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# Conversion of kodo millet (*Paspalum scrobiculatum* L.) flakes waste into a nutraceutical flour and study of its quality retention

**R. Packiyalakshmi*◆, G. Gurumeenakshi*, M. Ilamaran*, B. Sivasankari*, G. Sashidevi** and P. Geetha*****

* *Department of Food Science and Nutrition, Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*

** *Department of Textile Science and Design, Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*

*** *Centre for Post Harvest Technology, Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore-641 003*

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**Abstract**

This study investigated the valorization of kodo millet (*Paspalum scrobiculatum* L.) flake waste, which typically comprises broken and unflaked grains. The waste was converted into nutritionally rich flour. The study evaluated its recovery efficiency, processing effects, bioactive composition and storage stability. Approximately 13% of flaking waste generated during processing retained higher levels of dietary fiber, protein, minerals and phenolic compounds compared to polished flakes. Processing treatments, particularly steaming followed by mechanical drying significantly reduced the antinutritional factors such as phytic acid (112.21 to 78.35 mg/100 g) and tannins (68.64 to 38.24 mg/100 g). These treatments maintained good retention of proximate and mineral composition during 120 days of storage. FTIR analysis confirmed the presence of functional groups associated with proteins, polyphenols, lipids and carbohydrates. At the same time, GC-MS analysis revealed the presence of fatty acid methyl esters. These included methyl oleate (38.98% of peak area) and methyl linoleate (23.37% of peak area) which have been established to have antimicrobial, antioxidant and cardioprotective properties. These findings highlight kodo millet flake waste flour as a promising functional ingredient with multiple health benefits. They support its incorporation into therapeutic foods, functional bakery products and sustainable nutrition solutions aligned with circular economy principles.

## 1. Introduction

India is recognized as a global leader in the production of minor millets such as kodo, foxtail, little, barnyard and proso. The country has witnessed growing attention toward value added processing techniques like flaking, particularly after the United Nations declared 2023 as the International Year of Millets (Yadav *et al.,* 2024). This global initiative has stimulated research and commercialization of convenient nutrient dense millet based foods including ready to cook flakes. These resemble traditional products such as millet rice poha. The flaking process includes cleaning, soaking, dehulling, hydration, steaming, drying and rolling the kernels into flakes. This process not only produces consumer ready products but also generates considerable by-products in the form of husk, bran rich fractions, broken pieces and fine dust. These by-products are collectively referred to as "flaking waste" (Nanje *et al.,* 2022). While these by-products are often relegated to animal feed they are nutritionally valuable and are particularly rich in fiber, minerals and antioxidant compounds concentrated in the outer layers of the grain (Rana and Bhandari, 2023).

**Corresponding author: Dr. G. Gurumeenakshi**
*Professor and Head, Department of Food Science and Nutrition, Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*
**E-mail: gurumeenakshi@rediffmail.com**
**Tel.: +91-9443855065**



During the flaking of kodo millet, not all kernels are successfully converted into uniform flakes. The process typically yields by-products such as broken grains and unflaked millet rice, collectively termed as flake waste. These fractions are often separated during grading and packaging. Conventionally, they are considered low value and diverted to animal feed or discarded as processing losses. However, emerging research highlights their nutritional richness. In many cases, they have a greater concentration of health promoting components compared to the flakes. Broken and unflaked rice retain most of the bran layer and germ, which are partially lost during flaking. They therefore preserve higher levels of dietary fiber, protein, phenolic compounds and essential minerals such as calcium, iron and zinc (Chauhan *et al.,* 2024). They are also excellent sources of bound polyphenols, particularly hydroxycinnamic acids and flavonoids. These compounds enhance antioxidant potential, reduce oxidative stress and contribute to protection against chronic diseases including cardiovascular disorders and diabetes. The higher fiber content further supports digestive health and moderates post prandial glycemic response. This is an important consideration in addressing the rising incidence of lifestyle related disorders in India. Moreover, studies on flaking by-products of small millets have demonstrated that retention of phenolic compounds and resistant starch is significantly higher in the broken and unflaked fractions than in the flakes. This underscores their potential application in therapeutic and functional foods.

Valorization of kodo millet flake waste in food applications presents an opportunity to address sustainability and nutrition simultaneously. Instead of being discarded, these by-products can be incorporated into bakery items, porridges, weaning foods, extruded snacks or flour blends thereby enhancing their dietary fiber and antioxidant density. Such utilization not only reduces post harvest losses but also creates functional food ingredients aligned with modern consumer demand for health promoting and sustainable foods. With India is growing emphasis on millet processing and its role in nutrition sensitive agriculture. The recovery and application of kodo flake waste (broken and unflaked grains) represent a circular economy approach, adding value at both the nutritional and economic levels (Kumar *et al.,* 2024).

This study focuses on the valorization of the kodo millet flake waste converted into flour. The waste recovery percentage, effect of processing on the phytonutrients, the nutritional composition, phytochemical profile and the storage studies were analyzed for the kodo millet flake waste converted flour.

## 2. Materials and Methods

### 2.1 Plant material and authentication

This research was carried out at the Department of Food Science and Nutrition, Community Science College and Research Institute, Tamil Nadu Agricultural University (TNAU), Madurai. Grains of kodo millet (*Paspalum scrobiculatum* L.) variety $CO_3$ were procured from the Department of Millets, TNAU, Coimbatore, Tamil Nadu, India. Kodo millet variety $CO_3$ is a TNAU released selection originally derived from the Georgia type and maintained by the Department of Millets, TNAU. It is characterized by crop duration of about 120 days, purple stem pigmentation and high tillering ability morphological traits routinely used for varietal identification and seed certification at TNAU (Agritech TNAU). Authenticated $CO_3$ seeds supplied by TNAU have been widely employed in experimental and breeding studies. The kodo millet grains thus procured were used in the present study and all chemicals used in the study were of analytical grade.

### 2.2 Procedure for the kodo millet flake waste converted into flour

The production of kodo millet flakes involves the following steps like cleaning, soaking, steaming, milling, rolling and drying to obtain a stable and ready to use product. Initially, raw grains are cleaned to remove dust, stones and foreign matters followed by soaking to soften the grains. The soaked grains are then subjected to steaming, which not only enhances flavor and texture but also reduces antinutritional factors and partially gelatinizes the starch. After steaming, the grains are milled or dehusked to remove the outer husk and obtain dehulled grains suitable for flaking. During the flaking process of millets, a considerable amount of by-products, such as broken grains and unflaked millet rice are generated. These broken and unflaked millet rice wastes were collected for further studies and millet waste recovery was calculated.

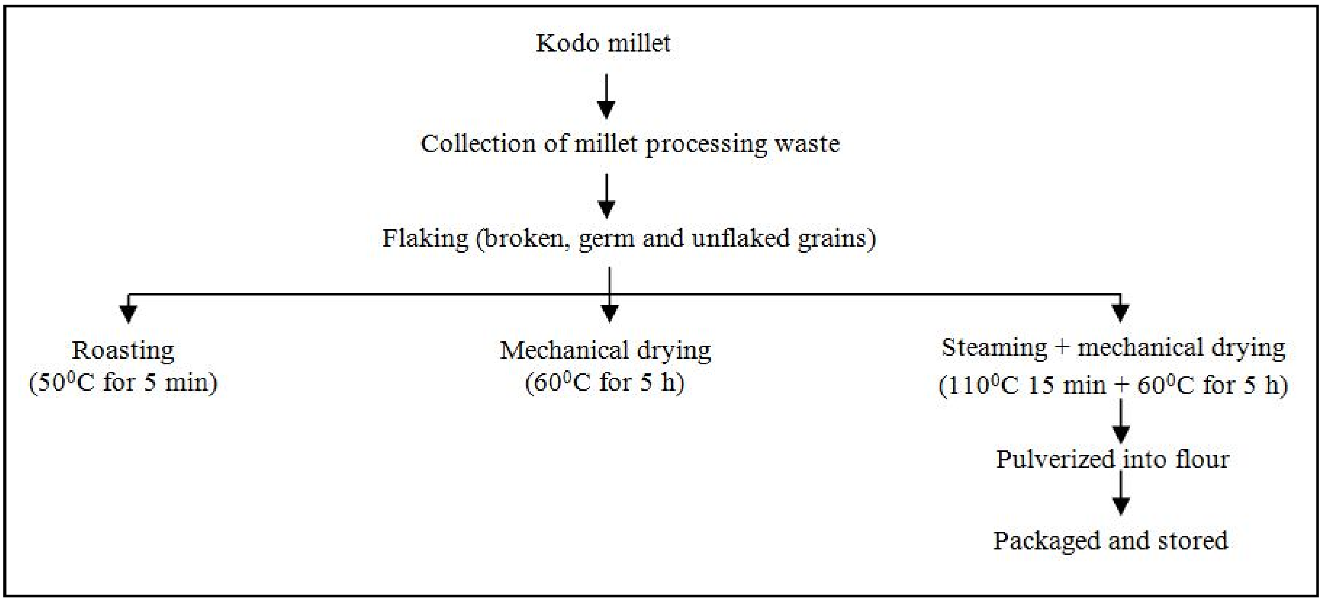


**Figure 1: Process flow chart for the preparation of kodo millet flake waste converted into flour.**

Figure 1 depicts the systematic process of converting kodo millet flake waste into flour. This offers a sustainable strategy for effective byproduct utilization. During flaking, broken and unflaked materials are generated as processing waste. These are subjected to three treatments: (i) Roasting (50$^0$C for 5 min), (ii) Mechanical drying (60$^0$C for 5 h), and (iii) Combined steaming (110$^0$C for 15 min) with mechanical drying (60$^0$C for 5 h). Each treatment has distinct influences on the nutritional and functional qualities of the material. Roasting and mechanical drying helped to moisture reduction, flavor development and shelf- life extension. Steaming with mechanical drying efficiently lowers antinutritional compounds such as phytates, tannins and improves protein digestibility and starch bioavailability. The processed byproducts are then finely pulverized into flour and packaged for storage. This facilitates their use in various food formulations.

### 2.3 Proximate analysis of kodo flake waste converted flour

The proximate analysis of the kodo milled flake waste converted flour determined the moisture content by using the hot air oven drying method. This followed the AOAC (1995) protocol. Protein was analyzed by the Kjeldahl method (AOAC, 2005). Fat content was estimated according to Carpenter (2010). Carbohydrate content was assessed using the procedure described by Kurzyna-Szklarek *et al.* (2022). Crude fiber was analyzed according to Sadasivam and Manickam (1996). Soluble and insoluble dietary fiber content was analyzed using a total dietary fiber assay kit (K-TDFR) based on AOAC (1995). The minerals, *viz.,* calcium, phosphorus, iron, sodium, potassium and zinc were estimated using the triple acid digestive method described by Renganna (1986). Phytic acid was estimated according to Aina *et al.* (2012). Tannin content was estimated using Schanderl (1970) and total phenol content by the procedure from Sadasivam and Manickam (2008). Fourier transform infrared (FTIR) spectroscopy was used to screen the functional groups and secondary structural components following Sundharaiya *et al.* (2025). Gas chromatography-mass spectrometry (GC-MS) analysis used a Shimadzu QP2020 system for compound identification and quantification using a method developed by Sathish *et al.* (2025).

### 2.4 Packaging and storage studies

The kodo millet flake waste converted flour was packed in polypropylene pouches and stored under ambient conditions for a period of 120 days to assess its shelf-life stability. Proximate composition analyses were carried out after the storage period to evaluate any changes in nutritional quality.

### 2.5 Statistical analysis

The experimental data were analyzed using one way ANOVA under a completely randomized design (CRD) with three replications. Statistical analyses were performed using AGRES software.

## 3. Results

### 3.1 Waste recovery of the kodo millet flaking process

The kodo millet flaking process naturally produces waste fractions including broken grains, germs and unflaked kernels. In this study, the percentage of waste recovery was evaluated.

**Table 1: Waste recovery of kodo millet flaking process**

| Flaked grains (%) | Broken, germ and unflaked grains (%) |
|---|---|
| 87 ± 0.66 | 13 ± 0.22 |

Based on the data presented in Table 1, the waste recovery of the kodo millet flaking process indicates that the efficiency of flake production is quite high. Out of the total millet rice processed 87 ± 0.66% of the grains were successfully flaked, which demonstrates a good yield of usable product. However, around 13 ± 0.22% of the material was recovered as by-products in the form of unflaked grains, broken and germ.

**Table 2: Effects of processing on the antinutritional properties of kodo millet flake waste converted to flour**

| S. No. | Parameters | Treatments | | | |
|---|---|---|---|---|---|
| | | $T_0$ | $T_1$ | $T_2$ | $T_3$ |
| 1 | Phytic Acid (mg/100 g) | $112.21^{a} \pm 2.66$ | $105.01^{b} \pm 2.02$ | $89.02^{c} \pm 0.23$ | $78.35^{d} \pm 1.06$ |
| 2 | Tannin (mg TAE/100 g) | $68.64^{a} \pm 0.65$ | $56.35^{b} \pm 0.57$ | $46.12^{c} \pm 1.16$ | $38.24^{d} \pm 1.19$ |
| 3 | Total Phenols(mg GAE/100 g) | $123.25^{ab} \pm 0.41$ | $117.36^{ab} \pm 1.67$ | $106.16^{c} \pm 0.65$ | $98.45^{d} \pm 1.80$ |

Each value is expressed as the mean ± standard deviation (SD) based on three replicate analyses (n=3). Superscript letters within the same row indicate values that are significantly different at $p<0.05$. $T_0$ - Control; $T_1$- Roasting (50$^0$C for 5 min); $T_2$- Mechanical drying (60$^0$C for 5 h); $T_3$- Steaming (110$^0$C 15 min) + Mechanical drying (60$^0$C for 5 h).

### 3.2 Effects of processing on the antinutritional properties of kodo millet flake waste converted flour

The antinutritional properties of kodo millet flake converted flour were evaluated under different processing treatments.

Table 2 illustrated the effect of different processing methods on the antinutritional factors of kodo millet flake waste converted flour showing significant variations across treatments. Phytic acid content was highest in the control sample (112.21 mg/100 g) and declined progressively with processing. Roasting ($T_1$) caused a modest reduction (105.01 mg/100 g), whereas mechanical drying ($T_2$) produced a more substantial decrease (89.02 mg/100 g). The lowest concentration was recorded in the combined steaming and drying treatment $T_3$ (78.35 mg/100 g) highlighting the superior efficacy of steaming with mechanical drying processing in promoting phytate degradation.

Similarly, tannin content declined significantly from 68.64 mg TAE/100 g in the control to 56.35 mg TAE/100 g with roasting and further to 46.12 mg TAE/100 g with mechanical drying. The greatest reduction was again achieved in the steaming with mechanical drying treatment (38.24 mg TAE/100 g), suggesting that steaming helps in reducing condensed tannins through hydrolysis and leaching. This reduction is beneficial as tannins are known to interfere with protein digestibility and mineral absorption.

Variations in total phenol content were also observed among treatments. The control sample contained 123.25 mg GAE/100 g and the roasted flour had 117.36 mg GAE/100 g both maintaining relatively higher levels. In contrast, mechanical drying led to 106.16 mg GAE/100 g and steaming with drying further lowered this to 98.45 mg GAE/100 g. This suggests that phenolic compounds, which support antioxidant activity and other health benefits, are partially lost during processing due to their sensitivity to heat and moisture.

Overall, the results highlight that processing techniques such as steaming combined with mechanical drying are highly effective in reducing undesirable antinutritional factors like phytic acid and tannins, thereby improving the nutritional bioavailability of kodo millet flake waste converted flour.

### 3.3 Assessment of nutritional quality of the kodo millet flake waste converted flour during storage

During storage, the moisture content in both control ($T_0$) and treated ($T_3$) samples varied only slightly. At the start, $T_0$ had a moisture content of 6.14%, and $T_3$ had 6.21%. After 120 days, $T_0$ decreased to 6.08%, and $T_3$ was 6.15%. This indicates that treatment helped retain stable moisture, important for shelf life stability. Protein content was marginally higher in treated samples. Initially, $T_0$ contained 9.56 g/100 g, while $T_3$ had 9.01 g/100 g. After storage, the protein content in $T_3$ was 9.12 g/100 g, compared to 9.24 g/100 g in $T_0$, suggesting that treatment reduced protein loss. Fat levels were similar in both groups. At the initial stage, $T_0$ had 2.21 g/100 g fat and $T_3$ had 2.03 g/100 g. After 120 days, $T_0$ and $T_3$ had 2.11 g/100 g and 2.07 g/100 g fat, respectively, indicating minimal influenced fat stability. Carbohydrate content fluctuated slightly. At the beginning, $T_0$ had 62.11 g/100 g and $T_3$ had 61.73 g/100 g. After 120 days, $T_3$ retained 61.88 g/100 g carbohydrates compared to 62.04 g/100 g in $T_0$, which suggests better carbohydrate retention in $T_3$.

Initially, total fiber was higher in the control (5.14 g/100 g) than in the treated samples (4.75 g/100 g). After 120 days, total fiber decreased in both with the treated samples retaining 4.98 g/100 g compared to 5.08 g/100 g in the control, indicating treatment reduced fiber degradation. At the initial stage, soluble dietary fiber was also higher in the control (1.34 g/100 g) versus treated (1.28 g/100 g). After storage, treated samples (1.21 g/100 g) retained nearly the same level as control (1.22 g/100 g) which suggests improved stability of soluble fibers in treated samples. Insoluble fiber was higher in the control (7.60 g/100 g) than the treated (7.27 g/100 g) at the start. After storage, the control retained 6.89 g/100 g; the treated had 6.83 g/100 g pointing to a slight protective effect from treatment.

Calcium decreased in both control (20 to 19 mg/100 g) and treated samples (17 to 18 mg/100 g). Treated samples started lower but showed better stability over storage. Phosphorus content was higher in the control initially (158 mg/100 g) compared to the treated (121 mg/100 g). After storage, the control retained 149 mg/100 g, while the treated dropped further to 137 mg/100 g. This indicates some loss in phosphorus due to treatment. Iron levels were slightly higher in the control (1.05 mg/100 g) compared to the treated (0.95 mg/100 g) initially. After storage, the treated (0.98 mg/100 g) showed almost similar values to the control (1.01 mg/100 g), indicating minimal effect of treatment. Sodium was slightly higher in the control (3.21 mg/100 g) than in the in the treated (3.01 mg/100 g) at initial days. During storage, both remained stable $T_0$ - 3.1mg/100 g and $T_3$ - 3.0 mg/100 g showing negligible differences. Potassium levels were higher the control (21mg/100 g) than in the in the treated (19 mg/100 g) initially. After storage, the control retained 201 mg/100 g, while treated samples had 198 mg/100 g, indicating better stability in treated samples. Zinc was slightly higher in the control (1.01 mg/100 g) compared to the treated (0.96 mg/100 g) at the initial day. After 120 days $T_0$ (1.00 mg/100 g) and $T_3$ (0.97 mg/100 g) having the minimal difference due to treatment.

Phytic acid decreased drastically in treated samples (112.11 to 78.30 mg/100 g) compared to the control (112.21 to 78.35 mg/100 g). This reduction in treated flour is beneficial as it improves mineral bioavailability showing the positive role of treatment. Tannin content decreased more sharply in treated samples (68.58 to 38.18 mg/100 g) than in the control (68.64 to 38.24 mg/100 g). The greater reduction in treated flour enhances protein digestibility and palatability. Phenolic compounds decreased in both groups but treated samples (123.18 to 98.37 mg/100 g) showed slightly greater loss compared to control (123.25 to 98.45 mg/100 g).

The nutrient and nutraceutical composition of kodo millet flaked waste flour was evaluated to assess the impact of processing (steaming with mechanical drying) and prolonged storage (120 days) on its stability and quality. The findings clearly demonstrate that both processing and storage influenced the proximate composition, mineral content and bioactive constituents, although the magnitude of change varied between untreated ($T_0$) and treated ($T_3$) samples (Figure 2).

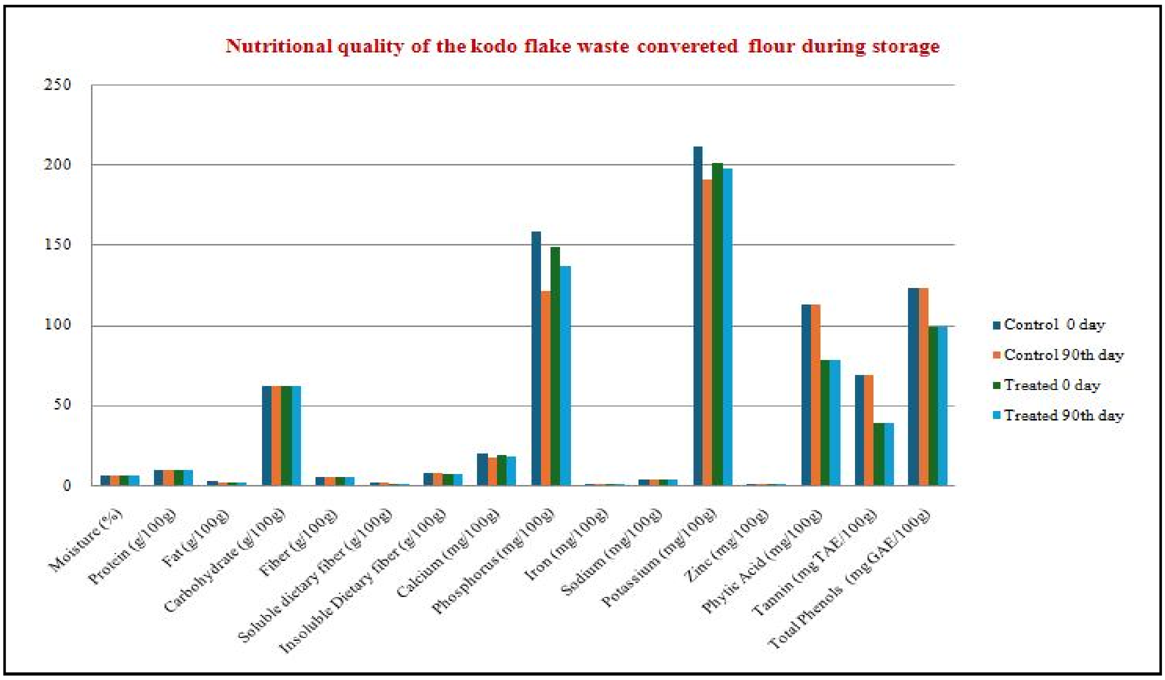


**Figure 2: Assessment of nutritional quality of the kodo millet flake waste converted flour during storage.**

### 3.4 Fourier transform infrared spectroscopy (FTIR) screening of kodo millet waste converted flour

Figure 3. illustrates the fourier transform infrared (FTIR) spectrum of the kodo millet flake waste converted flour. This confirms the presence of several functional groups associated with bioactive and nutritional compounds. Each absorption bond corresponded to a specific class of biomolecules. This indicates phenols, proteins, lipids, carbohydrates and other metabolites that enhance the nutritional and therapeutic values of the flour. A strong broad band at ~3404 $cm^{-1}$ was attributed to O-H stretching vibrations of hydroxyl groups from alcohols and phenols. This is consistent with polyphenolic compounds such as phenolic acids and flavonoids as reported in earlier studies on millets. The absorption peak at 2925 $cm^{-1}$ represented C-H stretching of alkanes. These are typically linked to long chain fatty acids and lipids, which play vital roles in energy supply, brain development, cell membrane structure and absorption of fat soluble vitamins (A, D, E, and K). The band at 1657 $cm^{-1}$ corresponded to C=O stretching vibrations characteristic of amide I in proteins as well as carbonyl groups in ketones and aldehydes. This reflects the proteinaceous nature of the sample. Peaks in the region of 1405-1445 $cm^{-1}$ were assigned to alkane bending vibrations. Those between 1382-1036 $cm^{-1}$ were associated with C-O stretching of carbohydrates and phenolic esters, confirming the presence of starch and dietary fiber components. A distinct absorption at 1026 $cm^{-1}$ corresponded to C-O vibrations in alcohol hydroxyl groups, further reinforcing the presence of carbohydrates and polyols. In addition, the low frequency peak at 469 $cm^{-11}$ was indicative of alkyl halides, which may be related to trace minerals or protein mineral complexes. Collectively, the FTIR analysis demonstrated the presence of diverse biomolecular functional groups. This establishes that kodo millet flake waste flour is rich in polyphenols, proteins, fatty acids, carbohydrates and minor metabolites all of which contribute significantly to its nutritional quality.

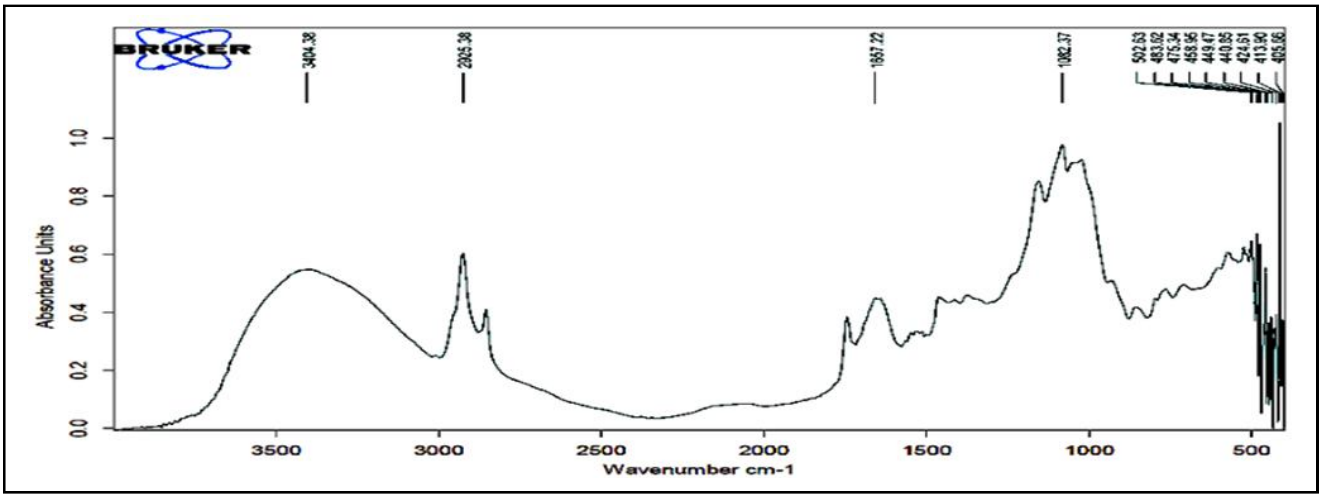


**Figure 3: Fourier transform infrared spectroscopy (FTIR) chromatogram to identify the functional groups of kodo millet flake waste converted flour.**

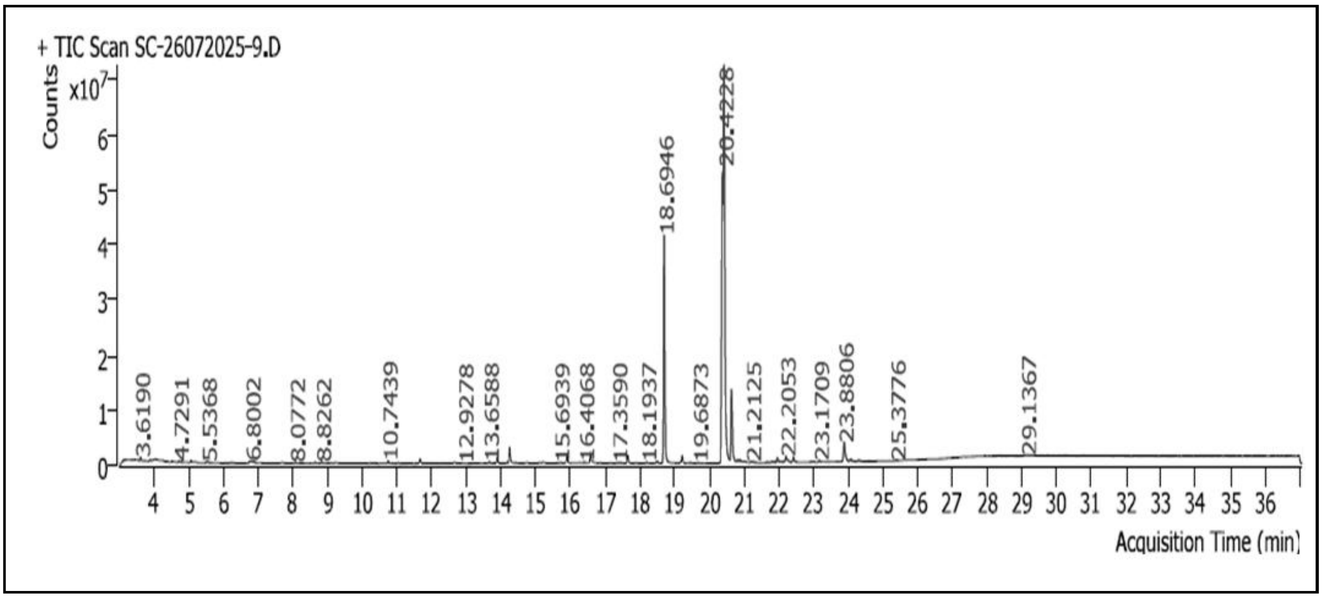


**Figure 4: Gas chromatography-mass spectrometry (GC-MS) chromatogram of kodo millet flake waste converted flour.**

### 3.5 Gas chromatography-mass spectrometry (GC-MS) screening of kodo millet waste converted flour

Figure 4 and Table 4 show the gas chromatography-mass spectrometry (GC-MS) analysis of kodo millet flake waste converted flour. This reveals distinct peaks corresponding to different compounds based on their retention times and peak areas. The chromatogram showed that at a retention time of 20.42 min, the major compound identified was methyl oleate with the highest peak area of 38.98%. At 20.37 min the detected compound was methyl linoleate with a peak area of 23.37%. Another prominent peak appeared at 18.69 min corresponding to methyl palmitate which accounted for 17.82% of the total composition. At 20.63 min methyl stearate was identified with a peak area of 6.12%. In addition to these dominant peaks several minor compounds were observed. At 23.88 min methyl erucate was detected with a peak area of 2.17%. At 22.03 min methyl gondoate was identified with 0.789%. A peak at 22.41 min corresponded to methyl 10-methylheneicosanoate with 0.465%. At 24.07 min methyl behenate was found with 0.248%. Furthermore, phenolic compounds were also present in smaller quantities. At 6.80 min 2,5-dihydroxyacetophenone was identified with a peak area of 0.404%. At 6.88 min phenol and 2,6-dimethoxyphenol were detected with 0.214%.

**Table 4: Identification of bioactive compounds with biological activity of kodo millet flake waste converted flour**

| Retention time (Min) | Area (%) | Compound name | Molecular formula | Molecular weight (g/mol) | Biological activity | References |
|---|---|---|---|---|---|---|
| 20.42 | 38.98 | Methyl oleate | $C_{19}H_{36}O_2$ | 296.50 | Anti-inflammatory, Cardioprotective, Antioxidant and Hypocholesterolemic | Mensink, 2016 |
| 20.37 | 23.37 | Methyl linoleate | $C_{19}H_{34}O_2$ | 294.47 | Essential fatty acid, Cholesterol-lowering and antiobesity | Shahidi and Ambigaipalan, 2018 |
| 18.69 | 17.82 | Methyl palmitate | $C_{17}H_{34}O_2$ | 270.45 | Antifibrotic and anti-inflammatory | Ayadi *et al.*, 2022 |
| 20.63 | 6.12 | Methyl stearate | $C_{19}H_{38}O_2$ | 298.51 | Energy source and mild antimicrobial activity | Elghaffar *et al.*, 2022 |
| 23.88 | 2.17 | Methyl erucate | $C_{23}H_{44}O_2$ | 352.6 | Anti-inflammatory, Neuroprotective andlipid metabolism regulation | Sudhanva *et al.*, 2025 |
| 22.03 | 0.789 | Methyl gondoate | $C_{21}H_{40}O_2$ | 324.5 | Nutritional lipid and antioxidant role | Nzikou *et al.*, 2009 |
| 22.41 | 0.465 | Methyl 10-methylhenei cosanoate | $C_{21}H_{42}O_2$ | 326.6 | Antimicrobial and metabolic regulator | Khaled *et al.*, 2024 |
| 6.80 | 0.404 | 2,5-Dihydroxyacet-ophenone, | $C_{14}H_{24}O_3Si_2$ | 308.5 | Antioxidant, antimicrobial, Anti-inflammatory and Anticancer potential | Cushnie and Lamb, 2005 |
| 24.07 | 0.248 | Methyl behenate | $C_{23}H_{46}O_2$ | 354.6 | Caloric lipid source | Shahidi and Zhong, 2010 |
| 6.88 | 0.214 | Phenol (2,6-dimethoxy-phenol) | $C_{21}H_{29}ClN_2O_5SSi$ | 484.1 | Potent antioxidant, Antimicrobial and Anti-inflammatory | Rice-Evans *et al.*, 1997 |

## 4. Discussion

The present study highlights the potential of kodo millet flake by-products as a nutritionally rich resource when transformed into flour and subjected to appropriate processing methods. This approach offers a dual benefit like minimizing processing losses while enhancing the nutritional functionality of millet derived by-products, thereby aligning with sustainable utilization and value addition strategies.

During the flaking process, approximately 13% of the raw material was recovered as broken and unflaked grains. Although, often regarded as waste, these fractions retain the bran and germ layers, making them nutritionally superior compared to polished flakes. Similar observations have been reported in earlier studies which demonstrated that flaking by-products of small millets are enriched with dietary fiber, protein, polyphenols and essential minerals (Chauhan *et al.,* 2024; Rana and Bhandari, 2023).

Processing treatments also had a marked influence on anti-nutritional factors (Rao and Prabhavathi, 2015). Steaming followed by mechanical drying proved to be the most effective intervention, lowering phytic acid from 112.21 to 78.35 mg/100 g and tannins from 68.64 to 38.24 mg/100 g. These findings are consistent with the reports of Aina *et al.* (2012) and Kumar *et al.* (2024)*,* who attributed such reductions to moist heat, induced enzymatic degradation and leaching effects. The decline in these compounds is nutritionally advantageous as it enhances mineral bioavailability and protein digestibility, thereby improving the overall efficiency of the flour.

Conversely, a reduction in total phenolic content was recorded after processing. Since phenolic compounds are highly sensitive to thermal and moisture stress, partial degradation during steaming and drying was expected in line with the results of Nanje *et al.* (2022). Nevertheless, a considerable proportion of phenolics was retained, indicating that the flour can still serve as a meaningful source of antioxidant activity.

Shelf-life evaluation over a 120 day storage period demonstrated that both proximate composition and mineral content remained largely stable. Moisture levels were maintained within safe thresholds, supporting extended storage stability. Protein, fat and carbohydrate levels showed only minor fluctuations with processed samples exhibiting superior retention compared to untreated controls. Similarly, minerals such as calcium, iron and potassium experienced slight reductions though greater stability was noted in treated samples. Importantly, soluble and insoluble dietary fiber fractions were better preserved in processed samples, a finding of particular relevance given the role of fiber in regulating glycemic response and maintaining gastrointestinal health. These results corroborate the findings of Yadav *et al.* (2024), who demonstrated that optimized processing and packaging enhance the storage stability of millet based foods without compromising nutritional quality.

The FTIR analysis provided insight into the biochemical constituents of kodo millet flake waste converted flour. A broad absorption at ~3404 $cm^{-1}$ was attributed to hydroxyl and amide groups confirming the presence of phenolics, polysaccharides and proteins. The band at 2925 $cm^{-1}$ corresponded to aliphatic C-H stretching of fatty acids and lipids, while a strong absorption at 1637 $cm^{-1}$ was associated with amide I groups in proteins and aromatic C=C stretching of polyphenols. A peak at 1026 $cm^{-1}$ reflected carbohydrate related vibrations and a minor signal at ~469 $cm^{-1}$ suggested the presence of alkyl halides representing secondary metabolites in trace amounts. These findings are in agreement with previous FTIR investigations on millet flours (Sundharaiya *et al.,* 2025; Hashimoto and Kameoka, 2008), confirming the presence of key macronutrients and bioactive compounds.

The GC-MS analysis of kodo millet flake waste converted flour revealed several bioactive compounds with diverse biological activities as supported by previous studies. Among them, methyl oleate exhibited significant antioxidant, cardioprotective and anti-inflammatory properties, which align with earlier findings reported by Mensink (2016). Similarly, methyl linoleate, an essential fatty acid has been associated with cholesterol lowering, anti obesity and cardioprotective roles corroborating the study of Shahidi and Ambigaipalan (2018). These unsaturated fatty acid esters play a crucial role in lipid metabolism and overall cardiovascular health.

In addition, methyl palmitate demonstrated anti-fibrotic and anti-inflammatory activities, which is consistent with the observations of Avadi *et al.* (2022). Likewise, methyl stearate was found to serve as an energy source with mild antimicrobial potential in agreement with the work of Elghaffar *et al.* (2022). Another important component methyl erucate showed neuroprotective effects and regulation of lipid metabolism as reported by Sudhavna *et al.* (2025) highlighting its therapeutic potential.

Furthermore, methyl gondoate has been identified as a nutritional lipid with antioxidant roles (Nziku *et al.,* 2009) while methyl 10-methylheneicosanoate contributed to antimicrobial activity and metabolic regulation as described by Khaled *et al.* (2024). Polyphenolic derivatives such as 2,5-dihydroxyacetophenone displayed strong antioxidant and anticancer activities supported by Cushnie and Lamb (2005) thereby suggesting their role in disease prevention. Similarly, methyl behenate was reported to act as a caloric lipid source in line with findings from Shahidi and Zhong (2010). Finally, phenolic compounds such as 2,6-dimethoxyphenol exhibited potent antioxidant, antimicrobial and anti-inflammatory properties which agree with the earlier study of Rice-Evans *et al.* (1997).

Finally, the integration of findings from waste recovery, anti-nutrientional reduction, storage stability, FTIR and GC-MS analyses underscores the potential of kodo millet flake waste converted flour as a functional food ingredient. Its favorable nutrient retention, reduction in anti-nutritional load and bioactive composition support its incorporation into nutraceuticals, therapeutic formulations and value added foods such as porridges, baked products, weaning mixes and extruded snacks. Beyond its nutritional advantages, the valorization of flake by-products contributes to sustainable food systems and circular economy goals, offering both health and environmental benefits.

## 5. Conclusion

The present investigation demonstrated that kodo millet flake waste, often regarded as a low value byproduct can be effectively converted into nutraceutical flour with enhanced nutritional and functional properties. Processing treatments, particularly steaming followed by mechanical drying significantly reduced antinutritional factors while retaining proteins, dietary fiber, minerals and bioactive compounds confirmed by FTIR and GC-MS analyses. The flour exhibited stability in proximate composition and mineral content during storage underscoring its potential as a functional ingredient in health oriented foods. Future research should focus on clinical evaluation of its health benefits, incorporation into diverse food formulations such as bakery, extruded or weaning products and packaging technologies to extend shelf-life. Additionally economic feasibility studies, consumer acceptance trials are recommended to support its commercialization and integration into sustainable nutrition strategies.

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## Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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