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Research Article

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Proximate Composition and Functional Profiling of Oilseed Genotypes for Ketogenic Food Applications: Implications for Ingredient Design in Low-carbohydrate Foods

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Abstract

The growing demand for ketogenic foods has increased the need to identify natural functional ingredients that possess compositional characteristics suitable for ketogenic food formulations. This study evaluated eight oilseed genotypes-sesame (Phule til and JLT-7), groundnut (Phule Pragati and Dhanlaxmi), soybean (KDS 1344 and KDS 1270), and sunflower (GMU 1147 and GMU 1031) for their suitability in ketogenic food systems through comprehensive proximate composition and functional characterization. Phule Pragati groundnut exhibited the highest fat (48.4%) and protein (24.8%) contents, whereas KDS 1270 soybean had the lowest carbohydrate content (10.5%). Functional properties, including oil absorption capacity (OAC), swelling index, emulsification capacity, and antioxidant activity, demonstrated the potential suitability of these genotypes for ketogenic food formulations. High OAC (>59%) may enhance fat retention in high-fat food matrices, high swelling index (e.g., GMU 1147: 29.33) may be advantageous in starch-free formulations, and strong emulsification capacity (GMU 1031: 89.6%) may facilitate the development of emulsion-based products. KDS 1344 exhibited the highest ash content (4.90%), indicating a relatively high total mineral content and potential suitability for mineral-enriched ketogenic formulations. Phule til sesame exhibited the highest magnesium (Mg; 354 ppm) and iron (Fe; 9.75 ppm) content among the evaluated genotypes. The findings provide a scientific basis for selecting suitable oilseed genotypes for future studies on the development of ketogenic food formulations and other functional plant-based foods.

Keywords

Oilseeds, Ketogenic diet, Functional properties, Proximate composition, Antioxidant activity, Food ingredient design, Plant-based ingredients

Introduction

Oilseeds are an important component of human nutrition, providing fats, proteins, dietary fiber, essential vitamins, minerals, and bioactive phytochemicals. Common oilseed crops such as sesame (*Sesamum indicum*) (Figure 1), groundnut *(Arachis hypogaea)* (Figure 2), soybean (*Glycine max*) (Figure 3), and sunflower (*Helianthus annuus*) (Figure 4) differ considerably in composition, generally containing approximately 15 - 50% fat and 6 - 45% protein, depending on the species and genotype [1]. Their functional attributes, including emulsification, foaming, and water/oil binding, significantly affect food texture, stability, and shelf life [2].

Ketogenic diet is a fat-rich diet that usually contains 55 - 70% of energy from fat, 20 - 35% from protein and less than 10% from carbohydrates (generally <50 g/



Figure 1: Sesame seeds (Phule til and JLT-7).



Figure 2: Groundnut (Phule Pragati and Dhanlaxmi).



Figure 3: Soybean (KDS 1344 and KDS 1270).



Figure 4: Sunflower seeds (GMU 1147 and GMU 1031).

day), which results in nutritional ketosis due to the production of ketone bodies in the liver. The ketogenic diet was originally designed for the treatment of drug-resistant epilepsy and is currently being studied for the therapeutic benefits in obesity, type 2 diabetes, metabolic syndrome, and some neurological diseases [3].

While soybeans are botanically a legume, it is often categorized with oilseeds due to their dual protein–oil profile. In this study, soybean was included as the sole legume representative among predominantly oilseed crops. Soybean, sesame, groundnut and sunflower proteins and lipids have been shown earlier to possess desirable techno-functional properties in food systems, including emulsification, water and oil absorption and structural stability. They are significant in food processing and product quality to ensure better interactions between ingredients, food product texture and stability. The present study, however, only assessed the nutrient availability and the functional properties of the selected oilseed flours and did not assess nutrient bioavailability, controlled release or gastrointestinal nutrient delivery [4]. This study aimed to evaluate the proximate composition and functional properties of Indian varieties of sesame, groundnut, soybean, and sunflower, and to assess their application as an ingredient in a ketogenic food product. The results provide a scientific basis for selecting suitable oilseed genotypes for the production of food with high nutritional value for use in the formulation of a ketogenic diet and future research on their use in functional food systems.

Materials and Methods

The present study was carried out at the Department of Food Science and Technology, Shivaji University and the Department of Food Technology, College of Non-Conventional Vocational Courses for Women, Kolhapur, India. The oilseed genotypes of sesame (*S. indicum*) (Phule til and JLT-7), soybean (*G. max*) (KDS 1344 and KDS 1270), groundnut (*A. hypogaea*) (Phule Pragati and Dhanlaxmi), and sunflower (*H. annuus*) (GMU 1147 and GMU 1031) were procured from the authorized agricultural seed vendor of Kolhapur, Maharashtra. Only certified seed lots with official cultivar names and certification tags from the seed-producing agency were used. Before analysis, the varietal identity of each genotype was confirmed by the information on the certification labels and package information.

Physical properties of oilseeds

The physical properties of sesame, groundnut, soybean, and sunflower seeds were evaluated, including thousand-kernel weight, bulk density, angle of repose, hydration index, and swelling index.

1000 kernel weight

Thousand-kernel weight was determined by randomly selecting 100 seeds, weighing them using a precision balance (Wensar, accuracy ± 0.001 g), and multiplying the measured weight by 10 to estimate the weight of 1000 seeds.

Bulk density

Bulk density was determined according to the method described by Okaka and Potter [5]. A 50 g sample was placed into a 100 mL graduated cylinder and tapped 20 - 30 times to allow settling. The density was calculated using the formula.

$$Bulk\ density\ (g/mL) = \frac{Weight\ of\ sample}{Volume\ occupied\ by\ sample}$$

Angle of repose

The angle of repose was determined according to the method described by Jangam and Thorat [6]. An open-ended cylinder (15 cm diameter and 30 cm height) was positioned on a 70 cm diameter circular plate and filled with seeds while gently tapping to ensure uniform distribution. The cylinder was lifted vertically to allow the seeds to form a natural cone. The height of the cone was measured, and the angle was calculated using the formula:

$$tan\theta = \frac{H}{r}$$

Where, θ is the angle of repose, H is the height of the cone, and r is the base radius of the cone.

Hydration index

Hydration capacity was tested using the method by Williams et al. [7]. 10 g of seeds were weighed, counted, and placed in a measuring cylinder. 25 ml of water was added, and the cylinder was sealed with aluminum foil and kept at room temperature overnight. The following day, seeds were drained, blotted with filter paper, and weighed. Hydration index was computed followed by hydration capacity using these formulae:

$$Hydration\ capacity\ (per\ seed) = \frac{Increase\ in\ weight\ of\ seeds}{Number\ of\ seeds}$$

$$Hydration\ index = \frac{Hydration\ capacity\ per\ seed}{Weight\ of\ one\ seed}$$

Swelling index

A 10 g seed sample was counted and placed into a measuring cylinder, followed by the addition of 25 ml distilled water. The initial volume was recorded, and the seeds were left to soak for 24 h at room temperature (20 – 30 °C) [8]. After soaking, the new volume was measured. The swelling index was calculated followed by swelling capacity using these formulae:

$$Swelling\ capacity\ (per\ seed)\ (mL/g) = \frac{Increase\ in\ volume\ of\ seeds}{Weight\ of\ seeds}$$

$$Swelling\ index = \frac{Swelling\ capacity\ per\ seed}{Volume\ of\ one\ seed}$$

Color analysis (L*, a*, and b*)

The color of the samples was measured using a HunterLab color analyzer (Model 45/0LAV). The machine was calibrated using standard white and black ceramic tiles. The HunterLab colorimeter expresses sample color using three parameters: L^*, a^*, and b^*. The L^* value represents lightness, ranging from 0 (black) to 100 (white). Negative a^* values indicate greenness, whereas positive a^* values indicate redness. Positive b^* values indicate yellowness, whereas negative b^* values indicate blueness.

Functional properties of oilseed flour

Functional properties, including water absorption capacity (WAC), OAC, emulsifying capacity, and foaming properties, were determined using established methods [7, 9, 10]. Antioxidant activity was measured via 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging [11].

WAC

WAC was determined according to the method of Singh and Singh [9], with slight modifications. A 1.0 g flour sample was mixed with 10 mL of distilled water and left to stand at room temperature for 30 min. The mixture was centrifuged at 2000 rpm for 10 min. The supernatant was decanted, and the test tube was inverted and left to drain for 5 min on absorbent paper. The remaining residue was weighed, and WAC was expressed as the percentage of water retained per gram of flour.

$$WAC\ (\%) = \frac{Weight\ of\ sediment(after\ centrifugation) - Initial\ weight}{Initial\ weight} \times 100$$

OAC

OAC was determined according to the method of Singh and Singh [9], with slight modifications. Each 1.0 g flour sample was mixed with 10 mL of sunflower oil and allowed to stand at room temperature for 30 min. The mixture was centrifuged at 2000 rpm for 10 min; the oil supernatant was discarded. The tubes were then inverted for 5 min on absorbent paper to drain excess oil. OAC was calculated from the weight of the retained sediment after centrifugation and calculating how much oil was kept per gram of flour.

$$OAC\ (\%) = \frac{Weight\ of\ sediment(after\ centrifugation) - Initial\ weight}{Initial\ weight} \times 100$$

Emulsifying capacity

The emulsifying ability of the flour was tested as per the method outlined by Kinsella [10]. A 0.5 g flour sample was dispersed in 5 mL of distilled water in an Erlenmeyer flask and stirred at 1000 rpm for 15 min using a magnetic stirrer. Refined oil (5 mL) was added slowly over 5 min with continuous stirring, followed by an additional minute of mixing. The emulsion was then placed in a centrifuge tube, heated in a water bath at 85 °C, and centrifuged at 3500 rpm. The emulsifying capacity was expressed based on the height of the emulsion layer after oil separation.

Foam stability

Foaming properties were assessed according to Narayana and Rao [12], with modifications by Fagbemi and Oshodi [13]. Two grams of flour were added to 50 mL of distilled water at approximately 30 ± 2 °C in a 100 ml measuring cylinder. The mixture was vigorously shaken to generate foam. Foam volume was measured after 30 s to determine foam capacity, and again after 2 h to determine foam stability, which was expressed as a percentage of the original foam volume.

Antioxidant activity

Free radical scavenging activity was determined using the stable free radical DPPH. Aliquots of 1, 2, 3, 4, and 5 mL of each extract were transferred into separate 10 mL volumetric flasks. Subsequently, 3 mL of DPPH solution was added to each flask, and the volume was adjusted to 10

mL with methanol. The samples were then stored in the dark for 30 min. The absorbance was measured at 517 nm using an ultraviolet–visible spectrophotometer against the control. Antioxidant capacity was measured as follows [11].

$$Antioxidant\ activity\ (\%) = \frac{Absorbance\ of\ control - Absorbance\ of\ sample}{Absorbance\ of\ control} \times 100$$

Proximate analysis of oilseeds

Proximate composition (moisture, crude fat, crude protein, ash, crude fiber, and carbohydrate) was determined according to the relevant Association of Official Analytical Chemists (AOAC) Official Methods [11] of Analysis. Moisture, fat, protein, ash, and crude fiber were analyzed using AOAC Official Methods 925.40, 948.22, 950.48, 923.03, and the applicable AOAC method for crude fiber (978.10), respectively. Carbohydrate content was calculated by the difference method.

Moisture (AOAC Official Method 925.40)

Approximately 5 g of sample was weighed, placed in a Petri dish, and dried in a hot air oven (Lab-line, 100 - 110 °C) until a constant weight was obtained. The moisture content was calculated based on the loss in weight after drying [11].

$$Moisture\ (\%) = \frac{Initial\ weight - Final\ weight}{Total\ weight\ of\ sample} \times 100$$

Lipid (AOAC Official Method 948.22)

Approximately 5 g of sample was placed in a Soxhlet extraction thimble and extracted with hexane for 8 h. The defatted samples were dried overnight (10 - 12 h) in a hot air oven to remove residual traces of hexane before weighing, and the samples were weighed to calculate lipid content.

$$Lipid\ (\%) = \frac{Initial\ weight\ of\ full\ fat\ flour - Final\ weight\ of\ defatted\ flour}{Initial\ weight\ of\ full\ fat\ flour} \times 100$$

Protein (AOAC Official Method 950.48)

Total protein content was determined by the Micro-Kjeldahl method using 2 g of sample. Sample nitrogen content was calculated using the formula:

$$Protein\ (\%) = Total\ \%\ N \times Appropriate\ conversion\ factor\ for\ the\ sample$$

Ash (AOAC Official Method 923.03)

Approximately 2 g of sample was accurately weighed and placed in a pre-weighed ceramic crucible that had been previously heated and cooled to constant weight and subjected to ashing in a muffle furnace maintained at 550 °C until a constant final weight for ash was achieved.

$$Ash\ (\%) = \frac{Weight\ of\ crucible\ after\ ash - Weight\ of\ crucible\ before\ ash}{Weight\ of\ sample} \times 100$$

Carbohydrates

Total carbohydrate content was estimated by the difference method. It was calculated by subtracting the sum of percentage of moisture, fat, protein, ash, and fiber contents from 100 according to AOAC [11].

$$Total\ carbohydrate\ (\%) = 100 - (Moisture\ (\%) + Protein\ (\%) + Fat\ (\%) + Ash\ (\%) + Fibre\ (\%))$$

Crude fiber (AOAC Official Method 978.10)

2 g of defatted, dried sample were transferred to a beaker containing 200 mL of 1.25% sulfuric acid. The beaker containing the sample was heated on a hot plate and boiled for 30 min. After boiling, the contents of the beaker were filtered through Whatman filter paper no. 4. The residue retained on the filter paper was transferred to a beaker containing 200 mL of 1.25% sodium hydroxide. The contents were boiled for an additional 30 min. The residue was filtered and washed repeatedly with hot water followed by alcohol until free of alkali. The residue was transferred to pre-weighed silica crucibles, dried in a hot air oven at 100 °C, ignited in a muffle furnace at 600 ± 100 °C for 30 min, cooled in a desiccator, and weighed. The crucibles were then kept in a muffle furnace and ignited for 30 min at 600 ± 100 °C followed by cooling and weighing. The loss in weight after ignition represents the crude fiber and was calculated as follows:

$$Crude\ fibre\ (\%) = \frac{Loss\ in\ weight\ on\ ignition}{Weight\ of\ sample} \times 100$$

Mineral estimation

Mineral analysis was carried out according to the AOAC Manual of Laboratory Techniques. Accurately weighed samples were ashed in a muffle furnace at 600 °C for 6 h. The ash was dissolved in 6 M hydrochloric acid (HCl) to prepare the stock solution. Mineral estimation by inductively coupled plasma optical emission spectrometry (Shimadzu model: MY15230013) was performed using certified reference materials and multi-element standard solutions. Stock standard solutions were prepared in 6 M HCl. Calibration curves exhibited excellent linearity (R^2 = 0.99980).

Statistics

All physical, functional, color, and proximate analyses were conducted in triplicate, and the data are presented as mean ± standard deviation (SD). The data were statistically analyzed using one-way analysis of variance (ANOVA), IBM SPSS Statistics Version 26.0 and differences among means were considered statistically significant at $p < 0.05$.

Results and Discussion

Physical properties of oilseeds

Table 1 presents the physical properties of sesame, groundnut, soybean, and sunflower genotypes, including 1000-kernel weight, bulk density, angle of repose, hydration index, swelling index, and color characteristics. Among the sesame genotypes, Phule til exhibited a higher 1000-kernel weight and bulk density than JLT-7, indicating a more compact seed structure. The higher angle of repose indicates slightly lower flowability. Both genotypes exhibited similar hydration indices; however, Phule til showed a slightly higher swelling capacity, indicating greater expansion during hydration.

Table 1: Physical properties of oilseeds.

Sample	Genotype	1000 kernel weight (g)	Bulk density (g/mL)	Angle of repose (°)	Hydration index	Swelling index
Sesame seeds	Phule til	3.37 ± 0.05^{a}	0.66 ± 0.01^{a}	32.76 ± 0.30^{a}	0.65 ± 0.01^{a}	0.53 ± 0.01^{a}
	JLT-7	3.02 ± 0.03^{b}	0.53 ± 0.03^{b}	30.42 ± 0.40^{b}	0.63 ± 0.04^{b}	0.46 ± 0.01^{b}
Groundnut	Phule Pragati	534.23 ± 0.04^{b}	0.58 ± 0.005^{a}	18.5 ± 0.30^{a}	0.48 ± 0.01^{a}	0.13 ± 0.01^{a}
	Phule Dhanlaxmi	540.89 ± 0.01^{a}	0.47 ± 0.02^{b}	15.2 ± 0.01^{b}	0.42 ± 0.05^{b}	0.12 ± 0.05^{b}
Soybean	KDS 1344	100.07 ± 0.03^{a}	0.70 ± 0.01^{b}	28.56 ± 0.15^{a}	0.24 ± 0.01^{a}	7.26 ± 0.11^{a}
	KDS 1270	94.04 ± 0.02^{b}	0.85 ± 0.05^{a}	24.85 ± 0.01^{b}	0.21 ± 0.03^{b}	6.87 ± 0.02^{b}
Sunflower seeds	GMU 1147	68.49 ± 0.05^{a}	0.64 ± 0.03^{a}	20.41 ± 0.53^{b}	0.06 ± 0.002^{b}	29.33 ± 0.57^{a}
	GMU 1031	64.35 ± 0.04^{b}	0.56 ± 0.03^{b}	21.56 ± 0.05^{a}	0.08 ± 0.05^{a}	26.59 ± 0.05^{b}

Note: Values are expressed as mean ± SD (n = 3). Means within the same column and oilseed group followed by different superscript letters differ significantly (one-way ANOVA, $p < 0.05$).

Similar observations have been reported by Mathur et al. [14].

Among the groundnut genotypes, Dhanlaxmi exhibited a marginally higher kernel weight, whereas Phule Pragati showed higher bulk density, hydration index, and swelling capacity. The lower angle of repose of Dhanlaxmi indicates better flowability, which may facilitate handling and storage. However, Phule Pragati exhibited superior density and hydration properties, making it more suitable for applications requiring compactness and enhanced water absorption [14].

For soybean genotypes, KDS 1344 exhibited a higher kernel weight, whereas KDS 1270 showed higher bulk density and a lower angle of repose, indicating better flowability. Both genotypes exhibited relatively low hydration indices but high swelling capacities. KDS 1344 showed the highest swelling capacity, suggesting potential suitability in the future for expanded or structured food products such as puffed snacks and meat analogues.

The sunflower genotypes exhibited variation in their physical properties, with GMU 1147 having a slightly higher kernel weight and bulk density. Both genotypes had low hydration indices but very high swelling capacity, especially GMU 1147, which may be considered for future evaluation in extrusion-based products.

Overall, the evaluated genotypes exhibited distinct physical properties that may influence their processing behavior and end-use applications. Phule til, Phule Pragati, KDS 1344, and GMU 1147 all exhibited favorable combinations of density, hydration, and swelling properties, making them suitable for various food processing and product development uses.

Table 2 shows that the phule til genotype showed a slightly lower lightness ($L^* = 63.95$) compared to JLT-7 ($L^* = 65.53$), indicating that it was slightly darker. JLT-7 also has a slightly higher red component ($a^* = 6.8$) and a slightly lower yellow value ($b^* = 21.03$) compared to Phule til ($a^* = 6.3$, $b^* = 22.45$). This suggests that JLT-7 appeared slightly redder but less yellow than Phule til. Phule Pragati was significantly lighter ($L^* = 47.08$) than Dhanlaxmi ($L^* = 35.23$), indicating that Dhanlaxmi exhibited a darker appearance. Phule Pragati also has higher red ($a^* = 18.16$) and yellow ($b^* = 22.98$) values, giving it a more reddish-yellow appearance compared to the duller and darker Dhanlaxmi. KDS 1344 appears slightly lighter ($L^* = 62.3$) and more intensely red and yellow ($a^* = 8.68$, $b^* = 27.41$) than KDS 1270 ($L^* = 60.56$, $a^* = 7.45$, $b^* = 24.86$). These values indicate that KDS 1344 exhibited a brighter and more vibrant appearance. GMU 1031 exhibited higher lightness ($L^* = 63.47$) than GMU 1147 ($L^* = 60.41$). GMU 1147 exhibited a higher redness value ($a^* = 3.22$), whereas GMU 1031 showed a higher yellowness value ($b^* = 18.7$). The color differences between these two genotypes were quantified using the ΔE value. Among the seeds tested, sesame showed the smallest color variation (ΔE = 2.1824), followed by sunflower (ΔE = 3.5051). Soybean displayed a moderate difference (ΔE = 7.4133), while groundnut had the highest variation in color (ΔE = 12.3933). Overall, GMU 1031

Table 2: Color values of oilseeds.

Sample	Genotype	L^*	a^*	b^*	ΔE
Sesame seeds	Phule til	63.95 ± 0.15^{b}	6.3 ± 0.02^{b}	22.45 ± 0.05^{a}	2.1824
	JLT-7	65.53 ± 0.23^{a}	6.8 ± 0.06^{a}	21.03 ± 0.04^{b}	
Groundnut	Phule Pragati	47.08 ± 0.16^{a}	18.16 ± 0.19^{a}	22.98 ± 0.50^{a}	12.3933
	Phule Dhanlaxmi	35.23 ± 0.49^{b}	15.42 ± 0.26^{b}	20.60 ± 0.12^{b}	
Soybean	KDS 1344	62.30 ± 0.32^{a}	8.68 ± 0.16^{a}	27.41 ± 0.21^{a}	7.4133
	KDS 1270	60.56 ± 0.04^{b}	7.45 ± 0.48^{b}	24.86 ± 0.02^{b}	
Sunflower seeds	GMU 1147	60.41 ± 0.15^{b}	3.22 ± 0.08^{a}	17.2 ± 0.38^{b}	3.5051
	GMU 1031	63.47 ± 0.19^{a}	2.4 ± 0.06^{b}	18.7 ± 0.04^{a}	

Note: Values are expressed as mean ± SD (n = 3). Means within the same column and oilseed group followed by different superscript letters differ significantly (one-way ANOVA, $p < 0.05$). ΔE represents the total color difference between paired genotypes within each oilseed.

exhibited greater lightness and yellowness, whereas GMU 1147 showed relatively lower lightness and higher redness.

Functional properties of oilseed flour

Table 3 summarizes the functional properties of sesame, groundnut, soybean, and sunflower genotypes, including WAC, OAC, foaming capacity, emulsifying capacity, and antioxidant activity.

In groundnut, Phule Pragati recorded higher WAC, OAC, and emulsifying capacity than Dhanlaxmi, suggesting greater suitability for food systems requiring efficient water and oil retention. Conversely, Dhanlaxmi exhibited slightly higher foaming capacity and antioxidant activity, suggesting potential suitability for applications requiring enhanced aeration or oxidative stability. These findings are consistent with previous reports [14].

Both soybean genotypes exhibited favorable functional properties. KDS 1344 had higher WAC and OAC, indicating potential suitability for formulations requiring enhanced water and oil retention, whereas KDS 1270 exhibited higher foaming capacity and antioxidant activity, suggesting potential suitability for aerated food products and antioxidant-rich formulations. The emulsifying capacities of the two soybean genotypes were comparable.

The sunflower genotypes exhibited relatively low WAC but high OAC. Both genotypes demonstrated good emulsifying properties, particularly GMU 1031. The high emulsifying capacity and antioxidant activity of GMU 1031 highlights its suitability for products such as dressings, spreads, and functional food formulations.

Overall, the soybean and sunflower genotypes exhibited favorable functional properties, particularly with respect to oil absorption, emulsification, and antioxidant activity, indicating their potential for diverse food processing and product development applications.

Proximate analysis of oilseeds

Table 4 presents the proximate composition of sesame, groundnut, soybean, and sunflower genotypes, including ash, fat, protein, crude fiber, moisture, and carbohydrate contents.

Among sesame genotypes, Phule til contained higher fat (45.58%) but lower protein (20.05%) and crude fiber (10.50%) than JLT-7, which showed lower fat (43.05%) but higher protein (21.70%) and fiber (16.99%). Phule til also exhibited slightly higher ash and moisture contents, while JLT-7 showed higher carbohydrate levels. These differences indicate that JLT-7 may be more suitable for high-protein and high-fiber formulations, whereas Phule til provides a comparatively higher lipid content.

Table 3: Functional properties of oilseed flour.

Sample	Genotype	WAC	OAC	Foaming capacity (%)	Emulsifying capacity (%)	Antioxidant activity (%)
Sesame seeds	Phule til	129.00 ± 0.03^{b}	52.00 ± 0.02^{a}	42.64 ± 0.40^{a}	49.28 ± 0.16^{a}	54.66 ± 0.50^{a}
	JLT-7	132.00 ± 0.04^{a}	47.00 ± 0.01^{b}	35.51 ± 0.20^{b}	43.52 ± 0.10^{b}	47.12 ± 0.20^{b}
Groundnut	Phule Pragati	89.00 ± 0.02^{a}	59.00 ± 0.04^{a}	14.34 ± 0.13^{b}	51.33 ± 0.19^{a}	41.33 ± 0.50^{b}
	Phule Dhanlaxmi	77.00 ± 0.04^{b}	42.00 ± 0.03^{b}	17.35 ± 0.40^{a}	46.23 ± 0.04^{b}	42.56 ± 0.04^{a}
Soybean	KDS 1344	181.13 ± 0.04^{a}	75.00 ± 0.03^{a}	80.65 ± 0.26^{b}	48.34 ± 0.11^{b}	64.66 ± 0.50^{b}
	KDS 1270	156.23 ± 0.2^{b}	65.00 ± 0.04^{b}	89.42 ± 0.50^{a}	49.23 ± 0.40^{a}	68.23 ± 0.05^{a}
Sunflower seeds	GMU 1147	32.50 ± 0.02^{a}	64.00 ± 0.03^{b}	18.41 ± 0.16^{b}	84.58 ± 0.05^{b}	64.00 ± 0.50^{b}
	GMU 1031	31.12 ± 0.05^{b}	65.00 ± 0.05^{a}	19.56 ± 0.04^{a}	89.56 ± 0.03^{a}	74.00 ± 0.04^{a}

Note: Values are expressed as mean ± SD (n = 3). Means within the same column and oilseed group followed by different superscript letters differ significantly (one-way ANOVA, $p < 0.05$).

Table 4: Proximate composition of oilseeds.

Raw materials (%)	Genotype	Ash (%)	Fat (%)	Protein (%)	Crude fiber (%)	Moisture (%)	Carbohydrate (%)
Sesame seed	Phule til	4.50 ± 0.01^{a}	45.58 ± 0.01^{a}	20.05 ± 0.02^{b}	10.50 ± 0.01^{b}	4.50 ± 0.03^{a}	18.63 ± 0.02^{b}
	JLT-7	4.13 ± 0.02^{b}	43.05 ± 0.03^{b}	21.70 ± 0.28^{a}	16.99 ± 0.05^{a}	3.30 ± 0.04^{b}	20.83 ± 0.05^{a}
Groundnut	Phule Pragati	3.16 ± 0.02^{a}	48.40 ± 0.01^{a}	24.81 ± 0.01^{a}	2.60 ± 0.02^{b}	5.30 ± 0.05^{a}	15.73 ± 0.01^{b}
	Phule Dhanlaxmi	2.11 ± 0.07^{b}	42.96 ± 0.04^{b}	23.69 ± 0.05^{b}	10.38 ± 0.18^{a}	6.97 ± 0.02^{a}	16.46 ± 0.06^{a}
Soybean	KDS 1344	4.90 ± 0.01^{a}	20.00 ± 0.05^{a}	35.50 ± 0.04^{b}	13.85 ± 0.01^{a}	8.30 ± 0.02^{a}	13.45 ± 0.02^{a}
	KDS 1270	4.52 ± 0.01^{b}	19.42 ± 0.04^{b}	37.63 ± 0.08^{a}	12.53 ± 0.02^{b}	5.42 ± 0.04^{b}	10.46 ± 0.03^{a}
Sunflower seed	GMU 1147	4.19 ± 0.02^{a}	28.00 ± 0.05^{a}	20.41 ± 0.09^{b}	8.50 ± 0.05^{b}	4.00 ± 0.02^{a}	34.90 ± 0.01^{a}
	GMU 1031	3.44 ± 0.06^{b}	25.00 ± 0.02^{b}	23.53 ± 0.04^{a}	10.80 ± 0.06^{a}	3.53 ± 0.06^{b}	33.7 ± 0.04^{b}

Note: Values are expressed as mean ± SD (n = 3). Means within the same column and oilseed group followed by different superscript letters differ significantly (one-way ANOVA, $p < 0.05$).

In groundnut, Phule Pragati exhibited higher fat (48.40%), protein (24.81%), and ash (3.16%) contents than Dhanlaxmi. Conversely, Dhanlaxmi had greater crude fiber (10.38%) and moisture (6.97%). The carbohydrate content was slightly lower in Phule Pragati (15.73%) than in Dhanlaxmi (16.46%). Overall, Phule Pragati may be more suitable for applications requiring higher oil and protein contents, whereas Dhanlaxmi offers higher fiber content.

For soybean genotypes, KDS 1270 exhibited higher protein (37.63%) and crude fiber (12.53%) contents, with lower fat, ash, moisture, and carbohydrate contents than KDS 1344. Although KDS 1344 showed marginally higher ash and carbohydrate levels, both genotypes represent rich protein sources. Comparable proximate composition trends in oilseeds have been reported by Joshi et al. [15].

Among sunflower genotypes, GMU 1147 contained higher fat and carbohydrate levels, while GMU 1031 exhibited higher protein and crude fiber with lower moisture content. Ash content was comparable between the two genotypes. These results suggest that GMU 1147 may provide greater energy density, whereas GMU 1031 may be preferable for applications requiring higher protein and fiber contents.

From a formulation perspective, genotype-specific variations in fat, protein, and carbohydrate contents indicate their potential suitability for targeted food applications. Genotypes such as Phule Pragati, KDS 1270, and GMU 1031 possess favorable lipid, protein, and relatively low-carbohydrate profiles, suggesting their potential application in specialized food product development.

Mineral analysis of oilseeds

Table 5 presents the mineral composition (ppm) of four oilseed crops: sunflower seeds, peanuts, soybeans, and sesame seeds.

Both the genotypes Phule til and JLT-7 had significantly higher levels of essential minerals, especially calcium (Ca), Mg, Fe, and zinc (Zn) in comparison to the evaluated groundnut, soybean and sunflower germplasm. It was observed that the levels of Ca in JLT-7 were quite higher (1283.32 ppm) than those of Phule til (1041.25 ppm), while the content of Mg, copper (Cu), Fe, and Zn were found to be higher in phule til than in JLT-7. On the other hand, JLT-7 had slightly elevated manganese (Mn) and potassium (K*)* content. The results are in line with previous reports that sesame has genetic potential for mineral accumulation and is one of the most mineral-rich edible oilseed crops where minerals are efficiently partitioned in the seeds [16, 17]. Any differences between the two sesame genotypes are probably due to genotypic variation, which affects nutrient uptake, translocation, and storage during the seed development process [18].

The genotype Phule Pragati had slightly higher concentrations of Ca, Mg, Fe, Zn, and K as compared to the genotype Dhanlaxmi, and Dhanlaxmi had slightly higher concentrations of sodium (Na) and Cu as compared to Phule Pragati among the groundnut genotypes. The mineral concentrations in the groundnut were comparatively lower than those of sesame, but both genotypes of groundnut contributed

Table 5: Mineral content of oilseeds.

Raw materials (ppm)	Genotype	Al (396.152 nm)	Ca (393.366 nm)	Chromium (267.716 nm)	Cu (324.754 nm)	Fe (238.204 nm)	K (766.491 nm)	Mg (279.553 nm)	Mn (257.610 nm)	Na (588.995 nm)	Nickel (231.604 nm)	Zn (213.857 nm)
Sesame seed	Phule til	0.48 ± 0.02^{b}	1041.25 ± 0.06^{b}	0.06 ± 0.07^{a}	2.3 ± 0.04^{a}	9.75 ± 0.01^{b}	459.91 ± 0.06^{a}	354 ± 0.01^{a}	2.8 ± 0.12^{b}	5 ± 0.03^{a}	0.45 ± 0.05^{a}	4.84 ± 0.04^{a}
	JLT-7	0.52 ± 0.01^{a}	1283.32 ± 0.04^{a}	0.01 ± 0.07^{a}	1.52 ± 0.02^{b}	10.56 ± 0.03^{a}	441.03 ± 0.02^{b}	253.00 ± 0.19^{b}	3.20 ± 0.04^{a}	3.20 ± 0.02^{b}	0.32 ± 0.05^{b}	3.45 ± 0.06^{b}
Groundnut	Phule Pragati	0.19 ± 0.04^{b}	37.69 ± 0.06^{a}	0.02 ± 0.01^{a}	0.44 ± 0.07^{b}	1.54 ± 0.03^{a}	245.15 ± 0.07^{a}	57.42 ± 0.04^{a}	0.79 ± 0.01^{a}	3.42 ± 0.07^{b}	0.03 ± 0.23^{a}	1.67 ± 0.07^{a}
	Phule Dhanlaxmi	0.26 ± 0.03^{a}	28.10 ± 0.04^{b}	0.02 ± 0.01^{a}	0.50 ± 0.07^{a}	1.48 ± 0.02^{b}	225.00 ± 0.06^{b}	54.30 ± 0.08^{b}	0.50 ± 0.1^{b}	4.56 ± 0.07^{a}	0.01 ± 0.4^{b}	1.00 ± 0.07^{b}
Soybean	KDS 1344	0.17 ± 0.12^{b}	21.41 ± 0.46^{b}	0.02 ± 0.05^{b}	0.08 ± 0.04^{a}	0.57 ± 0.2^{b}	123.89 ± 0.06^{b}	16.69 ± 0.08^{b}	0.23 ± 0.02^{b}	0.07 ± 0.10^{a}	0.03 ± 0.04^{a}	0.26 ± 0.07^{a}
	KDS 1270	0.50 ± 0.001^{a}	30.6 ± 0.05^{a}	0.03 ± 0.01^{a}	0.04 ± 0.002^{b}	0.82 ± 0.001^{a}	156.04 ± 0.01^{a}	20.6 ± 0.06^{a}	0.42 ± 0.03^{a}	0.04 ± 0.20^{b}	0.02 ± 0.002^{b}	0.19 ± 0.001^{b}
Sunflower seed	GMU 1147	0.34 ± 0.13^{b}	15.85 ± 0.19^{a}	0.03 ± 0.1^{b}	0.60 ± 0.04^{a}	2.30 ± 0.06^{b}	238.24 ± 0.2^{a}	73.86 ± 0.04^{b}	0.51 ± 0.01^{b}	0.92 ± 0.03^{a}	0.06 ± 0.04^{b}	1.05 ± 0.02^{b}
	GMU 1031	1.33 ± 0.50^{a}	10.45 ± 0.04^{b}	0.05 ± 0.01^{a}	0.5 ± 0.1^{b}	3.36 ± 0.05^{a}	234.00 ± 0.04^{b}	96.00 ± 0.3^{a}	0.60 ± 0.02^{a}	0.06 ± 0.40^{b}	0.07 ± 0.08^{a}	2.03 ± 0.90^{a}

Note: Values are expressed as mean ± SD (n = 3). Means within the same column and oilseed group followed by different superscript letters differ significantly (one-way ANOVA, $p < 0.05$).

an appreciable amount of K and Mg. Mineral differences have been described in groundnut and are often linked to variations in nutrient uptake efficiency, in soil nutrient availability, in fertilizer management, and in irrigation practices during crop cultivation [19, 20].

Compared with the other soybean genotypes, the mineral contents of these were comparatively low. The Ca, Mg, K, and Mn content were higher in KDS 1270 than in KDS 1344, and the aluminum (Al) and Zn content were slightly higher in KDS 1344 than in KDS 1270. The differences among soybean cultivars have been attributed to differences in their genetic makeup and to the environment's effects on mineral absorption and translocation. The availability of nutrients in the soil and thus the quantity of nutrients accumulated in the seeds could be affected by climatic conditions during crop growth, specifically temperature and precipitation [18, 21].

The sunflower genotypes showed different levels of biofortification of selected minerals. GMU 1031 had significantly higher levels of Mg, Fe, Zn, and Al, while GMU 1147 had more Ca, K, and slightly more Cu. The results of these findings revealed moderate differences among sunflower varieties in terms of mineral composition, which can be attributed to the differences in genotype, soil physicochemical properties, plant growth environment, and cultivation practices. In the case of oilseed crops, mineral composition is known to be highly dependent upon the interactions between genotype and environment, and similar sources of variability have been reported [19, 21].

The general trend was that there was a considerable difference between the mineral composition of the different oilseed genotypes evaluated. The mineral profile of seeds is primarily influenced by genetic factors, but soil mineral profile, fertilizer application, irrigation, climate, and crop management can make a significant contribution to the overall mineral profile of seeds.

Functional properties and ketogenic applications

The functional attributes of oilseed flours are critical determinants of their performance in food systems, especially in the context of ketogenic formulations where ingredient functionality must compensate for the absence of starches, sugars, and conventional binders. Each functional property evaluated in this study provides insight into the suitability of oilseed flours for specific ketogenic-compatible food applications.

High OAC (≥59%) is essential in high-fat food matrices, where structural integrity and sensory mouthfeel depend on the ingredient's ability to bind and retain lipids. In ketogenic bars, fat-rich cookies, or energy bites, excessive free oil can lead to greasiness, phase separation, and reduced shelf life. Phule Pragati groundnut (OAC: 59%) and KDS 1344 soybean (OAC: 75%) exhibited comparatively higher oil-holding capacity, likely due to their porous protein-fiber matrix and surface hydrophobicity. These characteristics may enable them to contribute to fat stabilization, thereby reducing oil separation while contributing to improved texture.

High swelling index (≥7) is a rare and valuable trait in low-carbohydrate ingredients, as most ketogenic formulations lack starch-the primary driver of expansion in extruded or puffed foods. KDS 1344 soybean (swelling index: 7.26) and GMU 1147 sunflower (29.33) demonstrate remarkable water-driven volumetric expansion despite minimal carbohydrate content. This property may facilitate the development of starch-free puffed snacks, breakfast cereals, or textured meat analogs through extrusion or puffing technologies. Notably, GMU 1147 exhibited the highest swelling index among the evaluated genotypes, suggesting future potential use in expanded or structured ketogenic food products, offering crispness and bulk without compromising macronutrient targets.

High emulsifying capacity (≥84%) is important for creating stable oil-in-water systems in the absence of egg yolks or synthetic emulsifiers, which are often restricted in clean-label or plant-based ketogenic products. GMU 1031 sunflower (89.56%) and GMU 1147 (84.58%) likely contain amphiphilic proteins and phospholipids that effectively reduce interfacial tension between oil and aqueous phases. This may make them suitable for formulating ketogenic mayonnaise, creamy dressings, sauces, and dairy-free cheese analogs, where long-term emulsion stability and smooth texture are critical. Their plant-based origin further aligns with vegan ketogenic trends.

High antioxidant activity (≥68%) addresses a major challenge in high-fat foods: lipid oxidation, which leads to rancidity, off-flavors, and nutrient degradation. GMU 1031 sunflower (74%) and KDS 1270 soybean (68.23%) may contain higher levels of antioxidant compounds such as phenolics, tocopherols, and flavonoids that scavenge free radicals and chelate pro-oxidant metals. Incorporating these flours into ketogenic products—such as nut butters, fat bombs, or frozen meals—not only enhances oxidative stability but also adds functional health benefits, supporting the growing demand for "clean-label" preservation without synthetic additives like butylated hydroxyanisole or butylated hydroxytoluene.

Synergistic functionality further enhances application potential. For example, GMU 1031 combines high emulsifying capacity (89.56%) with the highest antioxidant activity (74%), making it a potential multifunctional ingredient for shelf-stable, clean-label ketogenic dressings that resist both phase separation and oxidative spoilage. Similarly, KDS 1344 pairs high swelling (7.26) with strong oil absorption (75), suggesting potential suitability in expanded, high-fat snack pellets that remain crisp and non-greasy potential addressing issues in ketogenic snack development.

Collectively, these findings move beyond compositional analysis to provide a functionality-driven selection framework for oilseed genotypes in targeted ketogenic applications, providing information useful for future formulation studies between agricultural diversity and food product innovation.

Mineral profiling

Mineral profiling revealed that the essential micronutrients such as Mg, Fe, and Zn concentrations in the sesame

genotypes (specifically Phule til) were comparatively high as compared to the genotypes under evaluation for groundnut, soybean and sunflower. These minerals play an important role in the regulation of normal physiological functions such as those in energy metabolism, oxygen transport, bone health, antioxidant defense and immune function. Mg, Ca, K, Fe, and Zn are essential dietary micronutrients, and deficiencies of these minerals have been reported in people with a poorly planned ketogenic diet, as several food groups which contain these minerals are restricted [4, 22]. The relatively higher mineral content of Phule til, from a nutritional point of view, indicates that it could be a good source of minerals in plant-based ketogenic food formulations. Incorporation of mineral-rich oilseed flours into the KDs may contribute to improving mineral intake in the diet and still preserve the macronutrient profile of KDs. The contribution of these ingredients to the adequacy of the diet for minerals, however, should be substantiated with formulation studies, bioavailability evaluation, and nutritional evaluation of the complete product.

Conclusion

This study was conducted to evaluate the physical, functional, proximate, mineral, and color characteristics of oilseed genotypes of India, such as sesame (Phule til and JLT-7), groundnut (Phule Pragati and Dhanlaxmi), soybean (KDS 1344 and KDS 1270), and sunflower (GMU 1147 and GMU 1031). Nutritional composition and functional properties of the oilseed flours were found to vary significantly for the different genotypes, suggesting genotype dependency in the quality attributes of the oilseed flours. Soybean had the highest protein content, while groundnut had the highest fat content, and sesame was comparatively higher in terms of minerals and crude fiber, while the genotypes of sunflower showed higher emulsifying capacity and antioxidant activity among the evaluated genotypes. Other differences in the techno-functional properties are found in the water absorption, oil absorption, swelling properties, and emulsifying capacities of the oilseed flours. The findings obtained from the present study would be helpful as baseline data for making an appropriate selection of genotypes of oilseeds concerning their nutritional and functional attributes. However, product formulation, processing, storage, sensory evaluation, and commercial application studies were not included in the present investigation. Hence, these oilseed flours could be explored for their potential use in the development of food products for the ketogenic diet, which needs experimental validation. The present study provides baseline compositional and functional data that could help in selecting appropriate oilseed genotypes for the formulation of ketogenic and other functional foods.

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Conflict of Interest

None.

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