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Original Article

Influence of Geographical Diversity and Processing Methods on Nutritional Attributes of Finger Millet and Flax Seeds

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ABSTRACT

Objectives: Finger millet (*Eleusine coracana*) and flax seeds (*Linum usitatissimum*) are nutritious seeds and have multiple health benefits. But the nutrients, bioavailability, and functional quality of these foods may change a lot depending on their geographical locations and processing parameters. This study examines the effect of geographic factors on the concentration of essential nutrients such as calcium, iron, dietary fiber, omega-3 fatty acids, lignans, and antioxidants in finger millet and flax seeds. **Materials and Methods:** Sprouting was performed as one of the processing parameters. For evaluation of the seeds proximate analysis and roasting effect were analysed to check the impact of geography and processing parameters. **Results:** The current study shows a nutritive difference due to the process of germination. Sprouting led to an increase in crude protein in both flax seeds (from 19.22 to 19.33 g/100 g) and finger millet (from 6.22 to 8.27 g/100 g). Also increase in the concentration of amino acids like Threonine and Tyrosine was observed. **Conclusion:** The interaction between regional farming methods and post-harvest processing is very important for getting the best nutritional value out of these seeds. This study underscores the necessity for region-specific and process-optimized strategies to fully exploit the nutritional potential of finger millet and flax seeds.

Keywords: Finger Millet, Flax Seeds, Geographical Diversity, Nutritional Composition, Processing Methods.

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INTRODUCTION

In recent years, there has been a growing emphasis on the promotion and utilization of nutritionally rich, climate-resilient crops, especially those of indigenous origin. Among these, finger millet (*Eleusine coracana*) and flax seeds (*Linum usitatissimum*) have emerged as highly valued for their exceptional nutrient profiles and functional benefits. With the increasing global burden of lifestyle-related diseases such as diabetes, cardiovascular disorders, and obesity, dietary interventions using naturally nutrient-dense foods are gaining attention. Both finger millet and flax seeds are promising candidates in this regard due to their unique composition of macro- and micronutrients, bioactive compounds, and health-promoting properties (Devi *et al*., 2014; Goyal, 2014; Saleh, 2013; Malleshi, 2003).

Finger millet is one of the oldest cultivated millets, predominantly grown in India and Africa. It is a staple food crop in semi-arid regions, appreciated for its drought resistance, low input requirement, and excellent storage properties. Nutritionally, finger millet surpasses many common cereals in its calcium, iron, dietary fiber, and polyphenol content. Its low glycemic index and high antioxidant capacity make it particularly suitable for diabetic and geriatric nutrition. Similarly, flax seeds, cultivated extensively in temperate climates, especially Canada, Russia, China, and parts of India, are known for their high content of α-Linolenic Acid (ALA), a plant-based omega-3 fatty acid. Flax seeds also contain lignans phytoestrogens with antioxidant and anticancer properties and soluble fiber that supports cardiovascular and digestive health (Rizvi, 2024; Shukla, 2024; Gopalan, 2012; Chandra, 2016; Morris, 2007).

Despite their well-documented nutritional benefits, there exists a significant variation in the nutritional quality of these crops across different geographic regions. The geographical diversity-comprising soil characteristics, altitude, climate, and rainfall play a crucial role in influencing the growth conditions and nutrient uptake in plants. For instance, finger millet cultivated in Satara, a district in Maharashtra characterized by semi-arid to

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sub-humid climate, lateritic and red soils, and moderate rainfall ranging from 800 to 1200 mm, differs nutritionally from the same crop grown in the Konkan region, which experiences a humid tropical climate, acidic lateritic soils rich in organic matter, and high annual rainfall between 3000 and 4000 mm. These environmental conditions directly influence the accumulation of polyphenols, minerals, and antioxidants in the grain.

Similarly, flax seeds show significant variation depending on their growing location. In Jammu & Kashmir, flax is cultivated under temperate to sub-temperate climates, where the cool and dry weather, loamy to clay loam soils, and moderate rainfall of 700-1000 mm provides ideal conditions for oil accumulation and lignan biosynthesis. On the other hand, in Satara, flax is grown under semi-arid to sub-humid conditions with black and medium black soils, known for their good moisture retention and moderate fertility, and an average rainfall of 900-1200 mm, influencing its fiber quality and oil yield.

Therefore, understanding the impact of geographical origin on the nutritional attributes of these seeds is essential for their effective use in health-based food systems and nutritional planning (Kaur, 2014; Epaminondas, 2011; Jacob, 2024; Who, 2007).

Furthermore, the processing methods applied to these seeds have a profound impact on their nutrient availability, digestibility, and functional quality. Traditional methods such as roasting, germination, and fermentation are widely practiced across cultures to enhance the sensory qualities and nutritional potential of cereals and seeds. Roasting, for example, reduces moisture, enhances flavor, and lowers microbial load, but may also result in partial loss of heat-sensitive vitamins. Germination or sprouting activates endogenous enzymes that degrade antinutritional factors like phytates and tannins, thereby improving the bioavailability of minerals such as iron and calcium. The metabolic transformation during sprouting also increases the content of certain amino acids and vitamins. Therefore, it is essential to systematically analyze the nutrient changes occurring during processing in both finger millet and flax seeds to identify their most beneficial form for consumption (Khare, 2021; Chandrasekara, 2010; Umeta, 2000; Satheesh, 2020).

Despite considerable studies conducted on the nutritional properties of these seeds, there is a lack of integrated data comparing the effects of geographic variation and traditional processing methods on their nutrient composition. Most available literature focuses either on raw seeds or on a single processing technique, often without considering the environmental or agro-climatic background of the crop. Additionally, studies on finger millet and flax seeds have traditionally been performed independently, overlooking the potential of comparing a cereal and an oilseed that are both nutrient-dense and underutilized. This research, therefore, attempts to fill the knowledge gap by comprehensively evaluating the influence of both geographical diversity and processing methods namely raw, roasted, and germinated forms on the nutritional attributes of these two crops (Lemmens, 2019; Vadivambal, 2007; Shahidi, 2015).

In the context of rising interest in functional foods and nutraceuticals, there is an urgent need to explore indigenous crops that can meet nutritional deficiencies and contribute to preventive healthcare. Finger millet can be an excellent source of calcium and iron in rural diets, especially in regions where dairy consumption is low. Flax seeds, rich in omega-3 fatty acids, can serve as a plant-based alternative to fish oils in vegetarian populations. However, for large-scale acceptance and optimal health benefits, it is important to understand how geography and processing influence their nutritional content. This is particularly vital for policy makers, food manufacturers, nutritionists, and farmers, who need accurate data to promote and market these crops effectively.

Objectives

- To evaluate the nutritional composition of finger millet and flax seeds sourced from different geographical locations with varying soil and climate conditions.
- To assess the effect of processing methods (raw, roasted, and germinated forms) on the nutrient content and bioavailability in both crops.
- To compare and correlate the influence of geographic diversity and processing techniques on the retention or loss of key nutrients such as protein, fiber, fat, calcium, iron, and omega-3 fatty acids.
- To provide recommendations for the optimal form (raw or processed) and sourcing region of finger millet and flax seeds for maximizing their nutritional benefits in dietary interventions.

The rationale behind the study stems from three interconnected observations:

Geographical variability has a direct influence on the nutrient profile of agricultural produce, but limited comparative data exists for finger millet and flax seeds from different regions.

Traditional processing methods, while beneficial for enhancing nutritional bioavailability, may also lead to losses of certain nutrients, depending on the method and intensity applied.

A comparative evaluation of these two nutritionally significant crops representing a cereal and an oilseed has the potential to provide a holistic understanding of how both environment and processing shape their final nutritional value.

By combining geographical and processing variables in one systematic investigation, this study aims to provide evidence-based insights into optimizing the nutritional use of finger millet and flax seeds for human consumption (Taylor, 2015; Das, 2023).

MATERIALS AND METHODS

Materials

Flax seeds were procured from Jammu & Kashmir and Satara, representing two contrasting agro-climatic zones temperate and semi-arid, respectively. Likewise, finger millet was sourced from Satara and the Konkan region of Maharashtra, which differ significantly in rainfall patterns, soil type, and humidity. These variations were intended to reflect the diverse growing conditions that influence nutrient uptake and composition in crops. The amino acid profiling of the raw, roasted & sprouted samples was carried out at Opal Analytical Labs, a certified facility known for precision in nutritional analysis. The proximate analysis of raw, roasted, and sprouted samples collected from these geographically diverse regions was conducted at Oxyfood Lab, a reputed food testing laboratory specializing in compositional and nutritional assessments of agro-based products. This comprehensive analytical approach enabled a robust comparison of processing effects and regional influences on the nutritional quality of both crops (Patil, 2023; Gaikwad, 2021; Xiang, 2019).

Proximate analysis

Proximate analysis is a fundamental method used to evaluate the basic nutritional composition of food materials. It involves the determination of key parameters such as moisture, ash, protein, fat, fiber, and carbohydrate content. In this study, proximate analysis was conducted on finger millet and flax seeds in their raw, roasted, and germinated forms to assess the effect of processing and geographical variation on their nutritional attributes. These findings help in understanding the suitability of each form for specific dietary applications and functional food development (Singh, 2018; Desai, 2010; Hiremath, 2019).

Comparative nutritive study of crude seeds & the effect of roasting, germination on the nutritional values

The present study aimed to evaluate the effect of processing methods-roasting and germination-on the nutritional attributes of finger millet and flax seeds. All seeds were subjected to a standard protocol for processing to ensure uniformity and reproducibility of results.

The crude seeds served as the baseline for comparison. These seeds were procured, cleaned, and milled into powder form to facilitate analysis. Being unprocessed, crude seeds retain their natural nutritional composition, including protein, fat, fiber, moisture, ash, and carbohydrates. However, they may also contain antinutritional factors such as phytates, oxalates, and enzyme inhibitors that limit nutrient bioavailability. Roasting was performed at 50°C for 5-8 min. This mild heat treatment helps in reducing the moisture content, which contributes to increased shelf life and microbial safety. Roasting is also known to enhance aroma and palatability. It can lead to slight alterations in nutritional content such as minimal losses in heat-sensitive vitamins but may also reduce certain antinutrients and improve digestibility. The denaturation of proteins during roasting may slightly enhance protein digestibility while modifying fiber and fat content depending on the seed matrix.

Germination, a biological process involving soaking, sprouting, and drying, had a more profound impact on the nutritional quality. Seeds were first washed and soaked in water for 12 hr to initiate hydration and enzyme activation. After soaking, they were wrapped in a muslin cloth and kept for 72 hr to sprout, during which a sprout length of 0.5 to 0.8 inches was obtained (Figure 1). The sprouts were then dried in shade to preserve heat-sensitive nutrients before being milled. Germination is known to enzymatically break down complex molecules carbohydrates into simpler sugars, proteins into peptides and amino acids, and release bound minerals by reducing phytate content. It also increases the levels of certain vitamins (like Vitamin C and B-complex) and improves the digestibility of both macronutrients and micronutrients.

The comparative analysis across the three forms revealed notable trends:

- Moisture content tends to increase initially during germination due to water uptake but decreases after drying. Roasting reduces moisture more effectively, enhancing storability.
- Protein levels may appear higher post-germination due to enzymatic hydrolysis and concentration effects from carbohydrate breakdown.
- Fat content may slightly reduce after germination due to metabolic utilization during sprout development, whereas roasting generally preserves it.
- Fiber content tends to increase during germination due to cell wall modification and sprout growth.
- Ash content remains relatively stable, but the bioavailability of minerals improves significantly in germinated samples due to phytate breakdown.
- Carbohydrates often decrease slightly after germination due to their utilization as an energy source for sprouting, while roasting has minimal effect.

Overall, germination emerged as the most beneficial method in enhancing the nutritional quality and bioavailability of nutrients, while roasting contributed to improved shelf life, taste, and partial enhancement of digestibility. The comparative nutritive study highlights how simple processing techniques can be employed to significantly upgrade the functional and nutritional value of traditionally used seeds like finger millet and flax (Dharmaraj, 2011; Chauhan, 2018; Bhatt, 2023).

Statistical Analysis

All analysis was performed in triplicate and results are expressed as Mean±SD. Statistical analysis was carried out using Jamovi software. Statistical analysis using Student's t-test demonstrated significant differences ($p<0.05$) in proximate composition of flaxseed and finger millet sourced from different geographical locations. One-way ANOVA was applied separately for flaxseed and finger millet to evaluate the effect of processing methods (plain, roasted, sprouted). The parameters applied here were crude protein content and amino acid composition. Normality and homogeneity of variances were assessed using Shapiro-Wilk and Levene's tests respectively. Tukey's HSD *post hoc* test was employed for pairwise comparisons. The differences were considered significant at $p<0.05$.

RESULTS AND DISCUSSION

Proximate Analysis

The comparative data from Table 1 clearly indicates that geographical origin has a measurable influence on the nutritional composition of both flax seeds and finger millet. This variability is largely attributed to differences in climatic conditions, soil properties, altitude, and rainfall in the respective regions of cultivation.

For flax seeds, samples sourced from Jammu & Kashmir-a region characterized by a cooler temperate climate, loamy soils, and moderate rainfall-recorded higher protein (30.12±0.15 g/100 g) and fat (25.80±0.20 g/100 g) contents compared to those from Satara, which has a semi-arid to sub-humid climate with black soils. This suggests that cooler climates may favor oil accumulation and amino acid synthesis in oilseeds like flax, potentially due to slower maturation rates and better nutrient retention in seed development. Moreover, the higher dietary fiber (21.60±0.30%)

Figure 1: Sprouts of A) Flax seed & B) Finger millet.

Table 1: Nutritional Composition of Finger Millet and Flax Seeds (per 100 g).

Test Parameter	Flaxseed (J&K)	Flaxseed (Satara)	*p*-value	Finger Millet (Satara)	Finger Millet (Konkan)	*p*-value
Moisture (%)	4.80±0.10	5.20±0.10	0.008	7.20±0.10	7.80±0.10	0.005
Total Ash (%)	2.70±0.05	2.30±0.05	0.004	2.40±0.05	2.60±0.05	0.012
Protein (g/100 g)	30.12±0.15	29.20±0.20	0.006	20.45±0.20	21.08±0.15	0.018
Total Fat (g/100 g)	25.80±0.20	24.40±0.25	0.004	0.61±0.03	0.69±0.03	0.021
Carbohydrate (g/100 g)	36.18±0.30	39.26±0.35	0.003	68.90±0.40	68.20±0.30	0.092
Energy (kcal/100 g)	500.2±2.0	491.0±2.5	0.005	361.8±2.2	365.0±2.0	0.041
Sugar (g/100 g)	1.05±0.05	1.15±0.05	0.087	<1.0	<1.0	-
Dietary Fibre (%)	21.60±0.30	20.60±0.25	0.019	14.80±0.20	15.20±0.20	0.033

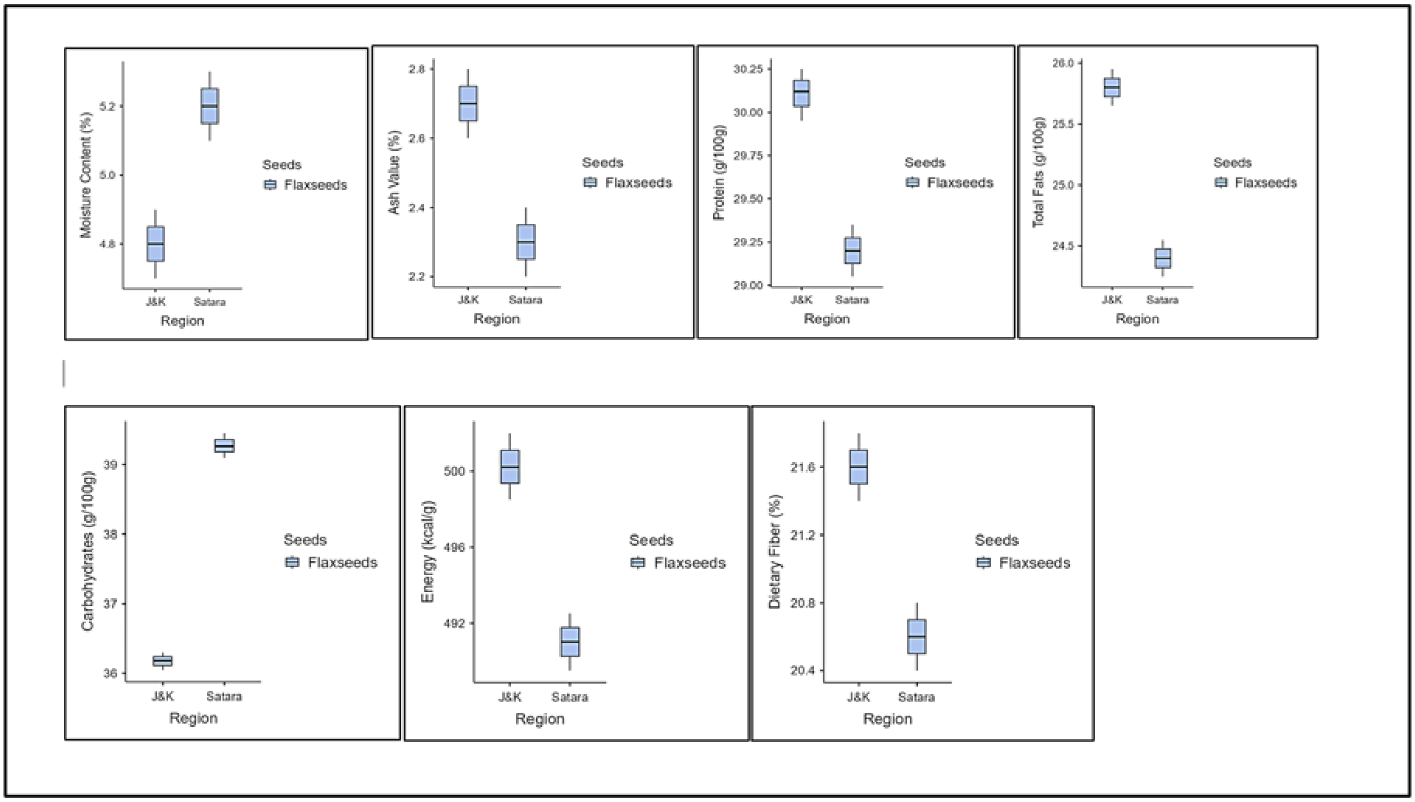

Figure 2: Proximate analysis of flax seed varieties from Jammu-Kashmir and Satara. Student's *t*-test revealed statistically significant differences ($p<0.05$) in proximate composition of flaxseed across Jammu-Kashmir and Satara as geographical variation.

and lower moisture content in J&K samples support better storage stability and functional use in high-fiber formulations (Figure 2).

Conversely, flax seeds from Satara showed slightly higher carbohydrate (39.26±0.35 g/100 g) and sugar content (1.15±0.05 g/100 g), possibly due to faster metabolic turnover in warmer, more sunlit conditions, which can influence seed composition through enhanced photosynthesis and sugar partitioning.

In the case of finger millet, the Konkan region, with its humid tropical climate and heavy annual rainfall, produced samples with slightly higher protein (21.08±0.15 g/100 g) and ash content (2.60±0.05%) than those from Satara, a drier zone with lateritic soils and more moderate rainfall. These differences may be associated with higher soil organic matter and better micronutrient availability in Konkan soils, resulting in improved mineral deposition and nitrogen uptake. Additionally, the fiber content (15.20±0.20%) in Konkan samples was marginally higher, reinforcing the importance of soil moisture and organic richness in modulating plant cell wall development (Figure 3).

Overall, the J&K flax seeds and Konkan finger millet showed slightly superior nutrient profiles for protein, ash, and fiber, whereas Satara-sourced seeds reflected higher carbohydrate values, suggesting their potential for energy-dense dietary applications. These region-specific differences underscore the critical role of agro-climatic factors in shaping seed nutrient quality and point toward the need for location-aware sourcing strategies in functional food development and nutrition planning.

As this study also includes processed forms (roasted and sprouted), subsequent sections delve into how processing interacts with regional variation to further influence bioavailability, functional properties, and overall nutritional value.

Comparative Nutritive study

Table 2 reflects the impact of processing methods (roasting and sprouting) on the crude protein content and amino acid profile of flax seed and finger millet. Overall, the results highlight the beneficial effects of germination, while the impact of roasting is variable.

Crude Protein

Sprouting led to an increase in crude protein in both flax seeds (from 19.22 to 19.33 g/100 g) and finger millet (from 6.22 to 8.27 g/100 g). This can be attributed to enzymatic hydrolysis of complex macromolecules during germination and possible loss of dry matter (carbohydrate), which concentrates the protein content. Roasting, however, decreased crude protein in flax (to 16.21 g/100 g), likely due to protein denaturation and Maillard reactions, while slightly increasing it in finger millet (to 6.91 g/100 g), possibly due to moisture loss.

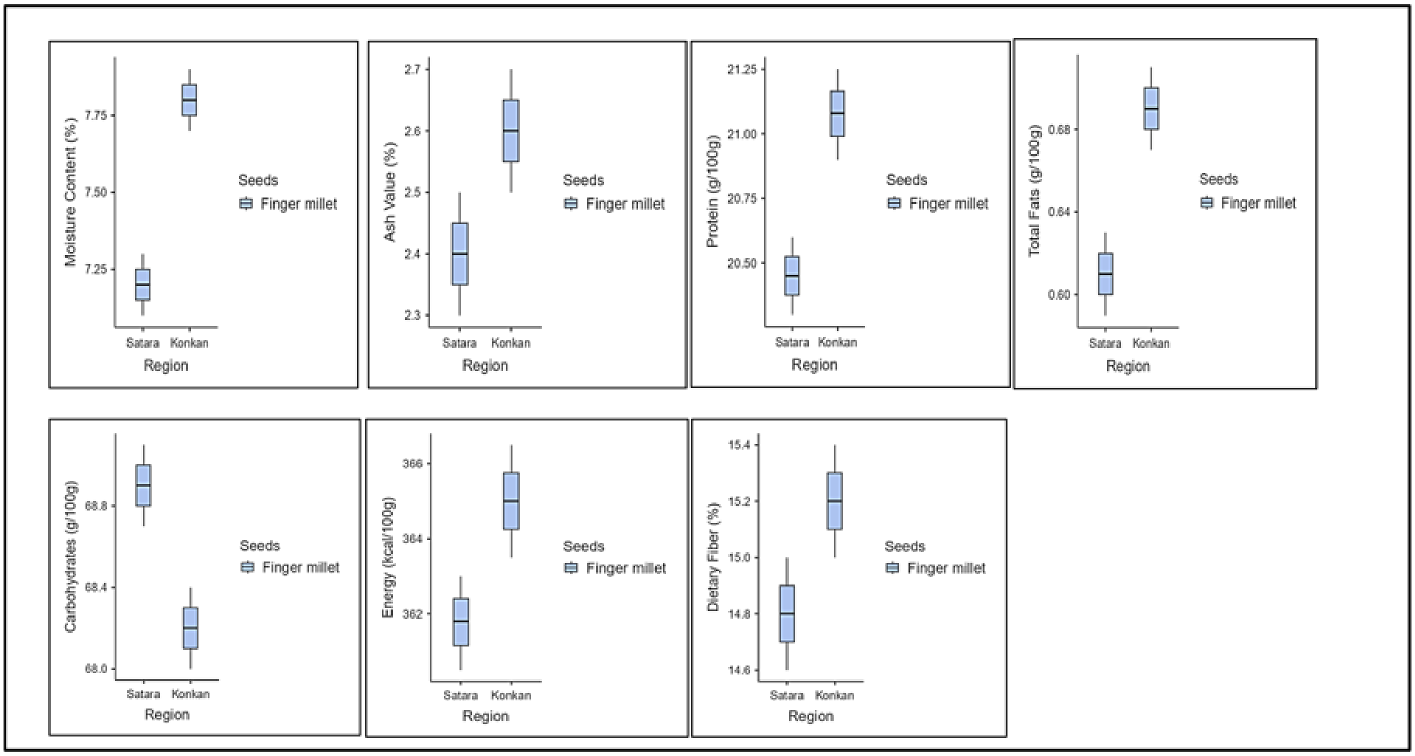

Figure 3: Proximate analysis of Finger millet variety from Satara and Konkan. Student's *t*-test revealed statistically significant differences ($p<0.05$) in proximate composition of Finger millet across Satara and Konkan as geographical variation.

Amino Acids

Valine, Leucine, and Iso-leucine (BCAAs): These essential branched-chain amino acids increased significantly after sprouting in both seeds, supporting improved nutritional and functional value. For instance, valine increased from 1.88 to 3.29 g/100 g in flax and from 1.32 to 4.27 g/100 g in finger millet.

Methionine and Lysine: These sulfur-containing and limiting amino acids also showed notable improvement post-germination. Flax seeds exhibited a significant methionine increase (from 1.14 to 4.18 g/100 g), while lysine in finger millet increased from 0.32 to 2.15 g/100 g, improving the biological value of millet protein.

Threonine and Tyrosine: Both amino acids increased steadily with germination. Threonine rose from 2.81 to 3.09 g/100 g in flax and from 2.76 to 5.20 g/100 g in finger millet. Tyrosine nearly tripled in finger millet (from 1.25 to 4.27 g/100 g), indicating better amino acid availability.

Tryptophan: As an essential amino acid and precursor for serotonin, tryptophan showed a marked increase post-sprouting. Flax seeds increased from 13.88 to 16.19 g/100 g, and finger millet from 8.59 to 12.33 g/100 g, indicating improved neuro-nutritional value.

Histidine and Phenylalanine: These remained relatively stable, with minor variations. Notably, histidine levels in finger millet were consistently high across all forms, showing resilience to processing.

Roasting Effect

Roasting at 50°C had a moderate to minimal effect on amino acid content. While it preserved or slightly enhanced some amino acids (like methionine in flax and tyrosine in both), it led to reduced levels in others, possibly due to partial degradation or structural changes. The amino acid changes after roasting were less consistent and generally less beneficial than sprouting.

The data clearly demonstrate that germination is more effective than roasting in enhancing the protein quality and amino acid composition of both flax seeds and finger millet. This processing method significantly increases the levels of essential amino acids, particularly lysine, methionine, tryptophan, and branched-chain amino acids, making germinated forms more nutritionally valuable. These findings support the inclusion of germinated flax and finger millet in functional and therapeutic food products, especially for protein enrichment and dietary supplementation.

Statistical analysis

Statistical analysis using Student's *t*-test demonstrated significant differences ($p<0.05$) in proximate composition of flaxseed and finger millet sourced from different geographical locations, indicating the influence of agro-climatic conditions on nutritional attributes.

One-way ANOVA in flaxseed indicated significant differences among plain, roasted, and sprouted forms (Figure 4), *post hoc* Tukey analysis demonstrated that roasted flaxseed exhibited a significantly lower crude protein content compared to both

Table 2: Effect of Processing on Crude Protein and Amino Acid Composition.

Parameter	Flaxseed - Plain	Flaxseed - Sprouted	Flaxseed - Roasted	Finger millet - Plain	Finger millet - Sprouted	Finger millet - Roasted
Crude protein	19.22±0.08	19.34±0.10	16.22±0.08	6.22±0.08	8.27±0.08	6.92±0.08
Valine	1.88±0.04	3.30±0.05	2.18±0.04	1.32±0.04	4.27±0.05	3.23±0.05
Leucine	4.40±0.05	4.30±0.05	3.86±0.04	3.43±0.05	5.18±0.08	4.28±0.07
Iso-leucine	12.66±0.06	12.92±0.08	10.22±0.08	14.18±0.08	15.25±0.10	14.18±0.08
Threonine	2.81±0.04	3.10±0.05	2.83±0.04	2.76±0.06	5.20±0.10	3.90±0.05
Methionine	1.15±0.03	4.19±0.05	3.19±0.05	0.77±0.03	1.20±0.05	0.38±0.03
Lysine	0.98±0.04	2.10±0.05	0.72±0.03	0.32±0.03	2.15±0.05	1.27±0.03
Phenylalanine	2.75±0.05	3.11±0.07	2.90±0.05	1.90±0.05	1.90±0.05	1.55±0.05
Histidine	16.20±0.10	14.08±0.08	13.97±0.08	14.20±0.10	14.15±0.10	13.98±0.08
Tyrosine	1.48±0.04	3.16±0.06	2.91±0.04	1.26±0.04	4.27±0.08	3.20±0.05
Tryptophan	13.88±0.08	16.20±0.10	14.33±0.08	8.60±0.05	12.33±0.13	10.40±0.10

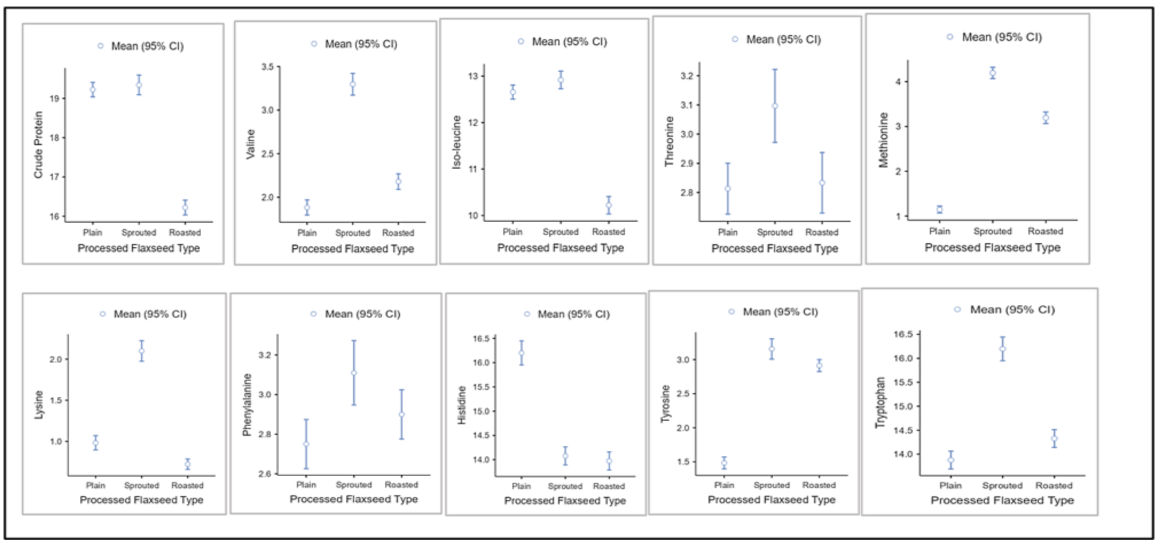

Figure 4: Effect of processing on Flax seeds nutritional analysis. One-way ANOVA followed by Tukey's *post hoc* test showed significant differences ($p<0.05$) among processing techniques for nutritional parameters of flaxseeds.

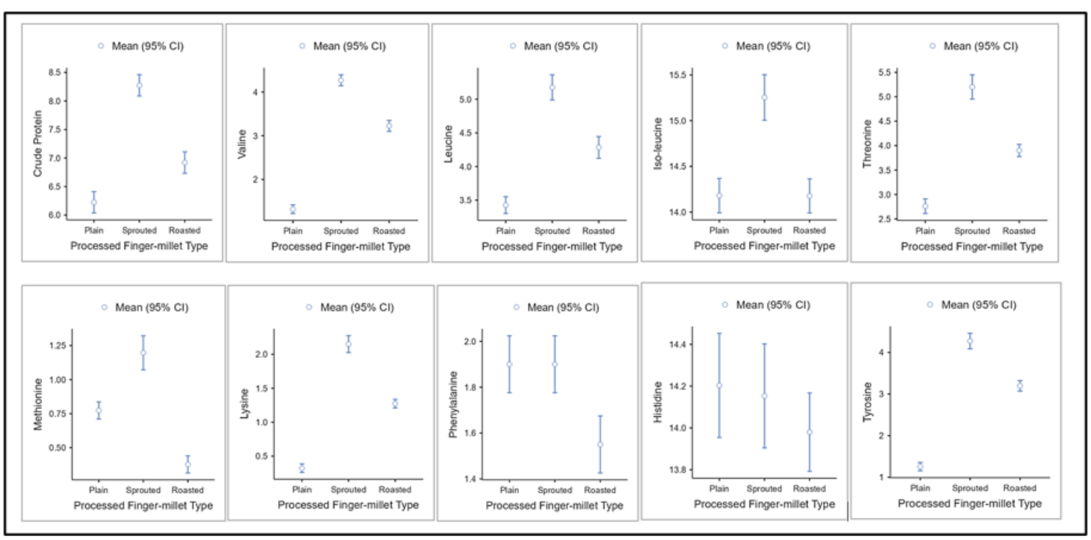

Figure 5: Effect of processing on Finger millet seed nutritional analysis. One-way ANOVA followed by Tukey's *post hoc* test showed significant differences ($p<0.05$) among processing techniques for nutritional parameters of finger millet.

plain as well as sprouted samples ($p<0.001$). While no significant difference was observed between plain and sprouted forms. It was depicted that sprouting process significantly enhanced several essential amino acids, including valine, methionine, lysine, tyrosine, and tryptophan ($p<0.001$). This indicates improved protein quality and amino acid bioavailability due to enzymatic activation during germination.

Similarly in finger millet showed response to processing particularly sprouting (Figure 5). It resulted in significant increases in crude protein and most essential amino acids when compared to plain and roasted samples ($p<0.001$). Roasting produced intermediate values which suggests partial retention of nutrients but lower enhancement compared to sprouting. Certain amino acids such as histidine, exhibited relatively minor variation across processing methods, indicating greater stability to thermal and germination treatments.

From the overall analysis it can be said that the statistical analysis confirms that sprouting is the most effective processing method for improving protein quality and amino acid composition in both flaxseed and finger millet. A consistent intra-seed trend of sprouted > roasted > plain was observed for nutritionally important amino acids. This expresses the potential of simple bioprocessing techniques to enhance the functional and nutritional value of seeds.

CONCLUSION

The present study comprehensively evaluated the impact of geographical diversity and traditional processing methods such as roasting and germination on the nutritional attributes of finger millet and flax seeds. Geographical locations do not change the nutritional contents & processing techniques enhance the nutritive values. Among the processing methods, germination proved to be the most effective, consistently enhancing the bioavailability of essential amino acids and crude protein content in both crops. This transformation can be attributed to enzymatic activation during germination, which reduces anti-nutritional factors and improves digestibility.

In summary, the study highlights that the strategic combination of flax seeds and finger millet, when processed through germination, offers a scientifically sound approach to enhancing dietary quality through natural, plant-based means. The outcomes pave the way for the development of value-added nutraceuticals, clinical nutrition products, and functional foods with specific health benefits. Future research may explore long-term clinical implications, stability of bioactive components, and formulation into various pharmaceutical dosage forms for wider therapeutic applications.

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ABBREVIATIONS

ALA: α-Linolenic Acid; **BCAAs:** Branched-Chain Amino Acids.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORS CONTRIBUTION

YS - Research work, Literature survey, Manuscript preparation, data collection. GD - Supervision, project administration

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