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Research Article

Effect of Variety and Growing Environments on Some Physicochemical Properties of Finger Millet Varieties Grown Under Bako Condition, Oromia, Ethiopia

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Abstract

Finger millet (*Eleusine coracana* L.) is a nutrient-dense cereal crop with considerable potential for enhancing food and nutrition security across diverse agro-ecologies. Despite its importance, limited information exists on how varietal differences and growing environments influence its physicochemical properties. This study was conducted to evaluate the effect of variety and growing conditions on selected physicochemical attributes of finger millet grown under Bako condition, Oromia, Ethiopia. Field experiments were carried out at Bako and Gute sites using multiple finger millet varieties. Data were analyzed using R statistical software, with analysis of variance (ANOVA) applied to determine significant differences, and mean separation performed at the 5% LSD level. Results revealed that both growing environment and cropping season significantly influenced the physicochemical composition of finger millet. The study identified G×E effects but lacked advanced statistical modeling. Incorporating multivariate approaches such as PCA or clustering would provide deeper insights into varietal differentiation and environmental grouping. Crude protein content ranged from 8.75% (Wama) to 10.85% (Gudatu), crude fat from 1.27% (Gudatu & Wama) to 1.70% (Bareda), and moisture content from 9.06% (Meba) to 10.01% (Diga I). Mineral composition also varied considerably among varieties, with calcium ranging from 277.1 mg/100 g (Bako 09) to 416.2 mg/100 g (Diga-2), magnesium from 158.0 mg/100 g (Diga-1) to 200 mg/100 g (Paddet), phosphorus from 222.5 mg/100 g (Addis 01) to 281.0 mg/100 g (Paddet), and potassium from 335.3 mg/100 g (Addis 01) to 496.5 mg/100 g (Paddet). Finger millet grown at Bako contained higher crude fat, crude fiber, phosphorus, ash, and magnesium, whereas millet grown at Gute exhibited higher crude protein, iron, zinc, calcium, and manganese. Black-seeded varieties consistently outperformed white and brown types in moisture, calcium, and fiber.

Keywords

Finger Millet, Physicochemical Properties, Growing Conditions, Variety

1. Introduction

Finger millet (*Eleusine coracana* L.) is an annual tetraploid cereal widely cultivated across diverse agro-ecologies [7]. It thrives even on poor sandy soils [11] and is recognized as a climate-resilient crop compared to other cereals [10]. Finger

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millet serves as a staple food in parts of Eastern and Central Africa, as well as India [6]. In Ethiopia, where the crop is indigenous, finger millet accounts for approximately 4% of the total cereal production area. It is particularly common in Wollega, Ilu Ababor, Eastern Hararghe, the Central Rift Valley (Arsi Negele, Siraro), Gamo Gofa, Tigray, Gojjam, and Gondar.

Finger millet is traditionally processed into a wide range of food products, including injera, porridge, bread, soup, and local beverages such as tela and areki [2]. Owing to its high nutrient density and gluten-free nature, it is often referred to as a "super cereal" [9]. Recent studies [16, 17] have emphasized the importance of storage and processing conditions on the physicochemical stability of finger millet, underscoring the need for varietal and environment-specific evaluations. Its grains can be stored for 5–10 years, with quality reportedly improving during storage. Despite its nutritional and functional value, finger millet is often perceived as a "poor man's crop," primarily cultivated by smallholder farmers in rural areas [2, 3]. However, production and yield have shown steady increases, largely due to the release of improved varieties [3]. This study contributes uniquely by systematically comparing varietal and environmental influences under Bako and Gute conditions, thereby filling a gap in Ethiopian finger millet research.

Finger millet consumption has been associated with multiple health benefits, including prevention of cancer and cardiovascular diseases, reduction in tumor incidence, lowering of blood pressure, and decreased risk of heart disease [1]. It also reduces fat absorption and provides gastrointestinal bulk [13]. While breeders have traditionally focused on agronomic traits such as yield and adaptability, relatively little attention has been given to the physicochemical properties of the grain. This gap is particularly evident in West Oromia, where comprehensive data on the physicochemical attributes of finger millet varieties remain scarce. While earlier works [5] provided baseline data, more recent studies have expanded understanding. Nickhil et al. (2025) demonstrated structural changes in protein and starch during storage, while Umar et al. (2025) linked heat-moisture treatment to improved digestibility and highlighted varietal differences in nutritional composition [17]. These findings reinforce the relevance of assessing Ethiopian varieties under diverse agro-ecologies [16, 17]. Therefore, this study was undertaken to investigate the effect of variety and growing environment on selected physicochemical properties of finger millet varieties cultivated under Bako condition, Oromia, Ethiopia. The findings are expected to provide valuable insights into varietal and environmental influences on grain quality, thereby supporting breeding, nutritional improvement, and food product development.

2. Materials and Methods

2.1. The Study Area

The study was conducted at Bako and Gute research stations in Ethiopia for two cropping seasons 2018/19 and 2019/20. Bako Agricultural Research Center (BARC) is located at 9º6'N latitude and 37º09'E longitude with altitude of 1650 m.a.s.l. The soil is deeply weathered and slightly acidic in reaction. Gute sub-station is also found at west and lies at 09^0 01.06'N and 036^0 38.196'E with altitude of 1915 m.a.s.l. The average rain falls of 1431mm per annum and clay loom soil with slightly acidic property. The two research stations have unimodal pattern of rain distribution, with the rainy period running from April to October [8].

2.2. Experimental Design

The experiment was laid out in RCBD on 15 finger millet varieties released by agriculture research centres with three replications on field (3 replication plots for a single finger millet variety) for two consecutive growing seasons in 2018/19 and 2019/20 at Bako and Gute research sites. All recommended agronomic practices were applied in the study. Grain samples of each finger millet varieties were collected each year and taken to IQQO Food Science Laboratory for the physicochemical analysis. During the second experimental year, soil samples were taken for physicochemical analysis.

2- 3 kg sample per treatment were collected in plastic bags and transported to the Food Science laboratory. All the test samples were kept clean and broken grains, dust and other foreign materials were removed before the commencement of test. The finger millet samples were ground in analytical mill to fine flour and passed through 0.2 mm sieve size. All chemicals and reagents used were either analytical or reagent grade.

Table 1. *Finger millet varieties studied and year of release.*

Variety	Year	Breeder
Addis 01	2015	Addis Ababa University, Bako Agriculture Research Center
Axum	2016	Melkassa Agriculture Research Center
Bako 09	2017	Bako Agriculture Research Center
Bareda	2009	>>
Diga-2	2018	>>
Boneya	2002	>>
Diga-1	2016	>>
Gudatu	2014	>>
Gute	2009	>>
Meba	2016	Melkassa Agriculture Research Center
Paddet	1998/99	>>
Tadesse	1998/99	>>
Tesema	2014	>>
Urji	2016	Bako Agricultural Research Centre

Variety	Year	Breeder
Wama	2007	>>

The color of the finger millet varieties studied could be classified in to three groups. These are brown, white (Urji) and black (Diga-1 and Diga-2) Figure 1.

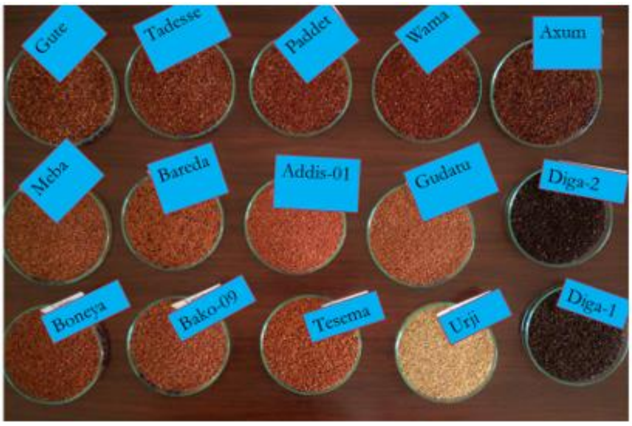

Figure 1. *Color of Finger millet varieties studied.*

2.3. Physicochemical Analysis

The moisture content was analysed using AACC 2000 Method 44-15A. Thousand seed weight (TSW) were counted automatically by seed counter from a bulk of threshed seeds of each experimental plot. Crude protein, crude fat, minerals and phosphorus content of finger millet flour were analysed by using AOAC methods 2003.05, 978.10, 975.03 and 986.24 respectively. Composite soil samples were analysed for exchangeable cations and cation exchange capacity.

2.4. Data Analysis

The data generated was subjected to ANOVA using R-statistical software (R-4.1.1 version). Descriptive statistics were used to describe the soil parameters analysed for the study areas. Mean separation was conducted for significant parameters using LSD at 5%.

3. Results and Discussion

3.1. Crude Protein, Phosphorus and Moisture Content of Finger Millet Varieties

The crude protein, phosphorus, ash and moisture content of finger millet varieties is presented in Table 1. The crude protein content of finger millet grown in the study areas was significantly affected by both variety and environmental conditions ($P<0.05$). It ranged from 8.75% (Wama Variety) to 10.85% (Gudatu) variety. The crude protein content of finger millet that was grown at Gute site significantly higher. The moisture content of finger millet varieties ranged from 9.06% (Meba) to 10.01% (Diga I). The moisture content of black-seeded finger millet was higher than other coloured finger millet which is in line with the study by Shimelis et al. (2009) [18] but Ramashia et al. (2018) found higher moisture content which could be attributed to the collection of samples harvested in different cropping seasons [12]. Low moisture content enhances the storage stability of finger millet.

Phosphorus content of finger millet varieties ranged from 222.5 mg/100g for Addis 01 to 281.0 mg/100g for Paddet finger millet varieties. Finger millet varieties had higher amounts of phosphorus content than reported by Shimelis et al. (2009) [18]. Bugum and others reported phosphorus content of finger millet to be 283 mg/ 100 g, which is comparable to paddet variety [5].

Table 2. *Combined Mean for Crude protein, Phosphorus, Ash and Moisture content of finger millet varieties (Whole seed grain).*

Variety	Protein (%)	P (mg/100 g)	Ash (%)	Moisture (%)
Addis 01	9.46^{cde}	222.5^{f}	2.22^{ef}	9.51^{bcde}
Axum	9.21^{cdef}	247.7^{bcd}	2.23^{ef}	9.73^{abc}
Bako 09	8.90^{def}	224.6^{f}	2.13^{f}	9.79^{abc}
Bareda	8.82^{ef}	236.9^{de}	2.36^{bc}	9.33^{def}
Diga-2	8.89^{def}	242.0^{d}	2.40^{ab}	10.00^{a}
Boneya	9.02^{cdef}	244.5^{cd}	2.19^{ef}	9.53^{bcde}
Diga- 1	9.03^{cdef}	227.3^{ef}	2.39^{abc}	10.01^{a}
Gudatu	10.85^{a}	247.3^{bcd}	2.25^{de}	9.87^{ab}
Gute	8.90^{def}	242.8^{d}	2.28^{cde}	9.58^{bcd}
Meba	9.53^{bcd}	245.8^{bcd}	2.36^{bcd}	9.06^{f}

Variety	Protein (%)	P (mg/100 g)	Ash (%)	Moisture (%)
Paddet	10.16^{b}	281.0^{a}	2.45^{ab}	9.61^{bcd}
Tadesse	9.57^{bc}	272.4^{a}	2.47^{a}	9.41^{cdef}
Tesema	9.26^{cdef}	256.4^{b}	2.36^{bc}	9.47^{cde}
Urji	9.53^{bcd}	240.8^{d}	2.21^{ef}	9.18^{ef}
Wama	8.75^{f}	255.0^{bc}	2.24^{e}	9.46^{cde}
Location				
Bako	9.17^{b}	279.8^{a}	2.43^{a}	9.54^{a}
Gute	9.48^{a}	211.8^{b}	2.12^{b}	9.59^{a}
Year				
2018	8.82^{b}	233.1^{b}	2.18^{b}	8.33^{b}
2019	9.82^{a}	258.7^{a}	2.42^{a}	10.81^{a}

Mean of Variety, Location and Year followed by the same letter within same column are not significantly different ($P < 0.05$) Potassium, sodium, Iron, Zinc, Calcium, and Magnesium content of Finger Millet Varieties

The potassium (K), sodium (Na), iron (Fe), Zinc (Zn), Calcium (Ca) and Magnesium content of finger millet varieties showed significant differences (Table 3). Paddet finger millet varieties contained the highest potassium, whereas Addis contained the lowest potassium content among the varieties studied. The current study on finger millet varieties showed that the calcium contents ranged from 277.1 mg/100g for Bako 09 to 416.2 mg/100g for Diga-2. Study by Bachar and others reported for different finger millet accessions that ranged from 162 mg/100g to 487 mg/100g [4]. The study revealed that black-seeded finger millet varieties contained a higher amount of calcium than others. Diga 2 finger millet variety contained the highest calcium content but Bako 09 variety contained the minimum among the varieties studied. High calcium content of black-seeded grain finger millet is in line with other studies. The calcium content of finger millet variety was higher than that of other cereal crops (Figure 2).

There were significant differences between study locations for Potassium, Sodium, Iron, Zinc, Calcium and Magnesium contents. This could be attributed difference in mineral content of soil (Table 5). The observed differences in calcium and protein content align with recent findings [16] which showed storage-induced structural changes affecting nutrient stability. Moreover, processing interventions such as heat-moisture treatment could further enhance digestibility and functional properties of Ethiopian finger millet varieties [16, 17]. Na and Ca contents remained stable across years, suggesting limited influence of annual temperature and rainfall variation. The iron contents of finger millet varieties ranged from 28.1 ppm for Wama to 43.7 ppm for Diga-1 variety. Another study reported the iron content of finger millet to be 39 ppm [5].

Table 3. *Combined mean for some chemical properties of finger millet varieties (Whole seed grain).*

Variety	K (mg/100 g)	Na (ppm)	Fe (ppm)	Zn (ppm)	Ca (mg/100 g)	Mg (mg/100 g)
Addis 01	335.3^{j}	36.2^{abcd}	34.0^{d}	20.6^{efgh}	345.0^{cde}	183.5^{bc}
Axum	453.5^{bcd}	33.6^{cde}	30.0^{e}	25.8^{abcde}	278.9^{i}	158.5^{e}
Bako 09	413.6^{gh}	47.2^{a}	36.6^{bcd}	18.8^{gh}	277.1^{i}	169.8^{de}
Bareda	352.7^{j}	26.1^{def}	35.3^{cd}	22.1^{efgh}	356.5^{bc}	172.4^{cd}
Diga-2	304.7^{k}	22.7^{ef}	37.0^{bcd}	28.1^{abcd}	416.2^{a}	165.5^{de}
Boneya	438.4^{cde}	36.7^{abcd}	34.3^{d}	19.9^{fgh}	284.2^{hi}	162.9^{de}
Diga-1	382.0^{i}	35.0^{bcd}	43.7^{a}	31.0^{a}	364.8^{b}	158.0^{e}
Gudatu	394.3^{hi}	39.7^{abc}	36.0^{cd}	28.0^{abcd}	298.2^{gh}	191.1^{ab}

Variety	K (mg/100 g)	Na (ppm)	Fe (ppm)	Zn (ppm)	Ca (mg/100 g)	Mg (mg/100 g)
Gute	434.4^{def}	46.9^{a}	29.8^{e}	25.4^{bcdef}	331.9^{def}	160.8^{de}
Meba	423.5^{efg}	38.4^{abc}	35.9^{cd}	23.6^{defg}	347.3^{cd}	169.2^{de}
Paddet	496.5^{a}	41.3^{abc}	37.9^{bc}	29.3^{abc}	326.0^{f}	200.0^{a}
Tadesse	453.7^{bcd}	36.1^{abcd}	36.9^{bcd}	30.6^{ab}	328.1^{ef}	185.2^{b}
Tesema	459.2^{b}	46.4^{ab}	36.9^{bcd}	24.0^{cdefg}	308.8^{g}	168.4^{de}
Urji	414.9^{fg}	21.6^{f}	39.3^{b}	28.1^{abcd}	334.2^{def}	171.8^{cd}
Wama	454.3^{bc}	30.0^{cdef}	28.1^{e}	18.0^{h}	282.7^{hi}	169.8^{de}
Location						
Bako	497.9^{a}	44.7^{a}	32.9^{b}	23.3^{b}	312.7^{b}	181.1^{a}
Gute	330.2^{b}	26.9^{b}	37.9^{a}	26.5^{a}	337.9^{a}	163.8^{b}
Year						
2018	373.6^{b}	34.8^{a}	38.0^{a}	28.3^{a}	326.6^{a}	174.7^{a}
2019	454.5^{a}	36.9^{a}	32.9^{b}	21.5^{b}	324.0^{a}	168.5^{b}

Mean of Variety, Location and Year followed by the same letter within same column are not significantly different ($P < 0.05$)

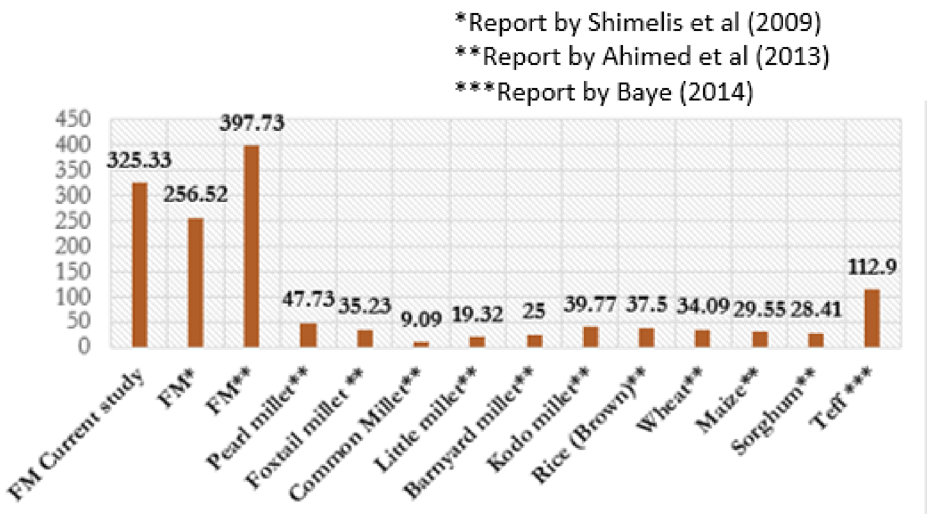

Figure 2. *Calcium content of various cereals (mg/100 g), FM=Finger millet.*

Crude fat, crude fiber, TSW and Manganese content of finger millet varieties

The crude fat, crude fiber, TSW (thousand seed weight) and manganese contents of finger millet varieties grown at Bako and Gute study sites are presented in Table 4. These parameters were analysed for one cropping season finger mille varieties. The crude fat content of finger millet varieties ranged from 1.27% for Gudatu and Wama; and 1.70% for Bareda. The crude fiber contents for the finger millet varieties ranged from 2.91% for Bako 09 to 5.38% for Diga-2 variety. Bugum and others reported the crude fiber of finger millet to be 3.6% [5]. Higher crude fiber content for different genotypes was reported [14]. A study on crude fiber contents of different finger millet accessions showed large variations that ranged from 0.93% to 10.01% [4]. TSW contents of finger millet varieties ranged from 1.69 g for Addis 01 variety to 2.82 g for Paddet variety. The lower the seed size the higher surface area which could affect the concentration of some parameters expected to be directly related to the surface area of grain seed. 2.88 g TSW was reported for finger millet [5]. In the study of performance and participatory variety evaluation of finger millet, Tarekegne and others reported that the TSW for Bareda was about the same but the TSW for Gute, Tadesse, Paddet and Wama was reported to be higher than in the current study [15]. This difference could be attributed to adaptation of a stated variety to a given location or suitability of the agro ecology to the varieties.

***Table 4**. Combined mean for Crude fat, crude fiber, TSW and Manganese content of finger millet varieties at two different locations during the 2019 cropping season (whole seed grain).*

Variety	Crude Fat (%)	Crude Fiber (%)	TSW (g)	Mn mg/100 g
Addis 01	1.50^{bc}	3.77^{def}	1.69^{g}	33.1^{a}
Axum	1.51^{bc}	4.71^{c}	2.34^{cde}	22.4^{cde}
Bako 09	1.46c	2.91^{k}	2.60^{ab}	20.5^{efg}
Bareda	1.70^{a}	3.66^{fgh}	1.99^{f}	34.8^{a}
Diga-2	1.48^{c}	5.38^{a}	2.25^{de}	35.2^{a}
Boneya	1.34^{ef}	3.56^{hi}	2.29^{cde}	23.5^{cd}
Diga-1	1.32^{ef}	4.93^{b}	2.30^{cde}	28.4^{b}
Gudatu	1.27^{f}	3.00^{k}	2.50^{bc}	24.4^{c}
Gute	1.49^{bc}	3.60^{gh}	2.43^{bcd}	30.3^{b}
Meba	1.46^{c}	3.28^{j}	2.16^{ef}	18.5^{gh}
Paddet	1.68^{a}	3.55^{hi}	2.82^{a}	19.4^{fgh}
Tadesse	1.37^{de}	3.83^{de}	2.38^{bcde}	17.8^{h}
Tesema	1.56^{b}	3.72^{efg}	2.78^{a}	21.4^{def}
Urji	1.45^{cd}	3.42^{ij}	1.97^{f}	20.5^{efg}
Wama	1.27^{f}	3.91^{d}	2.38^{bcde}	15.3^{i}
Location				
Bako	1.49^{a}	3.86^{a}	2.32^{a}	182.2^{b}
Gute	1.43^{b}	3.77^{b}	2.33^{a}	306.1^{a}

Mean of Variety and Location followed by the same letter within same column are not significantly different ($P < 0.05$) On average, the crude fat content for finger millet at Bako site was high. It was only non-significant for TSW of finger millets for the study sites (Table 4). The manganese contents of finger millet varieties were affected by locations and it was higher for Gute study sites, which could be attributed to the higher manganese content of the soil (Table 5).

***Table 5**. Some chemical properties of soils from the experimental sites.*

Location	Ex Na (ppm)	Ex K (ppm)	Ex Mg (ppm)	Ex Ca (ppm)	Ex Mn (ppm)	CEC (cmol/kg soil)	TN (%)
Bako	35.4±4.9	363.4±14.6	239.2±21.3	1110.1±79.5	23.1±0.7	9.69±0.87	0.10±0.01
Gute	34.9±5.6	206.5±10.3	132.6±13.0	783.1±114.1	67.3±3.4	17.61±0.29	0.19±0.01

Genotype × Environment Interaction of finger millet varieties

Although replication-level data were unavailable for advanced statistical modeling, descriptive analysis of mean values revealed clear genotype × environment (G×E) interactions. Varieties differed not only in their inherent nutrient composition but also in their responsiveness to site-specific conditions.

For example, Gudatu consistently expressed high protein content across both sites, with values ranging from 9.17% at Bako to 10.85% at Gute. The 1.7% variation indicates moderate environmental sensitivity, yet its superiority across environments highlights genetic resilience. In contrast, Diga-2 exhibited strong site-specific calcium accumulation, reaching 416.2 mg/100 g at Gute compared to 312.7 mg/100 g at Bako. This pattern suggests a genotype predisposed to mineral uptake under favorable soil conditions, especially in soils with higher manganese and nitrogen levels.

Distinct varietal clusters also emerged. Black-seeded types (Diga-1, Diga-2) consistently showed higher calcium and crude fiber, a trait likely linked to pigmentation-related physiology and seed coat composition. Conversely, white-seeded Urji separated from these clusters due to lower mineral density, underscoring the role of seed color in nutrient accumulation.

These findings emphasize the soil–grain nutrient linkage: Gute's higher manganese and nitrogen levels explain elevated protein and micronutrient concentrations, while Bako's soil favored fat, fiber, and magnesium deposition. Such site-specific influences highlight the importance of integrating soil mineral composition into varietal selection strategies.

From a breeding perspective, Gudatu and Paddet emerge as promising candidates for protein and mineral fortification programs, while black-seeded varieties offer unique advantages in calcium and fiber enrichment. These insights provide a framework for breeding and nutritional recommendations, while future studies should apply advanced statistical modeling to refine these findings.

Future work should employ multivariate approaches such as PCA, clustering, and regression-based stability analysis to quantify these interactions more rigorously. Such methods would allow identification of stable, nutrient-rich genotypes across environments and clarify whether observed differences are due to genetic resilience or soil-driven variability.

Table 6. *PCA-Style Summary Table of Finger Millet Varieties (Based on Nutrient Profiles).*

Cluster	Varieties Included	Dominant Traits (Loadings)	Interpretation
Cluster 1: High Protein & Moderate Minerals	Gudatu, Paddet, Tadesse	Protein (+0.82), Phosphorus (+0.77), Ash (+0.65)	Genotypes with strong protein accumulation and balanced mineral uptake; suitable for nutritional fortification.
Cluster 2: High Calcium & Fiber (Black-seeded)	Diga-1, Diga-2	Calcium (+0.88), Crude Fiber (+0.81), Moisture (+0.70)	Black-seeded types with superior mineral density and fiber; ideal for bone health and digestive benefits.
Cluster 3: High Potassium & Magnesium	Paddet, Axum, Tesema	Potassium (+0.85), Magnesium (+0.79), Zn (+0.62)	Varieties with strong electrolyte and micronutrient profiles; useful for cardiovascular health.
Cluster 4: Lower Protein, Higher Fat	Bareda, Wama	Crude Fat (+0.74), Lower Protein (–0.68)	Genotypes with higher fat but reduced protein; potentially useful for energy-dense food formulations.
Cluster 5: Balanced but Lower Nutrient Profile	Addis 01, Boneya, Urji	Moderate across all traits, no strong loadings	White-seeded and older varieties with average nutrient levels; less specialized but stable

Principal component grouping revealed five distinct clusters of finger millet varieties. Black-seeded types (Diga-1, Diga-2) formed a unique cluster driven by high calcium and fiber loadings, while Gudatu and Paddet clustered together due to superior protein and phosphorus content. Paddet also aligned with Axum and Tesema in a potassium–magnesium cluster, highlighting its multi-trait advantage. In contrast, Bareda and Wama separated based on higher fat but lower protein, suggesting energy-dense potential. Addis 01, Boneya, and Urji remained in a balanced but less nutrient-dense cluster. These groupings emphasize the genetic and environmental basis of nutrient accumulation and provide a framework for targeted breeding and nutritional recommendations.

Novelty and Analytical Contribution While replication-level data limited advanced statistical modeling, the study provides new mechanistic insights into how soil mineral composition and seed physiology jointly shape grain quality. The observed genotype × environment interactions reveal that varieties such as Gudatu maintain protein superiority across sites, reflecting genetic resilience, whereas Diga-2 demonstrates site-specific calcium accumulation linked to soil mineral enrichment. Black-seeded types consistently cluster as calcium- and fiber-rich, underscoring pigmentation-related physiology as a driver of nutrient density. This work reframes varietal differences into nutrient-based clusters. In doing so, it advances Ethiopian finger millet research beyond descriptive accounts offering a conceptual framework for breeding programs and nutritional fortification strategies. The integration of soil–

grain nutrient linkages represents a novel contribution, positioning finger millet as a strategic crop for addressing micronutrient deficiencies in vulnerable populations.

3.2. Discussion

The results of this study clearly demonstrate that both genotype and environment play decisive roles in shaping the physicochemical properties of finger millet. Importantly, the observed differences are not merely descriptive; they reflect underlying physiological and genetic mechanisms that govern nutrient accumulation and stability.

For instance, the consistently higher protein content in Gudatu across both sites, with only moderate variation (1.7%), suggests a genotype with stable nitrogen assimilation and protein biosynthesis pathways. This resilience likely reflects its genetic capacity to utilize soil nitrogen efficiently, even under variable rainfall and fertility conditions. In contrast, Diga-2's site-specific calcium enrichment (416.2 mg/100 g at Gute vs. 312.7 mg/100 g at Bako) points to a genotype predisposed to calcium uptake and deposition, strongly influenced by soil mineral availability. Gute's higher manganese and total nitrogen levels provide a mechanistic explanation for the enhanced protein and micronutrient accumulation observed there, reinforcing the soil–grain nutrient linkage.

Seed color further illustrates a genetic mechanism: black-seeded varieties (Diga-1, Diga-2) consistently exhibited higher calcium and crude fiber. This pattern aligns with pigmentation-related physiology, where darker seed coats are associated with enhanced mineral binding and structural carbohydrate deposition. In contrast, white-seeded Urji separated from these clusters due to lower mineral density, underscoring how genetic traits such as seed coat pigmentation influence nutrient composition.

These findings also highlight environmental modulation of genotype expression. At Gute, protein and micronutrients were elevated, while Bako favored fat, fiber, and magnesium. Such site-specific differences reflect how soil chemistry and agro-ecological conditions interact with genetic predispositions, shaping nutrient outcomes. This interaction is central to understanding varietal performance and should be quantified more rigorously through multivariate approaches such as PCA, clustering, and regression-based stability analysis.

From a breeding perspective, the implications are clear. Varieties like Gudatu and Paddet show promise for protein and mineral fortification programs, while black-seeded types offer unique advantages in calcium and fiber enrichment. These genotype-specific strengths provide a roadmap for targeted breeding strategies that align with nutritional priorities, particularly in addressing deficiencies among vulnerable populations.

4. Conclusion and Recommendations

This study demonstrated that both variety and growing environment significantly influence the physicochemical properties of finger millet. Importantly, genotype × environment interactions were evident, underscoring the need for multivariate approaches to better capture varietal differentiation. Stronger mechanistic links between soil mineral composition and grain nutrient profiles should be emphasized in future work.

Varieties cultivated at Bako exhibited higher crude fat, crude fiber, phosphorus, ash, and magnesium, whereas those grown at Gute contained higher crude protein, iron, zinc, calcium, and manganese. Black-seeded finger millet showed superior moisture, calcium, and crude fiber compared to white- and brown-seeded types, underscoring the importance of varietal selection in nutritional enhancement. These findings highlight finger millet's unique nutritional profile, particularly its exceptionally high calcium content, which distinguishes it from other cereals and positions it as a valuable dietary source for vulnerable groups such as children, pregnant and lactating mothers, and the elderly.

Overall, the results confirm that both genetic and environmental factors play critical roles in determining grain quality, and that targeted varietal and site-specific cultivation strategies can maximize nutritional outcomes. Nevertheless, the omission of anti-nutritional factors, mineral bioavailability, and functional properties reduces the nutritional relevance of the findings. These aspects should be analyzed in future studies.

Food products processed from finger millet can serve as an excellent source of calcium for children, pregnant and lactating mothers, and the elderly population. Further research should investigate the anti-nutritional content, mineral bioavailability, and consumer preferences for different seed colors (brown, white, and black). Understanding these dimensions will ensure that finger millet is not only recognized for its high calcium content compared to other cereals but also strategically promoted as a functional food crop for nutrition-sensitive agriculture.

Abbreviations

AOAC	Association of Official Analytical Chemists
AACC	American Association of Cereal Chemists
RCBD	Randomized Complete Block Design
BARC	Bako Agricultural Research Center
TSW	Thousand Seed Weight
ANOVA	Analysis of Variance
LSD	Least Significant Difference
CEC	Cation Exchange Capacity
TN	Total Nitrogen
Ex Na, Ex K, Ex Mg, Ex Ca, Ex Mn	Exchangeable Sodium, Potassium, Magnesium, Calcium, Manganese

PCA	Principal Component Analysis
G×E	Genotype × Environment Interaction
FM	Finger Millet

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

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