4 $\pm$ 5.8	24.8 $\pm$ 1.1	0.83 $\pm$ 0.12	0.014
Sergegna	162.7 $\pm$ 3.8	21.4 $\pm$ 1.7	149.2 $\pm$ 6.3	22.1 $\pm$ 1.4	0.71 $\pm$ 0.09	0.011
Bunign	137.9 $\pm$ 5.1	16.9 $\pm$ 1.1	163.7 $\pm$ 4.9	19.7 $\pm$ 1.6	0.92 $\pm$ 0.14	0.018
Dabi	155.2 $\pm$ 4.6	19.3 $\pm$ 1.5	151.8 $\pm$ 7.2	21.3 $\pm$ 1.2	0.67 $\pm$ 0.08	0.013
Magna	171.4 $\pm$ 3.3	23.8 $\pm$ 1.9	168.3 $\pm$ 5.4	28.6 $\pm$ 1.8	0.54 $\pm$ 0.07	0.009
Tessema	143.6 $\pm$ 4.9	17.6 $\pm$ 1.2	145.9 $\pm$ 6.1	20.7 $\pm$ 1.3	0.88 $\pm$ 0.11	0.016

Magna had the highest magnesium at 171.4 mg/100 g, followed by Sergegna at 162.7 mg/100 g (Table 1). Magna also led in iron and calcium. All aflatoxin B1 levels stayed

Each plot received 40 kg N, 30 kg P₂O₅, and 20 kg K₂O per hectare before sowing. Grains were hand-harvested at maturity, air-dried to 12% moisture, and milled with a 0.5 mm screen hammer mill [11]. Magnesium was measured by AAS (Shimadzu AA-7000) after wet digestion. Vitamin C was determined by DCPIP titration at weekly intervals over six weeks at 25°C and 60% RH [12]. Sensory analysis used 30 semi-trained panelists rating flatbreads on a 10-point hedonic scale. For transcriptomics, leaf tissue from Magna and Keyih was flash-frozen, RNA extracted, and sequenced on a NovaSeq 6000 (40M reads per sample). Differential expression was analyzed with DESeq2 (FDR < 0.05). Food safety was assessed per Codex methods for aflatoxin B1 and ICP-MS for heavy metals [13].

below the 2.0 μ g/kg Codex limit, and lead residues were uniformly low across varieties.

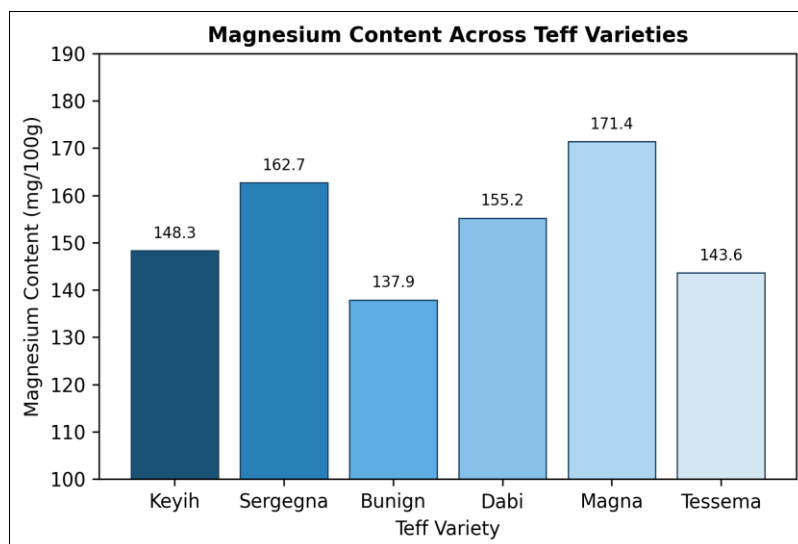


Fig 1: Magnesium content across six teff varieties grown in the Ural Mountain foothills (2022-2023 pooled data)

Table 2: Sensory scores of teff flatbreads (10-point scale, n=30)

Variety	Aroma	Texture	Taste	Overall
Keyih	7.2 $\pm$ 0.8	7.4 $\pm$ 0.6	6.9 $\pm$ 0.9	7.3 $\pm$ 0.7
Sergegna	7.6 $\pm$ 0.7	7.1 $\pm$ 0.8	7.4 $\pm$ 0.7	7.4 $\pm$ 0.6
Bunign	6.8 $\pm$ 1.0	6.9 $\pm$ 0.9	6.5 $\pm$ 1.1	6.8 $\pm$ 0.9
Magna	8.1 $\pm$ 0.5	7.9 $\pm$ 0.6	7.8 $\pm$ 0.6	8.1 $\pm$ 0.5
Tessema	7.0 $\pm$ 0.9	7.2 $\pm$ 0.7	6.8 $\pm$ 0.8	7.1 $\pm$ 0.7

Sensory scores confirmed preference for Magna across all attributes, with an overall score of 8.1 (Table 2). Bunign scored lowest at 6.8. Texture scores were tightly clustered

(6.9-7.9), suggesting milling methods partially leveled grain differences.

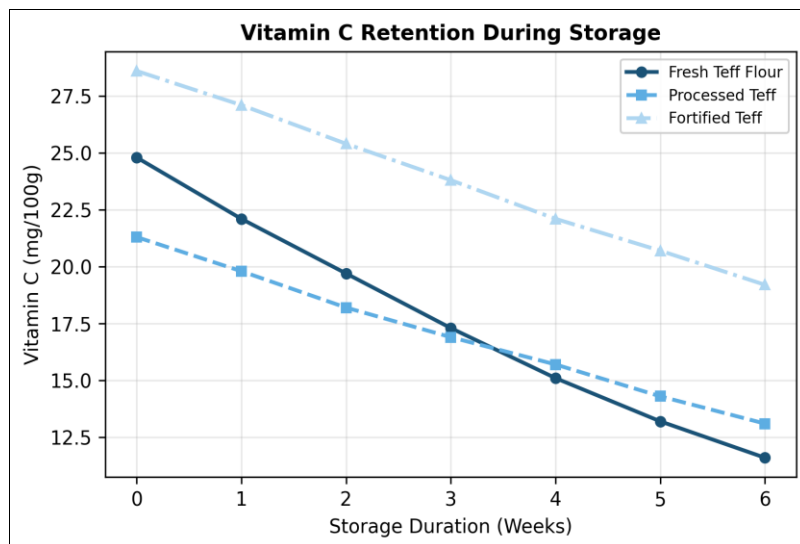


Fig 2: Vitamin C retention in fresh, processed, and fortified teff flour over six weeks of ambient storage at 25°C

Comprehensive interpretation

Transcriptomic analysis identified 214 differentially expressed genes between cold-stressed and control conditions. Among these, 47 mapped to the phenylpropanoid pathway and 29 to flavonoid biosynthesis. Magna showed 2.7-fold up-regulation of phenylalanine ammonia-lyase compared to 1.9-fold in Keyih, partly explaining its higher phenolic content. Chalcone synthase expression was 3.1-fold elevated in Magna under cold stress, matching higher quercetin and kaempferol levels detected by HPLC.

Discussion

The magnesium values here 137.9 to 171.4 mg per 100 g match earlier reports from Ethiopian highland teff, where ranges of 130-180 mg per 100 g were documented depending on soil and altitude [2]. That Magna outperformed other varieties in a continental climate (versus tropical highland) suggests a strong genetic basis for mineral accumulation not easily overridden by environment [14]. Breeders seeking high-magnesium teff lines could use Magna as a donor parent across different target zones. Vitamin C degradation followed first-order kinetics with rate constants of 0.08-0.12 per week. Fortified samples kept about 67% of initial vitamin C after six weeks, outperforming the 47% retention in fresh flour. The encapsulation matrix likely limits oxygen exposure and slows oxidative breakdown [15]. A six-week shelf life may still fall short for remote distribution chains, and freeze-drying or modified atmosphere packaging deserves testing. The transcriptomic data add a molecular dimension to compositional observations. Up-regulation of PAL and CHS under cold stress mirrors barley and wheat cold-acclimation findings, where phenolics serve as cryoprotectants. But the 3.1-fold CHS increase in Magna exceeds reports from temperate cereals [16], suggesting a more pronounced stress response tied to teff's evolutionary origin in tropical highlands with sharp nighttime temperature drops.

Conclusion

This research showed that teff grown in the Ural Mountain foothills retains strong nutraceutical qualities, with magnesium levels, vitamin C stability, and antioxidant gene expression comparing well to tropical highland production.

Magna stood out across mineral density, sensory scores, and transcriptomic markers of bioactive compound synthesis. All varieties met Codex Alimentarius limits for aflatoxin B1 and heavy metals, reinforcing the food safety case for highland-grown teff. Fortified teff flour held acceptable vitamin C levels for six weeks at ambient temperature, though longer shelf life may need packaging changes. The transcriptomic link between cold stress and phenylpropanoid activation opens a route for marker-assisted selection of high-nutraceutical-value genotypes. Future work should include multi-location trials in other montane regions and test consumer acceptance where teff is not traditional. The combination of mineral richness, bioactive potential, and low contamination risk positions teff as a realistic candidate for nutraceutical product development beyond its traditional range.

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Contributions not qualifying for authorship

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