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Sustainable Valorisation of Mango Seed Kernels: Nutritional Profiling, Antioxidant Properties, and Application in Mango–Chickpea Cookies

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ABSTRACT: Mango seed kernels (MSK), an underutilised by-product of the mango processing industry, possess remarkable nutritional and functional potential. In our study, we examined the value addition of MSK by assessing its nutrient profile and antioxidant attributes, and by applying it in formulating mango–chickpea cookies to demonstrate its functional potential. The processed mango seed kernel flour (MSKF) demonstrated a 90.1% recovery rate, with a water absorption capacity of 0.82 ± 0.01 and an oil retention capacity of 0.79 ± 0.02. Nutritional analysis revealed that MSK contains 42.34% carbohydrates, 9.83% protein, and 13.2% fibre. The kernel extracts exhibited substantial antioxidant activity, with a total phenolic content of 33.2 mg GAE/g. To demonstrate practical application, MSKF was blended with chickpea flour (30–50%) for cookie preparation. The blended formulations showed improved antioxidant retention, appealing sensory characteristics, and potential as a gluten-free, high-fibre snack. Therefore, this study supports circular economy-based food systems by converting mango waste into a high-fibre, antioxidant-rich flour suitable for gluten-free bakery applications

1. INTRODUCTION

Mango (*Mangifera indica* L.), often called the "king of fruits," is among the world's most produced tropical fruits and belongs to the family Anacardiaceae. Global production of mangoes is rising, with over 57–62 Mt around 2021–2023 according to FAO and OECD projections, and is anticipated to continue increasing over the next decade by expanding cultivation in Asian countries (Padaliya & Pundir, 2022). Because mango is a seasonal fruit, about 20% of the fruits are processed for products such as puree, leather, pickles, and canned slices. Several varieties of known cultivars are alphonso, balady, pairi, mabroka, zebda and succary for these purposes. Moreover, mango processing generates substantial by-products, mainly peel and seed, which

together constitute 35–60% of the fruit mass, creating a rich source of value addition and a challenge in waste management. The seed roughly accounts for 10–25% of the whole fruit weight, while the kernel comprises the major portion of the seed. The mango seed kernel (MSK) is particularly enriched with dietary fibre, phenolic compounds, flavonoids, lipids (particularly oleic and linoleic acids), and essential minerals, thus making it a promising candidate for utilisation as a functional food ingredient (Hussain et al., 2024). Many researchers have reported that MSK and its by-products deliver high antioxidant capacity and techno-functional properties, including water and oil binding, relevant to bakery systems, snacks, and nutraceuticals. (Saleem et al., 2023). Emerging work has increasingly focused on sustainable green extraction and processing approaches. Ultrasound-assisted extraction (UAE) is one such technique used for kernel starch and bioactive compounds to enhance the efficiency and yields from mango seed kernels. Investigations conducted in earlier studies demonstrate that incorporating mango peel or kernel fractions can significantly increase fibre and antioxidant content and facilitate fat reduction in the food industry (biscuits/cookies) (Ashoush et al., 2011). Thereby, making it feasible to expand the nutrient-based worth and antioxidant characteristics of specific food goods by adding powdered mango peels, pulp, and kernels. (Sogi et al., 2013). However, the broader use of mango seed kernel (MSK) is limited by anti-nutritional factors such as tannins and cyanogenic compounds, which cause bitterness and restrict direct application. In this light, researchers focused on detoxification and debittering using traditional methods (soaking/fermentation) and pretreatment processes such as ultrasound, microwave, and vacuum, aimed at reducing anti-nutrients and quality losses. (Bethapudi et al., 2023; Chauhan et al., 2022). Parallelly, sustainability-oriented work frames have positioned mango by-product enhancement within a circular economy, extending its potential applications beyond food to areas such as bioactive packaging films and functionalized biopolymers (Fang et al., 2025).

Although the compositional and bioactive attributes of MSK have been well-documented, evidence linking its functional potential to practical product development, particularly in bakery applications, remains limited. Therefore, this research work aims at the development of mango–chickpea composite cookies and a comprehensive analysis of MSK's nutritional and antioxidant potential, its feasible substitution ranges, and product attributes using accessible processing. The study positions MSK valorisation as a sustainability-aligned route to enhance fibre and antioxidant intake while reducing fruit-processing waste and enhancing the MSKF's viability in real formulations. This paper's novelty lies in integrating mango seed kernel flour with chickpea flour for bakery applications, combined with antioxidant profiling and pre-treatment comparison (sulphite + blanching).

2. MATERIALS AND METHODOLOGY

2.1 Procurement of Mango Seed Samples

Mature mango seeds (*Mangifera indica* L.) from Indian cultivars were collected from local fruit outlets in Bhiwadi, Pataudi, and Dwarka (Haryana, India) during the peak summer processing season. The seeds were washed thoroughly to remove adhering pulp residues and impurities, then oven-dried at 60°C for 24 hours in a hot-air oven for moisture reduction. The dried seeds were manually dehulled using a sterile knife for kernel extraction.

2.2 Preparation of Mango Seed Kernel Flour (MSKF)

For Flour preparation, the acquired kernels were kept overnight for oven-drying at 60°C to achieve uniform dehydration. The detoxification step was further carried out by soaking the kernels in 0.2% (w/v) sodium sulfite solution for 72 h in fed-batch conditions until they became colourless. The detoxified kernels were then blanched at 90°C for 10–15 minutes, chopped into smaller fragments, and re-dried overnight at 60°C. Using a Philips HR7762 laboratory blender, the dried material was ground and sieved through a 40-mesh stainless-steel sieve to obtain fine flour, which was further stored in airtight, opaque containers at room temperature until further experimental analysis.

2.3 Determination of Functional Properties

To study the feasibility of utilising MSKF in food formulations, various functional characteristics such as water absorption capacity (WAC), oil retention capacity (ORC), bulk density, swelling index, and water solubility index (WSI) were evaluated. WAC and ORC were measured according to (Beuchat, n.d.) with slight modifications. Bulk density and specific gravity were measured following the method of (Okaka & Potter, n.d.), while the gravimetric method was utilised to determine the **s**welling and solubility indices.

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2.4 Nutritional Analysis

Various parameters, including protein, fat, moisture, ash, fibre, and carbohydrate, were assessed following AOAC (2019) standard methods to proximate nutritional composition of MSKF. Primarily, crude protein content was determined using a nitrogen conversion factor (6.25) (Kayode et al., 2013), while crude fat was evaluated with petroleum ether at a boiling range of 40–60 °C (Sarkiyayi et al., 2013). Further, a hot-air oven and a muffle furnace were used to measure moisture and ash content gravimetrically. (Rashid et al., 2019). Additionally, crude fibre was also determined through sequential acid–alkali digestion followed by total carbohydrate profile. The saturated and unsaturated fatty acid, vitamins, and minerals determining the nutritional properties of MSKF oil was also assessed.

2.5 Antioxidant Activity

The antioxidant potential of MSKF was evaluated using ethanolic and aqueous extracts. Briefly, the Folin-Ciocalteu reagent and Denis's method were utilised to determine the total phenolic content (TPC, **mg gallic acid equivalent** (GAE)/g) and total flavonoid content (TFC, expressed as (QE)/g), followed by tannin and alkaloid contents, which were estimated by titrimetric and gravimetric procedures, respectively. Moreover, the DPPH radical-scavenging activity was assessed spectrophotometrically at 517 nm (Shimadzu UV-1900)(Brand-Williams et al., 1995). A comparative study was also conducted with other conventional flours, such as Chickpea and wheat flour, to evaluate the MSKF's potential properties.

2.6 Development of Mango–Chickpea Composite Cookies

To demonstrate the practical applicability, MSKF was incorporated into chickpea flour for the development of composite cookie formulations. Initially, the MSKF was substituted at different levels 0%, 30%, 50%, 70%, and 100% into chickpea for cookie preparation. A cookie base formulation comprising palm sugar (25%), rice bran oil (20%), baking powder (2%), and desiccated coconut (3%) was also combined. These dry ingredients were thoroughly mixed, followed by the gradual addition of oil to form a uniform dough. The prepared dough was rolled to a thickness of approximately 0.5 cm and cut into circular discs using a cutter. Finally, for over 180 °C for 20 minutes, cookies were baked in a preheated oven (IFB 30 L) and cooled to ambient temperature. In the final step, the cookies were packed in airtight containers. Visual observations such as colour, aroma, texture, and overall acceptability criteria were also recorded.

2.7 Statistical Analysis

All experiments were conducted in triplicate (n = 3) and expressed as Mean ± SD. Data were analysed using one-way analysis of variance (ANOVA) followed by Tukey's Honestly Significant Difference (HSD) post-hoc test to evaluate significant differences among means at the 95% confidence level ($p < 0.05$). All statistical computations were performed using IBM SPSS Statistics Version 25.0.

3. RESULTS

3.1. Functional and Nutritional Properties of MSKF

The MSKF displayed favourable functional traits essential for food applications. The water absorption capacity (WAC) was recorded at 0.82 ± 0.01 g/mL, which indicated a moderate ability to absorb water and influence dough hydration and texture. The oil retention capacity (ORC) at 0.79 ± 0.02 mL/g proved suitable for mixing the oil in the baking process. Bulk Density (0.84 ± 0.01 g/mL), swelling Index (0.07 ± 0.02 mg/L), and water Solubility Index (0.12 ± 0.01 mg/L) obtained suggested that MSKF is lightweight and exhibits low solubility in water, as represented in **Table 1**. These properties indicate that MSKF can maintain product consistency and texture in baked goods.

Table 1. Functional Properties of MSKF

Parameter	**Mean ± SD**
Water Absorption Capacity (g/mL)	0.82 ± 0.01
Oil Retention Capacity (mL/g) |	0.79 ± 0.02

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Bulk Density (g/mL)	0.84 ± 0.01
Swelling Index (mg/L)	0.07 ± 0.02
Water Solubility Index (mg/L)	0.12 ± 0.01

All values are (mean ± SD) of three observations

(gm = grams, ml = milliliters, mg = milligrams, l = liters)

The nutritional composition of MSKF revealed a balanced macronutrient profile. The flour contained 42.34% carbohydrates, 9.83% protein, and 13.2% crude fibre, indicating its potential as a partial flour substitute. Moreover, the moisture content of 17.2% and ash content of 9.2% recorded showed its efficiency in baking processes, as depicted in **Table 2**.

Table 2. Nutritional Composition of MSKF

Parameter	**Content (% or mg/100g)**
Carbohydrate	42.34 ± 1.90
Protein	9.83 ± 0.02
Fat	13.2 ± 0.08
Fiber	13.2 ± 0.01
Moisture	17.2 ± 0.01
Ash	9.2 ± 0.07

all values are (mean ± SD) of three observations mg = milligrams

3.2. Antioxidant Profile

The antioxidant potential of MSKF was significantly driven by its phenolic and flavonoid contents, as shown in **Table 3 and Figure 1**. The total phenolic content recorded at 33.2 ± 0.6 mg GAE/g and Total Flavonoids at 17.8 ± 0.33 mg QE/g were relatively high, indicating antioxidant, anti-inflammatory, and other bioactive properties. The alkaloids (4.3 ± 0.24 mg/g are noticeable, which may contribute to health benefits. Therefore, all the parameters promoted MSKF's potential as a natural antioxidant source for nutraceutical and bakery formulations.

Table 3. Antioxidant Activity of MSKF

Parameter	**Value (Mean ± SD)**
Total Phenolic Content (mg GAE/g)	33.2 ± 0.6
Total Flavonoids (mg QE/g)	17.8 ± 0.33
Alkaloids (mg/g)	4.3 ± 0.24
DPPH Scavenging Activity (mg/g)	0.97 ± 0.04

All values are (mean ± SD) of three observations

Graphic evaluation of comparative antioxidant parameters in MSKF (phenolic, flavonoid, alkaloid, and DPPH values).

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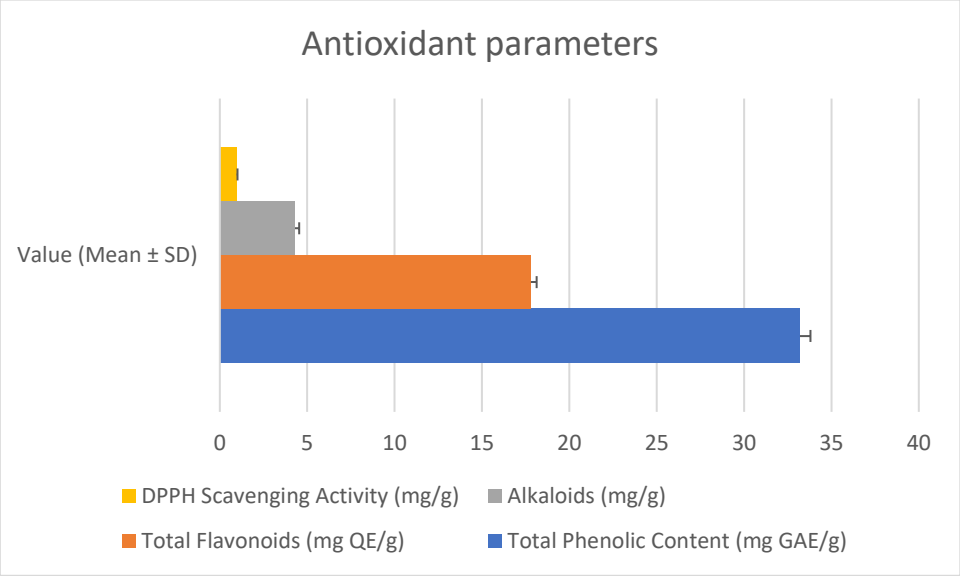


Fig. 1 Bar chart representing comparative antioxidant parameters in MSKF (phenolic, flavonoid, alkaloid, and DPPH values). Bars with different numbers don't differ significantly ($p < 0.05$)

3.3. Comparative Analysis

To determine MSKF's value, a qualitative comparative evaluation was performed with commonly used flours such as wheat and chickpea flour. MSKF presented a moderate protein source (≈10%), as compared to chickpea and wheat flour, confirming it as a potent protein ingredient. The high fat content in MSKF (~13%), in contrast to Chickpea flour (6%) and wheat flour (1–2%), was relatively leaner, thereby contributing to the energy and richness of the product. MSKF demonstrated a strong and high metabolic advantage in fibre and antioxidants over conventional flours, making it ideal for functional and gluten-free formulations. The mango kernel flour also showed high water absorption and oil retention, conferring an advantage in fat-rich formulations when compared to wheat and chickpea flours, as illustrated in **Table 4**.

Table 4. Comparison of MSKF with Wheat and Chickpea

Parameter	**MSKF**	**Wheat Flour**	**Chickpea Flour**
Antioxidants	Very High	Moderate	Moderate–High
Protein	Moderate (≈10%)	Moderate–High (10–12%)	High (18–20%)
Fat	Moderate (13%)	Low (1–2%)	Moderate (6%)
Fiber	High (13%)	Low (3–4%)	Moderate (7–8%)
Water Absorption	High	Moderate	Moderate
Oil Retention	High	Low	Moderate
Gluten	Absent	Present	Absent

All values are (mean ± SD) of three observations

4. FATTY ACID, MINERAL, AND VITAMIN COMPOSITION

The composition of oil plays a major role in determining its nutrient-based quality, texture, and shelf life in flour formation. The MSKF oil contained a higher proportion of unsaturated fatty acids (30.63%- 35.86%), dominated by oleic and linoleic acids, than saturated ones (6.58%) composed of palmitic acid, stearic acid, and caprylic acid, as demonstrated in **Table 5 and**

Figure 2. Moreover, the mineral analysis showed considerable levels of potassium (6.47 mg/100g), magnesium (8.11 mg/100g), and calcium (2.91 mg/100g).

Table 5. Fatty Acid Profile of MSKF Oil

Fatty Acid	Content (% Mean ± SD)
Palmitic Acid	6.58 ± 0.01
Stearic Acid	2.24 ± 0.26
Oleic Acid	35.86 ± 0.02
Linoleic Acid	30.63 ± 0.02
Caprylic + Lauric Acids	1.5 ± 0.03

All values are (mean ± SD) of three observations

Chromatographic evaluation of vitamin compounds present in mango seed kernel flour.

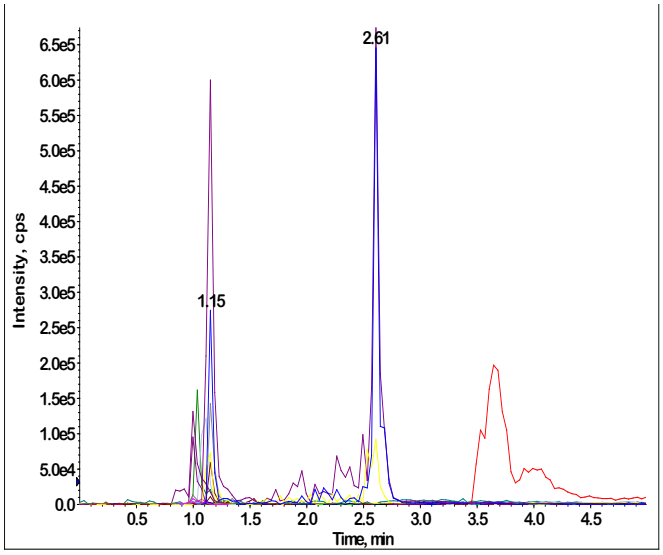


Fig. 2 Chromatogram illustrating Vitamin compounds of Mango seed kernel flour.

5. COMPARISON BETWEEN UNTREATED AND TREATED FLOURS

5.1. Physicochemical Properties of Treated and Untreated Flour

The influence of different pre-treatments on flour properties, microbial safety, cookie characteristics, and sensory attributes of flour was evaluated. A notable variation in physicochemical and quality characteristics of treated blanched flour and a combination of sulphite and blanched treatments is summarised in **Table 6 and Figure 3.** A significant increase in lightness (L*) of flour was observed following treatments, with the highest brightness recorded in sulphite-blanched 81.2 ± 0.8 samples, compared to blanched 77.8 ± 1.0 and control (72.3 ± 1.2) samples.

This progressive increase in L* value indicated effective pigment removal and reflects the inhibition of enzymatic browning. Moisture content, however, decreased gradually from 11.8 ± 0.4 % in the control to 10.4 ± 0.2 % in the combined treatment, likely due to partial dehydration. Protein in flour remained relatively unaffected (9.3–9.6 %), confirming minimal thermal denaturation. A substantial reduction was recorded in total microbial load from 2.4×10^5 CFU g^{-1} in untreated flour to 0.4×10^5 CFU g^{-1} after sulphite-blanching. These results demonstrated a synergistic antimicrobial efficacy of thermal and chemical treatment.

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Table 6. Comparative Study of Treated and Untreated Flour and Cookies

Parameter	Untreated Control	Blanched Only	Sulphite + Blanched	One-way ANOVA p	Tukey post-hoc interpretation
Flour lightness (L*)	72.3 ± 1.2^{a}	77.8 ± 1.0^{b}	81.2 ± 0.8^{c}	<0.001	All groups are significantly different
Moisture (%)	11.8 ± 0.4^{a}	10.9 ± 0.3^{b}	10.4 ± 0.2^{b}	0.004	Control differs from both treatments; treatments NS
Protein (%)	9.6 ± 0.2^{a}	9.3 ± 0.1^{a}	9.4 ± 0.2^{a}	0.178	No significant difference
Total microbial count (CFU/g)	2.4×10^{5a}	1.2×10^{5b}	0.4×10^{5c}	<0.001	All groups are significantly different
Cookie spread ratio	7.1 ± 0.2^{a}	7.5 ± 0.3^{a}	7.8 ± 0.2^{b}	0.031	Control vs sulphite + blanching significant; other pairs NS
Cookie hardness (N)	36.2 ± 1.1^{a}	33.8 ± 0.9^{b}	31.5 ± 0.8^{b}	0.003	Control differs from both treatments; treatments NS
Overall sensory score (9-point)	6.8 ± 0.3^{a}	7.6 ± 0.2^{b}	8.6 ± 0.2^{c}	<0.001	All groups are significantly different

All values are the mean ± SD of three observations

Graphical evaluation of comparative effects of different flour treatments (untreated (control)), blanched, and sulphite + blanched on flour lightness (L*), cookie sensory score, and microbial load.

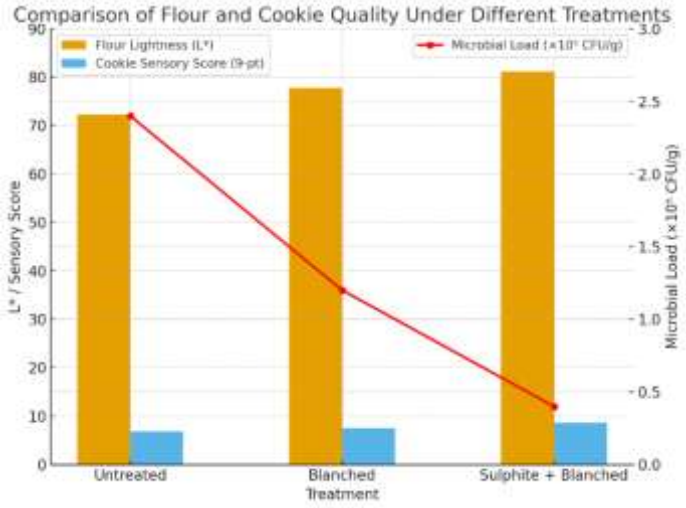


Fig. 3 Comparative effects of different flour treatments (untreated (control)), blanched, and sulphite + blanched on flour lightness (L*), cookie sensory score, and microbial load.

5.2. Quality Characteristics of Cookies Prepared from Treated Flours

Cookies prepared using the differently treated flours exhibited distinct variations in physical and sensory attributes. In cookie evaluation, an improved spread ratio (7.8 ± 0.2) and decreased hardness (36.2 ± 1.1 N) were observed. Both blanching and the sulphite-balanced combination markedly elevated these parameters, thereby reflecting a crisp and tender texture.

The overall organoleptic (Sensory) score increased from 6.8 ± 0.3 for control cookies to 8.6 ± 0.2 for cookies prepared from sulphite- and blanched flour. Thus, the treated cookies showed enhanced colour, uniform spread, and mouthfeel aroma. The

sulphite-blanched treatment proved to be the most effective in enriching flour properties and its influence on superior cookie quality.

6. COOKIE FORMULATION COMPARISON

The substitution of Mango Seed Kernel Flour (MSKF) in chickpea notably influenced the organoleptic and physical properties of the product. At 0% substitution (control), the product showed a light cream appearance and a soft texture typical of traditional flour formulations. However, the 30% and 50% MSKF levels enhanced the colour to a golden brown, pleasantly crisp texture, and a mild, rich nutty aroma, yielding high palatability. Further, the addition of 70% and 100% MSKF resulted in a dark brown product with a hard texture and noticeable bitterness, thereby reducing consumer appeal, as depicted in **Table 7 and Figure 4**. Thus, moderate substitution levels between 30% and 50% are optimal for achieving desirable food-related properties.

Table 7. Comparative Evaluation of Cookie Blends vs. Control

MSKF Substitution (%)	Appearance	Texture	Aroma	Overall Acceptability
0% (Control)	Light cream	Soft	High	High
30%	Golden brown	Crisp	Pleasant	Very High
50%	Deep golden	Firm, crunchy	Rich nutty	High
70%	Dark brown	Hard	Slight bitterness	Moderate
100%	Very dark	Tough	Bitter	Low

All values are the mean ± SD of three observations

Pictorial depiction of Mango–chickpea cookies at different MSKF substitution levels (0%, 30%, 50%, 70%, and 100%).

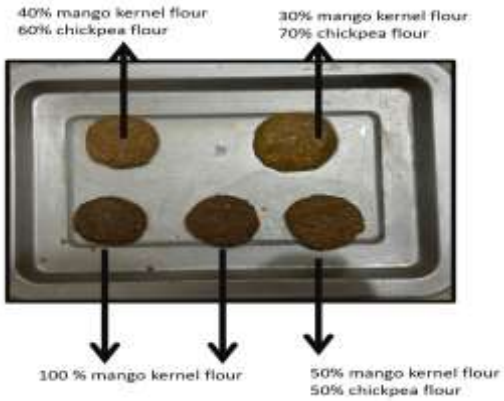


Fig. 4 Mango–chickpea cookies at different MSKF substitution levels (0%, 30%, 50%, 70%, and 100%).

7. DISCUSSION

The present study demonstrated that mango seed kernel flour (MSKF) possesses significant nutritional and functional potential that can be effectively utilised in sustainable food applications. The functional and nutrient-rich properties recorded in our study were found to be consistent with previous findings reported by Yatnatti et al. 2014). Comparable water absorption (0.82 ± 0.01 g/mL) and oil retention capacities (0.79 ± 0.02 mL/g) were present. These values indicated favourable binding and moisture-retention characteristics that enhance product texture and mouthfeel in bakery formulations. Furthermore, the fibre (13.2%) and carbohydrate (42.34%) contents observed in the present study fall within the given range of 12–15% and 40–45%

for MSKF derived from Indian cultivars. The moisture (17.2% and ash (9.2% align with findings from Lakshmi et al. n.d.) and Mas'ud et al. 2020). This emphasised the high nutrient-dense nature of MSK, making it suitable for baking processes.

Additionally, the phenolic and flavonoid concentrations, 33.2mg gallic acid and 17.8mg of quercetin, emphasised the strong antioxidant and radical-scavenging properties of MSKF, which were comparable to observations illustrated by (Mwaurah et al., 2020; Sogi et al., 2013). These studies identified mango seed kernel as a source of potent bioactive compounds such as tocopherols, phytosterols, and carotenoids. These components contribute to oxidative stability and may extend the shelf life of composite flour products. The Alkaloids, on the other hand, are nitrogen-containing secondary metabolites that show diverse pharmacological effects such as anti-inflammatory, antimicrobial, and analgesic effects. Therefore, the alkaloid content of 4.3 $\pm$ 0.24 mg/g present in our mango kernel flour exhibited bioactive properties and was presumed to contribute to health benefits.

Furthermore, we also evaluated the physicochemical properties and quality of flour with blanched and a blend of sulphite and blanched. We found that the flour after pretreatment with a mixture of blanched and sulphite was significantly ($p < 0.05$) lighter (81.2 $\pm$ 0.8), and the moisture content (10.4 $\pm$ 0.2 %) was also reduced. These results clearly demonstrate the anti-browning action of sulphite, which prevents dark pigment formation and inhibits polyphenol oxidase during heating. Parallelly, a reduction in moisture and microbial load (0.4×10^5 CFU/g) confirms synergistic preservation of blends, ensuring improved hygiene and longer shelf life without altering protein content. Several studies (Nguyen et al., 2025) reported similar findings, which enhanced the flour texture post-thermal treatments.

Looking into these attributes, we prepared treated flour cookies. The cookies revealed superior spread, lower hardness, and the highest overall acceptability (8.6 $\pm$ 0.2).

The enhanced characteristics can be attributed to reduced dough viscosity and uniform starch gelatinisation, and the appealing golden hue of the final product, thereby influencing consumer perception.

Notably, the use of MSKF reflects a sustainable, zero-waste approach, transforming mango-processing by-products into bio-nutritional commodities. Therefore, its incorporation into bakery products such as cookies and other food categories, for instance, pasta, snack bars, and nutraceutical beverages, presents a viable model for sustainable agri-food innovation. Significantly, the integration of MSKF with chickpea flour for cookie formulations influenced the physical, nutritional, and sensory balance in product development. Incorporating 30%- 50% of MSKF yielded the most desirable texture and flavour, such as a golden-brown colour, with a crispy texture and a mild, rich nutty aroma without adverse bitterness or excessive hardness in cookies. Previous studies showed similar results with optimal sensory profiles within moderate substitution ratios. (Yatnatti et al., 2014). At these levels, cookies exhibited elevated antioxidant retention, supporting the premise that kernel phenolics remain active post-baking and can function as natural preservatives. Additionally, the fatty acid composition of MSKF oil, predominantly oleic (35.8%) and linoleic acids (30.6%), mirrors patterns reported by Yadav et al. (2017) and reinforces the kernel's potential role in cardiovascular health and lipid regulation. The mineral profile demonstrated its richness in potassium, magnesium, and calcium (2.91 mg/100g-8.11 mg/100g), which corroborates the findings of Damerau et al. (2020) and provides a nutraceutical and dietary rationale.

From an industrial perspective, valorisation of mango seed kernel flour (MSKF) aligns with the circular economy and sustainable food innovation principles by transforming fruit processing residues into a value-added ingredient. In developing nations, utilisation of by-products not only mitigates environmental burdens but also fosters new economic opportunities. The transformation of mango kernel waste into high-value functional food components contributes directly to the achievement of the United Nations Sustainable Development Goal 12 (Responsible Consumption and Production). Therefore, optimisation, detoxification, flavour standardisation, and quality consistency will be essential to ensure consumer acceptance and regulatory compliance.

In light of the current study, future research should focus on refining detoxification processes, such as vacuum, microwave, and fermentation methods (Mustafa, 2025), to further improve consumer safety and organoleptic quality. Moreover, expanding the applications of MSKF beyond bakery items to include cereals, snack bars, and nutraceutical powders could significantly contribute to food system sustainability and rural livelihood development.

8. CONCLUSION

This study highlights mango seed kernel flour as a versatile, nutrient-rich, and eco-sustainable ingredient with broad potential in functional food development. The incorporation of MSKF into mango-chickpea cookies successfully illustrates its practical utility in creating high-fibre, antioxidant-rich snacks. Therefore, future research should focus on detailed physicochemical profiling, shelf-life assessment, and bioavailability studies to enable large-scale commercialization.

Data Availability: All data supporting the findings of this study are available within the paper and its Supplementary Information.

Author's contribution: Kirty Rani carried out all experiments, interpreted the results, and wrote the manuscript, with guidance on study design from Dr Meenal Rehman. The experiments were performed under the supervision of Dr Tripti Bhatnagar. Dr Mahesh Seth supervised and edited the manuscript and also helped with the interpretation of the data. Gyan Vandana Yadav and Dr Tanvir Kaur helped with the analysis and interpretation of tables and figures.

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