



3D Printed Kodo Millet Cookies Incorporated with Date Seed Powder (*Phoenix dactylifera* L.)

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ABSTRACT

Background: This study focuses on the differences between unpolished and polished Kodo millet flours in terms of their nutritional composition, antioxidant activity and sensory acceptability when used for 3D-printed cookies. Kodo millet is known for its nutritional richness and the study aims to determine whether polishing affects its suitability for 3D food printing.

Methods: Cookies were formulated using five different combinations: standard, 30% incorporation and 50% incorporation levels of both polished (PKMF) and unpolished Kodo millet flour (UKMF) along with date seed powder. These formulations were analyzed for nutritional content, antioxidant activity and sensory attributes, including texture, form and overall acceptability. Sensory evaluation scores were used to assess consumer acceptance and product quality.

Result: Cookies prepared with 50% unpolished Kodo millet flour showed greater nutritional properties, with high dietary fiber (6.8 g), calcium (77 mg), phosphorus (128 mg) and antioxidant components. However, sensory evaluation indicated that cookies made with polished Kodo millet flour, particularly with 30% incorporation, achieved higher scores for texture (up to 7.95/9), form and overall acceptability due to their smooth and soft texture. The study concluded that while unpolished millet enhances nutritional value, polished millet flour is more suitable for functional processing in 3D food printing. Thus, 3D food printing presents a promising approach to developing customized, nutrient-rich cookies.

Key words: 3D food printing, Dates seed powder, Food innovation, Kodo millet, Nutritional properties, Polished 3D cookies, Textural attributes, Unpolished 3D cookies.

INTRODUCTION

Cereal grains have nourished humanity for centuries and continue to constitute a fundamental component of the daily diet for billions of people worldwide (Saleh *et al.*, 2013). Despite their global importance, ensuring food security remains a major challenge for scientists working in food production, processing, storage and nutrition, particularly in the context of climate change and resource limitations (Shahidi and Chandrasekara, 2013).

Among cereal crops, millets have gained increasing attention due to their exceptional nutritional value and environmental resilience. Millets are rich sources of dietary fiber, minerals, antioxidants and bioactive compounds and they are well adapted to drought-prone and marginal agro-climatic regions, particularly in Asia (Gupta *et al.*, 2021; Sudharshana *et al.*, 1988). Kodo millet (*Paspalum scrobiculatum*) is especially valued for its high fiber content, micronutrient density and potential health benefits, making it a promising ingredient for the development of functional and sustainable food products.

In parallel with advances in food ingredients, three-dimensional (3D) food printing has emerged as a novel additive manufacturing technology in the food sector. Also referred to as food-layered fabrication, 3D food printing enables the production of foods with customized shapes, textures and nutritional compositions using computer-aided design (CAD) tools (Lipson and Kurman, 2013; Berman, 2013). Unlike conventional automated food processing,

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extrusion-based 3D printing allows precise control over ingredient distribution and structural design, thereby supporting product personalization and targeted nutrition (Dekka *et al.*, 2023; Kumar *et al.*, 2015; Sun *et al.*, 2015). Recent studies have demonstrated the growing applicability of extrusion-based 3D printing for cereal- and millet-based food formulations (Nachal *et al.*, 2019; Kokane *et al.*, 2025).

A critical factor influencing the suitability of millet flours for 3D food printing is grain polishing, a common post-harvest processing technique that removes the outer bran and germ layers (Saleh *et al.*, 2013) (Kavitha *et al.*, 2025). Unpolished millet retains these layers, resulting in higher levels of dietary fiber, minerals, antioxidants and phenolic

compounds. However, the presence of bran may negatively affect particle uniformity, dough smoothness and flow behavior. In contrast, polished millet flour exhibits improved processing functionality and extrusion behavior, which are essential for additive manufacturing applications, albeit at the cost of reduced nutritional density.

Although numerous studies have reported the nutritional advantages of unpolished millets in conventional cereal-based foods, there is limited research examining how polishing influences printability, textural properties and consumer acceptability in 3D-printed food systems, particularly for Kodo millet. Therefore, the present study aimed to comparatively evaluate polished and unpolished Kodo millet flour in 3D-printed cookies with respect to nutritional composition, antioxidant activity, printability, textural properties and sensory acceptability. By integrating grain processing with additive manufacturing, this research seeks to identify formulations that enable the development of nutrient-optimized, functionally printable and consumer-acceptable millet-based food products.

MATERIALS AND METHODS

Procurement and Pre - Preparation of ingredients

Kodo millet (*Paspalum scrobiculatum*) Grains - Unpolished of the Varietal name Varagu ATL-1 seeds were obtained from TNAU Agriscart, India. In addition, Ajwa date sugar and date seed powder, as natural sweeteners and functional ingredients, respectively, were used from a certified farm in the Kingdom of Saudi Arabia. The rest of the ingredients- wheat flour, oats, butter and other baking components- were procured from a local market in Coimbatore, Tamil Nadu, India.

Clean millet grains were cleaned manually to remove foreign materials, washed and oven-dried at 60°C for 6 h to reduce the moisture content. Dried grains were milled using a laboratory-scale hammer mill, Model: HM-210, Make: Retsch GmbH, Germany, in order to obtain fine flours. To ensure uniformity in particle size, a very critical factor for extrusion and subsequent layer deposition during 3D food printing, the flour was sieved through a 250 µm stainless-steel mesh. Processed flour was stored in airtight containers at ambient temperature of 25±2°C till further use in cookie formulation.

Formulation of cookie variations

Five cookie recipes were made to test how the type and amount of Kodo millet flour affected the printability and other characteristics of the cookies. A control sample (S) was made with only all-purpose flour, sugar and butter, with no millet flour. This was the reference formulation. We made two formulations using unpolished Kodo millet flour (UKMF):

- V1: 50% UKMF mixed with 50% wheat flour.
- V2: 30% UKMF mixed with 30% wheat flour.

Two formulations were also made with polished Kodo millet flour (PKMF):

- V3: 50% PKMF mixed with 50% wheat flour.
- V4: 30% PKMF mixed with 30% wheat flour.

Table 1 shows that all of the experimental formulations (V1-V4) also had oats, date sugar (DS), date seed powder (DSP) and butter in set amounts. Food ink is the name for the smooth, homogeneous paste that was made by mixing the dry and wet ingredients.

We put the prepared food inks into a syringe and used a 3D food printer that works by extruding and fusing layers of material to make precise cookie shapes. The material was put through a food-grade nozzle to make the cookie shapes. This formulation strategy made it possible to compare polished and unpolished Kodo millet flours directly at two different levels of incorporation with the standard cookie formulation.

Processing techniques

3D food printing process

The first step in 3D food printing was making food ink, which involved mixing all the ingredients together and turning them into a smooth paste that could be extruded. A delta-type, extrusion-based 3D food printer was made and used to print the cookies. We chose cookie designs from an online library of printing-related designs that already had a set shape. We then standardized the dimensions (width, length and height) to get shapes that were all the same and easy to recognize (Fig 1). The chosen designs were processed with computer-aided design (CAD) software (CURA version 15.04.3), which turned the digital models into step-by-step instructions for printing. The prepared food ink was then put into a food-grade syringe and attached to the printer's extrusion system. When the printing process started, the dough was pushed through a nozzle in a controlled, layer-by-layer way. This made three-dimensional cookie structures with a consistent shape and size. We used a custom, food-safe extrusion-based printer to print all of the cookie samples under the same conditions to make sure they could be reproduced. One of the best things about 3D food printing is that it lets you change the shape, internal structure, texture and ingredient distribution of a product very precisely, which lets you change the nutrient composition in a targeted way. This level of customization makes the technology especially useful for making millet-based functional foods that are tailored to certain groups of people, like older people who need softer textures, kids who need snacks that are high in nutrients, or people who have specific dietary needs.

3D printing parameters

The cookies were fabricated using an extrusion-based, food-grade 3D printer, which was carefully configured to ensure optimal print quality, shape retention and structural integrity of the printed Cookies. A high infill density of 90% was selected to ensure the Cookies had a dense internal structure, contributing to their firmness and textural consistency after baking. The print parameters were set after testing: nozzle size (1.2 mm outer diameter, 0.8 mm

inner diameter), print rate (20 mm/s), extrusion temperature (ambient) and layer thickness (2 mm). The 3D printer's bed was preheated and maintained at a temperature of 70°C. This elevated bed temperature helped in promoting adhesion between the printed layers and the printing platform, minimizing warping and ensuring dimensional accuracy. The dimensions of the printed Cookies were precisely defined, with a width (X-axis) of 52.60 mm, a depth (Y-axis) of 50.43 mm and a height (Z-axis) of 10.00 mm. These dimensions were chosen to standardize the product for consistent baking and sensory evaluation. A layer height of 1.5 mm was utilized, allowing each layer of dough to be extruded with sufficient thickness to support the subsequent layers while maintaining a smooth surface finish. The shell thickness was set at 4 mm, which provided a sturdy outer wall that helped to retain the shape of the biscuit during and after the printing process. The print speed was maintained at a relatively slow rate of 10 mm/s.

This slow extrusion rate ensured precise deposition of the dough and reduced the risk of structural collapse or deformation during printing as shown in Fig 2. The printing temperature was set at 25°C, which was ideal for food materials such as cookie dough, as it helps to maintain the dough's consistency without premature drying or cooking.

The printed Cookies were then baked under identical conditions for a proper comparison.

Nutrient analysis

Every sample of baked Cookies were analysed for nutritional examination using standard protocols established by the Association of Official Analytical Chemists (AOAC), the concentration of macronutrients, such as carbohydrate, protein, fat and dietary fibre and other nutrients like iron, calcium and phosphorus was evaluated. It highlights the nutritional benefit of employing unpolished millet in functional food formulations.

Statistical analysis

The descriptive statistics like the mean, standard deviation, standard error, confidence interval, median and interquartile range to find the central tendency and variability across samples for each sensory attribute were used using sigma plot 14.1 software. When the data met the assumptions of normality and equal variance, Repeated Measures ANOVA were used to draw conclusions. The Tukey test was used to compare groups after the fact and find statistically significant differences between cookie formulations in pairs. The analysis kept a significance level of $P < 0.05$ throughout and the power of the statistical tests was calculated.



Fig 1: Designing of shape for printing of cookies.

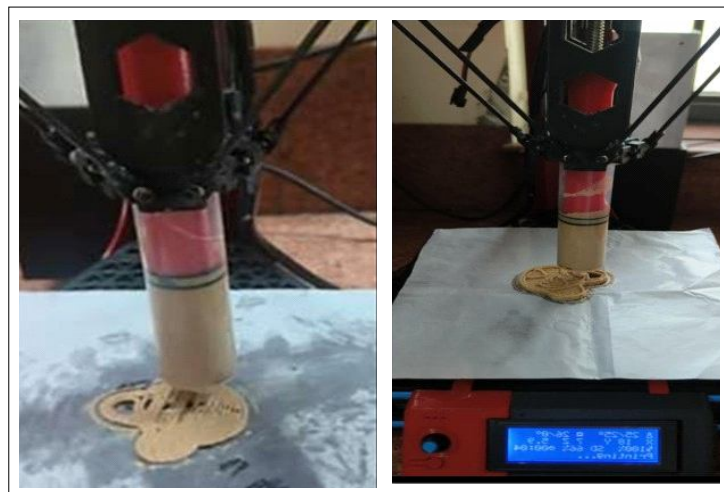


Fig 2: Printing of 3D cookies using fabricated 3D Food printer.

Brine shrimp lethality assay (Toxicity test of date seed powder)

Brine shrimp lethality test were conducted to check whether date seed powder (DSP) was safe to use as a functional ingredient in recipes. DSP at different levels (100, 250, 500, 1000 and 1500 µg/mL) were evaluated and added thirty brine shrimp nauplii to each test solution. At 1, 2, 4, 6 and 24 hours after exposure, death was seen. To make sure the test was accurate, there was also a positive control with 1 mg/mL potassium dichromate, which is a recognized toxicant and a negative control with merely saline water. The low death rates seen at all DSP doses showed that it is safe and not harmful for use in food. Adding it to cookie recipes gives them functional advantages without putting people's health at risk, which proves that it is a safe and healthy element that can be used in a sustainable way.

Sensory evaluation

Sensory evaluations were conducted in a quiet, well-lit space with free from odours (Kim *et al.*, 2025) (Kokane *et al.*, 2025). The nine-point hedonic scale were used for evaluating a food product with 1 indicating extreme dislike and 9 indicating extreme like. Thirty semi-trained panel members evaluated the prepared cookies in Food Sensory Laboratory Centre, Avinashilingam Institute of Home Science and Higher Education for Women, Coimbatore as

shown in Fig 3a and 3b. For the panel members four variations and one control sample were served separately. Then the panel members scored the marks based on the acceptability and organoleptic characteristics like appearance, texture, taste, colour of the prepared Cookies. Ethical clearance was obtained from the Institutional Human Ethical Committee (IHEC) of Avinashilingam Institute for Home Science and Higher Education for Women, Coimbatore. In this work, all experimental procedures, from ingredient preparation to cookie formulation, 3D printing, baking, nutritional analysis, toxicity assessment and sensory tests, were strictly performed in standardized and controlled conditions for the generation of reproducible and representative results.

RESULTS AND DISCUSSION

This section covers the measured outcomes of 3D-printed cookies prepared with polished and unpolished Kodo millet flour, including their baking behavior, nutritional composition, sensory attributes, textural evaluation, statistical comparisons and antioxidant activity.

To clarify, S refers to the standard control cookie; V1-V4 are experimental formulations as described in Table 1; STEX is used to represent the texture score of the standard sample; V1TEX-V4TEX is used to refer to the texture scores of the respective formulations.



Fig 3: a and 3b sensory evaluation of 3D food printed cookies for their acceptability.

Table 1: Cookie formulations with varying proportions of kodo millet flour.

Ingredient(in g)	S (Standard)	V1 (50% UKMF)	V2 (30% UKMF)	V3 (50% PKMF)	V4 (30% PKMF)
All-purpose flour	100	-	-	-	-
Wheat flour	-	50	30	50	30
Unpolished KMF	-	50	30	-	-
Polished KMF	-	-	-	50	30
Oats	-	20	20	20	20
Date sugar (DS)	-	50	50	50	50
Date seed powder (DSP)	-	5	5	5	5
Butter	50	30	30	30	30
Sugar	50	-	-	-	-

Baking parameters

The baking temperature for cookies made with unpolished Kodo millet flour was higher than those made with polished Kodo millet flour. In fact, baking temperature for cookies made with unpolished flour was at 150°C for a period of 40-45 minutes while those made with polished Kodo millet flour were baked at a temperature of 130°C for 20-25 minutes. These parameters were standardized for each formulation.

Nutritional composition of cookies

Table 2 reveals the nutritional composition of the cookie dough formulations. Cookies made with unpolished Kodo millet flour expressed higher values of dietary fiber, calcium, phosphorus and iron compared to cookies made with polished Kodo millet flour. In all formulations, formulation V1 (containing 50% unpolished Kodo millet flour) presented the highest values of dietary fiber (6.8 g), calcium (77 mg), phosphorus (128 mg) and iron (3.8 mg).

Formulation V2 (30% up flour) showed modestly lower but comparable values for nutrients. On the other hand, a reduction in mineral and dietary fiber was seen in the cookies prepared using polished Kodo millet flour (V3 and V4). Energy, carbohydrate, protein and fat contents for various formulations have been presented in Table 2.

Sensory characteristics of 3D-Printed cookies

Appearance, texture, shape, color, flavor, taste, as well as overall acceptance score values are shown graphically in

Fig 4. These score values were recorded using a nine-point hedonic scaling technique where 1 = dislike extremely and 9 = like extremely.

Among all the formulations, V4 with 30% polished Kodo millet flour scored maximum on total acceptability with a value of 7.73/9 and it scored max on texture, shape and taste parameters. The cookies prepared with unpolished Kodo millet flour V1 and V2 scored less on texture and appearance parameters.

Statistical analysis of texture scores

Table 3a describes the descriptive statistics of the texture scores. Formulation V4TEX had the highest mean texture value of 7.967±0.718, followed by V3TEX and STEX. Formulations V1TEX and V2TEX had lower values in terms of mean texture scores.

Before conducting the inferential test, normality of the data and sphericity were assessed. Results of the one-way repeated measures ANOVA (Table 3b) showed a significant difference in the scores of the textures of the formulation at a significance level of $P = 0.001$ and a power of 0.992.

Tukey post-hoc comparison

The results of Tukey's test on pairwise comparisons of texture score are shown in Table 4. Significant differences between V4TEX and all other formulations except V3TEX existed ($P < 0.05$). Neither V2TEX nor V4TEX showed significant differences, while STEX, V1TEX and V3TEX had no significant differences.

Table 2: Nutritional composition of cookies.

Nutrient	V1 - Unpolished Kodo (50%)	V2 - Unpolished Kodo (30%)	V3 - Polished Kodo (50%)	V4 - Polished Kodo (30%)
Energy (kcal)	459.3	441.6	446.9	437.4
Carbohydrates (g)	66.5	63.5	67.2	64.9
Protein (g)	7.6	7.3	7.4	7.1
Fat (g)	18.1	17.6	16.5	16.6
Iron (mg)	3.8	3.6	3.6	3.4
Dietary Fiber (g)	6.8	5.7	3.9	3.2
Calcium (mg)	77	75	68	64
Phosphorus (mg)	128	116	90	85

Table 3a: Descriptive statistics for texture.

Column	Mean	Std. Dev	Std. Error	Median	25%	75%
Sensory attributes of cookies - (texture)						
STEX	7.000	0.743	0.136	7.000	6.00	8.00
V1TEX	6.200	0.805	0.147	6.000	6.00	7.00
V2TEX	6.367	0.964	0.176	6.000	6.00	7.00
V3TEX	7.067	0.785	0.143	7.000	6.00	8.00
V4TEX	7.967	0.718	0.131	8.000	7.00	8.25

Table 3b: One-way repeated measures ANOVA.

Source of variation	DF	SS	MS	F	P
Between subjects	29	18.240	0.629		
Between treatments	4	58.440	14.610	22.194	<0.001
Residual	116	76.360	0.658		
Total	149	153.040	1.027		

Antioxidant activity of cookies

The DPPH radical scavenging activity of all cookie formulations is summarized in Table 5. Antioxidant activity increased with increasing sample concentration (20-100 μ L) across all formulations.

Formulation V1 (50% unpolished Kodo millet flour) exhibited the highest percentage inhibition ($74.2 \pm 1.3\%$ at 100 μ L) and the lowest IC_{50} value (44.9 μ L), followed by V2. Polished millet formulations (V3 and V4) showed lower inhibition percentages and higher IC_{50} values. The standard sample (S) demonstrated the lowest antioxidant activity among all samples.

Mean inhibition values were statistically grouped using alphabetic notation, with V1 and V2 classified as group "a" and V3 and V4 as group b ($P < 0.05$).

In general, the results presented in the Results section clearly show the existence of a difference among the different types of cookies with regard to baking characteristics, nutritional values, organoleptic qualities, texture and antioxidant properties, based on the analysis carried out and presented in Table and Fig from 1 to 4.

In the current study, the type of flour used-whether polished or unpolished Kodo millet-demonstrated profound influences on the nutritional composition, antioxidant activity, textural behavior and sensory acceptability of the 3D-printed

cookies. One of the major findings is a clear trade-off between enhanced nutritional value and processing performance when using unpolished millet flour in extrusion-based food printing systems.

Among these, cookies prepared with unpolished Kodo millet flour (V1 and V2) showed a better nutritional profile, especially in terms of dietary fiber, calcium, phosphorus and iron content. The highly increased dietary fiber found in V1 (6.8 g) when compared to the polished flour formulation, for example-V4: 3.2 g, corroborates various studies where the retention of bran and germ layers maintains fiber, minerals and micronutrients in millets (Saleh *et al.*, 2013; Devi *et al.*, 2014; Shobana *et al.*, 2013; Chandrasekara and Shahidi, 2011; Thapliyal and Singh, 2015). These findings further confirm the nutritional benefits of using unpolished millet flour in functional food formulations.

Similarly, unpolished millet cookies showed considerably greater antioxidant activity, as estimated from the DPPH radical scavenging effect. These findings are consistent with previous claims suggesting drastic reduction of phenolic components and flavonoids, generally found abundantly in the outer layer of grains, after polishing millet (Krishnan and Meera, 2018; Patel *et al.*, 2017; Rai and Raj, 2023).

Higher antioxidant activity in V1 and V2 suggests favorable prospects or application of unpolished Kodo

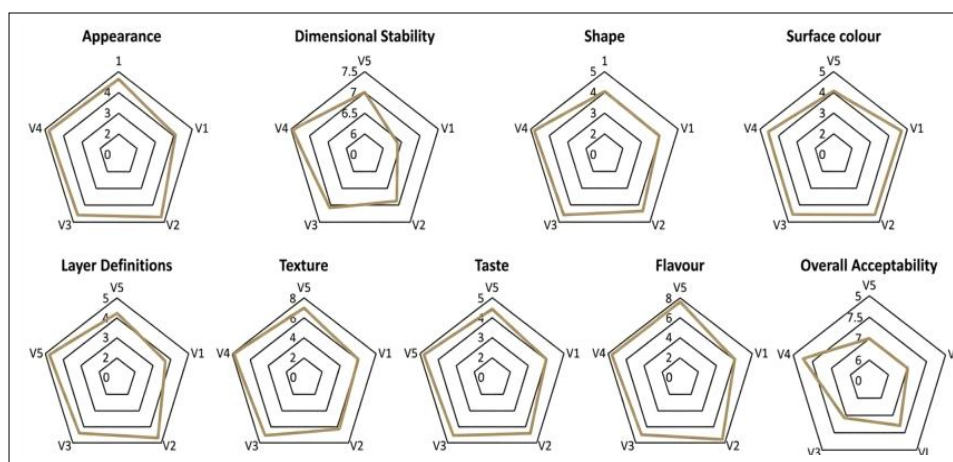


Fig 4: sensory attributes of 3D printed cookies.

Table 4: Tukey test.

Comparison	Mean diff	q-value	P-value	Significant ($P < 0.05$)
V4TEX vs. V1TEX	1.767	11.926	<0.001	Yes
V4TEX vs. V2TEX	1.600	10.801	<0.001	Yes
V4TEX vs. STEX	0.967	6.526	<0.001	Yes
V4TEX vs. V3TEX	0.900	6.076	<0.001	Yes
V3TEX vs. V1TEX	0.867	5.851	<0.001	Yes
V3TEX vs. V2TEX	0.700	4.726	0.010	Yes
V3TEX vs. STEX	0.067	0.450	0.998	No
STEX vs. V1TEX	0.800	5.401	0.002	Yes
STEX vs. V2TEX	0.633	4.276	0.025	Yes
V2TEX vs. V1TEX	0.167	1.125	0.931	No

Table 5: Antioxidant activity of cookies.

Sample	20 µL	40 µL	60 µL	80 µL	100 µL	IC50 µL	Mean±SD
S (Standard)	12.5±0.8	18.9±1.1	24.6±1.2	30.1±0.9	36.7±1.4	92.4	24.6±8.6
V1 (50% UKM F)	28.3±1.2	41.7±1.3	55.6±1.5	66.8±1.2	74.2±1.3	44.9	53.3±17.1 ^a
V2 (30% UKM F)	24.1±0.9	36.2±1.1	48.5±1.1	60.7±1.1	69.1±1.1	62.5	47.7±18.1
V3 (50% PKMF)	21.7±1.1	32.4±1.1	46.2±1.1	58.4±1.1	66.3±1.1	66.2	47.7±18.1
4 (30% PKMF)	19.6±0.8	30.8±1.1	43.7±1.1	55.9±1.1	64.5±1.1	70.3	47.7±18.1

Values are mean±standard deviation (SD) of triplicates. Alphabets (a and b) indicated significant differences ($p < 0.05$, paired t-test).

millet flour to formulate value-added food items to harness greater benefits associated with ideal human health.

Despite the presence of these nutritional advantages, unpolished millet flour created some difficulties regarding printability and structural properties. Sensory and texture analysis indicated that formulations having a higher amount of unpolished flour tended to result in lower attributes regarding shape retention, layer development and crispness. These aspects can be related to the increased levels of insoluble fibers and particle size in unpolished flour, which may cause hindrances in dough cohesiveness and stability in the extrusion process, thus resulting in inaccuracy in dimensions in 3D printing (Godoi *et al.*, 2016; Ranjan *et al.*, 2023; Nirubana V *et al.*, 2020).

In contrast, polished Kodo millet flour formulations, particularly V4 (30% PKMF), demonstrated superior sensory acceptability and textural performance, achieving the highest overall acceptance score (7.73/9). The improved smoothness, uniformity and structural integrity of these cookies are consistent with prior studies indicating that reduced bran content enhances flow behavior, extrusion consistency and surface finish in 3D-printed foods (Mantihal *et al.*, 2020; Yao *et al.*, 2020). Such characteristics are particularly desirable for extrusion-based fabrication, where precise layer deposition is essential.

Notably, the soft texture and uniform structure of 3D-printed cookies observed across formulations align with earlier findings that extrusion-based printed foods often retain higher moisture content and softer mouthfeel compared to conventionally baked products (Rathi *et al.*, 2024; Liaqat *et al.*, 2025). These attributes may be advantageous for specific consumer groups, such as children and older adults, who often prefer foods with reduced hardness and easier chewability (Kim *et al.*, 2025) (Sharmili *et al.*, 2021).

Overall, the results suggest that while unpolished Kodo millet flour enhances nutritional and antioxidant properties, polished millet flour-particularly at moderate substitution levels-offers better functional performance for 3D food printing. Balancing these two aspects is essential for optimizing both health benefits and consumer acceptability in millet-based 3D-printed foods.

CONCLUSION

This study compared the nutritional content, antioxidant activity, texture and taste of 3D-printed cookies made with polished and unpolished Kodo millet flour. The results show that how grains are processed is very important for both the nutritional quality and printability of millet-based formulations. Cookies made with unpolished Kodo millet flour had more fiber and minerals, while those made with polished flour were better for printing, held together better and tasted better.

The findings suggest that 3D food printing provides an effective medium for creating millet-based baked goods with regulated shape, texture and nutritional content. Extrusion-based printing, in particular, makes it possible to make custom food products for specific groups of people, like older adults, children and people who need different textures or specific nutritional profiles. A balanced blend of polished and unpolished millet flour may thus offer an effective approach to enhance both health benefits and functional performance in 3D-printed foods.

Future research should concentrate on refining printing parameters, including nozzle diameter, extrusion rate and layer height, alongside post-processing conditions such as baking temperature and duration. Additional research on glycemic response, shelf life, packaging compatibility and the feasibility of large-scale production is essential to facilitate the commercial utilization of 3D-printed millet-based functional foods.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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