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Analytical Methods

Comparative proximate analysis and nutrient labelling compliance of cow milk and plant-based milk alternatives: Implications for consumer choice and food policy

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ABSTRACT

This study compared the nutritional composition of cow milk and plant-based milk alternatives (PBMAs) available in South African retail markets and assessed nutrient labelling compliance. Proximate and mineral analysis was conducted on 60 PBMA samples (soy, almond, oat, rice, coconut) and 39 cow milk samples using standardised analytical methods. Results demonstrated significant nutritional differences between product categories ($p < 0.05$). Cow milk demonstrated significantly higher nutrient density, particularly for protein and key bone-building minerals including calcium, phosphorous, and zinc. Conversely, PBMAs showed higher iron, copper, and manganese levels, though bioavailability may be compromised by antinutrients. Labelling non-compliance was identified for calcium and dietary fibre overreporting for PBMAs, and sodium underreporting across both categories. These findings indicate that PBMAs are not nutritionally equivalent to cow milk and highlight the need for improved regulatory oversight of nutritional labelling to prevent consumer misinformation.

1. Introduction

The global food system currently faces a dual challenge: addressing various forms of malnutrition while mitigating environmental degradation and resource depletion (FAO and WHO, 2019; Macdiarmid et al., 2012). This has driven transitions toward diets that are simultaneously environmentally sustainable and conducive to better health (FAO and WHO, 2019; Roös et al., 2018). Transitions are driven by multiple factors, including health concerns (milk allergies, lactose intolerance, energy intake, prevalence of non-communicable diseases), environmental considerations (greenhouse gas emissions, land use), and lifestyle choices (vegan, flexitarian diets) (Antunes et al., 2022; Chalupa-Krebzdak et al., 2018; Geburt et al., 2022; Roös et al., 2018; Sethi et al., 2016; Wickramasinghe et al., 2021). Plant-based milk alternatives (PBMAs) represent one of the most rapidly expanding segments globally within this transition (de Jong et al., 2024), with declining cow milk consumption alongside substantial growth in PBMA sales and product diversity (Aydar et al., 2020; Bridges, 2018; Moore et al., 2023; Sethi et al., 2016; Silva et al., 2020). Market growth does not necessarily indicate improved diet quality, in part because consumers cannot discern the health consequences of their food choices during purchase, especially for newly introduced or reformulated products, such as PBMAs (Masters et al., 2022).

Recent research indicates limited evidence supporting the nutritional adequacy of substituting animal sources with plant-based sources (Macdiarmid et al., 2012). Replacing dairy with plant-based products positioned as nutritionally equivalent substitutes and alternatives may promote nutritional deficiencies in vulnerable groups (i.e., children, adolescents, pregnant women, lactating women, and the elderly) (Chalupa-Krebzdak et al., 2018; Collard & McCormick, 2021; de Jong et al., 2024; Geburt et al., 2022). For food to be regarded as a good source of calcium, it must have both high calcium content and high bioavailability (Muleya et al., 2024).

Cow milk is considered a good source of calcium, providing approximately 96 mg of absorbable calcium per 240 ml (30 % bioavailability) (Muleya et al., 2024). Cow milk is considered a complete (whole), nutritious food with high-quality protein and high digestibility (Antunes et al., 2022; Brooker et al., 2023; Clegg et al., 2021; Guetouache et al., 2014; Haug et al., 2007; Headey et al., 2024; Roös et al., 2018). Lactose-free products contain lactase enzyme that breaks down

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Abbreviations: PBMAs, Plant-based milk alternatives; UPFs, Ultra Processed Foods; FCDBs, Food Composition Databases; NIP, Nutrient Information Panel.

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lactose into simple sugars while maintaining the nutrient profile (Ajmera, 2023; Rizzo et al., 2020). Cow milk is a single-ingredient product, and is classified as a minimally processed food (NOVA group 1) (Haug et al., 2007; Monteiro et al., 2019).

PBMAs are classified as NOVA group 4, ultra-processed foods (UPFs) (Monteiro et al., 2018, 2019), have complex formulation and manufacturing requirements, and require extensive industrial processing to transform raw plant materials into milk-like beverages (Aydar et al., 2020). Unlike cow milk, PBMAs do not have a standardised composition, which makes a comparative analysis challenging (Drewnowski et al., 2021; Walther et al., 2022). PBMAs are water-based beverages made from extracts of nuts, cereals, legumes, and seeds with additives (preservatives, stabilisers, emulsifiers, flavouring, sweeteners, and salt) added to improve safety, freshness, taste, texture, or appearance (Aydar et al., 2020; Bridges, 2018; Sethi et al., 2016). Recent studies classify PBMAs into four categories: nut-based (almond, coconut, walnut, hazelnut), cereal-based (oat, rice, corn, spelt), legume-based (soy, peanut, lupin, cowpea), and seed-based (sesame, flax, hemp, sunflower) (Adamczyk et al., 2022; Sethi et al., 2016; Verduci et al., 2019; Yang & Dharmasena, 2020).

The absence, however, of minimum nutritional composition requirements and industry standards for plant-based milk alternatives (PBMAs) represents a critical regulatory gap with significant public health implications. As PBMAs gain market share, they are increasingly perceived by consumers as nutritionally equivalent to cow milk, despite compositional differences (Drewnowski et al., 2021; SACN and COT, 2025). To address this issue Drewnowski et al. (2021) proposed evidence-based nutrient standards for PBMAs marketed as milk alternatives, establishing minimum protein thresholds ($\geq$ 2.2 g/100 g), protein quality requirements (PDCAAS $\geq$0.8–0 0.9), maximum added sugar ($<$ 5.3–6.25 g/100 g), low saturated fat ($<$ 0.75 g/100 g) and fortification benchmarks for calcium and vitamins D, A, and B12 at levels comparable to cow milk. These proposed standards for PBMAs are yet to be adopted by the food industry, regulatory authorities, and international standardisation bodies such as Codex Alimentarius, facilitating global harmonisation of PBMA quality standards.

The lack of regulatory standards is further compounded by the scarcity of reliable analytical data on PBMA composition. The majority of PBMA nutrient comparisons have been conducted using declared nutrient information panel (NIP) values from food composition databases (FCDBs) (Redan et al., 2023; Walther et al., 2022), with analytical proximate and mineral composition limited to studies by Smith et al. (2022) in New Zealand, Walther et al. (2022) in Switzerland, Redan et al. (2023) in the United States (US), Antunes et al. (2022) in Portugal, Astolfi et al. (2020) in Italy, and Moore et al. (2023) across European markets. Dependence on secondary data is problematic because FCDBs frequently contain borrowed international data that may not reflect local market formulations, are limited, incompletely documented, old, or unreliable (Ferraz de Arruda et al., 2023). The South African (SA) context exemplifies this challenge: only 44 % of the national FCDBs consist of locally-referenced analytical data, with more than half derived from borrowed international sources (Pretorius et al., 2023; SAFOODS, n.d.). This lack of standardisation, combined with limited analytical data, raises concerns about potential consumer misinformation and nutritional inadequacy in vulnerable populations. High-quality food composition data are essential for evidence-based decision-making across multiple sectors, including food security, health policy, regulatory enforcement, clinical nutrition, and nutrition research (Greenfield & Southgate, 2003; Pretorius et al., 2025).

Addressing these gaps, the objective of the study was to determine the nutrient composition of PBMAs commercially available in the SA retail market and to compare this data to the nutrient composition of cow milk, lactose-free cow milk, and compliance of NIP values with nutrition labelling regulation. Given the knowledge gaps identified, it was hypothesised that:

H_1: PBMAs available in the SA retail market are not nutritionally equivalent to cow milk in terms of macronutrients, minerals, and trace elements.

H_2: The declared nutrient values on the NIP of cow milk and PBMAs comply with the permitted tolerances for nutrient declaration in nutrition labelling as specified in Guideline 5, R.146 of 2012 (Regulation 146, 2012).

These hypotheses guided the research design and analytical approach used to evaluate the nutrient composition and labelling compliance of PBMAs compared to cow milk in the SA market.

2. Materials and methods

2.1. Product inclusion and exclusion criteria

PBMAs in SA are typically UHT-treated and sold in cartons with extended shelf life. This study focused on UHT cow milk in similar packaging, excluding fresh, chilled, or frozen products with short shelf life. Only single-ingredient PBMAs without added flavourings were selected to ensure category comparability and obtain precise category-specific data. Four PBMA categories were included based on market availability. All selected products represent options commercially available to SA consumers in major retail stores.

2.2. Product sampling and preparation

For this analysis, a total of 60 PBMAs and 39 UHT cow milk product samples were selected. To ensure a representative sample from different batches, the same brands of PBMAs and cow milk products with three different production dates were chosen. The cow milk samples included full cream ($n = 3$ brands), low fat (n = 3 brands), fat free ($n = 3$ brands), full cream lactose-free ($n = 2$ brands), and low fat lactose-free ($n = 2$ brands). The PBMA varieties consisted of sweetened soy (n = 3 brands), unsweetened soy (n = 3 brands), sweetened almond (n = 3 brands), unsweetened almond (n = 3 brands), unsweetened oats ($n = 4$ brands), unsweetened rice ($n = 2$ brands), and unsweetened coconut (n = 2 brands).

To ensure a representative sample, each carton was thoroughly shaken before combining equal volumes from different brands and within each category to create a composite sample. These mixtures were prepared in 500 mL containers and repeated three times. Each sample was assigned a unique code, and both production dates and the dates products were sampled in the laboratory were recorded for traceability. Before sampling, the products were stored at room temperature, and frozen at −4 °C after sampling. Samples were transported to the laboratory under cold conditions to preserve integrity. Upon arrival, samples were thawed at room temperature and blended thoroughly to ensure uniformity before analysis. This meticulous preparation aimed to provide accurate and reliable analytical results. The laboratory conducted internal method validations in alignment with ISO/IEC 17025:2017 accreditation standards, ensuring the reliability and accuracy of analytical procedures. To assess the precision of protein, fatty acid, and mineral analyses, the laboratory utilised certified reference materials (CRMs).

2.3. Analytical methodology

2.3.1. Proximate analysis

The proximate analysis of the samples was done using the standard methods of the Association of Official Analytical Chemists (AOAC, 2000). The samples were analysed for moisture, ash, crude fat, crude protein, dietary fibre, and sugar content, in duplicate by LabWorldSA, Johannesburg, South Africa.

2.3.1.1. Moisture and ash. Total ash was gravimetrically determined during combustion in a furnace at 550–600 °C overnight until constant weight was achieved, according to AOAC 942.05 (AOAC, 2000). Ash represents the mineral content after carbon, oxygen, sulfur, and water have been driven off. Moisture was also gravimetrically determined after it had been dried in an oven at 105 °C for 16 h according to AOAC 934.01 (AOAC, 2000). Weight loss was used to calculate dry matter content.

2.3.1.2. Crude fat. Crude fat was determined using the Rose–Gottlieb method, an international reference method for fat analysis in (IDF, 2010). This gravimetric method involves fat extraction using a mixture of organic solvents (diethyl ether and petroleum ether) with ammonium hydroxide under heat treatment to dissociate lipid-protein complexes (O'Sullivan, 2011). Cholesterol content analyses were excluded from the study, as PBMAs are inherently cholesterol-free due to their plant origin, preventing meaningful comparative analysis.

2.3.1.3. Crude protein. Crude protein was determined with the Dumas method AOAC 992.15 (AOAC, 2000), where total nitrogen is measured as nitrogen gas after complete combustion. A product-specific nitrogen to protein conversion factor of 6.25 was used to calculate the protein content. To account for the varying amino acid compositions and nitrogen content of proteins from different food sources, the Jones factors (Milk: 6.38, Soy: 5.71, Almonds: 5.18, Rice: 5.95, Oats: 5.83, Coconut: 5.30) that provide more accurate protein estimates than the general 6.25 factor were used to recalculate total protein content (FAO, 2003).

2.3.1.4. Total carbohydrate and sugar. The total carbohydrate content was estimated as the difference obtained after subtracting the values of protein, fat, ash, and fibre from the total dry matter, and calculated based on the following difference calculation (FAO, 2003):

$$\text{Carbohydrate} = 100\ \% - (\%\ \text{moisture} + \%\ \text{ash} + \%\ \text{crude protein} + \%\ \text{fat})$$

Sugar content was determined by direct quantification of individual sugars (fructose, galactose, glucose, lactose, maltose, sucrose, and xylose) using UFLC (Ultra-Fast Liquid Chromatography), with total sugar content calculated as the sum of all measured sugar components (Shimadzu HPLC UFLC-XR with RI detector, Midrand, South Africa).

2.3.1.5. Energy value. The energy value was calculated by using The Atwater general energy conversion factors, *ie.* 17 kJ/g for protein, 37 kJ/g for fat, and 17 kJ/g for carbohydrates, calculated by taking the sum of the energy value of the crude fat, crude protein, and total carbohydrates (Greenfield & Southgate, 2003).

2.3.1.6. Dietary fibre. Dietary fibre for the PBMA samples (cow milk samples excluded) was analysed manually with acid and alkaline hydrolysis to remove readily available carbohydrates, leaving behind the fibre components. The remaining residue, which comprises the dietary fibre, is then isolated and quantified gravimetrically according to AOAC 985.29 (AOAC, 2000).

2.3.2. Mineral analysis

Mineral analysis involved the ashing, acid digestion, and quantification with Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). Minerals (calcium, magnesium, sodium, potassium, iron, copper, manganese, zinc, phosphorous and sulfur) were determined using the AOAC 942.05 (AOAC, 2005) and AOAC 984.27 (AOAC, 2007), and involved acid digestion with nitric acid, followed by an ICP-OES (Avio® Max ICP-OES, PerkinElmer, Midrand, South Africa).

2.3.3. NIP compliance

NIP values were systematically recorded to enable comparison with laboratory-analysed proximate values and assess labelling accuracy across all product categories. For each product sample, nutritional values and ingredient data were recorded in an Excel spreadsheet and cross-verified to ensure accuracy. The following parameters were documented: brand name, product name, production date, energy (kJ/100 g), protein (g/100 g), fat (g/100 g), saturated fat (g/100 g), trans fat (mg/100 g), cholesterol (mg/100 g), carbohydrates (g/100 g), sugar (g/100 g), fibre content (g/100 g), sodium content (mg/100 g), complete ingredients list (in order of prevalence), and declared allergens.

2.4. Data collection and data treatment

Data collection comprised two primary components: (1) laboratory analytical results from proximate and mineral composition analysis, and (2) nutritional information collected from the nutrient panel declared on product packaging.

Laboratory analysed results were provided as duplicate measurements for each sample. Mean values were calculated from duplicates and converted to standardised units: g/100 g for macronutrients, mg/100 g for minerals and trace elements, and kJ/100 g for energy. Derived values were determined according to the described analytical methodology.

For the data processing of the NIPs, values were standardised per 100 g for direct comparison with analysed values. Where manufacturers reported values per serving or alternative units, conversions were performed using product-specific information. Nutrient values which were declared on packaging as '<' (less than) were recorded as their upper limit (e.g., <1 was recorded as 1). Products lacking complete nutritional declarations were recorded as "not declared (ND)" and "not analysed (NA)" to distinguish from zero values.

Both datasets were integrated into a comprehensive datasheet, enabling direct comparison between analysed and declared values. Data integrity was verified through cross-checking of product identifiers, batch information, and measurement units. Discrepancies, analytical outliers or inconsistencies exceeding expected analytical variation were flagged for further investigation.

2.5. Data analysis

Descriptive statistics were calculated for all nutritional parameters across product groups (cow milk, soy, almond, oat, rice, and coconut PBMAs), and results are reported as mean ± standard deviation (SD) in Table 1, with lower-case letters within the same row that indicate significant differences ($p < 0.05$) between product groups. Statistical analyses were performed using GenStat for Windows (VSN International, 2022) software.

For proximate and mineral composition comparisons, each nutrient group was tested using a one-way analysis of variance (ANOVA) to assess significant differences across product groups (cow milk, soy, almond, oat, rice, and coconut PBMAs), followed by a Fisher's protected *t*-test least significant difference (LSD) at 5 % level of significance ($p < 0.05$).

NIP compliance was assessed by comparing declared and analysed values against Guideline 5, R.146 (Regulation 146, 2012) tolerance limits. Deviations were calculated as [(analysed - declared) / declared] × 100. Products exceeding tolerance limits were classified as non-compliant. Non-compliant nutrients are shown in Table 2 with means ± SD, mean differences, percentage differences, and tolerance range comparisons.

3. Results and discussion

3.1. Nutrient composition and NIP labelling compliance analysis

The energy, proximate content (protein, fat, moisture, ash, and carbohydrate), mineral content, and corresponding NIP values of the composite samples are presented in Table 1. For all the products in the

Table 1
Analysed nutrient content of cow milk and PBMA’s vs declared NIP values.

	Per 100 g	Cow milk full cream *n* = 9 (3 brands)	Cow milk low fat n = 9 (3 brands)	Cow milk Fat free n = 9 (3 brands)	Cow milk lactose free full cream *n* = 6 (2 brands)	Cow milk lactose free low fat n = 6 (2 brands)	Soy PBMA (S) n = 9 (3 brands)	Soy PBMA (US) *n* = 9 (3 brands)	Almond PBMA (S) n = 9 (3 brands)	Almond PBMA (US) n = 9 (3 brands)	Oat PBMA (US) *n* = 12 (4 brands)	Rice PBMA (US) n = 6 (2 brands)	Coconut PBMA (US) n = 6 (2 brands)	*p*-value Analysed
Energy	**Energy kJ Analysed (Calculated)**	269 ± 9.83a	185 ± 1.76b	155 ± 9.28b	244 ± 29.9b	196 ± 6.39b	173 ± 6.91b	140 ± 4.34b	144 ± 10.1b	72.7 ± 3.41c	195 ± 32.7b	194 ± 51.4b	449 ± 453a	0,094
	Energy kJ Declared	269 ± 5.67	185 ± 4.58	150 ± 5.03	260 ± 17.7	155 ± 1.41	149 ± 20.6	105 ± 33.1	122 ± 36.4	73.7 ± 35.4	160 ± 39.8	219 ± 20.6	428 ± 445	–
Carbohydrates	**Carbohydrates g Analysed**	5.16 ± 0.497b	4.75 ± 0.323b	4.90 ± 0.306b	5.81 ± 0.223b	5.09 ± 0.064b	3.81 ± 0.070b	1.92 ± 0.025b	4.43 ± 0.411b	0.933 ± 0.299b	7.34 ± 1.27b	9.06 ± 2.49b	30.9 ± 38.5a	0,080
	Carbohydrates g Declared	4.67 ± 0.577	4.33 ± 1.15	4.33 ± 1.15	5.00 ± 0.00	3.50 ± 2.12	5.67 ± 5.51	1.00 ± 0.00	3.67 ± 1.15	1.33 ± 1.15	5.25 ± 2.39	10.5 ± 0.707	3.45 ± 0.778	–
	Total Sugar g Analysed	4.36 ± 0.120a	4.12 ± 0.124b	4.72 ± 0.111a	4.51 ± 0.374a	4.25 ± 0.193a	2.36 ± 0.073c	0.508 ± 0.030e	3.95 ± 0.272b	0.097 ± 0.016e	2.75 ± 0.156c	3.848 ± 1.15b	1.97 ± 0.064d	<0,001
	Total Sugar g Declared	4.47 ± 0.416	4.47 ± 0.252	4.30 ± 0.90	4.50 ± 0.00	3.05 ± 2.05	3.67 ± 2.89	0.367 ± 0.115	3.53 ± 1.10	0.467 ± 0.473	2.08 ± 1.46	4.05 ± 0.919	2.25 ± 0.071	–
	Lactose g Analysed	4.34 ± 0.152a	4.11 ± 0.131a	4.72 ± 0.111a	0.00 ± 0.00c	0.038 ± 0.040b	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c	0.708 ± 1.19b	0.00 ± 0.00b	0.00 ± 0.00b	<0,001
	Lactose g Declared	ND	ND	ND	0.250 ± 0.354	0.100 ± 0.141	ND	ND	ND	ND	ND	ND	ND	–
	Fibre g Analysed	NA	NA	NA	NA	NA	0.100 ± 0.00a	0.100 ± 0.00a	0.100 ± 0.00a	0.100 ± 0.00a	0.100 ± 0.00a	0.100 ± 0.00a	0.100 ± 0.00a	0,270
	Fibre g Declared	<0.367# ± 0.231	<0.367# ± 0.231	<0.367# ± 0.231	<0.300# ± 0.283	<0.750# ± 0.354	0.500# ± 0.00	0.767# ± 0.252	0.500# ± 0.436	0.467# ± 0.473	0.225# ± 0.206	0.550# ± 0.636	0.350# ± 0.354	–
Protein	**Total Protein g Analysed**	3.47 ± 0.058a	3.47 ± 0.153a	3.53 ± 0.058a	3.27 ± 0.231a	3.53 ± 0.058a	2.80 ± 0.100b	2.67 ± 0.058b	0.567 ± 0.058c	0.400 ± 0.000d	0.653 ± 0.200c	0.100 ± 0.028d	1.05 ± 1.20c	<0,001
	Total Protein g Declared	3.33 ± 0,31	3.47 ± 0.115	3.43 ± 0.306	3.15 ± 0.212	3.40 ± 0.566	3.10 ± 0.173	2.83 ± 0.600	0.600 ± 0.173	0.367 ± 0.153	0.850 ± 0.100	0.250 ± 0.071	1.00 ± 1.41	–
Lipids	**Total Fat g Analysed**	3.31 ± 0.180b	1.23 ± 0.188b	0.300 ± 0.137b	2.42 ± 0.693b	1.35 ± 0.145b	1.65 ± 0.150b	1.67 ± 0.105b	1.59 ± 0.252b	1.35 ± 0.067b	1.61 ± 0.728b	1.03 ± 0.233b	10.4 ± 12.3a	0,052
	Total Fat g Declared	3.40 ± 0.00	1.13 ± 0.231	0.300 ± 0.200	3.45 ± 0.071	1.45 ± 0.212	1.73 ± 0.058	1.50 ± 0.794	1.37 ± 0.378	1.57 ± 0.569	1.20 ± 0.668	1.10 ± 0.141	9.60 ± 11.6	–
	SFA g Analysed	2.17 ± 0.095b	0.773 ± 0.083b	0.227 ± 0.120b	1.58 ± 0.538b	0.890 ± 0.121b	0.363 ± 0.038b	0.307 ± 0.015b	0.187 ± 0.038b	0.137 ± 0.006b	0.282 ± 0.061b	0.185 ± 0.035b	9.65 ± 11.4a	0,024
	SFA g Declared	2.33 ± 0.115	0.800 ± 0.173	0.100 ± 0.00	2.05 ± 0.354	1.00 ± 0.283	0.300 ± 0.00	0.600 ± 0.424	0.133 ± 0.06	0.233 ± 0.231	0.233 ± 0.058	0.250 ± 0.212	9.05 ± 11.1	–
	MUFA g Analysed	1.04 ± 0.075a	0.323 ± 0.015b	0.070 ± 0.020b	0.753 ± 0.140a	0.417 ± 0.032b	0.373 ± 0.045b	0.410 ± 0.020b	1.07 ± 0.181a	0.917 ± 0.049a	0.903 ± 0.541a	0.515 ± 0.177b	0.625 ± 0.714a	<0,001
	MUFA g Declared	0.90 ± 0.00	0.323 ± 0.015	0.100 ± 0.00	ND	0.417 ± 0.032	0.400 ± 0.00	0.450 ± 0.071	0.933 ± 0.231	1.00 ± 0.300	0.633 ± 0.058	0.300 ± 0.00	ND	–
	PUFA g Analysed	0.107 ± 0.006c	0.137 ± 0.097c	0.010 ± 0.00c	0.097 ± 0.032c	0.047 ± 0.006c	0.917 ± 0.093a	0.960 ± 0.082a	0.337 ± 0.040b	0.303 ± 0.021b	0.430 ± 0.175b	0.335 ± 0.375b	0.095 ± 0.106c	<0,001
	PUFA g Declared	0.100 ± 0.00	0.100 ± 0.00	0.300 ± 0.00	ND	ND	1.10 ± 0.00	0.900 ± 0.283	0.300 ± 0.10	0.367 ± 0.058	0.667 ± 0.058	0.550 ± 0.071	ND	–
	Trans Analysed	0.14 ± 0.010a	0.04 ± 0.00d	0.007 ± 0.006e	0.100 ± 0.020b	0.053 ± 0.006c	0.007 ± 0.006e	0.00 ± 0.00e	0.003 ± 0.006e	0.00 ± 0.00e	0.00 ± 0.00e	0.005 ± 0.007e	0.00 ± 0.00e	<0,001
	Trans Declared	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	ND	ND	0.100 ± 0.00	0.100 ± 0.00	0.100 ± 0.00	0.100 ± 0.00	0.100 ± 0.00	0.100 ± 0.00	0.00 ± 0.00	–

(*continued on next page*)

Table 1 (*continued*)

	Per 100 g	Cow milk full cream *n* = 9 (3 brands)	Cow milk low fat n = 9 (3 brands)	Cow milk Fat free n = 9 (3 brands)	Cow milk lactose free full cream *n* = 6 (2 brands)	Cow milk lactose free low fat n = 6 (2 brands)	Soy PBMA (S) n = 9 (3 brands)	Soy PBMA (US) *n* = 9 (3 brands)	Almond PBMA (S) n = 9 (3 brands)	Almond PBMA (US) n = 9 (3 brands)	Oat PBMA (US) *n* = 12 (4 brands)	Rice PBMA (US) n = 6 (2 brands)	Coconut PBMA (US) n = 6 (2 brands)	*p*-value Analysed
Minerals	**Calcium mg Analysed**	123 ± 23.1a	120 ± 10.0a	123 ± 11.5a	110 ± 10.0a	130 ± 0.00a	70.0 ± 10.0b	100 ± 10.0a	96.7 ± 5.77a	103 ± 40.4a	47.5 ± 25.0b	45.0 ± 49.5b	60.0 ± 70.7b	0,002
	Calcium mg Declared	116 ± 6,07	116 ± 2.30	117 ± 3.98	111 ± 5.16	107 ± 41.3	120 ± 0.00	96.4 ± 0.00	123 ± 3.54	115 ± 19.6	84.1 ± 38.2	102 ± 0.00	96.0 ± 0.00	–
	Sodium mg Analysed	53.3 ± 15.3a	53.3 ± 5.77a	50.0 ± 10.0b	43.3 ± 5.77b	43.3 ± 5.77b	66.7 ± 5.77a	50.0 ± 0.00b	46.7 ± 5.77b	43.3 ± 5.77b	30.0 ± 11.5c	20.0 ± 0.00c	35.0 ± 7.07b	<0,001
	Sodium mg Declared	36.7 ± 3.21	43.0 ± 3.61	41.3 ± 0.577	42.5 ± 7.78	39.5 ± 3.54	44.7 ± 36.5	28.0 ± 25.2	30.3 ± 18.3	31.3 ± 25.0	46.3 ± 12.1	24.5 ± 4.95	19.2 ± 8.27	–
	Potassium mg Analysed	140 ± 26.5a	130 ± 10.0b	130 ± 10.0b	120 ± 10.0b	130 ± 10.0b	143 ± 5.77a	163 ± 5.77a	30 ± 0.00c	26.7 ± 5.77c	37.5 ± 22.2c	10.0 ± 0.00c	110 ± 70.7b	<0,001
	Potassium mg Declared	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	45.7 ±	–
	Phosphorous mg Analysed	1.07 ± 0.208a	1.00 ± 0.00a	1.07 ± 0.0577a	0.833 ± 0.0577b	0.900 ± 0.00b	0.600 ± 0.00d	0.733 ± 0.0577c	0.300 ± 0.00e	0.300 ± 0.00e	0.150 ± 0.0577f	0.100 ± 0.00f	0.010 ± 0.00 g	<0,001
Trace elements	**Iron mg Analysed**	0.275 ± 0.018c	0.314 ± 0.092c	0.399 ± 0.250c	0.305 ± 0.130c	0.252 ± 0.035c	0.634 ± 0.019b	0.600 ± 0.029b	0.551 ± 0.093b	0.476 ± 0.055b	0.299 ± 0.066c	0.292 ± 0.112c	0.965 ± 0.457a	<0,001
	Copper mg Analysed	0.075 ± 0.021c	0.069 ± 0.010c	0.066 ± 0.011c	0.043 ± 0.012d	0.040 ± 0.009d	0.208 ± 0.037a	0.220 ± 0.047a	0.115 ± 0.005b	0.092 ± 0.028c	0.131 ± 0.035b	0.095 ± 0.001c	0.161 ± 0.052b	<0,001
	Zinc mg Analysed	0.502 ± 0.106a	0.475 ± 0.038a	0.526 ± 0.045a	0.450 ± 0.039a	0.509 ± 0.020a	0.378 ± 0.016a	0.424 ± 0.028a	0.240 ± 0.096b	0.235 ± 0.063b	0.210 ± 0.126b	0.173 ± 0.033b	0.471 ± 0.37a	<0,001
	Manganese mg Analysed	0.015 ± 0.002b	0.022 ± 0.008b	0.019 ± 0.018b	0.012 ± 0.001b	0.012 ± 0.002b	0.113 ± 0.008b	0.144 ± 0.013b	0.055 ± 0.009b	0.054 ± 0.011b	0.075 ± 0.037b	0.028 ± 0.003b	0.460 ± 0.455a	0,005
Ash	**Ash g Analysed**	0.79 ± 0.135a	0.74 ± 0.010a	0.86 ± 0.113a	0.67 ± 0.064b	0.74 ± 0.010a	0.60 ± 0.035b	0.747 ± 0.042a	0.333 ± 0.015c	0.487 ± 0.272c	0.25 ± 0.089d	0.10 ± 0.113d	0.45 ± 0.042c	<0,001
Moisture	**Moisture g Analysed**	87.3 ± 0.354b	89.8 ± 0.278b	90.4 ± 0.316b	87.8 ± 1.03b	89.3 ± 0.206b	91.1 ± 0.253b	93.0 ± 0.175a	93.1 ± 0.461a	96.8 ± 0.023a	90.1 ± 1.31b	89.7 ± 2.64b	84.3 ± 13.7c	0,012
Ratio	**Ca:P**	1.09 ± 0.29a	1.20 ± 0.10a	1.14 ± 0.13a	1.41 ± 0.15a	1.44 ± 0.00a	1.17 ± 0.17a	1.33 ± 0.17a	3.33 ± 0.19b	4.00 ± 1.35b	2.00 ± 1.84a	5.00 ± 4.95b	2.00 ± 2.36a	<0,001

Note:

The data is presented as mean ± SD.

S = Sweetened; US = Unsweetened, SFA = saturated fatty acids; MUFA = monosaturated fatty acids; PUFA = polyunsaturated fatty acids.

Values expressed per 100 g.

NIP = Nutrient Information Panel.

NA = Not Analysed.

ND = Not Declared.

#AOAC 985.29, 991.43.

Different lower-case letters within a row indicate significant differences between product categories (Fisher's Least Significant Difference test; $p < 0.05$).

– No value.

Table 2
Non-compliance with R.146 thresholds – analysed vs declared nutrient values.

Nutrients	Product group	Analysed (Mean ± SD)	Declared (Mean ± SD)	Mean difference	% Mean difference	Tolerance range*	Compliance
Total Sugars (g/100 g)	Almond S	3.95 ± 0.272	3.05 ± 2.05	0.420	11.9	−1.5 % to +1.5 %	Underreported
	Oat US	2.75 ± 0.156c	2.08 ± 1.46	0.680	32.8		Underreported
Calcium (mg/100 g)	Soy S	70.0 ± 10.0	120 ± 0.00	–50.0	−41.7	−20.0 to +50 %	Overreported
	Almond S	96.7 ± 5.77	123 ± 3.54	– 25.8	−21.1		Overreported
	Oat US	47.5 ± 25.0	84.1 ± 38.2	–36.6	−43.5		Overreported
	Rice US	45.0 ± 49.5	102 ± 0.00	–56.7	−55.8		Overreported
	Coconut US	60.0 ± 70.7.0	96.0 ± 0.00	–36.0	−37.5		Overreported
Sodium (mg/100 g)	Cow milk FC	53.3 ± 15.3.0	36.7 ± 3.21	16.7	43.5	±20 %	Underreported
	Soy S	66.7 ± 5.77.0	44.7 ± 36.5	22.0	49.3		Underreported
	Soy US	50.0 ± 0.00	28.0 ± 25.2	22.0	78.6		Underreported
	Almond S	46.7 ± 5.77	30.3 ± 18.3	16.3	96.6		Underreported
	Almond US	43.3 ± 5.77.0	31.3 ± 25.0	12.0	53.8		Underreported
	Coconut US	35.0 ± 7.07	19.2 ± 8.27	15.9	82.8		Underreported
Fibre (g/100 g)	Soy S	0.10 ± 0.00	0.500 ± 0.00	−0.400	−80.0	±1.5 %	Overreported
	Soy US	0.10 ± 0.00	0.767 ± 0.252	−0.667	−87.6		Overreported
	Almond S	0.10 ± 0.00	0.500 ± 0.436	−0.400	−80.0		Overreported
	Almond US	0.10 ± 0.00	0.467 ± 0.473	−0.376	−78.6		Overreported
	Oat US	0.10 ± 0.00	0.225 ± 0.206	−0.125	−55.6		Overreported
	Rice US	0.10 ± 0.00	0.550 ± 0.636	−0.450	−81.8		Overreported
	Coconut US	0.10 ± 0.00	0.350 ± 0.354	−0.250	−71.4		Overreported

Note:
The data is presented as mean ± SD.
S = Sweetened; US = Unsweetened; SFA = saturated fatty acids; MUFA = monosaturated fatty acids; PUFA = polyunsaturated fatty acids; FC = Full cream
Values expressed per 100 g.
* *for protein and carbohydrates (< 10 g/100 g: ±2 g; ≥ 10 g/100 g: ± 25 %); for fat (< 3 g/100 g: ± 1.5 g; 3–10 g/100 g: ± 2.5 g; ≥ 10 g/100 g: ± 25 %); for fatty acids (sum of SFAs, MUFAs, PUFAs) (≤5 g/100 g: ±1 g; 5–40 g/100 g: ± 15 %; ≥ 40 g/100 g: ≥ 8 g), for sugars and fibre (< 8 g/100 g: ± 1.5 %; ≥ 8 g/100 g: ± 20 %); for sodium (± 20 %); for naturally occurring minerals (−30 to + 40 %); and for added minerals (−20 to + 50 %) (Regulation 146, 2012).*

study, the mineral content for sulfur (<0.10 g/100 g) and magnesium (<0.5 g/100 g) was below the limit of quantification (<LOQ) of the laboratory and will therefore not be discussed.

3.1.1. *Energy*

Appropriate and balanced consumption of macronutrients is necessary to meet recommended daily energy requirements (Trumbo et al., 2002). Statistical analysis revealed significant differences in energy content between cow milk and PBMAs ($p < 0.05$). Full-cream cow milk contained the highest energy content (269 kJ/100 g), while fat-free cow milk showed the lowest energy among dairy options (155 kJ/100 g). Among PBMAs, coconut demonstrated the highest and most variable energy content (449 kJ/100 g) due to high fat content in one brand, while unsweetened almond showed the lowest energy content (72.7 kJ/100 g). Oat (195 kJ/100 g) and rice (194 kJ/100 g) PBMAs demonstrated energy levels comparable to low-fat cow milk varieties.

The energy gap between cow milk and plant-based alternatives potentially has implications for dietary substitution, with a typical 200 ml serving of unsweetened almond PBMA providing approximately and on average 145 kJ, compared to 538 kJ from full cream cow milk. Lower energy content may benefit weight management goals but requires consideration for populations with high energy requirements, such as young children or individuals with increased metabolic needs (Verduci et al., 2019).

3.1.2. *Carbohydrates*

Statistically significant differences were observed in total carbohydrate content across product categories. PBMAs varied substantially by type: coconut demonstrated extremely high and variable carbohydrate content (30.9 g/100 g) due to one outlier brand, while rice (9.06 g/100 g) and oat (7.34 g/100 g) contained higher carbohydrate content than cow milk varieties (range: 4.75–5.81 g/100 g). Unsweetened soy (1.92 g/100 g) and unsweetened almond (0.93 g/100 g) contained significantly lower carbohydrate levels. While neither cow milk nor PBMAs serves as a major carbohydrate source relative to the recommended daily allowance (RDA) of 130 g for adults (Institute of Medicine, 2005; Trumbo et al., 2002), the lower carbohydrate content in soy and almond PBMAs may benefit individuals following carbohydrate-restricted diets or managing glycaemic control.

3.1.2.1. Sugar content. Total sugar content varied significantly ($p < 0.05$) across all product types. Cow milk contained the highest sugar levels (4.36 g/100 g), primarily from lactose. Among PBMAs, sweetened almond (3.95 g/100 g) and rice (3.85 g/100 g) showed the highest sugar content, while unsweetened almond (0.10 g/100 g) and unsweetened soy (0.51 g/100 g) contained minimal sugars. This compares with the sugar content reported for New Zealand by Smith et al. (2022), with 4.57 g/100 g for rice, 2.93 g/100 g, while unsweetened almond had concentrations below 0.5 g/100 g. The higher sugar content in rice and oat PBMAs likely derives from natural sugars and starches intrinsic to these cereal-based ingredients.

NIP labelling compliance analysis (Table 2) revealed sugar content was underreported in sweetened almond (11.9 % deviation) and oat (32.8 % deviation) PBMAs, exceeding the ±1.5 % tolerance limit (Regulation 146, 2012).

3.1.2.2. Fibre content. Dietary fibre is an essential nutrient that not only promotes satiety to help reduce energy intake and, therefore, the risk of obesity, but also helps diminish blood glucose and cholesterol concentrations, thereby reducing the risk of coronary heart disease (Trumbo et al., 2002). All PBMA samples demonstrated negligible fibre content (<0.10 g/100 g) across all varieties (soy, almond, oat, rice, and coconut), despite NIP labelling representing an overreporting of actual fibre content that exceeded the 1.5 % tolerance limit (Regulation 146, 2012).

Smith et al. (2022) in New Zealand found mean dietary fibre contents of PBMAs ranged from 0.09 to 0.85 g/100 g, with rice PBMAs with the lowest and oat PBMAs with the highest fibre content. These values align with SA findings, where all PBMAs demonstrated negligible fibre content (<0.10 g/100 g). Drewnowski et al. (2021) proposed that 1–2 g of fibre per 100 g was a suitable target for plant-based beverages; however, only nine of 103 New Zealand products surveyed stated fibre contents above 1 g per 100 g (Smith et al., 2022) This supports SA findings of significant overreporting on NIP labels, where declared values of up to 2 g per serving exceeded actual analytical content.

Given that adults require 25–38 g of daily fibre intake for optimal digestive and cardiovascular health (Institute of Medicine, 2005; Trumbo et al., 2002), PBMAs do not contribute meaningfully to meeting these requirements, with a typical 200 ml serving of PBMAs providing less than 0.2 g of dietary fibre compared to label claims of up to 2 g per serving for rice and soy PBMAs. Labelling discrepancies are concerning as they may mislead consumers who specifically choose plant-based alternatives, expecting enhanced fibre benefits, when these products offer no fibre advantage over cow milk, despite their plant origins, due to extensive filtration and processing that causes loss of fibre (Sethi et al., 2016).

Fibre analysis of cow milk samples was omitted from the proximate analysis, since dairy products do not naturally contain fibre. NIP labels on cow milk products reported values of <0.5 g/100 g, consistent with regulatory requirements for reporting nutrients below detection thresholds (Regulation 146, 2012).

3.1.3. Protein

Protein content demonstrated substantial nutritional disparities and significant differences ($p < 0.05$) between cow milk and PBMAs ($p < 0.001$), with cow milk varieties containing the highest protein levels (3.27–3.53 g/100 g), while soy varieties (sweetened: 2.80 g/100 g; unsweetened: 2.67 g/100 g) showed the most comparable protein content to cow milk. In contrast, rice PBMA contained minimal protein (0.10 g/100 g), followed by unsweetened almond (0.40 g/100 g), sweetened almond (0.57 g/100 g), and oat (0.65 g/100 g). Cow milk protein values (3.45 g/100 g) for this study aligned closely with international data: US (3.28 g/100 g) (Redan et al., 2023) New Zealand (3.3–3.9 g/100 g) (Smith et al., 2022), and Switzerland (3.5 g/100 g) (Walther et al., 2022), with <5 % variance demonstrating analytical consistency and minimal inter-laboratory variability.

In contrast, PBMA composition showed greater variability across studies, with the soy PBMA protein content (2.67–2.80 g/100 g) aligned with New Zealand, SA (3.2 g/100 g) (Smith et al., 2022), and Switzerland (4.3 g/100 g) (Walther et al., 2022), where soy drinks provided slightly more protein than other PBMAs, and all other PBMAs contained less than 1.1 g protein per 100 g, consistent with SA findings for almond, rice, and oat PBMAs, and confirmed that except for cow milk and soy drinks, most milk alternatives contained ≤1 % protein and were not considered good protein sources.

These protein variations have important implications for meeting daily requirements. A 200 ml serving of cow milk contains approximately 6.9 g protein, and soy PBMA provides 5.3 g, a considerable contribution to the 46–56 g of the RDA for adults (Institute of Medicine, 2005), in contrast with the other PBMAs that contribute minimal protein.

The protein deficiency in non-soy PBMAs is particularly concerning for vulnerable populations, including children, adolescents, pregnant women, and elderly individuals who rely on milk as a primary protein source. Protein quality also differs, as cow milk supplies complete protein of high biological value, whereas most plant sources of protein lack one or more indispensable amino acids and have lower digestible scores (FAO, 2011b; Schaafsma, 2000), thereby contributing to the nutritional gap when there is direct substitution without dietary compensation. Protein labelling met regulatory compliance standards across all product categories, with declared values within permitted tolerances.

3.1.4. Fats

Fats are an important energy substrate and are necessary for vitamin and nutrient absorption, cellular integrity, hormone production, and organ protection, while overconsumption of saturated and trans fat is closely linked with higher concentrations of LDL cholesterol and heart disease risk (Antunes et al., 2022; Haug et al., 2007). Fat labelling accuracy was within regulatory tolerances for total fat content across all categories (Table 2).

Total fat content varied significantly across product categories (Table 1). Full-cream cow milk contained the highest fat among dairy options (3.31 g/100 g), while fat-free cow milk contained minimal fat (0.30 g/100 g). Among PBMAs, coconut demonstrated very high and variable fat content (10.4 g/100 g), while other PBMAs ranged from 1.03 g/100 g (rice), 1.35–1.59 g/100 g (almond) to 1.67 g/100 g (unsweetened soy). Lipid contents were similar among the PBMAs in Italy, with the lowest found in oat (0.37 g/100 g) and the highest in almond-based beverages (1.99 g/100 g) (Moore et al., 2023).

Fat quality varied markedly by product type. Cow milk varieties had higher saturated fatty acid (SFA) content (0.23–2.17 g/100 g) compared to most PBMAs (0.14–0.36 g/100 g), except coconut PBMA, which had exceptionally high SFA (9.65 g/100 g). PBMAs demonstrated higher polyunsaturated fatty acid (PUFA) content, with soy varieties showing the highest levels (sweetened: 0.92 g/100 g; unsweetened: 0.96 g/100 g) compared to cow milk (0.01–0.14 g/100 g). Trans fat content was higher in cow milk varieties (0.007–0.14 g/100 g) compared to PBMAs (0.00–0.007 g/100 g), though levels were minimal in both product types.

Fat quality patterns in SA PBMAs reflected international findings in Portugal (Antunes et al., 2022) and Italy (Moore et al., 2023), where coconut fatty acid profile was dominated by SFAs, whereas MUFAs or PUFAs were dominant in other PBMAs. These findings support the higher PUFA content observed in SA soy PBMAs (0.92–0.96 g/100 g) compared to cow milk (0.01–0.14 g/100 g), providing cardiovascular advantages for PBMAs.

3.1.5. Minerals

Statistical analysis revealed significant differences in mineral content across product categories ($p < 0.05$). Cow milk had a higher mineral density overall, as indicated by higher ash content (0.76 /100 g) compared to PBMAs (0.10–0.75 g/100 g). and lower moisture content (87.3–90.4 g/100 g) compared to most PBMAs (89.7–96.8 g/100 g). These differences reflect the more nutrient-dense composition of cow milk versus the greater water content of plant-based alternatives.

Calcium showed significant variation across categories, with cow milk varieties containing higher calcium levels (110–130 mg/100 g), PBMAs showed substantial variation with unsweetened soy (100 mg/100 g) and unsweetened almond (103 mg/100 g) approaching cow milk levels, whereas oat (47.5 mg/100 g), rice (45.0 mg/100 g), and coconut (60.0 mg/100 g) contained significantly lower calcium and are not considered good sources. Bioavailability considerations further amplify these differences: cow milk calcium demonstrates approximately 30 % bioavailability, while plant-based calcium sources typically exhibit 5–60 % bioavailability depending on the presence of antinutrients such as phytates and oxalates. (Aydar et al., 2020; Moore et al., 2023; Muleya et al., 2024). Antinutrients present in significantly impair calcium absorption by forming insoluble complexes, thereby reducing its bioavailability. This effect is particularly associated with oxalates in almond-based products and phytates in soy and oat-based products, which bind calcium and reduce its bioavailability (Chalupa-Krebzdak et al., 2018). When accounting for bioavailability, soy PBMAs fortified with calcium carbonate may deliver approximately 24–36 mg of absorbable calcium per 100 g, assuming a 25–30 % absorption rate, though this may further be potentially affected by antinutrients (Weaver et al., 1999).

Calcium disparities between SA and international markets were notable between most of the studies, with New Zealand PBMAs similar concentrations to cow milk, whereas SA PBMAs averaged only 65 % of cow milk calcium content (Antunes et al., 2022; Astolfi et al., 2020; Moore et al., 2023; Smith et al., 2022). Differences observed in Calcium contents between these studies may be attributed to the different levels of fortification during PBMA manufacturing (Roös et al., 2018; Vanga & Raghavan, 2018). Interestingly, Walther et al. (2022) reported that the addition of seaweed (*L. calcareum*) improved the calcium concentration to a level comparable with that in cow milk.

Labelling compliance analysis (Table 2) shows systematic over-reporting of calcium across multiple PBMA categories. Sweetened soy showed the largest discrepancy (41.7 % overreported), followed by rice (55.8 %), oat (43.5 %), coconut (37.5 %), and sweetened almond (21.1 %). These overreporting levels exceeded the −20 % to +50 % tolerance range for added minerals, potentially creating misconceptions about the calcium content and nutritional adequacy of PBMAs.

Phosphorous demonstrated the largest relative significant difference between product types, with cow milk containing higher phosphorous (0.83–1.07 mg/100 g) compared to PBMAs (0.01–0.73 mg/100 g). This difference has particular relevance to bone and tooth health, since phosphorous plays a synergistic role with calcium in bone homeostasis and osteoporosis prevention (Antunes et al., 2022; Cashman, 2006). All cow milk varieties demonstrated optimal calcium-to-phosphorous (Ca:P) ratios (1.09–1.44), falling within the acceptable range that supports efficient calcium absorption and skeletal development (Heaney, 2000). Among PBMAs, only soy varieties approached optimal ratios (sweetened: 1.17; unsweetened: 1.33). However, other PBMAs had elevated Ca:P ratios: almond (3.33–4.00), rice (5.00), and oat and coconut (2.00 each). Ca:P ratios reported by Antunes et al. (2022) ranged from 1.4 (soy), 1.9 (oat), to 2.3 (almond), and can mostly be attributed to higher levels of either phosphorous or calcium in PBMAs.

Ratios greater than 2:1 can result in reduced phosphorous levels, which can impact magnesium absorption and may also compromise bone mineralisation in the presence of adequate calcium intake (Razzaque, 2011). The imbalanced ratios in most PBMAs suggest that despite fortification efforts to match calcium levels, the failure to maintain appropriate phosphorous content creates new nutritional inadequacies that may compromise the intended bone health benefits (Takeda et al., 2012). The Ca:P analysis is presented in Table 1.

Potassium content was significantly higher in cow milk varieties (120–140 mg/100 g) and soy PBMAs (143–163 mg/100 g) compared to other PBMAs. Almond (26.7–30.0 mg/100 g), oat (37.5 mg/100 g), and rice (10.0 mg/100 g) contained substantially lower potassium levels. Bioavailability of potassium is generally high (> 90 %) from animal and plant sources, making the absolute differences in content particularly meaningful for blood pressure regulation and cardiovascular health (Stone et al., 2016).

Mineral bioavailability is of particular concern for vulnerable groups such as children, pregnant/lactating women, and the elderly due to their higher requirement of minerals and possibly greater risk of deficiencies when cow milk is replaced by PBMAs (Gibson et al., 2010). The combination of lower content and potentially reduced bioavailability of bone-building minerals potentially implicates that the direct replacement of cow milk by PBMAs without dietary compensation or supplementation may undermine nutritional adequacy. Research into the bioavailability of minerals for PBMAs, however, is still lacking (Moore et al., 2023).

Sodium levels varied across categories, with soy PBMAs showing the highest levels (sweetened: 66.7 mg/100 g) and rice the lowest (20.0 mg/100 g). Smith et al. (2022) reported much higher sodium values for PBMAs, with rice the highest (71.4 mg/100 g) and almond the lowest (57.3 mg/100g). Labelling compliance analysis (Table 2) revealed that sodium was consistently underreported across multiple product categories. Full-cream cow milk showed 43.5 % underreporting, while PBMA underreporting ranged from 49.3 % (sweetened soy) to 96.6 % (sweetened almond), all exceeding the ± 20 % tolerance limit.

The 7–9 mg/100 g sodium underreporting present in both groups, albeit a small difference, constitutes a 17–20 % reduction that might be significant for consumers monitoring sodium intake for cardiovascular health. These findings support the necessity of improving the accuracy of mineral analysis in food labelling, especially PMBAs, where the levels of fortification may not align with the declared values.

3.1.6. Trace elements

The trace element profile revealed contrasting patterns across product categories, though bioavailability differences must be considered. Iron content was significantly higher in soy (0.60–0.63 mg/100 g), almond (0.48–0.55 mg/100 g), and coconut (0.97 mg/100 g) PBMAs compared to cow milk varieties (0.25–0.40 mg/100 g). Antunes et al. (2022) mentioned that all macromineral and trace element content between cow milk and PBMAs were significantly different, with the exception of iron (0.16 mg/kg), with much lower iron values than SA PBMA findings. Smith et al. (2022) and Walther et al. (2022) reported similar iron values ranging from <0.05 mg/100 g (rice), 0.1 mg/100 g (almond), and 0.38–0.59 mg/100 g (soy), respectively. Higher iron levels are, however, offset by the bioavailability differences: non-heme iron in PBMAs has 2–20 % absorption compared to 15–35 % for heme iron, and is further inhibited by phytates, polyphenols, and calcium present in plant-based products (Hurrell & Egli, 2010).

Copper content was significantly higher in soy PBMAs (0.21–0.22 mg/100 g) compared to cow milk varieties (0.04–0.08 mg/100 g). Copper is necessary for iron absorption and utilisation, and adequate bioavailability (30–70 %) from plant sources (Linder & Hazegh-Azam, 1996) suggests higher PBMA copper concentrations may promote bioaccessible copper intake.

Zinc content was significantly higher in SA cow milk varieties (0.45–0.53 mg/100 g) and soy PBMAs (0.38–0.42 mg/100 g) compared to other PBMAs (0.17–0.47 mg/100 g), with implications for immune function. Similar zinc values were reported for New Zealand, which ranged from 0.35 mg/100 g (cow milk) and 0.14 mg/100 g (soy) as the highest zinc value between the PBMAs (Smith et al., 2022). These differences are amplified by bioavailability: zinc absorption from animal sources (20–40 %) substantially exceeds plant sources (10–15 %) due to phytate interference, potentially creating functional zinc deficiency despite moderate levels in some PBMAs (Sandström, 2001).

Manganese content was significantly higher in PBMAs, particularly coconut (0.46 mg/100 g) and soy (0.11–0.14 mg/100 g), compared to cow milk (0.01–0.02 mg/100 g). Although manganese bioavailability is relatively low across all dietary sources (1–5 %), the substantially higher concentrations in PBMAs likely result in increased bioavailable manganese intake (Aschner & Erikson, 2017).

3.2. NIP ingredient declaration

3.2.1. Base ingredients content

Base ingredient percentages varied considerably across PBMA types and showed regional differences when compared with European products. Moore et al. (2023) analysed ingredient declarations across Italian market PBMAs, providing a useful benchmark for SA PBMAs (Table 3).

Soy PBMAs in SA contained 6.2–8.7 % soybean content, making up less than 10 % of the product, comparable to Moore et al. (2023), who reported 5.6–13.5 % soya content across Italian brands. Almond PBMAs showed the lowest base ingredient content in both markets: SA products contained 2–4 % almonds, while Moore et al. (2023) reported greater variability (2–11 %), suggesting some European brands offer higher nut content options. Oat PBMA content was similar between markets, ranging from 8 to 16 % in SA compared to 10–16 % according to Moore et al. (2023). Rice PBMA content was comparable (SA: 11–15 %; Italy: 14–17 %), with the most notable difference observed for coconut PBMAs: SA products contained substantially higher coconut content (79.6–99.9 %) compared to the highly variable Italian market (4–60 % coconut), where many products relied heavily on water, rice starch, and thickeners to achieve volume (Moore et al., 2023).

Table 3
List of ingredients declared on NIPs.

Product type	Ingredient list	Allergens
Cow Milk Full-cream	Full Cream Milk (Cow's Milk)	Cow's Milk
Cow Milk Low-fat	Low Fat Milk (Cow's Milk)	Cow's Milk
Cow Milk Fat-free	Fat Free Milk (Cow's Milk)	Cow's Milk
Lactose Free Cow Milk Full-cream	Full Cream Milk (Cow's Milk), Lactase enzyme, Vit D	Cow's Milk
Lactose Free Cow Milk Low-fat	Medium Fat Milk (Cow's Milk), Tricalcium Citrate, Lactase enzyme, VitD3	Cow's Milk
Soy 1 S	Soya Base (water, hulled soya beans 8,7 %), Sugar, Acidity regulators (Potassium Phosphates), Calcium Carbonate, Flavourings, Sea Salt, Emulsifier, Stabiliser (Gellan Gum), Flavouring, Vitamins (A, D2 and E)	Soya
Soy 2 S	Water, Soy Protein (6,2 %), Sucrose, Stabiliser, Emulsifier (Soy Lecithin, Silicon Dioxide), Acidity Regulator (Potassium Citrate), Salt, Flavouring	Soy
Soy 3 S	Water, Ground Whole Soybeans (7 %), Fructose, Minerals (E341), Inulin, Acidity Regulator (E332), Salt, Flavouring, Stabiliser (E460, E466), Vitamin B2, Vitamin B12	Not declared
Soy 1 US	Soya Base (water, hulled soya beans 8,7 %), Acidity regulators (Potassium Phosphates), Calcium Carbonate, Flavourings, Sea Salt, Emulsifier, Stabiliser (Gellan Gum), Flavouring, Vitamins (A, D2 and E)	Soya
Soy 2 US	Water, Soy Protein (6,2 %), Stabiliser, Emulsifier (Soy Lecithin, Silicon Dioxide), Acidity Regulator (Potassium Citrate), Salt, Flavouring	Soya
Soy 3 US	Water, Ground Whole Soybeans (7 %), Minerals (E341), Inulin, Acidity Regulator (E332), Salt, Flavouring, Stabiliser (E460, E466), Vitamin B2, Vitamin B12	Not declared
Almond 1 S	Water, Sugar, Almonds (2 %), Calcium Carbonate, Sea Salt, Emulsifier (Sunflower Seed Lecithin), Stabiliser (Gellan Gum), Vitamins (A, D2 and E)	Tree Nuts (Almond)
Almond 2 S	Water, Sugar, Almonds (4 %), Emulsifier (Sunflower Lecithin), Sea Salt	Nuts
Almond 3 S	Water, Sugar, Almond (2,3 %), Tricalcium Phosphate, Sea Salt, Stabilisers (Locust Bean Gum, Gellan Gum), Emulsifier (Sunflower Lecithin), Vitamins (B2, B12, E, D2)	Not specified
Almond 1 US	Water, Almonds (2 %), Calcium Carbonate, Sea Salt, Emulsifier (Sunflower Seed Lecithin), Stabiliser (Gellan Gum), Flavouring, Vitamins (A, D2 and E)	Tree Nuts (Almond)
Almond 2 US	Water, Thickener, Almonds (2 %), Calcium Carbonate, Stabilisers, Flavouring, Salt	Tree Nuts
Almond 3 US	Water, Almond (2,3 %), Tricalcium Phosphate, Sea Salt, Stabilisers (Locust Bean Gum, Gellan Gum), Emulsifier (Sunflower Lecithin), Vitamins (B2, B12, E, D2)	Nuts
Oat 1 US	Water, Gluten-Free Oats (8 %), Canola oil (2 %), Salt, Calcium Carbonate, Tricalcium citrate, Acidity Regulator (Potassium citrate)	Traces Tree Nuts
Oat 2 US	Water, Italian oats (16 %), Cold-pressed Sunflower Seed Oil, Sea Salt	Gluten traces
Oat 3 US	Water, Oats (11 %), Calcium Carbonate	Oats, Gluten
Oat 4 US	Water, Oats (11 %), Calcium Carbonate	Gluten
Rice 1 US	Water, Rice (15 %), Vegetable Oil (Sunflower seed 1 %), Sea Salt	Not declared
Rice 2 US	Water, Rice (11 %), Vegetable Oil (Sunflower seed), Calcium carbonate, Salt	Not declared
Coconut 1 US	Fresh Coconut Milk (99,9 %), Xanthan Gum E415, Guar Gum E412	Coconut
Coconut 2 US	Coconut Milk (79,60 %), Coconut Water (20 %), Natural Calcium Complex, Natural Flavour, Stabiliser (Xanthan Gum, Gellan Gum)	Coconut

Note:
S = Sweetened; US = Unsweetened.

3.2.2. *Additives and fortification*

SA PBMAs demonstrated heavy reliance on functional additives to achieve milk-like properties. Emulsifiers (soy lecithin, sunflower lecithin), stabilisers (gellan gum, xanthan gum, guar gum, locust bean gum), and acidity regulators (potassium phosphates, potassium citrate) were common across categories. Moore et al. (2023) reported similar additive (E473, E407, E412) profiles in European products, most prevalent in coconut and almond varieties.

Calcium fortification was nearly universal across SA PBMA categories, typically as calcium carbonate or tricalcium phosphate. Vitamin fortification (A, D2, E, B2, B12) was primarily limited to soy and almond products in SA, consistent with European fortification patterns.

These findings highlight that most PBMAs contain less than 20 % of their base ingredient, with water constituting the predominant component. The reliance on additives and variable fortification underscores the need for standardised compositional requirements to ensure nutritional adequacy when PBMAs are used as cow milk substitutes.

4. Limitations of the study

The study was limited to single raw plant-based formulations without added flavourings or mixed PBMA types to ensure comparability, which may not fully represent the diverse product landscape that consumers encounter. Additionally, while the research identified the presence of antinutrients and discussed potential bioavailability concerns, actual bioavailability and absorption studies were not conducted, limiting conclusions about the practical nutritional impact of the measured nutrient differences. The analytical scope, though comprehensive for macronutrients and minerals, did not include vitamin analysis, and some measurements fell below detection limits. Finally, the study's focus on nutritional composition alone did not consider other factors such as consumer perceptions, taste, environmental impact, or long-term health outcomes from regular consumption, which would provide a more holistic evaluation of these products as dairy alternatives. It is further proposed that this research be expanded to examine the protein quality of PBMAs, including amino acid content and contribution to daily intakes.

5. Conclusion and recommendations

This study tested two hypotheses regarding PBMAs in the SA retail market. H_1 was supported when PBMAs demonstrated significant nutritional differences from cow milk across macronutrients, minerals, and trace elements ($p < 0.05$). H_2 was partially supported with some products' declared nutrient values that fell outside the permitted tolerances specified in R.146, with calcium, fibre, and sodium showing the largest deviations. Cow milk provided superior protein content and maintained optimal Ca:P ratios (1.09–1.44) for bone health, while PBMAs exhibited category-dependent nutritional profiles. Soy-based alternatives most closely approximated cow milk composition, while rice, almond, and oat varieties showed substantial deficits. The higher trace element content in PBMAs is functionally limited by antinutrient interference in bioavailability.

Labelling non-compliance for critical nutrients was identified, with systematic overreporting of calcium (21–56 % deviation) and dietary fibre (56–88 % deviation) in PBMAs, and underreporting of sodium content (43–97 % deviation) across both cow milk and PBMAs. These discrepancies can mislead consumers managing specific health conditions requiring accurate nutritional information. Unlike other studies that rely primarily on NIP data, the analytical verification of this study reveals overreporting not documented in other markets, particularly for dietary fibre ($p < 0.05$). This finding is unique to the SA market and justifies regulatory intervention and the need to establish specific regulatory standards for PBMA composition.

In conclusion, while PBMAs can serve as alternatives to cow milk for those with specific dietary requirements, they should not be considered nutritional equivalents. The nutritional composition, degree of processing, and nutrient bioavailability of these alternatives warrant careful consideration when making recommendations for substituting cow milk products with plant-based alternatives.

CRediT authorship contribution statement

Elaine Pieterse: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Data curation, Conceptualization. **Beulah Pretorius:** Writing – review & editing, Validation, Supervision, Investigation. **Hester Carina Schönfeldt:** Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used **ChatGPT** in order to **improve the readability and language of the manuscript**. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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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Data availability

Data will be made available on request.

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