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## Rice flakes muesli: A novel nutrient-dense gluten-free breakfast cereal

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### ABSTRACT

Rice flakes muesli is a gluten-free, nutrient-dense cereal developed using Indian landrace rice flakes, pigmented popped rice, and nuts, offering a functional alternative to commercial wheat, corn, and oat-based mueslis. This study utilized geographical indication-tagged rice landraces to produce innovative breakfast cereal alternatives addressing growing gluten-free food demand. Two muesli variants—jaggery-sweetened and chocolate-based—were developed, delivering distinct nutritional advantages enriched with dietary fiber, protein, essential minerals (iron, zinc, magnesium, copper, manganese), and elevated B-vitamins. The chocolate muesli provides 415.51 kcal per 100g, meeting 19.57 % of daily fiber needs and 9.74g protein, with significant mineral content including iron (68.33 mg/kg), zinc (21.86 mg/kg), and magnesium (1786.37 mg/kg), fulfilling up to 42.52 % of the daily requirement. The jaggery variant delivers 400.89 kcal per 100g, with 12.36 % fiber, and exceptional antioxidant properties, including total flavonoids (143.68 mg CE/100g), radical-scavenging activity (95.33 %), and FRAP value (8.48 mM/g). Both variants significantly contribute to daily mineral and fiber intake. Sensory evaluation using a 9-point hedonic scale with 26 semi-trained panelists revealed strong consumer preference for both formulations over a commercial option. The combination of gluten-free muesli variants with superior nutritional value and antioxidant-rich components exhibit appealing sensory characteristics, hence positions these products competitively in the functional food market, meeting needs of health-conscious consumers.

### 1. Introduction

Over half of the global population relies on rice as their primary source of energy, leading to the creation of numerous rice-based products. India, a leading producer, consumer, and exporter of rice, is renowned for its diverse array of high-quality, nutritionally rich rice varieties, some of these unique traditional landraces hold geographical indication tags (Longvah et al., 2021). Notably, in northeastern India primarily in Assam, Manipur, Meghalaya, and Mizoram there are a lot of rice varieties, with over 10,000 rice types, many of which are pigmented (Idrishi et al., 2024). These pigmented rice types are abundant in phenolic compounds and essential minerals including phosphorus, magnesium, manganese, and iron. Additionally, they contain important vitamins such as folic acid, thiamin, and niacin (Tiozon, Sartagoda, et al., 2023). Certain bioactive compounds demonstrate significant antioxidant, anti-inflammatory, and anti-cancer properties, contributing to their potential therapeutic and preventive roles in various chronic

diseases (Tiozon, Sartagoda, et al., 2023). However, the nutritional value of rice is determined by post-harvest practices like milling, processing, and preparation (Fukagawa & Ziska, 2019), highlighting the need to preserve nutrients while meeting consumer preferences. Recent studies have identified methods such as popping, flaking, and roasting which enhance rice's sensory qualities, transforming whole-grain rice into lighter, crispier textures (Itagi et al., 2023; Kasote et al., 2021) while retaining the nutrient-dense bran layer making these processes valuable for product development.

Muesli, originally developed in Switzerland in the early 20th century, has evolved beyond its traditional European origins and can now be recognized globally as a functional food product. Typically composed of rolled oats, dried fruits, seeds, and nuts, muesli offers a balance of essential nutrients, including fibers and proteins that promote overall wellness. The global packaged muesli market, valued at around USD 18 billion in 2023, is anticipated to hit more than USD 29 billion in the next 10 years, driven by rising consumer demand for nutritious and

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convenient breakfast options (Business Research Insights, 2025). However, there are currently limited offerings of muesli as a gluten-free and nutrient-rich option, which is expected to further drive increasing popularity among health-conscious consumers.

This market gap presents opportunities for innovation, particularly in regions with rich rice biodiversity. Asian adaptations of muesli to incorporate rice-based products such as rice flakes, roasted rice flakes, and popped rice, which are versatile, gluten-free ingredients that enhance the nutritional profile by adding dietary fiber and micronutrients, a preferred novel functional food. Additionally, variations across regions—such as African muesli with biltong or tropical fruits and spices—showcase its global appeal and adaptability. Despite this versatility, its role as a functional product can be further elevated, as the incorporation of pigmented and aromatic rice varieties in muesli remains underexplored. These rice types not only enhance dietary fiber and micronutrient content but also contribute a unique texture and nutty flavor, along with enriched antioxidant activity.

In this study, several geographical indicator-tagged rice landraces were utilized, leveraging their nutritional and physicochemical properties after processing methods such as flaking, roasting, and popping. These processed rice products were evaluated for their nutritional composition, *in-vitro* glycemic index, and sensory attributes. Multivariate analyses were also employed to decipher the relationship between nutritional properties and the potential for development of functional food. The findings highlight the gluten-free, nutrient-dense composition of these muesli variants, reinforcing their status as functional foods and positioning them as innovative and functional alternatives in the breakfast cereal market. This study highlights the potential of rice flakes-based muesli as a healthier functional food product, meeting the evolving demands of health-conscious consumers in India and other rice-centric regions. This growth is likely driven by rice muesli's inherent nutritional value—boasting high fiber, antioxidants, and protein content—making it a popular choice of healthy and satisfying meals.

## 2. Materials and methods

### 2.1. Procurement of raw materials

Popular geographical indicator-tagged rice landraces such as ChaKhao Black Rice (CRV-113), Karhani (Red Pigmented), Kalanamak, and Marcha rice (Aromatic rice) were cultivated during the Kharif season of 2022 in Varanasi, Uttar Pradesh. The harvested paddy was cleaned, stored in polyethylene bags at 4 °C, and later processed for analysis. Cashews, almonds, raisins, white sesame, chia seeds, chocolate chips, cocoa powder, and jaggery were sourced locally from the Varanasi supermarket, India.

### 2.2. Preparation of pigmented popped rice, thick rice flakes, roasted rice flakes and muesli formulations

Pigmented popped rice was prepared using moisture-conditioned paddies (17–18 %) roasted in salt at 250 °C for 35–40 s (Itagi et al., 2023). Rice flakes were made by soaking paddies overnight, draining them, then roasting them in the sand at 280 °C for 45–50 s and tempering for 3–4 min. The roasted paddies were flattened for 55–60 s, and husk and bran were manually separated using a sieve from the rice flakes, which were then roasted in salt at 230 °C for 10–12 s.

Jaggery sweetened rice flakes muesli was formulated by combining roasted Marcha rice flakes (750g), Kalanamak rice flakes (750g), Karhani popped rice (190g), and ChaKhao black popped rice (190g) with roasted white sesame (125g), chia seeds (125g), chopped cashews (175g), almonds (175g), and raisins (175g). Jaggery syrup (876g in 50 mL water) was added and mixed to prevent lumps, then the mixture was baked at 100 °C for 20 min (Table 1). The same process was used for chocolate muesli, with the addition of cocoa powder (50g) and

**Table 1**

Ingredient composition of Jaggery and Chocolate Rice Flakes Mueslis.

Ingredients	Muesli Variants	
	Jaggery Muesli	Chocolate Muesli
	Amount	
Roasted Marcha Rice Flakes	750 g	750 g
Roasted Kalanamak Rice Flakes	750 g	750 g
Karhani Red Popped Rice	190 g	190 g
ChaKhao Black Popped Rice	190 g	190 g
Cashew nut	175 g	175 g
Almond	175 g	175 g
Raisins	175 g	175 g
White sesame	125 g	125 g
Chia seeds	125 g	125 g
Jaggery	876 g	876 g
Water	50 mL	50 mL
Cocoa powder	–	50 g
Choco chips	–	200 g

chocolate chips (200g) (Table 1). Both mueslis were stored in airtight containers to preserve freshness and crispiness.

### 2.3. Physical characteristics of rice flakes muesli

Physical properties (length, breadth, thickness, length/breadth ratio, moisture, water activity, 1000-kernel weight, bulk density) were measured for Marcha and Kalanamak (paddy, brown rice, rice flakes, roasted flakes) and Karhani and Chakhao (paddy, brown rice, rice flakes, roasted flakes, popped rice). Expansion ratios (length, breadth, thickness) were assessed for Marcha and Kalanamak (flakes, roasted flakes), and Karhani and Chakhao (flakes, roasted flakes, popped rice). The popping percentage was analyzed only for popped rice samples. Color parameters ( $L^*$ ,  $a^*$ ,  $b^*$ , chroma, hue) were measured for all forms (except paddy) and both muesli variants.

The hot air oven-drying method was used to measure the moisture content, where samples were dried in an oven at 130 °C for 2 h. Water activity ( $a_w$ ) was measured using a Series 4TE Aqualab Water Activity Analyzer (Aqualab, Meter Group Inc., USA). Dimensions of paddies, brown rice, and processed rice kernels were obtained using a Vernier caliper, and the Length/Breadth ratio (L/B) was calculated. An automated grain counter (Shailron Technology) and an analytical balance (GR-202, A&D Co., Japan) were used to determine the 1000-kernel weight. Other parameters (length, breadth, thickness expansion ratio, expansion volume, bulk density, and popping percentage) were measured as per Itagi et al. (2023). The color values were obtained using a Konica Minolta Chroma Meter CR-400. These values represent color in the CIELAB color space, specifically  $L^*$  for lightness (0 = black, 100 = white),  $a^*$  for the red-green axis (positive = red, negative = green), and  $b^*$  for the yellow-blue axis (positive = yellow, negative = blue).

### 2.4. Nutritional characteristics and bioactive potential of ingredients and rice flakes muesli

Nutritional characteristics and bioactive potential were analyzed for Marcha and Kalanamak aromatic rice (brown rice, rice flakes, roasted flakes), Karhani red rice, ChaKhao black rice (brown rice, popped rice), and the two muesli variants.

#### 2.4.1. Nutrient composition

Protein and fat content were determined using the methods of Itagi et al. (2023), with protein measured by the Kjeldahl method (Kjeltec™ 8200, Foss, Sweden) and fat by Soxhlet extraction (Foss ST243, Foss, Sweden) using petroleum ether. The ash content was estimated by incinerating the samples at 550 °C in a muffle furnace according to AOAC (2000) guidelines. The total carbohydrate content was calculated by subtracting the sum of the moisture, protein, ash, and fat from 100

and was expressed as g/100g. As described by Eknayake et al. (1999), total energy (kJ/100 g dry matter) was determined using the formula: Energy (kJ/100 g) = (Protein × 16.7) + (Fat × 37.7) + (Total Carbohydrate × 16.7) (1). The resulting energy value was then converted into kilocalories (kcal) using the conversion factor: 1 kJ = 0.239006 kcal.

#### 2.4.2. Insoluble, soluble, and total dietary fiber content

A Megazyme K-TDFR kit (Megazyme, Ireland) was used to obtain the insoluble dietary fiber (IDF), soluble dietary fiber (SDF) and total dietary fiber (TDF) following Itagi et al. (2023), with IDF and SDF calculated using the Megazyme Mega-Calculation method. Samples underwent enzymatic digestion with  $\alpha$ -amylase, protease, and amyloglucosidase. IDF was recovered by filtration using a Foss Fibertec 1023 system, while SDF was precipitated with ethanol. Both fractions were dried, corrected for ash and protein, and calculated. The TDF was calculated by adding the IDF and SDF, with all values expressed on a dry weight basis.

#### 2.4.3. Total sugar, total starch, amylose content, and in-vitro glycemic index (GI)

Following Itagi et al. (2023), total starch was enzymatically determined using a Megazyme Total Starch Assay Kit (K-TSTA, Megazyme, Ireland), where starch was hydrolyzed to glucose using thermostable  $\alpha$ -amylase and amyloglucosidase, followed by glucose quantification. Total sugars were quantified by reacting sugars with anthrone reagent under acidic conditions to produce a colored complex measured spectrophotometrically (Roy et al., 2021). The formation of a blue-colored complex between amylose and iodine served as the basis for measuring amylose content, which was then quantified by its absorbance at 620 nm (Cuevas et al., 2018). The *in-vitro* GI of the muesli samples was determined using NutraScan GI20 Glycemic Index Analyzer for enzymatic digestion (Pautong et al., 2022). The predictive GI (pGI) of the samples was computed using this formula: pGI = 0.07821 × Area under the curve (AUC) (corrected) + 47.8876 (2) which was derived from a linear regression model established by Pautong et al. (2022) for predicting glycemic index based on *in-vitro* digestion results.

#### 2.4.4. Fatty acid profiling

The fatty acid profile of the samples was obtained following the procedure used by Itagi et al. (2023). The lipid fractions of the samples were extracted using hexane, centrifuged, and recovered by nitrogen evaporation. Using BF3 in methanol and toluene the lipid fractions were derivatized followed by trans-methylation. Gas chromatographic analysis of the lipid fractions was performed using an Agilent 7890B system interfaced with a Flame-Ionization Detector. Optimal chromatographic separation was achieved with injector and detector, temperatures maintained at 250 °C and 280 °C, respectively, and a temperature program ascending from 50 °C to 230 °C. Quantification of fatty acid methyl esters (FAMES) was facilitated by external calibration using FAME standards.

#### 2.4.5. Mineral content & heavy metal analysis

Minerals such as magnesium, potassium, phosphorus, manganese, iron, cobalt, copper, and zinc and heavy metals (arsenic, tin, and cadmium) were estimated using an Agilent 7800 ICP-MS, following the method of Itagi et al. (2023). Sample preparation involved microwave-assisted acid digestion using concentrated nitric acid at 180 °C to achieve complete mineralization. The digested samples were cooled, diluted with ultrapure water, and filtered through PVDF filters before analysis. This technique allows simultaneous multi-element detection at trace levels with high accuracy and precision using helium collision mode to minimize polyatomic interferences. Method validation was performed using NIST-certified Standard Reference Material (SRM 1568b) for recovery assessment in each batch.

#### 2.4.6. Vitamin B profiling

B Vitamins (thiamine, pyridoxine pantothenic acid, folic acid, biotin,

and riboflavin) were quantified via LC-MS/MS (Agilent 6470 Triple Quad), based on the method described by Itagi et al. (2023). Sample extraction involved homogenizing samples with phosphate buffer (pH 7.0), followed by enzymatic hydrolysis using  $\alpha$ -amylase and protease to release bound vitamins. Samples were then centrifuged filtered through nylon filters before injection into the LC-MS/MS system for separation and detection. Method validation was performed using NIST-certified Standard Reference Material (SRM 1869) for linearity and calibration purposes.

#### 2.5. Estimation of total phenolic content and antioxidant potential

The total phenolic content and antioxidant potential were evaluated for Marcha and Kalanamak aromatic rice (brown rice, rice flakes, roasted flakes), Karhani red rice, and ChaKhao black rice (brown rice, popped rice), as well as the two muesli variants.

##### 2.5.1. Extraction of phenolic content

Phenolic extracts were obtained using the method of Itagi et al. (2023) by incubating 1 g of homogenized rice sample with 10 mL of acidified methanol (1 % HCl) at 4 °C for 24 h. Subsequently, the mixture was centrifuged at 6953×g for 10 min. The supernatant was then carefully collected and maintained at 4 °C prior to analysis.

##### 2.5.2. Determination of antioxidant component and capacity

The total phenolic content (TPC) was quantified spectrophotometrically at 725 nm (Cuevas et al., 2018) with values obtained in milligrams of gallic acid equivalents (GAE) per 100 g of rice. Using pH differential method, the total anthocyanin content (TAC) was measured at 550 nm and 700 nm, with results reported as equivalents of cyanidin-3-O-glucoside (Cyn-3-Glu). Total flavonoid content (TFC) was estimated spectrophotometrically at 510 nm, presented as catechin equivalents (CE) per 100 g of rice. Additionally, antioxidant potential was evaluated through assays for total antioxidant capacity (TAC), hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) scavenging, DPPH radical scavenging, and ferric-reducing antioxidant power (Itagi et al., 2023). The total antioxidant capacity (TAC) was measured at 695 nm and expressed as quercetin equivalents (QE) per 100 g of sample, while the hydrogen peroxide scavenging activity was measured at 230 nm and expressed as mg quercetin equivalent (QE) per 100 g of sample. DPPH radical scavenging activity was quantified as percentage inhibition, with the absorbance measured at 517 nm (Tiozon, Sreenivasulu, et al., 2023).

##### 2.5.3. Targeted bioactive profiling

Prior to the targeted bioactive profiling, phenolic extracts were obtained from defatted samples following Jayaraman et al. (2019) and identified using LC-MS/MS. The targeted phenolic compounds included kaempferol, apigenin, luteolin, 4-hydroxybenzoic acid, epicatechin, sinapic acid, p-coumaric acid, caffeic acid, quercetin, trans-ferulic acid, syringic acid, and vitexin.

#### 2.6. Sensory evaluation

Sensory evaluation was conducted using a 9-point hedonic scale, ranging from 1 (Dislike Extremely) to 9 (Like Extremely), assessing the flavor, aroma, color, taste, texture, and overall acceptability of the chocolate and jaggery-sweetened rice flakes muesli variants (Naseer et al., 2021). Twenty-six semi-trained panelists from the International Rice Research Institute- South Asia Regional Centre (IRRI-ISARC) participated in the evaluation, held at the Center of Excellence in Rice Value Addition and Sensory Laboratory, IRRI-SARC, Varanasi, India. All participants were from the International Rice Research Institute- South Asia Regional Centre (IRRI-ISARC). Prior to evaluation, participants received detailed information about the study objectives, and evaluation procedures. The study protocol included standardized instructions for sample evaluation, explanation of the hedonic scale, and guidelines for

palate cleansing between samples. Written informed consent, and the study protocol were provided and explained, including product details and their right to withdraw which was clearly explained. All muesli samples were prepared under aseptic conditions. During the evaluation, the samples were served in randomized order with anonymized three-digit codes to reduce bias. Panelists were directed to cleanse their palates using plain water between the evaluation of successive samples.

2.7. Statistical analyses

All data were presented as mean ± standard deviation (n = 3 replicates). Statistical differences between groups were assessed using one-way analysis of variance (ANOVA) followed by Tukey's Honestly

Significant Difference (HSD) post-hoc test, with a significance level of  $\alpha = 0.05$  (Minitab Statistical Software). Relationships among physical qualities, texture profiles, nutritional content, bioactive compounds, and antioxidant activity of rice genotypes were examined via Pearson's correlation. Furthermore, hierarchical clustering was performed on the same datasets using an agglomerative nesting algorithm with Ward's linkage method. The resulting dendrogram and heatmap were visualized using R version 4.2.1 (Vienna, Austria). Sample variability and groupings were evaluated through Principal Component Analysis (PCA) on standardized data in R, with biplots of PC1 and PC2 illustrating variable contributions.

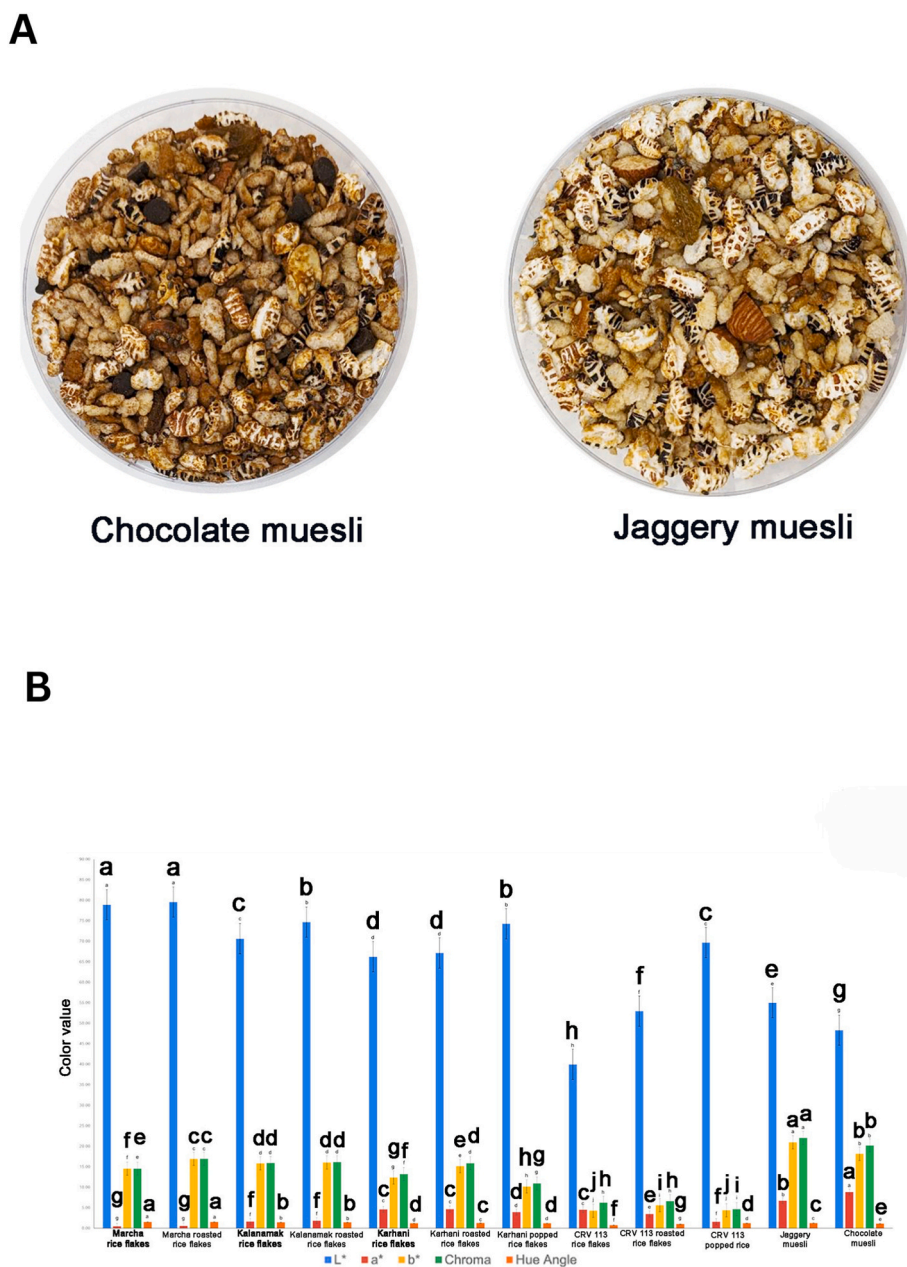


Fig. 1. Physical properties of rice flakes mueslis. (A) Appearance of chocolate and jaggery sweetened mueslis. (B) Color parameters of rice flakes mueslis. \*Different lowercase letters above the bars indicate statistically significant differences comparing each rice-based product derived from the distinct variety ( $p < 0.05$ ). Statistical analysis was performed using one-way ANOVA followed by Tukey's HSD post-hoc test. Error bars represent standard deviation (SD).

**Table 2**  
Physical properties of rice flakes Muesli and its rice ingredients.

Parameters	Marcha Aromatic Rice				Kalanamak Aromatic Rice				Karhani Red Rice					ChaKhao Black Rice (CRV-113)					Muesli Variants	
	Paddy	Brown Rice	Rice Flakes	Roasted Rice Flakes	Paddy	Brown Rice	Rice Flakes	Roasted Rice Flakes	Paddy	Brown Rice	Rice Flakes	Roasted Rice Flakes	Popped Rice	Paddy	Brown Rice	Rice Flakes	Roasted Rice Flakes	Popped Rice	Jaggery Muesli	Chocolate Muesli
Length (mm)	6.84 ± 0.40 cC	4.72 ± 0.22 bC	7.33 ± 0.54 bC	8.14 ± 0.44 aC	8.00 ± 0.37 bB	5.77 ± 0.15 cB	9.35 ± 0.52 aA	9.73 ± 0.30 aB	8.17 ± 0.37 cB	5.64 ± 0.18 dB	8.54 ± 0.45 cB	9.29 ± 0.57 bB	11.28 ± 0.81 aA	9.16 ± 0.35 bA	6.38 ± 0.24 cA	8.95 ± 0.41 bAB	11.22 ± 1.32 aA ± 0.81 aA	11.28 ± 0.81 aA	-	-
Breadth (mm)	3.25 ± 0.09 cA	2.87 ± 0.10 dA	4.71 ± 0.24 aA	4.37 ± 0.35 bA	2.27 ± 0.08 cD	1.88 ± 0.06 dD	3.35 ± 0.12 aC	3.18 ± 0.12 bC	3.00 ± 0.15 dB	2.55 ± 0.08 eB	4.09 ± 0.29 bB	3.78 ± 0.28 cB	5.29 ± 0.28 aA	2.72 ± 0.11 cC	2.19 ± 0.06 dC	3.83 ± 0.33 bB	4.14 ± 0.48 bAB	5.29 ± 0.28 aA	-	-
Thickness (mm)	2.28 ± 0.14 bA	2.12 ± 0.11 bA	1.10 ± 0.10 cA	2.77 ± 0.22 aA	1.79 ± 0.07 aC	1.64 ± 0.02 bC	0.69 ± 0.04 cC	1.75 ± 0.13 aB	2.05 ± 0.05 cB	1.82 ± 0.04 dB	0.99 ± 0.06 eB	2.75 ± 0.13 bA	4.39 ± 0.30 aA	1.90 ± 0.08 cC	1.62 ± 0.06 dC	0.92 ± 0.11 eB	2.74 ± 0.19 bA	4.39 ± 0.30 aA	-	-
Length/Breadth Ratio	2.10 ± 0.09 aC	1.65 ± 0.11 cD	1.56 ± 0.09 cD	1.87 ± 0.14 bC	3.52 ± 0.17 aA	3.08 ± 0.15 bA	2.79 ± 0.17 cA	3.06 ± 0.17 bA	2.73 ± 0.16 aB	2.22 ± 0.10 cC	2.10 ± 0.15 cC	2.46 ± 0.12 bB	2.09 ± 0.13 cA	3.38 ± 0.14 aA	2.91 ± 0.12 bB	2.35 ± 0.19 cB	2.74 ± 0.40 bB	2.14 ± 0.22 cA	-	-
Moisture %	13.02 ± 0.18 aB	11.64 ± 0.23 bB	10.77 ± 0.19 cB	5.67 ± 0.18 dA	13.15 ± 0.23 aB	11.55 ± 0.25 bB	10.65 ± 0.38 cB	5.23 ± 0.16 dB	13.83 ± 0.24 aA	12.11 ± 0.28 bB	10.90 ± 0.27 cB	5.87 ± 0.03 dA	13.11 ± 0.21 aA	14.43 ± 0.10 aA	13.15 ± 0.25 bA	11.97 ± 0.09 cA	6.04 ± 0.08 dA	13.34 ± 0.15 bA	-	-
Length Expansion Ratio	-	-	1.55 ± 0.06 aA	1.12 ± 0.10 bB	-	-	1.62 ± 0.08 aA	1.04 ± 0.07 bB	-	-	1.52 ± 0.11 aA	1.09 ± 0.07 cB	1.39 ± 0.14 bA	-	-	1.41 ± 0.08 aB	1.25 ± 0.13 bA	1.23 ± 0.09 bB	-	-
Breadth Expansion Ratio	-	-	1.64 ± 0.12 aAB	0.93 ± 0.07 bB	-	-	1.79 ± 0.12 aA	0.95 ± 0.04 bB	-	-	1.61 ± 0.13 bB	0.93 ± 0.09 cB	1.77 ± 0.15 aB	-	-	1.75 ± 0.17 bAB	1.09 ± 0.13 cA	1.95 ± 0.08 aA	-	-
Thickness Expansion Ratio	-	-	0.52 ± 0.06 bA	2.54 ± 0.30 aB	-	-	0.42 ± 0.02 bB	2.52 ± 0.14 aB	-	-	0.55 ± 0.03 cA	2.78 ± 0.25 aAB	2.15 ± 0.16 bB	-	-	0.57 ± 0.08 cA	3.05 ± 0.59 aA	2.31 ± 0.18 bA	-	-
Water Activity	0.67 ± 0.00 aA	0.55 ± 0.00 bAB	0.49 ± 0.00 cB	0.36 ± 0.00 dB	0.65 ± 0.00 aB	0.54 ± 0.00 bC	0.47 ± 0.00 cC	0.34 ± 0.00 dC	0.63 ± 0.00 bC	0.54 ± 0.00 cBC	0.49 ± 0.00 dB	0.36 ± 0.00 eB	0.65 ± 0.00 aB	0.62 ± 0.00 bC	0.55 ± 0.00 cC	0.51 ± 0.00 dA	0.37 ± 0.00 eA	0.69 ± 0.00 aA	-	-
1000 Kernel Weight (g)	23.79 ± 0.24 aB	20.02 ± 0.15 bB	16.86 ± 0.15 cB	15.77 ± 0.24 dA	15.27 ± 0.34 aC	13.02 ± 0.11 bC	11.66 ± 0.12 cC	11.03 ± 0.04 dC	26.15 ± 0.34 aA	22.02 ± 0.32 bA	17.76 ± 0.21 dA	16.31 ± 0.23 eA	18.73 ± 0.16 cA	23.76 ± 0.30 aB	19.89 ± 0.13 bB	16.66 ± 0.17 cB	14.56 ± 0.13 cB	15.85 ± 0.04 dB	-	-
Expansion Volume (ml/g)	-	-	1.39 ± 0.04 bA	3.16 ± 0.03 aC	-	-	1.45 ± 0.02 bA	3.24 ± 0.03 aC	-	-	1.19 ± 0.02 cB	4.03 ± 0.04 bB	4.33 ± 0.05 aB	-	-	0.93 ± 0.02 cC	6.10 ± 0.08 aA	4.77 ± 0.05 bA	-	-
Bulk Density (Kg/m <sup>3</sup> )	612.33 ± 7.01 bB	833.33 ± 0.00 aB	507.67 ± 5.53 cC	288.76 ± 2.18 dA	641.03 ± 0.00 bA	838.04 ± 6.66 aAB	453.18 ± 1.93 cD	280.12 ± 1.69 dB	622.43 ± 3.64 bB	852.33 ± 6.89 aA	595.29 ± 5.79 cA	223.05 ± 1.18 dC	230.80 ± 2.49 dA	479.24 ± 2.16 cC	785.38 ± 5.85 cC	528.18 ± 2.64 bB	157.49 ± 1.01 eD	209.81 ± 2.09 dB	-	-
Popping Percentage	-	-	-	-	-	-	-	-	-	-	-	-	61.00 ± 1.40 B	-	-	-	-	65.53 ± 0.83 A	-	-
L*	-	63.38 ± 1.11 bA	78.90 ± 0.40 aA	79.57 ± 0.54 aA	-	56.76 ± 0.43 cB	70.61 ± 0.12 bB	74.67 ± 0.30 aB	-	40.14 ± 0.58 cC	66.24 ± 0.39 bC	67.15 ± 0.55 bC	74.26 ± 0.79 aA	-	28.70 ± 0.21 dD	39.97 ± 0.20 cD	52.97 ± 0.31 bD	69.99 ± 0.46 aB	55.02 ± 2.13 A	48.31 ± 0.21 B
a*	-	3.27 ± 0.13 ac	0.46 ± 0.02 bC	0.57 ± 0.03 bD	-	2.51 ± 0.12 aD	1.65 ± 0.07 cB	1.86 ± 0.02 bC	-	11.12 ± 0.22 aA	4.60 ± 0.04 bA	4.67 ± 0.02 bA	3.95 ± 0.15 cA	-	5.39 ± 0.34 aB	4.55 ± 0.04 bA	3.48 ± 0.21 cB	1.59 ± 0.15 dB	6.74 ± 0.42 B	8.83 ± 0.18 A
b*	-	21.75 ± 0.55 aA	14.53 ± 0.09 cB	16.93 ± 0.14 bA	-	22.20 ± 0.21 aA	15.84 ± 0.08 bA	16.05 ± 0.17 bB	-	17.37 ± 0.37 aB	12.39 ± 0.08 cC	15.16 ± 0.17 bC	10.20 ± 0.17 dA	-	1.50 ± 0.17 cC	4.28 ± 0.08 bD	5.62 ± 0.18 aD	4.37 ± 0.26 bB	20.97 ± 0.79 A	18.18 ± 0.23 B
Chroma	-	21.99 ± 0.55 aA	14.54 ± 0.09 cB	16.94 ± 0.14 bA	-	22.34 ± 0.21 aA	15.92 ± 0.08 bA	16.16 ± 0.17 bB	-	20.62 ± 0.43 aB	13.22 ± 0.07 cC	15.86 ± 0.16 bB	10.93 ± 0.20 dA	-	5.60 ± 0.34 bC	6.24 ± 0.05 aD	6.61 ± 0.27 aC	4.65 ± 0.29 cB	22.03 ± 0.70 A	20.21 ± 0.25 B
Hue angle	-	1.42 ± 0.01 bB	1.54 ± 0.00 aA	1.54 ± 0.00 aA	-	1.46 ± 0.01 bA	1.47 ± 0.00 aB	1.46 ± 0.00 bB	-	1.00 ± 0.00 dC	1.22 ± 0.00 bC	1.27 ± 0.00 aC	1.20 ± 0.01 cB	-	0.27 ± 0.03 dD	0.75 ± 0.01 cD	1.02 ± 0.01 bD	1.22 ± 0.01 aA	1.26 ± 0.02 A	1.12 ± 0.01 B

Values are mean ± standard deviation of three independent determinations (n = 3); Small letters denote a significant difference (p < 0.05) within genotypes, while capital letters denote significant differences (p < 0.05) in each product or raw material classification (paddy, brown rice, rice flakes, roasted rice flakes, popped rice or muesli variants).



Fig. 2. Nutritional properties of rice flakes mueslis (A) Nutrition facts of chocolate and jaggery sweetened mueslis. (B) *t*-test of the biochemical scaled data of chocolate and jaggery sweetened mueslis. (C) Barplot comparing the nutritional properties. and (D) Sensory scores of chocolate and jaggery sweetened mueslis.

### 3. Results and discussion

#### 3.1. Changes in the physical properties of rice flakes muesli and its components

Fig. 1A shows the jaggery and chocolate-based muesli. To make jaggery sweetened rice flakes muesli, 750g each of roasted Marcha and Kalamamak rice flakes were used as primary ingredient, along with 190g of Karhani popped rice and 190g of ChaKhao black popped rice. Additional ingredients included roasted white sesame (125g), chia seeds (125g), chopped cashews (175g), almonds (175g), raisins (175g), and jaggery syrup (876g dissolved in 50 mL water). For the chocolate muesli variant, 200g of chocolate chips and 50g of cocoa powder were incorporated into the base jaggery muesli using the same procedure (Table 1). The physical properties of muesli and its rice ingredients—including color, moisture content, and dimensional attributes such as volume expansion—significantly influence the overall characteristics of the developed novel rice-based flakes of muesli product. These parameters remarkably affect texture and mouthfeel by balancing crunch and airiness, directly impacting sensory perception. A clear distinction in size and shape between the rice varieties and their corresponding rice flakes, roasted rice flakes, and popped rice was observed. The length-to-breadth (L/B) ratio of Kalamamak brown rice (3.08) was found to be the highest among the brown rice samples, giving it a slender shape. In contrast, Marcha (bold shape), Karhani (medium shape), and ChaKhao black rice (medium shape), had L/B ratios of 1.65, 2.22, and 2.91, respectively (Table 2). After processing (popping, flaking, and roasting), there is an increase in the dimensions in all the brown rice samples, although the expansion ratios of length, breadth, and thickness varied within the range of 0.42–3.05 (Table 2). Notably, rice flakes exhibited the highest

length expansion ratio, while roasted rice flakes obtained the highest thickness expansion ratio and popped rice the highest breadth expansion ratio among the processed rice types within each respective genotype (Table 2).

Popping, flaking, and roasting also reduce the bulk density due to volume expansion and moisture removal (Table 2). As a result, the processed rice kernels become lighter than their unprocessed brown rice or paddy counterparts (Mir et al., 2014). This reduction not only impacts packaging efficiency—by allowing more volume per package—but also provides larger serving portions by weight, thereby enhancing consumer perception. On the other hand, the popping percentages of Karhani red rice and ChaKhao black rice were 61.0 % and 65.5 %, respectively (Table 2). Previous studies on popped rice using different rice varieties have reported popping percentage of around 47.87–85.33 % (Itagi et al., 2023) indicating that both Karhani red rice and ChaKhao black rice may offer moderate yields for popped rice production. Previous studies have identified factors such as kernel size, moisture content, and the amylose-to-amylopectin ratio are important in estimating popped rice yield (Mariotti et al., 2006; Mir et al., 2014). The roasted rice flakes' water activity and moisture content exhibited the lowest values, contrasting with those of the popped rice samples (Table 2). This can be attributed not only to the higher water binding capacity of popped rice—caused by starch modifications during processing (Mariotti et al., 2006)—but also to structural differences between the muesli rice ingredients. Additionally, this may be influenced by soaking as a pre-treatment, which can affect moisture retention after thermal processing (Sharma et al., 2023).

In terms of visual characteristics, the CIELAB color system was employed to quantify the color values of the rice flakes muesli and some of its rice ingredients (Fig. 1B and Table 2). The average color values

**Table 3**  
Macronutrients, starch properties, *in-vitro* glycemic index of rice flakes Mueslis and its rice ingredients.

Rice Landraces	Marcha Aromatic Rice			Kalanamak Aromatic Rice			Karhani Red Rice		ChaKhao Black Rice (CRV-113)		Muesli Variants	
	Brown Rice	Rice Flakes	Roasted Rice flakes	Brown Rice	Rice Flakes	Roasted Rice flakes	Brown Rice	Popped Rice	Brown Rice	Popped Rice	Jaggery Muesli	Chocolate Muesli
<b>Macronutrients</b>												
Total Carbohydrate (%)	74.52 ± 0.18 bAB	74.53 ± 0.10 bB	85.17 ± 0.08 aA	74.59 ± 0.01 cA	75.35 ± 0.12 bA	84.69 ± 0.08 aB	74.18 ± 0.02 aB	73.45 ± 0.38 aA	73.58 ± 0.17 aC	73.58 ± 0.09 aA	74.56 ± 0.37 A	69.58 ± 0.21 B
Energy (kcal/100g)	359.69 ± 0.27 bB	344.14 ± 0.06 cB	380.74 ± 0.32 aA	365.15 ± 0.04 bA	347.96 ± 0.16 cA	380.63 ± 0.78 aA	356.86 ± 0.30 aC	349.86 ± 0.84 bB	359.29 ± 0.57 aB	353.57 ± 0.91 bA	400.89 ± 1.81 B	415.51 ± 1.16 A
Total Sugar (%)	2.56 ± 0.77 aB	2.50 ± 1.01 aA	2.13 ± 1.39 aA	4.00 ± 0.33 aA	3.39 ± 2.23 aA	2.22 ± 1.24 aA	1.89 ± 0.96 aB	1.00 ± 0.53 aA	2.33 ± 0.33 aB	1.40 ± 0.60 bA	19.61 ± 3.89 A	24.72 ± 5.18 A
Ash (%)	1.79 ± 0.05 aB	1.45 ± 0.02 bA	1.26 ± 0.05 cA	1.70 ± 0.01 aB	1.42 ± 0.01 bA	1.32 ± 0.04 cA	2.68 ± 0.10 aA	1.89 ± 0.05 bA	1.79 ± 0.04 aB	1.43 ± 0.05 bB	1.66 ± 0.07 B	2.05 ± 0.12 A
Fat (%)	2.55 ± 0.17 aB	1.14 ± 0.05 bB	0.73 ± 0.06 cA	2.91 ± 0.15 aA	1.18 ± 0.03 bA	0.74 ± 0.05 cA	2.32 ± 0.04 aC	2.03 ± 0.09 bB	2.80 ± 0.13 aA	2.65 ± 0.05 bA	7.26 ± 0.14 B	10.84 ± 0.18 A
Protein (%)	9.88 ± 0.13 aB	9.08 ± 0.09 bA	8.46 ± 0.15 cB	10.35 ± 0.01 aA	9.11 ± 0.16 bA	8.99 ± 0.11 bA	10.05 ± 0.08 aB	9.52 ± 0.08 bA	9.87 ± 0.08 aB	8.98 ± 0.09 bB	9.22 ± 0.09 B	9.74 ± 0.16 A
Insoluble Dietary Fiber (%)	3.77 ± 0.22 aA	1.71 ± 0.03 bB	1.68 ± 0.07 bA	3.26 ± 0.39 aA	2.05 ± 0.06 abA	1.68 ± 0.02 bA	4.79 ± 0.12 aA	3.03 ± 0.26 bA	4.12 ± 0.32 aA	3.86 ± 0.07 aA	3.28 ± 0.08 A	4.58 ± 0.38 A
Soluble Dietary Fiber (%)	0.55 ± 0.13 aA	0.39 ± 0.09 aA	0.15 ± 0.05 aA	0.26 ± 0.05 aA	0.10 ± 0.08 aA	0.35 ± 0.03 aA	0.75 ± 0.03 aA	0.30 ± 0.11 aA	0.74 ± 0.12 aA	0.30 ± 0.09 aA	0.18 ± 0.00 A	0.90 ± 0.30 A
Total Dietary Fiber (%)	4.32 ± 0.08 aAB	2.10 ± 0.12 bA	1.84 ± 0.02 bA	3.52 ± 0.44 aB	2.15 ± 0.14 aA	2.03 ± 0.06 aA	5.54 ± 0.09 aA	3.33 ± 0.16 bB	4.86 ± 0.45 aAB	4.16 ± 0.02 aA	3.46 ± 0.08 B	5.48 ± 0.08 A
<b>Starch Parameters</b>												
Total starch (%)	77.44 ± 1.01 bA	87.65 ± 1.61 aA	78.98 ± 3.61 bA	71.65 ± 2.02 bBC	83.79 ± 1.36 aB	81.39 ± 1.49 aA	75.33 ± 1.79 aAB	79.17 ± 5.23 aA	68.19 ± 2.45 bC	82.69 ± 4.10 aA	53.04 ± 2.30 A	45.86 ± 1.96 B
Total amylose (%)	19.33 ± 0.35 bB	20.89 ± 0.06 aA	21.03 ± 0.23 aA	20.16 ± 0.77 aB	20.71 ± 0.21 aA	21.05 ± 0.23 aA	21.84 ± 0.19 aA	21.53 ± 0.03 aA	11.80 ± 0.22 aC	11.40 ± 0.01 aB	12.40 ± 0.07 A	10.95 ± 0.33 B
Soluble amylose (%)	7.56 ± 0.23 aB	6.41 ± 0.09 bA	6.43 ± 0.32 bA	7.17 ± 0.32 aB	6.83 ± 0.62 aA	5.83 ± 0.81 aA	8.52 ± 0.34 bA	13.73 ± 0.09 aA	0.92 ± 0.08 bC	5.76 ± 0.03 aB	1.34 ± 0.26 A	1.21 ± 0.23 A
Insoluble amylose (%)	11.77 ± 0.41 bAB	14.49 ± 0.13 aA	14.60 ± 0.55 aA	13.00 ± 1.09 aA	13.87 ± 0.73 aA	15.22 ± 0.77 aA	13.32 ± 0.50 aA	7.80 ± 0.12 bA	10.87 ± 0.27 aB	5.63 ± 0.03 bB	11.06 ± 0.25 A	9.74 ± 0.55 B
Resistant Starch (%)	0.07 ± 0.02 bB	0.26 ± 0.09 aA	0.11 ± 0.01 bA	0.55 ± 0.42 aB	0.20 ± 0.04 aA	0.12 ± 0.02 aA	0.36 ± 0.11 aB	0.11 ± 0.05 bA	3.60 ± 1.49 aA	0.00 ± 0.00 bB	0.09 ± 0.02 A	0.14 ± 0.02 A
Digestible Carbohydrates (%)	82.04 ± 6.34 aA	89.79 ± 7.69 aA	88.80 ± 2.72 aA	85.36 ± 3.23 aA	85.90 ± 4.75 aA	88.78 ± 3.87 aA	77.77 ± 8.82 aA	86.97 ± 3.32 aA	70.43 ± 5.56 bA	81.17 ± 1.68 aA	35.94 ± 1.66 B	42.12 ± 0.29 A
<i>In-vitro</i> Glycemic Index (%)	56.99 ± 0.87 aB	69.78 ± 9.14 aA	65.76 ± 2.61 aA	56.04 ± 2.24 bB	75.58 ± 0.82 aA	67.31 ± 3.39 aA	56.72 ± 1.71 aB	64.26 ± 4.56 aA	73.59 ± 2.82 aA	79.95 ± 4.32 aA	94.99 ± 0.93 A	85.25 ± 2.18 B

Values are mean ± standard deviation of three independent determinations (n = 3); Small letters denote a significant difference (p < 0.05) within genotypes, while capital letters denote significant differences (p < 0.05) in each product or raw material classification (paddy, brown rice, rice flakes, roasted rice flakes, popped rice or muesli variants).

indicate that the chocolate muesli has a significantly darker appearance compared to jaggery muesli but exhibits lower yellowness. Chroma values of processed rice flakes and popped rice ranged from 4.65 to 16.94, indicating significant variations in color intensity (Table 2). Higher chroma values, associated with more vibrant colors, may be perceived by consumers as fresher or more appealing. However, the hue angle observed (0.27–1.54) suggests that these variations occur within a similar color spectrum, possibly reflecting a combination of brown and white starchy color—both of which can influence consumer perception (Li et al., 2022). Roasting did not affect the  $L^*$  and  $a^*$  values of Marcha and Karhani rice flakes. However, higher  $b^*$  values were observed in the roasted rice flakes, indicating a more yellowish hue than their non-roasted counterparts—possibly due to caramelization and Maillard browning (Shi et al., 2018; Yang et al., 2023). The findings are notable as it suggests that roasting can enhance visual appeal by increasing yellowness without compromising brightness or introducing red-brown discoloration, which is important for consumer acceptance of lightly processed cereal products (Aung et al., 2022). While popped rice from ChaKhao black rice and Karhani red rice exhibited higher  $L^*$  values than their roasted flakes, raw rice flakes, and brown rice counterparts, they showed lower  $b^*$  and  $a^*$  values (Table 2). The lighter color of popped rice is attributed to kernel expansion, which exposes its white interior endosperm.

### 3.2. Protein, dietary fibre, lipid composition and functionality of rice flakes muesli and its rice ingredients

From a dietary standpoint, rice flakes muesli offers a gluten-free alternative, comprised of rice flakes, roasted rice flakes, and popped rice—that collectively deliver notable health benefits (Fig. 2A, B and 2C). As such, it presents a promising substitute for traditional breakfast meals and snacks. An evaluation of its nutritional properties was undertaken to assess its potential health benefits, with results summarized in Table 3. A 100g serving of chocolate muesli ( $415.51 \pm 1.16$  kcal) contributes approximately 20.8 % of the daily calorie needs on a 2000-kcal diet, while jaggery muesli provides  $400.89 \pm 1.81$  kcal for the same serving size (Fig. 2A and Table 3). As shown in Fig. 2B, significant differences were observed in dietary fiber content between the two variants, with higher concentrations consistently found in chocolate muesli. Chocolate muesli delivers higher dietary fiber than jaggery muesli, providing 19.57 % and 12.36 % of recommended dietary allowances (RDA) per 100g, respectively (Fig. 2A and Table 3). The total protein content present in chocolate muesli (9.74g) and jaggery muesli (9.22g) provides 20 % and 18 % of RDA per 100g, respectively (Fig. 2A and Table 3). These findings highlight the potential of rice flakes muesli, particularly the chocolate variant, as a nutrient-rich breakfast or snack option. The higher dietary fiber content in chocolate muesli indicates its potential to support digestive health. While both variants offer substantial protein content, chocolate muesli may be particularly beneficial for individuals seeking enhanced fiber and iron intake.

In addition, the inclusion of jaggery as a natural sweetener in jaggery muesli provides a less-refined alternative to traditional sweeteners, potentially appealing to health-conscious consumers. Regarding individual rice ingredients, brown rice across all landraces exhibited higher ash, fat, and protein levels compared to their processed forms—namely rice flakes, roasted rice flakes, and popped rice (Table 3). This suggests that popping, flaking, and roasting may degrade certain macronutrients, as previously reported (Fukui et al., 2022; Kumar et al., 2018; Cabrera-Ramírez et al., 2023). This trend was especially evident in Marcha and Karhani brown rice, which displayed greater insoluble and total dietary fiber content compared to their processed counterparts (Table 3). However, soluble dietary fiber content remained consistent across treatments, likely due to the stability of components such as beta-glucans and pectins. This is consistent with the observations of Dong et al. (2018), who discussed the impacts of thermal processing on soluble fiber content in whole-grain oats.

Both muesli variants—Jaggery Muesli and Chocolate Muesli—contain a diverse profile of saturated, monounsaturated, and polyunsaturated fatty acids, as presented in Supplementary Table 1. Chocolate Muesli contains significantly higher levels of saturated fatty acids, including lauric acid (C12:0) at  $6.55 \pm 0.95$  %, and myristic acid (C14:0) at  $5.35 \pm 0.31$  % compared to Jaggery Muesli. Additionally, it contains higher amounts of the long-chain saturated stearic acid (C18:0) at  $11.45 \pm 1.65$  %. These elevated values are likely attributed to the inclusion of cocoa-derived ingredients, which are known sources of medium- and long-chain saturated fats. In contrast, the Jaggery Muesli shows higher levels of certain odd-chain saturated fatty acids such as tridecanoic acid (C13:0) at  $7.03 \pm 0.53$  %. More importantly, it contains significantly higher proportions of polyunsaturated fatty acids, including gamma-linolenic acid (C18:3 n6) at  $18.04 \pm 0.42$  % and alpha-linolenic acid (C18:3 n3) at  $18.67 \pm 0.82$  %. While both muesli types contain notable amounts of these polyunsaturated fatty acids (C18:3 n6 and C18:3 n3), the values are distinctly higher in the Jaggery variant compared to the Chocolate Muesli. Hence, both muesli variants can be considered balanced sources of dietary fats. Chocolate Muesli provides medium-chain and long-chain saturated fats, including stearic acid, which has a neutral effect on blood cholesterol (Hunter, Zhang, & Kris-Etherton, 2009). Jaggery Muesli, on the other hand, offers a richer profile of polyunsaturated fats (omega-3 and omega-6), supporting heart and metabolic health (Simopoulos, 2002).

Most of the brown rice samples exhibited a good balance of saturated fatty acids palmitic acid (C16:0) and unsaturated fatty acids C18:1 and C18:2. In Karhani, popping reduced the palmitic acid content from  $30.86 \pm 1.90$  % in brown rice to  $25.41 \pm 4.26$  % in popped rice. A similar decline was observed in Chakhao, where palmitic acid decreased from  $30.40 \pm 1.87$  % to  $22.63 \pm 3.68$  % post-popping. Additionally, in both Karhani and Chakhao, the unsaturated fatty acids—oleic and linoleic acids—also decreased after popping. For instance, linoleic acid in Karhani dropped from  $25.54 \pm 1.38$  % to  $21.22 \pm 1.91$  %, while in Chakhao, it declined from  $29.44 \pm 1.60$  % to  $21.05 \pm 1.81$  %. Thus, rice flakes and roasted rice flakes (lower-temperature processing), saturated fatty acids tend to decrease slightly, while unsaturated fatty acids can decrease modestly. Meanwhile, for popped rice (high-temperature processing), saturated fatty acids tend to decrease, and unsaturated fatty acids also generally decrease, but to a greater extent.

### 3.3. Carbohydrate composition and glycemic response of rice muesli variants and its rice ingredients

Chocolate muesli, enriched with cocoa and chocolate chips, exhibited a higher digestible carbohydrate content ( $42.12 \pm 0.29$  %) compared to jaggery-sweetened muesli ( $35.94 \pm 1.66$  %), although the latter had higher total starch and amylose levels. Both muesli variants were classified as high glycemic index foods (GI > 70) which may result in rapid digestion and blood sugar spikes, making them less suitable for individuals requiring glycemic control (Rakmai et al., 2020). However, these products can serve as quick sources of energy for glycogen replenishment and still maintain nutrient density despite their high GI. Individually processed rice grains generally have higher GI values than their corresponding brown rice forms, although not all differences were statistically significant (Table 3). The increase in GI may be attributed to thermal processing methods—such as flaking, roasting, and popping—which disrupt the starch granules, gelatinize starch, and improve enzymatic digestibility (Miraji et al., 2021). Elevated processing temperatures may also cleave bonds between polysaccharide chains, potentially converting insoluble dietary fiber to its soluble form (Ain et al., 2019). Among the unprocessed samples, intermediate amylose rice varieties like Marcha, Kalanamak, and Karhani brown rice displayed significantly lower GI values compared to low amylose ChaKhao black rice (Table 3). These results reinforce the role of amylose content in moderating glycemic response, as higher amylose levels generally correlate with slower digestion rates (Tiozon, Fettke, et al., 2023).

**Table 4**  
Minerals and B-vitamins content of rice flakes Muesli and its rice ingredients.

Rice Landraces	Marcha Aromatic Rice			Kalanamak Aromatic Rice			Karhani Red Rice		ChaKhao Black Rice (CRV-113)		Muesli Variants	
	Brown Rice	Rice Flakes	Roasted Rice flakes	Brown Rice	Rice Flakes	Roasted Rice flakes	Brown Rice	Popped Rice	Brown Rice	Popped Rice	Jaggery Muesli	Chocolate Muesli
<b>Minerals</b>												
Mg (mg/kg)	1624.92 ± 29.27 aA	1123.79 ± 15.97 cA	1198.27 ± 15.14 bB	1470.50 ± 15.65 aB	900.79 ± 9.73 cB	1348.66 ± 17.94 bA	1588.88 ± 15.33 aA	1636.37 ± 42.94 aA	1401.95 ± 14.84 bC	1486.27 ± 47.83 aB	1594.30 ± 17.44 B	1786.37 ± 59.59 A
P (mg/kg)	3845.65 ± 68.67 aB	2686.77 ± 22.61 cA	3004.98 ± 24.07 bA	3958.10 ± 21.95 aB	2538.17 ± 33.12 cB	2838.46 ± 25.79 bB	4194.41 ± 66.55 bA	4516.86 ± 99.05 aA	3458.43 ± 16.87 bC	3917.24 ± 94.03 aB	2966.26 ± 32.60 B	3178.83 ± 81.54 A
K (mg/kg)	3030.93 ± 73.73 aC	2124.11 ± 10.42 bA	2640.82 ± 34.75 cA	3191.94 ± 20.90 aB	2101.17 ± 24.45 cA	2703.44 ± 13.50 bA	3355.48 ± 52.92 aA	3403.85 ± 70.01 aA	3307.69 ± 27.85 aAB	3443.29 ± 92.91 aA	3569.52 ± 21.55 B	4302.53 ± 90.17 A
Mn (mg/kg)	24.44 ± 0.30 aB	15.43 ± 0.15 bB	17.15 ± 0.18 cB	24.29 ± 0.13 aB	18.5 ± 0.31 cA	21.95 ± 0.19 bA	28.14 ± 0.48 aA	27.13 ± 2.37 aA	15.16 ± 0.08 aC	15.59 ± 0.68 aB	15.13 ± 0.12 B	15.62 ± 0.12 A
Fe (mg/kg)	14.18 ± 0.62 cC	36.11 ± 0.89 bA	62.27 ± 0.86 aA	16.33 ± 0.94 cB	30.92 ± 0.29 bB	60.84 ± 0.97 aA	22.79 ± 0.58 aA	20.30 ± 1.51 aA	17.18 ± 0.44 aB	13.55 ± 0.32 bB	43.78 ± 0.91 B	68.33 ± 0.41 A
Co (mg/kg)	0.01 ± 0.00 bC	0.02 ± 0.00 aB	0.01 ± 0.00 bB	0.02 ± 0.00 aB	0.02 ± 0.00 bA	0.02 ± 0.00 aA	0.02 ± 0.00 aA	0.02 ± 0.00 bA	0.01 ± 0.00 aC	0.01 ± 0.00 aB	0.15 ± 0.00 A	0.84 ± 1.15 A
Cu (mg/kg)	3.21 ± 0.02 bB	2.81 ± 0.04 cA	13.43 ± 0.10 aA	3.10 ± 0.61 bB	1.65 ± 0.03 cB	12.80 ± 0.35 aA	5.14 ± 0.10 aA	4.54 ± 0.13 bA	3.37 ± 0.10 aB	3.14 ± 0.12 aB	7.15 ± 0.03 A	7.79 ± 0.57 A
Zn (mg/kg)	24.13 ± 0.07 aB	18.20 ± 0.09 cA	19.01 ± 0.15 bA	20.60 ± 0.26 aC	14.87 ± 0.16 bB	14.95 ± 0.06 bB	33.42 ± 0.39 aA	32.18 ± 0.94 aA	19.40 ± 0.13 aD	18.77 ± 0.22 bB	19.61 ± 0.21 B	21.86 ± 0.09 A
<b>B-Vitamins</b>												
Thiamine (µg/g)	1.00 ± 0.57 aB	0.29 ± 0.21 bA	0.26 ± 0.01 bB	1.23 ± 0.03 aA	0.55 ± 0.02 bA	0.31 ± 0.01 cA	0.75 ± 0.00 aC	0.12 ± 0.00 bB	0.55 ± 0.03 aD	0.13 ± 0.00 bA	0.04 ± 0.00 A	0.03 ± 0.00 B
Pyridoxine (µg/g)	0.57 ± 0.03 aB	0.37 ± 0.02 bA	0.63 ± 0.01 aB	0.76 ± 0.02 aA	0.42 ± 0.02 bA	0.80 ± 0.03 aA	0.64 ± 0.02 aB	0.49 ± 0.01 bB	0.74 ± 0.02 bA	0.99 ± 0.07 aA	0.99 ± 0.01 A	0.93 ± 0.02 B
Pantothenic acid (µg/g)	2.54 ± 0.03 bD	2.27 ± 0.05 cB	3.02 ± 0.04 aB	3.45 ± 0.04 aB	2.55 ± 0.05 bA	3.60 ± 0.07 aA	3.26 ± 0.06 aC	2.76 ± 0.01 bA	3.60 ± 0.02 aA	3.10 ± 0.22 bA	1.39 ± 0.05 A	1.37 ± 0.04 A
Folic acid (µg/g)	0.01 ± 0.00 bA	0.01 ± 0.00 cA	0.08 ± 0.00 aA	0.01 ± 0.00 bB	0.01 ± 0.00 bA	0.08 ± 0.00 aA	0.01 ± 0.00 bA	0.09 ± 0.00 aA	0.01 ± 0.00 bB	0.08 ± 0.00 aB	0.01 ± 0.00 A	0.00 ± 0.00 A
Biotin (µg/g)	0.00 ± 0.00 bA	0.00 ± 0.00 cA	0.00 ± 0.00 aA	0.00 ± 0.00 bB	0.00 ± 0.00 bA	0.00 ± 0.00 aA	0.00 ± 0.00 bA	0.00 ± 0.00 aA	0.00 ± 0.00 bB	0.00 ± 0.00 aB	0.00 ± 0.00 A	0.00 ± 0.00 A
Riboflavin (µg/g)	0.01 ± 0.00 bB	0.00 ± 0.00 c	0.06 ± 0.00 aB	0.01 ± 0.00 bB	0.00 ± 0.00 c	0.07 ± 0.00 aA	0.00 ± 0.00 bB	0.08 ± 0.00 aB	0.07 ± 0.01 bA	0.40 ± 0.02 aA	0.00 ± 0.00 B	0.01 ± 0.00 A

Values are mean ± standard deviation of three independent determinations (n = 3); Small letters denote a significant difference (p < 0.05) within genotypes, while capital letters denote significant differences (p < 0.05) in each product or raw material classification (paddy, brown rice, rice flakes, roasted rice flakes, popped rice or muesli variants).

**Table 5**  
Phytochemicals, antioxidant properties and phenolic profile of rice flakes Mueslis and its rice ingredients.

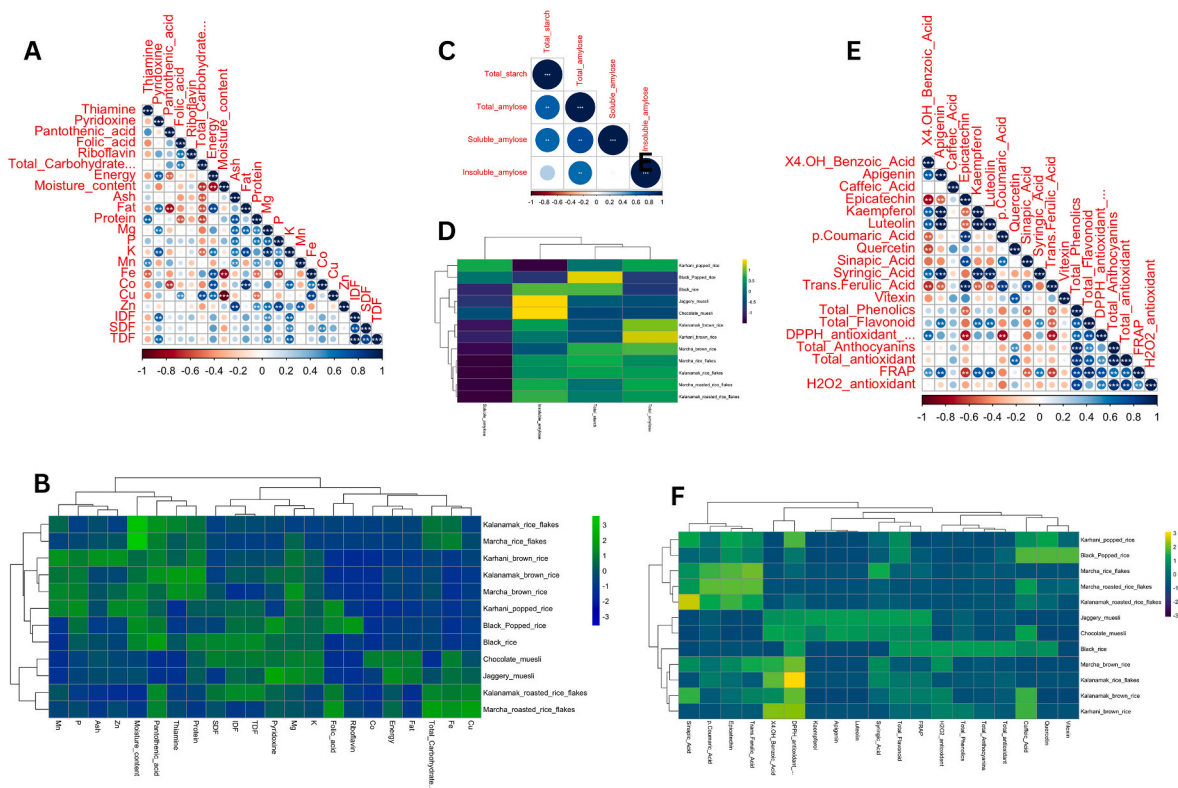
Rice Landraces	Marcha Aromatic Rice			Kalanamak Aromatic Rice			Karhani Red Rice		ChaKhao Black Rice (CRV-113)		Muesli Variants	
	Brown Rice	Rice Flakes	Roasted Rice Flakes	Brown Rice	Rice Flakes	Roasted Rice Flakes	Brown Rice	Popped Rice	Brown Rice	Popped Rice	Jaggery Muesli	Chocolate Muesli
<b>Phytochemicals and Antioxidant Activities</b>												
Phenolics (mg GAE/100g)	96.70 ± 7.34 aC	70.77 ± 4.46 bA	45.17 ± 4.19 cA	135.13 ± 5.07 aC	71.84 ± 7.72 bA	44.10 ± 0.77 cA	444.90 ± 18.15 aB	73.24 ± 1.67 bA	1161.82 ± 50.06 aA	53.56 ± 2.09 bB	424.92 ± 39.05 A	448.87 ± 27.85 A
Flavonoids (mg CE/100g)	18.22 ± 2.21 aD	17.70 ± 0.63 aA	8.92 ± 0.90 bB	71.33 ± 1.58 aB	32.84 ± 20.36 bA	16.24 ± 2.75 bA	38.23 ± 5.27 bC	72.09 ± 2.91 aB	139.83 ± 6.42 aA	93.16 ± 1.72 bA	143.68 ± 9.16 A	114.43 ± 9.82 B
Anthocyanins (ug C-3-G/100g)	128.02 ± 34.31 aB	72.36 ± 7.87 abA	43.89 ± 0.43 bB	172.49 ± 15.70 aB	95.73 ± 12.92 bA	49.82 ± 1.41 cA	316.15 ± 15.04 aB	16.43 ± 0.46 bB	1792.02 ± 212.21 aA	134.43 ± 9.39 bA	166.99 ± 23.62 A	200.39 ± 23.62 A
DPPH Antioxidant Activity (%)	56.38 ± 3.55 aC	15.94 ± 0.22 bB	9.32 ± 1.00 cB	94.50 ± 0.36 aA	72.40 ± 2.26 bA	27.86 ± 2.86 cA	87.83 ± 0.29 aB	74.26 ± 0.79 bA	99.21 ± 0.20 aA	51.25 ± 37.96 aA	95.33 ± 0.15 A	93.91 ± 0.28 B
Total Antioxidant Activity (mg GAE/100g)	9.55 ± 1.16 aC	4.64 ± 0.16 bA	1.27 ± 0.22 cA	37.41 ± 0.83 aB	14.00 ± 12.95 bA	1.80 ± 0.32 bA	17.36 ± 6.57 aC	16.74 ± 1.67 aB	183.36 ± 8.42 aA	55.90 ± 3.44 bA	37.68 ± 2.40 A	30.01 ± 2.58 B
FRAP (mM/g)	1.08 ± 0.13 aD	1.05 ± 0.04 aA	0.64 ± 0.04 bA	4.21 ± 0.09 aB	1.94 ± 1.20 bA	0.47 ± 0.05 bB	2.26 ± 0.31 aC	0.52 ± 0.04 bB	8.26 ± 0.38 aA	2.12 ± 0.17 bA	8.48 ± 0.54 A	6.76 ± 0.58 B
H <sub>2</sub> O <sub>2</sub> Antioxidant Activity (mg QE/100g)	70.68 ± 1.64 aD	2.63 ± 0.09 bA	1.03 ± 0.09 bA	110.12 ± 1.17 aB	4.88 ± 3.02 bA	0.65 ± 0.04 bB	85.54 ± 3.91 aC	8.41 ± 1.24 bB	218.14 ± 4.77 aA	12.84 ± 1.38 bA	21.34 ± 1.36 A	16.99 ± 1.46 B
<b>Bio-active compounds (mg/100g)</b>												
4-OH Benzoic Acid	0.08 ± 0.00 aB	0.00 ± 0.00 b	0.00 ± 0.00 b	0.11 ± 0.02 aAB	0.09 ± 0.00 a	0.00 ± 0.00 b	0.17 ± 0.04 aA	0.00 ± 0.00 b	0.00 ± 0.00 c	0.00 ± 0.00	0.17 ± 0.02 A	0.20 ± 0.03 A
Apigenin	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.07 ± 0.00 A	0.07 ± 0.00 A
Caffeic Acid	0.00 ± 0.00 bB	0.00 ± 0.00 b	0.12 ± 0.06 aA	0.14 ± 0.01 aA	0.00 ± 0.00 c	0.06 ± 0.01 bA	0.12 ± 0.02 aA	0.08 ± 0.05 aA	0.13 ± 0.01 aA	0.17 ± 0.04 aA	0.00 ± 0.00 B	0.17 ± 0.01 A
Epicatechin	0.23 ± 0.02 bA	0.24 ± 0.02 bA	0.58 ± 0.01 aA	0.27 ± 0.01 bA	0.16 ± 0.05 bB	0.44 ± 0.06 aB	0.14 ± 0.01 bB	0.39 ± 0.04 aA	0.17 ± 0.02 bB	0.42 ± 0.06 aA	0.09 ± 0.01 A	0.09 ± 0.00 A
Kaempferol	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.19 ± 0.04 A	0.13 ± 0.05 A
Luteolin	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.08 ± 0.01 A	0.07 ± 0.00 A
p-Coumaric Acid	0.14 ± 0.01 bA	0.19 ± 0.01 bA	0.66 ± 0.03 aA	0.13 ± 0.01 bA	0.13 ± 0.02 bB	0.40 ± 0.04 aB	0.00 ± 0.00 bC	0.20 ± 0.04 aA	0.09 ± 0.01 bB	0.25 ± 0.01 aA	0.15 ± 0.02 A	0.12 ± 0.00 B
Quercetin	0.00 ± 0.00 bB	0.00 ± 0.00 b	0.06 ± 0.01 aA	0.00 ± 0.00 bB	0.00 ± 0.00 b	0.07 ± 0.02 aA	0.00 ± 0.00 bB	0.22 ± 0.02 aB	0.32 ± 0.01 aA	0.36 ± 0.02 aA	0.00 ± 0.00	0.00 ± 0.00
Sinapic Acid	0.21 ± 0.01 bB	0.14 ± 0.02 bA	0.45 ± 0.05 aB	0.57 ± 0.09 aA	0.00 ± 0.00 bB	0.70 ± 0.03 aA	0.00 ± 0.00 bC	0.42 ± 0.03 aA	0.00 ± 0.00 bC	0.22 ± 0.01 aB	0.00 ± 0.00	0.00 ± 0.00
Syringic Acid	0.10 ± 0.01 aA	0.09 ± 0.01 aA	0.04 ± 0.01 bA	0.10 ± 0.01 aA	0.08 ± 0.01 aA	0.03 ± 0.01 bA	0.00 ± 0.00 bB	0.08 ± 0.02 aA	0.00 ± 0.00 bB	0.07 ± 0.02 aA	0.33 ± 0.07 A	0.27 ± 0.03 A
Trans-Ferulic Acid	0.49 ± 0.02 bB	0.42 ± 0.02 cA	1.03 ± 0.02 aA	0.58 ± 0.02 aA	0.15 ± 0.02 bB	0.66 ± 0.05 aB	0.19 ± 0.03 bD	0.54 ± 0.03 aA	0.26 ± 0.02 bC	0.58 ± 0.05 aA	0.11 ± 0.01 A	0.11 ± 0.01 A
Vitexin	0.00 ± 0.00 b	0.00 ± 0.00 b	0.04 ± 0.02 aA	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00 B	0.00 ± 0.00 b	0.05 ± 0.01 aB	0.00 ± 0.00 b	0.18 ± 0.00 aA	0.00 ± 0.00	0.00 ± 0.00

Values are mean ± standard deviation of three independent determinations (n = 3); Small letters denote a significant difference (p < 0.05) within genotypes, while capital letters denote significant differences (p < 0.05) in each product or raw material classification (paddy, brown rice, rice flakes, roasted rice flakes, popped rice or muesli variants).

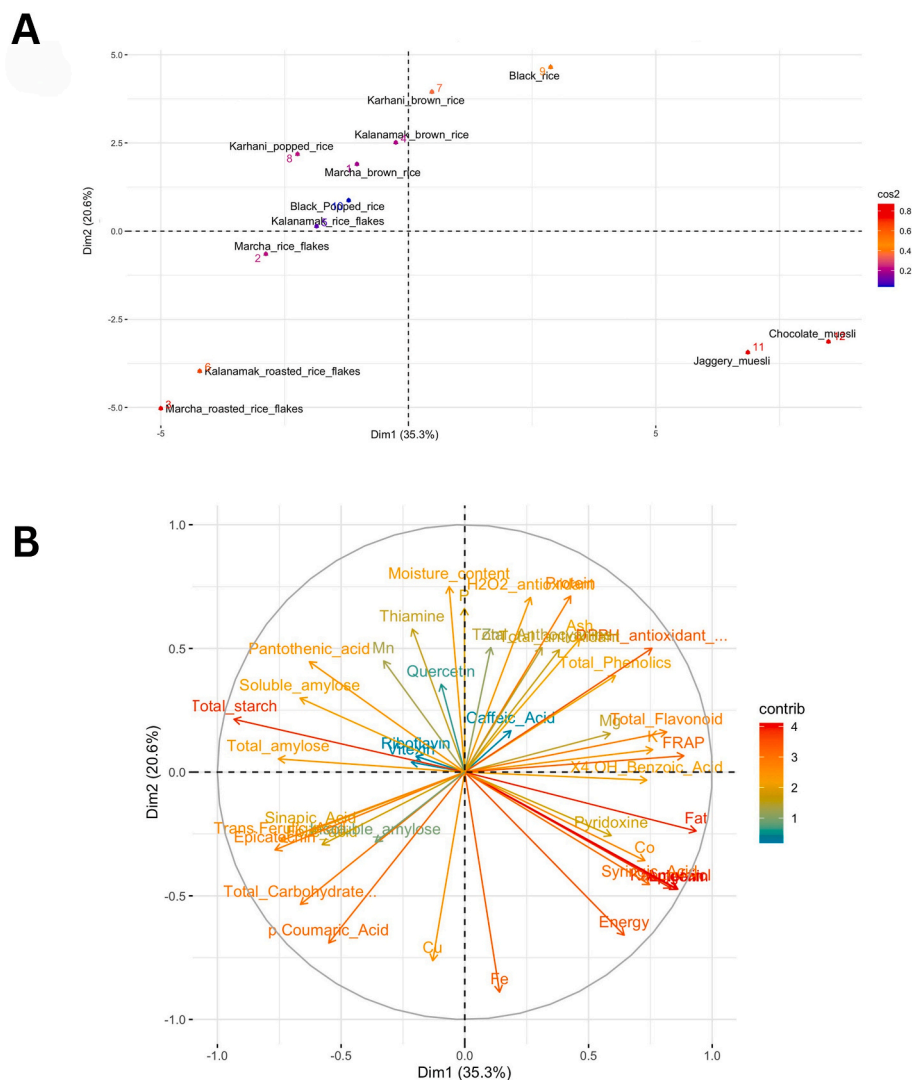
Therefore, intermediate-amylose rice varieties with a GI range of 56–69 are potentially more suitable for individuals looking to manage blood sugar levels. After processing, only roasted rice flakes (Marcha and Kalanamak), and popped Karhani red rice retained intermediate GI properties (Table 3), while others shifted into the high GI category. Measuring the GI of each rice ingredient allows the muesli to be tailor-fit for specific needs—whether for low-GI formulations suited to blood sugar management or higher-GI options for quick energy—offering a versatile functional food. All tested samples, including both muesli variants, contained less than 1 % resistant starch. However, the impact of processing on resistant starch levels varied notably by genotype. In Marcha rice, flaking and roasting increased resistant starch by 0.57–2.71 times, while the same processes reduced resistant starch in Kalanamak rice by 0.63–0.78 times. Popping, on the other hand, led to a reduction in resistant starch in both Karhani red rice and ChaKhao black rice. Such differences suggest that the structural response of rice starch to processing is highly genotype-dependent specifically in the inherent differences in starch composition including amylose-to-amylopectin ratios, granular structure, and starch–protein interactions (Tuaño et al., 2021; Yang et al., 2023; Vaidya & Sheth, 2010). Processing-induced retrogradation during flaking or roasting can either promote or hinder resistant starch formation depending on the rice variety’s starch characteristics (Vaidya & Sheth, 2010; Park et al., 2022). Furthermore, processing also reduced amylose content, with black rice (ChaKhao) showing the lowest endogenous amylose among the studied pigmented and brown rice samples, potentially explaining its higher digestibility and GI.

### 3.4. Multi-vitamin composition of rice muesli variants and its rice ingredients

The B vitamins of the two rice flakes mueslis were also evaluated (Fig. 2A, and Table 3), as rice-based products, both naturally provide considerable quantities of these essential micronutrients, which play a vital role in metabolic and neurological health. Jaggery-sweetened muesli contains higher levels of vitamin B5 (pantothenic acid) ( $1.39 \pm 0.05 \mu\text{g/g}$ ) and Vitamin B6 (pyridoxine) ( $0.99 \pm 0.01 \mu\text{g/g}$ ), while chocolate muesli contains  $1.37 \pm 0.04 \mu\text{g/g}$  of Vitamin B5 and  $0.93 \pm 0.02 \mu\text{g/g}$  of Vitamin B6. These findings indicate that a 100g serving of rice flakes muesli samples can contribute approximately 7–8 % of the RDA for B6 vitamin and 2–3 % for B5 vitamin (Fig. 2A and Table 3). Jaggery-sweetened muesli ( $0.04 \pm 0.00 \mu\text{g/g}$ ) and chocolate muesli ( $0.03 \pm 0.00 \mu\text{g/g}$ ) contains smaller amount of thiamine contributing to only <1 % of the RDA. On the other hand, Marcha and Kalanamak brown rice exhibited the highest thiamine content than their respective counterparts, as brown rice retains the outer bran layer that is rich in thiamine (Manzoor et al., 2023). This also explains why Karhani brown rice has higher thiamine ( $0.75 \pm 0.00 \mu\text{g/g}$ ), pyridoxine ( $0.64 \pm 0.02 \mu\text{g/g}$ ), and pantothenic acid ( $3.26 \pm 0.06 \mu\text{g/g}$ ) content compared to its popped rice counterpart (Table 3). However, popping led to increased levels of pyridoxine, folic acid, and riboflavin likely due to inherent heat stability and localization of the nutrient within the grain (Mangel et al., 2022). Conversely, reductions in thiamine and pantothenic acid reflect their greater susceptibility to thermal degradation (Fulias et al., 2014). Surprisingly, Marcha and Kalanamak roasted rice flakes showed higher B vitamins than their raw rice flakes form. This implies that roasting may better preserve or concentrate B vitamins compared to flaking, as the flaking process often involves soaking, which may result in the leaching of water-soluble B vitamins (Sumczynski et al., 2018), while roasting



**Fig. 3.** Correlation plots and heatmaps of parameters measured in rice-based mueslis and their rice ingredients. (A) Correlation plot of nutritional properties for rice-based muesli and its rice ingredients. (B) Correlation plot of starch properties for rice-based muesli and its rice ingredients. (C) Correlation plot of phenolics and antioxidant activities of rice-based muesli and its rice ingredients. (D) Heatmap of nutritional properties of micronutrients and vitamins, comparing rice-based mueslis with its rice ingredients. (E) Heatmap of starch properties, comparing rice-based mueslis with its rice ingredients. (F) Heatmap of phenolics and antioxidant activities, comparing rice-based mueslis with rice flakes, pigmented popped rice, and whole grain rice.



**Fig. 4.** Clustering of physical and nutritional parameters of rice flakes muesli variants and its rice ingredients (A) Principal component analysis (PCA) plot of samples (B) PCA biplot showing the relationship between the parameters.

primarily removes moisture, potentially concentrating these vitamins by weight and supporting the results (Hucker et al., 2012; Padonou, Hounghédji, Hounhouigan, Chadare, & Hounhouigan, 2023).

### 3.5. Mineral composition of rice muesli variants and its rice ingredients

In terms of mineral composition, the two variants are enriched with multiple micronutrients. Among them, chocolate muesli exhibited higher concentration of iron ( $68.33 \pm 0.41$  mg/kg), zinc ( $21.86 \pm 0.09$  mg/kg), copper ( $7.79 \pm 0.57$  mg/kg), manganese ( $15.62 \pm 0.12$  mg/kg) micronutrients, translates to approximately 37.94 %, 19.91 %, 87 % and 68 % of the RDA per 100g, respectively (Fig. 2A, and Table 4). As part of essential macro elements, chocolate muesli contain magnesium ( $1786.37 \pm 59.59$  mg/kg), phosphorus ( $3178.83 \pm 81.54$  mg/kg), and potassium ( $4302.53 \pm 90.17$  mg/kg) translates to RDA values of 42.52 %, 25 %, and 9.15 % of the RDA per 100g, respectively (Fig. 2A, and Table 4). This mineral-rich diet of chocolate mueslis will likely contribute significantly to overcome the iron deficiency to address anemia in children and pregnant women as more than 67 % of children and 57 % of women in India were found to be anemic (Srivastava & Boro, 2023). In addition, the two muesli variants contribute to the daily requirements of zinc, magnesium, and phosphorus intake, which are essential for bone health and cellular energy metabolism. All samples,

including the two muesli variants, brown rice, rice flakes, roasted rice flakes, and popped rice, were compliant with the Food Safety and Standards Authority of India (FSSAI) heavy metal limits (arsenic: 1.1 mg/kg, cadmium: 0.4 mg/kg, tin: 250 mg/kg) (Supplementary Table 2). Arsenic levels ranged from 0.07 to 0.35 mg/kg, cadmium from 0.02 to 0.33 mg/kg, and tin from 0.03 to 0.14 mg/kg. Hence, these functional muesli products, which are rich in multiple minerals, meets the food safety standards (Food Safety and Standards Authority of India, 2020).

Among the rice ingredients, Marcha and Kalanamak brown rice displayed the highest overall mineral content compared to their respective rice flakes and roasted rice flakes, except for iron and copper, which were found to be highest in their roasted rice flakes forms (Table 4). This suggests that certain processing techniques—such as roasting—may selectively enhance specific mineral concentrations, possibly due to the reduction of moisture and concentration effects. For instance, traditional roasting of cocoa beans has been shown to increase iron and phosphorus contents, likely because of moisture loss leading to a concentration of these minerals (Djikeng et al., 2018). On the other hand, popped ChaKhao black rice showed elevated levels of magnesium ( $1486.27 \pm 47.83$  mg/kg) and phosphorus ( $3917.24 \pm 94.03$  mg/kg) compared to its brown rice counterpart. However, its iron ( $17.18 \pm 0.44$  mg/kg) and zinc ( $19.40 \pm 0.13$  mg/kg) contents were lower, indicating a trade-off in mineral retention during the popping process (Table 4).

These observations underscore that processing significantly impacts the mineral composition of rice flakes, roasted rice flakes, and pigmented popped rice, primarily due to mechanisms such as leaching into water during soaking, volatilization, thermal degradation, or matrix restructuring (Kumar et al., 2022; Wu et al., 2017). As such, understanding the influence of specific processing methods on individual minerals can inform strategies for optimizing the nutritional profile of rice-based foods.

### 3.6. Antioxidant composition of rice muesli variants and its rice ingredients

Pigmented rice varieties, such as Karhani and ChaKhao are well recognized for their rich nutrient content and bioactive compounds as demonstrated by the results in Table 5, which corresponds to a range of health benefits. These food products rich in antioxidants act as free radical scavengers within the body, neutralizing oxidative molecules and mitigating the cellular damage induced by oxidative stress. Notably, these compounds have been shown to reduce the risk of several diseases including heart disease and cancer (Singh, 2024). The jaggery-sweetened muesli demonstrated high TFC content ( $143.68 \pm 9.16$  mg CE/100g), strong DPPH radical scavenging activity ( $95.33 \pm 0.15$  %) and  $H_2O_2$  scavenging activity ( $21.34 \pm 1.36$  mg QE/100g) and FRAP ( $8.48 \pm 0.54$  mM/g) attributed to its high TPC (Table 5). The chocolate muesli samples were observed to be slightly higher in phenolic ( $448.87 \pm 27.85$  mg GAE/100g) and anthocyanin content ( $200.39 \pm 23.62$   $\mu$ g C-3-G/100g). Brown rice from Karhani and ChaKhao black rice had higher antioxidant properties than their popped rice counterparts, suggesting that the popping process may significantly degrade these beneficial compounds. Similarly, Marcha and Kalanamak brown rice exhibited higher antioxidant properties than their raw and roasted rice flakes counterparts. Roasting also reduced antioxidant properties, as indicated by lower TPC and DPPH scavenging activity in roasted rice flakes compared to both brown rice and raw rice flakes counterparts. These observations agree with the previous studies, confirming that various processing technologies can negatively affect the levels of phenolic compounds, flavonoids, and antioxidant properties (Bagchi et al., 2021; Ghasemzadeh et al., 2018). Nevertheless, taking into consideration the differences in the antioxidant properties of varietal composition and the deployed effect of processing methods employed (Bagchi et al., 2021), we can optimize to retain significant levels of antioxidant contributing factors in the finished products.

The detection of specific flavonoids such as kaempferol, apigenin, and luteolin in both jaggery and chocolate rice flakes muesli samples—but not found in ingredients such as rice flakes, roasted flakes and popped rice—suggests that these flavonoids may have originated from other supplementary ingredients, such as raisins, chia seeds, and sesame seeds. While most bioactive compounds were comparable between chocolate and jaggery-sweetened muesli, some notable differences emerged. For instance, chocolate muesli contains higher levels of caffeic acid, whereas jaggery-sweetened muesli was richer in p-coumaric acid. Roasted Marcha rice flakes have higher caffeic acid, epicatechin, p-coumaric acid, quercetin, sinapic acid, trans-ferulic acid, and vitexin than their raw rice flakes and brown rice counterparts. In Marcha and Kalanamak rice, flaking and roasting increased compounds such as caffeic acid, epicatechin, p-coumaric acid, quercetin, sinapic acid, and trans-ferulic acid. Similar trends were observed in roasted Kalanamak rice flakes, although the increase was limited to p-coumaric acid, quercetin, and epicatechin. In contrast, compounds such as syringic acid and 4-hydroxybenzoic acid decreased following roasting. Popped rice from ChaKhao black rice and Karhani red rice, demonstrated elevated levels of epicatechin, p-coumaric acid, sinapic acid, syringic acid, trans-ferulic acid, and vitexin compared to their corresponding brown rice. These findings indicate that processing methods such as flaking, roasting, and popping influence the levels of bioactive compounds differently, depending on the rice variety, processing conditions, and

molecular stability of the compounds. These results suggest that popping and roasting promote the concentration of certain bioactive compounds under specific conditions (Bagchi et al., 2021). However, their effects are not uniform across all compounds, highlighting the variability in the stability and transformation of bioactive compounds in response to thermal treatment (Bagchi et al., 2021; Ghasemzadeh et al., 2018; Itagi et al., 2023).

### 3.7. Multivariate analysis of physicochemical and nutritional properties of rice-based mueslis

Considering the physicochemical and nutritional characteristics, a multivariate analysis was performed to group the samples (Figs. 3 and 4). Macromolecules such as protein, fat, and ash showed positive correlations with mineral content (Fig. 3A). Among minerals, strong positive correlations were observed among macroelements such as Mg, P, and K. For microelements, positive associations were found between Fe and Cu, as well as Zn and Mn (Fig. 3A). The observation aligns with Rezk et al. (2024), who reported positive correlations among Mg, K, Zn, and Fe, with K also correlating with protein content. These relationships suggest a co-occurrence of minerals and protein in nutrient-dense rice samples, supporting the potential for developing functional foods with a more balanced nutrient profile using the same processing techniques employed. On the other hand, correlation among B vitamins revealed only slight positive relationships between pantothenic acid, folic acid, and riboflavin (Fig. 3A). This weak correlation suggests that achieving consistently high levels of these B vitamins is challenging with the processing methods used in this study—such as flaking, roasting, and popping—as their synthesis and accumulation may be governed by distinct metabolic pathways or genetic factors (Mangel et al., 2022). Nonetheless, their presence in the rice flakes-based mueslis enhances the nutritional profile of individual B vitamins, supporting the development of functional foods that can address micronutrient deficiencies.

Fig. 3C illustrates the correlations among antioxidant compounds. The total flavonoid content (TFC), as determined by spectrophotometric analysis, was positively correlated with specific flavonoids including apigenin, p-coumaric acid, and luteolin indicating that these are the predominant flavonoids in the sample. Among the antioxidant contributors in muesli, TPC, TFC, and TAC collectively contributed to total antioxidant potential, as indicated by the correlation plot (Fig. 3C). In terms of antioxidant capacity, quercetin showed the strongest positive correlation with TAC, aligning with previous findings (Gogoi et al., 2024; Wan et al., 2022). Flavonoids such as apigenin, luteolin, and kaempferol exhibited the strongest correlations with FRAP-based antioxidant activity (Fig. 3C). Interestingly, epicatechin displayed negative correlations with antioxidant assays, possibly due to structural interference in the assays, concentration-dependent pro-oxidant behaviour, or its complex bioavailability that in vitro tests may not capture accurately (Chakraborty et al., 2023; Fiecke et al., 2024). Notably, several phenolic compounds, including 4-Hydroxybenzoic acid, apigenin, caffeic acid, epicatechin, kaempferol, luteolin, p-coumaric acid, and trans-ferulic acid, were correlated with minerals such as K, Fe, Co, and Cu. This suggests that rice processing methods like popping, flaking, and roasting may positively affect both phenolic and mineral content. Among the phenolic compounds, benzoic acid was detected in both muesli variants and can be traced to the brown rice samples as it is associated with DPPH-based antioxidant activity (Fig. 3C and Table 5).

On the other hand, the brown rice samples—Karhani red rice, Marcha, and Kalanamak—formed a distinct cluster characterized by higher protein content (9.88–10.35 %) and thiamine levels (0.55–1.23  $\mu$ g/g), underscoring the nutritional benefits of minimally processed landraces (Fig. 3D and Supplementary Fig. 1). However, processing into flakes resulted in an increased level of total starch, total amylose, and moisture content in the corresponding Marcha and Kalanamak rice flakes (Fig. 3E and Supplementary Fig. 1). These changes likely reflect the partial loss of proteins and heat-sensitive vitamins during flaking,

coupled with starch gelatinization and granule breakdown during hydrothermal treatment, enhancing extractable starch and amylose (Singh et al., 2006; Mathobo et al., 2020). Elevated flakes moisture content, stemming from increased post-treatment water-holding capacity, impacts texture and shelf life (Brett et al., 2009). Regarding starch-related properties, strong positive correlations were observed between total starch, total amylose, soluble amylose, and insoluble amylose (Fig. 3B). Interestingly, these starch components exhibited negative correlations with fat content and selected metabolites (Supplementary Fig. 1). This trend aligns with the nutritional comparison between chocolate muesli (10.84g fat, 69.58g carbs) and jaggery muesli (7.26g fat, 74.56g carbs, Fig. 2A), where the inverse fat-carbohydrate relationship supports the link between higher amylose starch and lower fat in processed rice products.

Targeted phenolic profiling confirmed the presence of kaempferol, apigenin, syringic acid, and luteolin in both rice flakes muesli variants, which clustered with total flavonoids and FRAP-based antioxidant activity (Fig. 3F and Table 5), suggesting a strong association between flavonoids content and antioxidant properties in the rice-based products. This clustering indicates that the overall antioxidant activity, as measured by FRAP, is largely driven by the presence of these specific phenolic compounds. Conversely, black rice and its popped counterpart formed a distinct cluster due to their high antioxidant activity and elevated bioactive components, such as caffeic acid and quercetin. Additionally, roasted rice flakes from Kalanamak and Marcha landraces shows increased levels of bioactive compounds such as epicatechin, trans-ferulic acid, and sinapic acid. However, these increases were accompanied by reduced protein content and diminished antioxidant capacity, as reflected in lower H<sub>2</sub>O<sub>2</sub> and DPPH radical scavenging activities (Fig. 3F and Supplementary Fig. 1). Roasting significantly altered the nutrient profile of brown rice samples; roasted Marcha and Kalanamak rice flakes exhibited enhanced levels of micronutrients like iron, copper, folic acid, and specific bioactive compounds. The heatmap further revealed that chocolate and jaggery-sweetened muesli clustered closely together, reflecting elevated concentrations of phenolic compounds such as syringic acid, kaempferol, luteolin, and apigenin. The increased fat content in these mueslis was attributed to the inclusion of nuts.

Supporting these observations, the Principal Component Analysis (PCA) illustrated in Fig. 4A shows a distinct separation of the chocolate and jaggery-sweetened muesli samples from other rice-based components, based on variables contributing to the first two principal components (PC1 and PC2). PC1 accounts for 35.3 % of the total variance, primarily influenced by energy, iron, and total carbohydrate content, while PC2 explains an additional 20.6 %, driven mainly by total starch and fat content. Notably, energy content was the most influential factor in distinguishing the muesli samples along the PCA axes (Fig. 4B).

### 3.8. Evaluating the sensorial properties of chocolate and jaggery sweetened rice flakes muesli and a commercial muesli sample

Sensory evaluation, particularly through hedonic scale, is valuable for understanding consumer preferences and guiding new product development. In this study, a 9-point hedonic scale was employed to assess and compare the sensory attributes—flavor, texture, and aroma—of two rice-based muesli variants: chocolate and jaggery-sweetened. These variants were evaluated alongside a commercial multigrain muesli that includes rice flakes as one of its cereal components, providing comparative insights into consumer acceptability as shown in Fig. 2D. Sensory scores were recorded for key attributes such as aroma, flavor, color, texture, taste, and overall acceptability. Both the chocolate and jaggery-sweetened mueslis received significantly similar ratings across all parameters, and both scored significantly higher than the commercial muesli. The preference for the chocolate and jaggery-sweetened muesli over the commercial option may be attributed to their balanced nutritional compositions and enhanced flavor profiles

derived from distinctive ingredients. For instance, the chocolate muesli's cocoa and chocolate chips likely contributed to a richer taste and aroma that aligns well with consumer expectations for an indulgent breakfast option. Similarly, the jaggery-sweetened muesli's use of traditional ingredients, such as jaggery and chia seeds, may have appealed to those preferring naturally sweet and wholesome foods. These findings suggest that muesli made from geographical indicator-tagged rice landraces not only offers nutritional advantages but also exceeds consumer sensory expectations. This enhanced consumer acceptance positions rice flakes-based mueslis as promising functional foods within the competitive breakfast segment, with strong potential for market success. Future development efforts could focus on optimizing flavor profiles and ingredient combinations to enhance sensory appeal and broaden market reach.

## 4. Conclusions

This study highlights the exceptional potential of geographical indication-tagged rice landraces, such as ChaKhao black rice, Karhani red rice, Kalanamak, and Marcha aromatic rice, in developing rice flakes muesli. Processing methods—flaking, roasting, and popping—not only modify physical traits like bulk density and morphology but also enhance nutrition by utilizing nutrient-dense landraces. The chocolate-based and jaggery-sweetened muesli variants are nutrient-dense with enriched multiple minerals, vitamins, bioactive compounds, and energy. Notably, higher nutrient density over calories was achieved by combining optimal processing with selected landraces dense in bioactives and micronutrients. Alongside high protein, dietary fiber, and essential minerals like iron, magnesium, phosphorus, zinc, and B vitamins, the muesli is antioxidant-rich, supporting active lifestyles and nutritional needs in rice-dependent regions. Additionally, sensory evaluation showed a strong preference for chocolate and jaggery-sweetened rice flakes mueslis over a commercially available product, with high scores in aroma, flavor, and overall acceptability. The combination of rice flakes, pigmented popped rice, and nutrient-dense ingredients positions the two muesli variants as gluten-free, multi-nutrient functional breakfasts, ideal for Asian consumers. Future work should expand prototyping low GI muesli with enriched micronutrients by exploring lower-GI ingredients or grain blends to boost health benefits and sensory testing across demographics. With continued innovation, rice muesli can address malnutrition and support modern dietary goals in health-conscious markets.

### CRedit authorship contribution statement

**Hameeda Banu Itagi:** Writing – review & editing, Supervision, Resources, Investigation, Conceptualization. **Nitesh Gupta:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Glenn Vincent Ong:** Writing – original draft, Formal analysis, Data curation. **Vipin Pratap:** Writing – review & editing, Methodology, Formal analysis. **Priyabrata Roy:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Ana Rose Ramos-Castrosanto:** Methodology, Formal analysis. **Vivek Kumar Singh:** Formal analysis, Data curation. **Rhowell Navarro Tiozon:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Nese Sreenivasulu:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

### Informed consent declaration

Informed consent was obtained from all panelists before they participated in the sensory evaluation. The research protocol was thoroughly explained, including details of the rice flakes muesli variants and their respective ingredients. Panelists were informed of their right to withdraw from the evaluation at any time without providing a reason.

The sensory evaluations were carried out at the Center of Excellence in Rice Value Addition, Product Development, and Sensory Laboratory, located at the IRRI South Asia Regional Center in Varanasi, Uttar Pradesh, India. Only rice flakes muesli variants deemed safe and suitable for consumption were included in the study.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.lwt.2025.118194>.

## Data availability

Data will be made available on request.

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