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Macromineral and trace element concentrations of dairy products and plant-based imitations in the UK: implications for population intakes

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ABSTRACT

UK diets rely on dairy to support mineral adequacy. Sales of plant-based dairy imitations (PBDI) are increasing. However, they are not nutritionally equivalent to dairy, and there is no UK analytical data on their mineral composition to assess potential dietary intake risks. We performed the first large-scale analysis of mineral concentrations in the most commonly consumed dairy products and PBDI, comparing semi-skimmed milk ($n = 40$), yoghurt ($n = 80$) and cheese ($n = 52$) with fortified almond, coconut, oat and soya plant-based beverages (PBB; $n = 138$), coconut and soya plant-based yoghurt imitations (PBYI; $n = 49$) and coconut oil plant-based cheese imitations (PBCI; $n = 40$). The data were used to estimate changes in the UK population's mineral intakes based on current consumption. PBDI were highly varied, with mineral concentrations determined by fortification and plant base. While fortified PBB contained similar calcium concentrations to milk, the fortification of PBYI was inconsistent, resulting in differences between soya and coconut-based yoghurt imitations. PBCI contained significantly less calcium than cheese despite frequent fortification, likely due to nutritional compromises made to preserve meltability. PBDIs were inadequately fortified with iodine. In PBCI, despite low levels of declared fortification, iodine concentrations suggested that other ingredients in the formulation enhanced the overall iodine content. PBDI were lower in potassium and zinc. Replacement of dairy with PBDI was more expensive and nutritionally detrimental, as adequate intakes of iodine and calcium could become inadequate in some age groups, and prevalence of low intakes of magnesium, potassium, and zinc could be exacerbated, increasing the risk of clinically significant deficiency outcomes.

1. Introduction

Animal-derived foods are significant providers of macro- and micronutrients in human diets, but their production also contributes to environmental footprint and non-communicable disease (Aleksandrowicz et al., 2016). Since 2016, UK dietary guidelines have incorporated increased plant-based sources of protein, such as beans and pulses, and 'dairy alternatives', including soya-based imitations of milk and yoghurt, to improve diets. Benefits to public health may include increasing fibre and reducing fat intake, while also lowering environmental impact (PHE, 2016a). In 2019, the Eat Lancet Commission described a universal healthy reference diet that increased consumption of plant foods and reduced reliance on animal-sourced foods, including milk and dairy, with the twin aims of improving dietary health and reducing the environmental footprint caused by food production systems (Willett et al., 2019).

Health and environmental concerns are the most frequently cited reasons for consumers including plant-sourced dairy imitations in their diets (Beacom et al., 2021; Euromonitor International, 2022d), supporting their broader appeal beyond the 6 % of UK consumers who identify as vegans (Euromonitor International, 2022c; Statista, 2024). A study investigating the use of plant-based imitations of meat and dairy in the UK National Diet and Nutrition Survey (NDNS) found that reported consumption rose from 6.7 % of individuals surveyed in 2008–2011 to 13.1 % in 2017–2019 (Alae-Carew et al., 2022). In 2024, Mintel reported that 37 % of consumers used dairy imitation products compared to 31 % the previous year (Mintel, 2024b). Additionally, in 2024, Euromonitor noted that the value of the plant-based dairy imitation market in the UK increased from £443 m in 2019 to £760 m, with milk imitations representing 65 % of this value, followed by 19 % for yoghurt

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imitations and 16 % for cheese imitations (Euromonitor International, 2024). While most consumers of dairy imitations also report consuming dairy products (Mintel, 2024b), household-level data show an accelerating decline in the volume of milk, yoghurt, and cheese purchased (DEFRA, 2025).

The effect of increased consumption of plant-based dairy imitations (PBDI) and apparent decreased consumption of dairy products on nutrient adequacy in the UK is currently unclear. However, one of the core concerns of existing research is that PBDI of the same type can have distinctly different concentrations of protein, fat, saturated fat, fibre, free sugars, sodium and micronutrients, and these concentrations may also be significantly different compared with the dairy product they aim to mimic (Clegg et al., 2021; Glover et al., 2022). Although the lack of nutritional equivalence is not necessarily a concern for all nutrients found in milk and dairy, the relative presence and concentration of specific micronutrients in plant-based dairy imitations are of particular concern because evidence shows that UK diets rely on dairy products to support micronutrient adequacy (Bates et al., 2020) and it is difficult to meet dietary recommendations for minerals, especially in groups with high requirements such as children and adolescents, without dietary patterns that include dairy (Weaver, 2014). Milk and the products derived from it, cheese and yoghurt, are the single most significant food group contributors of calcium (Ca) and iodine (I) and primary or secondary contributors of a broad spectrum of essential minerals, such as magnesium (Mg), potassium (K), and zinc (Zn), to diets across the lifespan (Bates et al., 2020). Adequate intakes of Ca and I are of particular importance because of the clinically significant consequences of deficiency, including increased risk of osteoporosis and neurodevelopmental impairments and congenital disabilities in babies born to mothers deficient in iodine (Hanafy et al., 2022; Prentice, 2004; SACN, 2014); and the existing inadequacy of these minerals for vulnerable groups such as adolescents 11–18 years in the UK, adolescent girls and women of child-bearing age, respectively (Bates et al., 2020).

There is a lack of relevant analytical data in the UK Composition of Foods Integrated Dataset or in the research for the most popularly consumed dairy imitations in the UK, so previous research examining the nutritional composition of plant-based dairy imitations (PBDI) in the UK is based on their product labels (Clegg et al., 2021; Glover et al., 2022). However, other analytical studies have described differences between labelled concentrations and analysed concentrations (Redan et al., 2023; Smith et al., 2022; Wall et al., 2025). There is also limited evidence on the concentrations of other minerals of public health importance, such as Mg, K, and Zn, in dairy imitations, despite the prevalence of low intakes across the population, as these are typically not fortified and are therefore not listed as ingredients or quantified on product labels. Given the importance of milk and dairy to mineral adequacy in the UK (Bates et al., 2020), positioning of dairy imitations as 'good alternatives' in UK dietary guidelines (NHS, 2024) and predicted sales growth of PBDI (Euromonitor International, 2024), it is essential to monitor the nutrient composition of PBDI and assess potential effects of their consumption on the adequacy of population nutrient intakes.

UK studies have also highlighted the increased cost of PBDI on a mass/volume equivalent basis, compared to dairy products (Clegg et al., 2021; Glover et al., 2022). Over recent years, the proportion of food-insecure households has increased (DEFRA, 2024a) due to the higher cost of living and rising food prices (Office for National Statistics, 2025). Increased pressure on household budgets has resulted in an overall reduction in the amount (−11.2 % to £63.50) spent on weekly food (DEFRA, 2024b). It makes sense, therefore, to compare the cost of 'functional replacement' of currently consumed amounts of milk, cheese and yoghurt with equivalent volumes of PBDI, but also the cost of equivalent minerals replacement, based on the minimum quantities of PBDI that would provide the same contributions of minerals provided by milk, yoghurt and cheese.

The aim of this work is therefore to (i) analytically determine and compare the mineral concentrations in milk, yoghurt and cheese with PBDI, accounting also for their different ingredients, styles, (such as Greek or standard yoghurt, or cheddar, mozzarella, and soft spreadable cheeses) and seasonal variation, (ii) model the changes in mineral intakes if dairy products were substituted for PBDI independently and in aggregate in current diets, and (iii) compare the cost both to replace current volumes of milk, yoghurt and cheese and equivalent concentrations of minerals provided by these dairy products with dairy imitations.

2. Materials and methods

2.1. Experimental design summary

The study was conducted in two phases. Phase 1 was aligned with the first study aim, which was to quantify minerals in dairy and PBDI. A detailed market survey was conducted across all major UK supermarkets (see Section 2.2) to record the nutrient composition, ingredients, and prices of all available plant-based dairy imitations of milk ($n = 190$), yoghurt ($n = 79$) and cheese ($n = 78$). These data were then used to refine the approach to collecting the same information for milk ($n = 118$), yoghurt (208) and cheese ($n = 248$) where availability and variety of style is greater. Following this, the inclusion criteria to define the sample set for laboratory analysis were determined, taking into consideration the primary ingredient, fat content, style and format, thermal processing, and added flavourings (see Section 2.2), and maximising public health relevance through the use of dairy consumption and PBDI sales data. PBDI ($n = 227$) were compared to dairy milk, yoghurt and cheese ($n = 172$). The second phase, aligned to the second and third study aims, utilised the laboratory-determined composition and survey-determined cost data for dairy and PBDI to model potential changes in mineral intakes within the UK population if dairy were substituted for PBDI, the cost to consume equivalent volumes or weights of PBDI, and finally the cost to replace the concentration of minerals provided by currently consumed volumes and weights.

2.2. Sample selection

This study analysed and compared semi-skimmed milk ($n = 40$) to fortified plant-based beverages (PBB) ($n = 138$; almond $n = 34$; coconut $n = 27$; oat $n = 38$, soya $n = 39$); yoghurts ($n = 80$) to plant-based yoghurt imitations (PBYI) ($n = 49$; coconut $n = 22$, soya $n = 27$) and cheese ($n = 52$) to plant-based cheese imitations (PBCI) ($n = 40$; coconut $n = 40$) available from major UK supermarkets. Products were identified *via* an online retail survey of major UK supermarkets representing 94 % retail market share (Kantar, 2024) conducted from March to May 2023. The nutrient composition and prices (expressed per 100 g) of dairy and PBB, PBYI, and PBCI were recorded using a method similar to that described by Clegg et al. (2021). Characteristics, which include the primary ingredient (for example milk or plant type), whole or lower fat content, 'style' (for example Greek or standard yoghurt, or cheddar or mozzarella cheese), format (for example grated or block cheese), thermal treatment (such as pasteurised or ultra heat treated (UHT) milk) and flavouring (whether plain or fruit flavoured in yoghurts), for each product category were prioritised for analysis based on published intake data for dairy (Bates et al., 2020), as well as sales data for dairy products and imitations in the UK (Euromonitor International, 2022a, 2022b, 2022e, 2022f). All dairy products were compared to PBDI with the most similar characteristics.

For the comparison of milk and PBB, pasteurised semi-skimmed milk was used to represent cows' milk in the dataset because it is the most consumed milk in the UK (Bates et al., 2020; Euromonitor International, 2022b). For PBB sales data showed that oat, soya, almond, and coconut drinks were the most popular, representing 70 % of plant-based drinks available in supermarkets and 80 % of value sales (Euromonitor International, 2022b); these were therefore included in the experimental design. In terms of thermal treatment, 95 % of milk sold is chilled and pasteurised (Euromonitor International, 2022b), while the majority of PBB (71 %) were shelf-stable ultra-heat treated (UHT), and 29 % were available in chilled/pasteurised format. Both formats were included in the experimental design for milk and PBB to account for potential variation in mineral concentrations resulting from thermal processing. 78 % of all PBB were fortified with at least one mineral. For this reason, this study compared the composition of fortified PBB with that of milk; previous work had examined the differences between unfortified PBB and milk (Wall et al., 2025).

For yoghurt and PBYI, standard and Greek-style were most widely available (86 % dairy yoghurts; 95 % PBYI), defined by the number of brands and distinct products available, so these styles were included in the experimental design. Plain and flavoured yoghurts and PBYI, and whole-fat and fat-free yoghurts (PBYI were not differentiated by fat content) were represented in the study design because most PBYI were flavoured, with a higher proportion of Greek-style available as plain, and 52 % of yoghurts were made with whole-fat milk, where 47 % of yoghurts were fat-free. The majority (80 %) of standard-style and Greek-style PBYIs were made from a soya or coconut base, so these plant bases were included in the experimental design. 84 % of PBYI were fortified with at least one mineral, and all were included in the analysis.

Cheddar is the most widely consumed cheese (Bates et al., 2020), followed by spreadable cream cheese and mozzarella (Mintel, 2024a). Plant-based imitations of cheddar, spreadable cream cheese, and mozzarella were also the most widely available, representing 80 % of all PBCI; therefore, these were included in the experimental design. There were fewer than three brands available for parmesan-style, feta-style, halloumi-style, and camembert-style PBCI products, so these were not included in the study. For 95 % of PBCI, irrespective of type, the primary ingredient after water was coconut oil; there were only two brands of almond-based and sunflower oil-based cheese imitations, so only coconut oil was included in the experimental design for PBCI. 85 % of PBCI were fortified with at least one mineral, and all were included in the study design.

The major private label brands and supermarket own label brands, representing approximately 68.8 % of milk, (Euromonitor International, 2022b) 69.1 % yoghurt (Euromonitor International, 2022f), and 53 % cheese market share (Euromonitor International, 2022a), together with brands representing 76 % market share of PBDI (Euromonitor International, 2024), were included in the experimental design. All products were collected in June/July 2023 and again in January/February of 2024 to account for the seasonal variation in mineral concentrations as previously observed in milk products (Newton, Pétursdóttir A, et al., 2023).

2.3. Sample collection and preparation

After purchase, all samples were transferred immediately to the laboratories of the University of Reading and aliquoted into 7 mL sterile polypropylene tubes (milk, yoghurt, PPBI and PBYI, spreadable cream cheese and spreadable PBCI) and into sterile bags for hard cheese and PBCI. Each sample was allocated a unique identifier. Cheeses and PBCI were subsequently freeze-dried and ground to a fine powder using a pestle and mortar. All samples were stored in the freezer at −20 °C. All samples were analysed at the University of Reading for macrominerals: calcium (Ca), magnesium (Mg), phosphorous (P) potassium (K), sodium (Na); trace elements: cobalt (Co), copper (Cu), iodine (I), manganese (Mn), molybdenum (Mo), zinc (Zn) and heavy metals: cadmium (Cd), chromium (Cr), nickel (Ni).

2.4. Minerals analysis

2.4.1. Milk and PBB and yoghurt and PBYI

Milk, PBB, yoghurt, and PBYI samples were defrosted overnight at 4 °C prior to analysis of mineral concentrations. These were determined using a modified protocol for microwave-assisted acid digestion, described by Newton, Theodoridou, et al. (2023) using inductively coupled plasma-optical emission spectrometry (ICP-OES) for macro minerals and inductively coupled plasma mass spectrometry (ICP-MS) for trace elements and heavy metals. In short, 1 mL milk and PBB, or 1 mL diluted yoghurt and PBYI (2 g yoghurt to 4 g ultra-pure water), were digested in 7.5 mL 67 % HNO_3 and 2.5 mL 37 % HCL (Fisher Chemical), both trace metal analysis grade, using an Ethos Easy Microwave Digestion system. The solutions were heated to 180 °C over a 15-min ramp period and then held at the same temperature for an additional 10 min before cooling to ambient temperature. The digestate was filtered through Cytiva Whatman 540 hardened ashless 125 mm diameter filter papers and diluted to 50 g with ultra-pure water in Corning Falcon 50 mL polypropylene centrifuge tubes, before a further dilution at a ratio of 1:4 in 15 mL Corning Falcon polypropylene centrifuge tubes. For each analysis, the ICP-MS (Agilent 7900, Agilent Technologies, Singapore) and ICP-OES (Avio 500, PerkinElmer, USA) were calibrated using single standards and multi-standard stock solutions. Calibration curves were prepared using six different concentrations between 0.1 and 50 μg/L for trace elements and four different concentrations between 1 and 20 mg/L for macro elements. Standards for Ca, Mg, K, and Na were created using VWR ARISTAR Multi-element calibration standard IV, 1000 mg/L (VWR, Leuven, Belgium). Standards for I were created using ROMIL PrimAg® Mono-Component Reference Solutions, 1000 mg/L (ROMIL, Cambridge, UK); for Zn and P, using PerkinElmer pure standard, 1000 mg/L (PerkinElmer, Shelton, USA) and SPEX CertiPrep multi-element standard 100 mg/L was used for Mn, Cu, Cr, Co, Ni, Mo, Cd (Spex Certiprep, Metuchen, USA). All standard stock solutions were diluted in HNO_3, HCL and ultra-pure water present in the same proportion as the samples. Correlation coefficients demonstrated excellent linearity (R^2 = 0.998–0.999) for all calibration curves. Analyte recovery was verified using ERM-BD150 certified reference material (CRM) skim milk powder. All analytical batches contained a minimum of two procedural blanks and two CRM. Recovery of all minerals was found to be within 91 % – 98 % of the ERM-certified values, except for Cu, for which recovery was 87 %. 30 % of the milk and PBB samples were analysed in duplicate. For yoghurt and PBYI, all samples were analysed in duplicate. All duplicate measures were within ±5 % of the original value. Operating conditions for the ICP-MS and ICP-OES, including limits of detection and quantification, are presented in tables S1 and S2.

2.4.2. Cheese and PBCI

Mineral concentrations in cheese and PBCI, except I, were determined using a modified method as described in dos Santos et al. (2023). Briefly, 0.15 g freeze-dried cheese, or PBCI, was digested in 6 mL 67 % HNO_3 and 2 mL H_2O_2 (Fisher Chemical), both trace analysis grade, using an Ethos Easy Microwave Digestion system. The solution was heated to 140 °C over a 20-min ramp period and then held at this temperature for an additional 20 min before cooling to ambient temperature. The digestate was filtered through Cytiva Whatman 540 hardened ashless 125 mm diameter filter papers into Corning Falcon 50 mL polypropylene centrifuge tubes and diluted to 30 g with ultra-pure water. The solution was further diluted at a 1:4 ratio into 15 mL Corning Falcon polypropylene centrifuge tubes for analysis by ICP-OES for macro minerals and ICP-MS for trace elements and heavy metals. As for milk and yoghurt, external standards were used to calibrate the ICP-MS and ICP-OES. Standard solutions were diluted in HNO_3, H_2O_2 and ultra-pure water present in the same proportion as the samples.

Concentrations of I in cheese and PBCI were determined using the AOAC First Action Official Method^{SM} 2012.15, adapted from Sullivan and Zywicki (2019). Briefly, 0.5 g of freeze-dried cheese and PBCI were digested in 3 mL 5 % KOH (made from 50 g Fisher Chemical extra pure SLR pellets dissolved in 1 L ultra-pure water) and 20 mL ultra-pure water in 50 mL Falcon Corning polypropylene centrifuge tubes. Samples were heated for one hour at 105 °C in the oven (Carbolite Gero, Carbolite, Derbyshire, UK). After this time, 0.6 mL of stabiliser concentrate (prepared from 10 % NH_4OH (Thermo Scientific) and 1 % $Na_2S_2O_3$

(Honeywell Fluka) in 500 mL of ultra-pure water) was added. The final sample weight was made up to 30 g with ultra-pure water. Samples were filtered into 15 mL Corning Falcon centrifuge tubes using Cytiva Whatman GD/X glass microfiber 45 μm syringe filter tips before ICP-MS analysis. The ICP-MS was calibrated using working standards made from Sigma Aldrich Iodide Standard for IC, Iodide in water 1000 mg/L solution, in six concentrations from 0.25 μg/L to 100 μg/L. The correlation coefficient demonstrated excellent linearity ($R^2 = 0.999$). Analyte recovery for all minerals in cheese was verified using a matrix-matched cheddar cheese reference material, from which 3 samples were taken from the same block and analysed in triplicate at Eurofins Food Testing UK Limited, Wolverhampton. All analytical batches contained a minimum of two procedural blanks and two reference materials. Recovery of all minerals was found to be within 92 %–105 % of the reference values. For cheese and PBCI, 30 % of samples were analysed in duplicate. All duplicate measures were within ±5 % of the original value. Operating conditions for the analysis of cheese using ICP-MS and ICP-OES, including limits of detection and quantification, are presented in tables S1, S2 and S3.

2.5. Statistical analysis

Statistical analysis was performed using Minitab®22.1. Data were analysed using linear mixed-effects models. For milk and PBB: using ingredient, thermal treatment, season, and their two-way and three-way interactions as fixed factors and unique sample ID as a random factor. Unique sample IDs were nested within style and thermal treatment. For yoghurt and PBYI: using ingredient, style, and season and their two-way and three-way interactions as fixed factors, and unique sample ID as a random factor. For cheese and alternatives to cheese: using ingredient, style and season and their two-way and three-way interactions as fixed factors and unique sample ID as a random factor. Unique sample IDs were nested within ingredient and style for yoghurt and cheese. Normality of the residuals was visually assessed for all variables and statistical models. For milk, PBB, yoghurt and PBYI, no variables showed deviations from normality, and they were analysed untransformed. For cheese, some of the variables (Co, Cu, Mn, Mo, Cd, and Ni) were log-transformed prior to analysis to achieve a normal distribution of the residuals. Where the effect of fixed factors was significant for a variable ($p < 0.05$), pairwise comparisons to assess significant differences between the means were conducted using Tukey's Honestly Significant Difference Test.

2.6. Changes in mineral intakes and implications for meeting reference nutrient intakes through substitution of dairy for PBDI

To estimate the potential impact of PBDI consumption on the mineral intakes of the UK population, a substitution analysis was conducted within a representative UK dietary dataset (UK National Diet and Nutrition Survey (NDNS)) for all minerals of public health concern: Ca, Mg, K, Na, I, and Zn. These are minerals for which the UK government have set daily dietary reference values (DRVs) (PHE, 2016b) and where intakes for these minerals are monitored in national dietary surveillance (Bates et al., 2020). Calculations used the mean values for minerals experimentally determined in this study. The mean volumes of milk, yoghurt and cheese consumed by age group were replaced with equivalent volumes of dairy imitations.

2.6.1. Milk, yoghurt, and cheese consumption estimates

Volumes of milk consumed by age group were calculated using data from NDNS (Bates et al., 2020) and mean energy values for whole milk, semi-skimmed milk and skimmed milk as published in Finglas (2015). Firstly, the number of kilocalories (kcal) consumed per day from each of whole milk, semi-skimmed milk, and skimmed milk by age group was determined using the percentage contribution to total dietary energy for each milk type, multiplied by total dietary energy intakes in kcal. This was converted to a volume for each milk type by dividing the actual energy contribution of each milk type (kcal) by the reported mean energy value (kcal) per 100 g for whole, semi-skimmed and skimmed milk (Finglas, 2015). Volumes for each milk type were combined to create a total daily milk consumption volume. Therefore, the intakes per age group applied in this study were: 1.5–3 years (247 mL/day), 4–10 years (170 mL/day), 11–18 years (121 mL/day), 19–64 years (121 mL/day), 65–74 years (137 mL/day) and 75+ years (193 mL/day). Volumes consumed by NDNS age groups using this method were similar to those reported in SACN-COT (2025).

The number of calories consumed per day, per age group, from 'yoghurt, fromage frais and other dairy desserts' was calculated as above. In the absence of detail on the energy value of yoghurts consumed, a mean energy value of 78 kcal per 100 g was calculated (and applied) based on dairy yoghurts recorded in the retail survey and analysed in this work. This value was also in line with the energy value for low-fat fruit yoghurt (Finglas, 2015). The only exception to this was for children aged 1.5–3 years, for whom published values for daily mean consumption of yoghurt and fromage frais were used instead (SACN, 2023). Therefore, the intakes per age group applied in this study were: 1.5–3 years (39 g/day), 4–10 years (45 g/day), 11–18 years (22 g/day), 19–64 years (35 g/day), 65–74 years (41 g/day) and 75+ years (45 g/day).

The number of calories consumed per day, per age group, from 'cheddar cheese' and 'other cheese' was calculated as above. For cheddar cheese, in the absence of details on the energy value of cheddar cheeses consumed, a mean value of 416 kcal per 100 g was calculated based on whole-fat dairy cheddar cheeses recorded in the retail survey and analysed in this work. This was also in line with the energy value for whole-fat cheddar cheeses reported in Finglas (2015). For 'other cheeses', a mean value of 275 kcals per 100 g was calculated based on whole-fat spreadable cream cheese and mozzarella cheeses recorded in the retail survey and analysed in this work. Total intakes (grams) of 'cheddar cheese' and 'other cheese' were added together to create a total consumed per day. Therefore, the intakes per age group applied in this study were: 1.5–3 years (10 g/day), 4–10 years (10 g/day), 11–18 years (13 g/day), 19–64 years (16 g/day), 65–74 years (16 g/day) and 75+ years (14 g/day). Published values for daily mean consumption of cheese for children 1.5–3 years (SACN, 2023) were in line with the calculated amount using this method.

2.6.2. Contributions of minerals from product substitution to daily intakes by age group

Mean daily volumes of milk, cheese and yoghurt consumed by age group were multiplied by the mineral concentrations in dairy and dairy imitation products measured in the present study. Values for the same minerals across milk, yoghurt and cheese were added together to create aggregate mineral intakes for dairy and dairy imitations.

2.6.3. Percentage contribution to daily reference nutrient intakes (RNIs) from product substitution

The proportion of daily mineral intakes or percentage RNI satisfied by milk, cheese, and yoghurt, and PBDI was calculated using estimated total contributions per day divided by the reference values outlined in PHE (2016b). The reference nutrient intake is the amount of a nutrient that is sufficient for almost every individual. Where individuals are meeting the RNI of a nutrient, they are unlikely to be deficient in that nutrient. UK DRVs are specified for age and sex demographics that do not align with intakes reported by age group in the NDNS. Therefore, for modelling, where reference values are differentially set for two age groups, for example for 4–6 years 450 mg Ca/day and for 7–10 years 550 mg Ca/day, and NDNS reports intakes for a combined age group of 4–10 years, a mid-point of 500 mg/day was applied as the reference intake in NDNS to calculate the % RNI for the age group.

Mineral intakes from dairy and PBDI were then calculated in the context of the whole diet to identify potential changes in population-level dietary adequacy through substitution, and the aggregate intakes of minerals were expressed as a proportion of the RNI for each mineral and age group.

2.6.4. *Comparison of cost to consume equivalent amounts of milk, yoghurt and cheese with PBDI*

The volumes consumed of milk, yoghurt, and cheese per age group per day were multiplied by the cost per litre and per kilogram to find the daily cost of consumption for each product. Daily costs were also extrapolated to annual costs (daily cost x 365 days/year).

2.6.5. *Cost to achieve the same minerals intakes provided by currently consumed volumes of milk, yoghurt and cheese with PBDI*

The mineral contributions of current volumes of milk, cheese and yoghurt by age group were the ‘reference standard’, for example, 121 mL of milk per day for adolescents 11–18 years, provides 148 mg Ca, 22 g yoghurt per day provides 35 mg Ca and 13 g of cheese per day provides 64 mg Ca. The volume required for each PBDI category and plant base to meet the same contribution as dairy per age group was calculated based on experimentally derived concentrations. The most limited mineral for each PBDI type and plant base determined the minimum volume of PBDI that would need to be consumed to meet the same concentration of all minerals provided by currently consumed quantities of dairy. This volume was multiplied by the cost per litre or kilogram for each PBDI and plant base to determine the cost of meeting the same mineral intakes as provided by dairy.

3. Results

3.1. *Mineral concentrations in milk and plant-based beverages*

A total of 40 conventionally produced milk samples and 138 conventionally produced fortified PBBs were analysed. The PBBs were derived from four different primary plant bases: almond, coconut, oat and soya. All PBBs were labelled to contain calcium (calcium phosphate or calcium carbonate) ($n = 138$) and fewer ($n = 62$) listed iodine as an ingredient (potassium iodide). Salt (sodium) was also listed as an ingredient in all PBBs.

3.1.1. *Effect of milk or PBB primary ingredient*

There were no significant differences in concentrations of Ca found between calcium-fortified PBBs and milk (Table 1). For all other macrominerals, there were significant differences between the primary ingredients ($P < 0.001$). Soya was significantly higher in Mg than milk (+27.5 mg/kg), and milk was significantly higher in Mg than all other PBB (relative to almond, +41.7 mg/kg; coconut +71.6 mg/kg; oat +83.3 mg/kg). Although milk contained the highest concentrations of P and K, the differences compared to levels in soya were not statistically significant. Both milk and soya contained significantly higher concentrations of both minerals (P+ >380 mg/kg and K+ >630 mg/kg) than all other PBB. Except for coconut, milk was significantly lower in Na than all PBB (ranging between almond, −216 mg/kg; to oat, −112 mg/kg). Almond contained more Na than all other plant-based drinks (+ > 100 mg/kg), albeit not significantly different from oat. The concentrations of trace elements, except Co, varied by primary ingredient ($P < 0.001$). Soya contained more Cu (+ > 65 mg/kg), Mn (+ > 1 mg/kg), and Mo (+ > 46 μg/kg) than all other PBB. Milk contained significantly more I than all PBB (relative to soya, +157 μg/kg; oat +172.4 μg/kg; almond +190.6 μg/kg; coconut +200.4 μg/kg). Milk was also significantly higher in Zn than all PBB (relative to soya +1.41 mg/kg; almond +3.18 mg/kg; coconut +3.58 mg/kg; oat +3.71 mg/kg). Of all PBB, soya contained the most Zn and was significantly higher than almond (+1.77 mg/kg), coconut (+2.17 mg/kg), and oat (+2.3 mg/kg). The concentrations of Cd, Cr, and Ni varied by ingredient ($P < 0.001$). Soya contained the highest amounts of all three heavy metals but was only significantly different from other PBB and milk for Cd (+ >3.21 μg/kg).

Table 1
Means and standard errors for the effect of ingredient, thermal treatment and season on price and mineral profiles of milk and plant-based beverages.

	Ingredient					SE	P-value[a]	Thermal treatment		SE	P-value[a]	Season		SE	P-value[a]
	Cow	Almond	Coconut	Oat	Soya			Pasteurised	UHT			Summer	Winter		
Parameters	n = 40	n = 34	n = 27	n = 38	n = 39			*n* = 84	*n* = 94			*n* = 91	*n* = 87		
Price (GBP/L)	1.16^{C}	1.49^{AB}	1.75^{A}	1.60^{AB}	1.35^{BC}	0.075	**<0.001**	1.50	1.44	0.048	0.459	1.47	1.48	0.035	0.947
Macrominerals (mg/kg)															
Calcium (Ca)	1222	1190	1090	1007	1111	67.8	0.167	1134	1113	43.5	0.738	1130	1118	35.5	0.740
Magnesium (Mg)	112.0^{B}	70.3^{C}	40.4^{D}	28.7^{D}	139.5^{A}	4.21	**<0.001**	80.7	75.6	2.70	0.188	76.0	80.4	2.03	**0.001**
Phosphorus (P)	1039^{A}	610^{B}	554^{B}	628^{B}	1009^{A}	48.8	**<0.001**	806	730	31.3	***0.093***	806	730	25.9	**0.006**
Potassium (K)	1594^{A}	192^{C}	339^{BC}	674^{B}	1305^{A}	105.7	**<0.001**	842	799	67.7	0.651	844	797	50.5	0.140
Sodium (Na)	354^{C}	570^{A}	418^{BC}	480^{AB}	466^{B}	26.5	**<0.001**	472	443	17.0	0.232	453	462	12.8	0.287
Trace elements (μg/kg unless otherwise stated)															
Cobalt (Co)	4.11	3.25	5.16	4.68	6.63	1.138	0.283	5.64	3.90	0.729	***0.096***	7.37	2.16	0.719	**<0.001**
Copper (Cu, mg/kg)	0.05^{C}	0.17^{B}	0.12^{BC}	0.12^{BC}	0.82^{A}	0.021	**<0.001**	0.27	0.25	0.013	0.302	0.24	0.28	0.011	**0.001**
Iodine (I)	257.8^{A}	67.2^{B}	57.4^{B}	85.4^{B}	100.4^{B}	18.38	**<0.001**	115.6	111.7	11.78	0.814	93.0	134.3	9.20	**<0.001**
Manganese (Mn, mg/kg)	0.04^{C}	0.42^{B}	0.47^{B}	0.41^{B}	1.47^{A}	0.045	**<0.001**	0.58	0.54	0.029	0.340	0.60	0.52	0.026	**0.019**
Molybdenum (Mo)	20.8^{C}	14.3^{C}	11.4^{C}	58.0^{B}	104.9^{A}	3.46	**<0.001**	43.2	40.5	2.22	0.389	37.0	46.8	1.86	**<0.001**
Zinc (Zn, mg/kg)	4.13^{A}	0.95^{C}	0.55^{CD}	0.42^{D}	2.72^{B}	0.127	**<0.001**	1.87	1.64	0.082	***0.085***	1.86	1.65	0.078	***0.051***
Heavy metals (μg/kg)															
Cadmium (Cd)	0.02^{C}	0.55^{BC}	0.62^{BC}	0.92^{B}	4.13^{A}	0.168	**<0.001**	1.18	1.31	0.108	0.400	1.32	1.18	0.093	0.198
Chromium (Cr)	48.4^{B}	21.4^{B}	10.1^{B}	90.5^{A}	110.4^{A}	10.96	**<0.001**	61.5	50.9	7.02	0.290	59.6	52.7	7.04	0.490
Nickel (Ni)	49.4^{B}	15.8^{B}	18.2^{B}	140.5^{A}	180.3^{A}	12.11	**<0.001**	84.3	77.4	7.75	0.538	80.6	81.1	7.02	0.961

SE = standard error, UHT = ultra-high temperature, n = number of samples, GBP = pounds sterling.

[a] Significances were declared at $P < 0.05$ and trends at $0.05 < P < 0.10$. Means within a row and variable with different upper-case superscript letters are significantly different according to Tukey's Honestly Significant Difference test ($P < 0.05$).

Oat was found to contain similar levels of Cr and Ni to soya. Almond and coconut contained similar levels of Cd, Cr, and Ni, which were comparable to those in milk. Milk was less expensive than almond (−£0.33/L), coconut (−£0.59/L) and oat (£0.44/L) ($P < 0.001$), and also less expensive than soya (−£0.19/L), although the price difference did not reach statistical significance.

3.1.2. Effect of thermal treatment

Concentrations of macrominerals, trace elements and heavy metals did not differ when comparing pasteurised with ultra-heat-treated

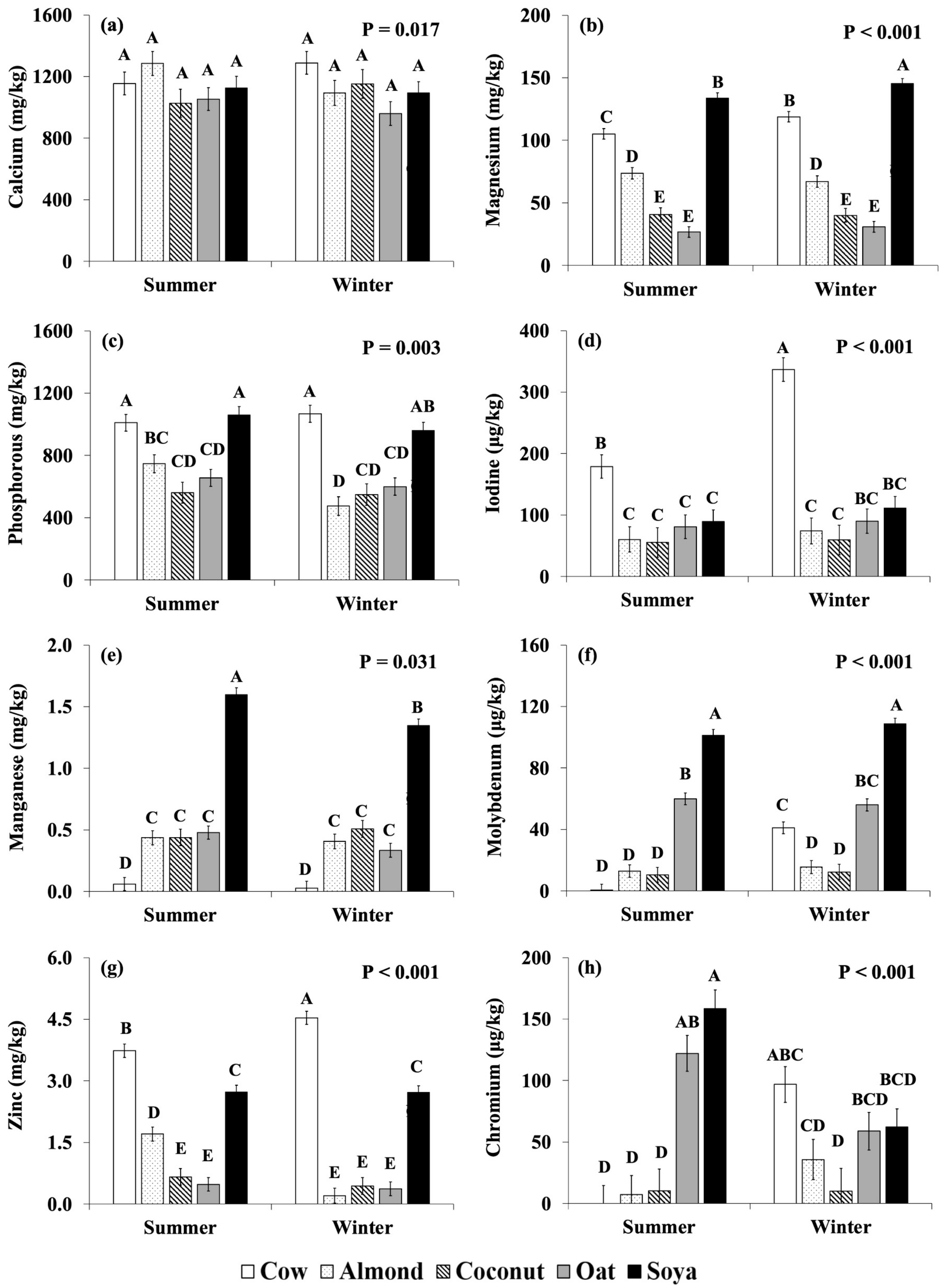

Fig. 1. Interaction means (bars) ± SE (standard error bars) for the effects of ingredient (Cow, Almond, Coconut, Oat, Soya) and season (summer, winter) on mineral profiles of milk and plant-based beverages. P represents the P-value for the interaction. Means with different upper-case letters are significantly different according to Tukey's Honestly Significant Difference test ($P < 0.05$).

(UHT) milk and PBB, and there were no differences in the price of milk and PBB associated with pasteurisation or ultra-heat treatment (Table 1).

3.1.3. Effect of season

Mg and P showed statistically significant variation in concentration according to season ($P < 0.05$); however, there was no clear pattern that applied to both minerals (Table 1). The concentration of Mg was higher in winter (+4.4 mg/kg; $P = 0.001$), where the concentration of P was higher in summer (+76 mg/kg; $P = 0.006$). Concentrations of trace elements varied by season. Cu (+0.04 mg/kg; $P = 0.001$), I (+41.3 μg/kg; $P < 0.001$), and Mo (+9.8 μg/kg; $P < 0.001$) were highest in winter, where Co (+5.21 μg/kg; $P < 0.001$) Mn (+0.08 mg/kg; $P = 0.019$) and Zn (+0.21 mg/kg; $P = 0.051$) were highest in summer. There were no seasonal differences in the concentrations of heavy metals. The mean price per litre of milk and PBB did not vary between summer 2023 and winter 2024.

3.1.4. Significant interactions between main ingredient, thermal treatment, and season

The interaction between the main ingredient and season showed statistically significant variations in the concentration of some minerals (Fig. 1; Table A1 in Supplement 1). For milk, Mg was significantly higher in winter (+13.6 mg/kg) than in summer, and the same direction of interaction in milk was observed for I (+157.8 μg/kg), Mo (+40.6 μg/kg), Zn (+0.8 mg/kg) and Cr (+96.8 μg/kg). For soya, the concentration of Mg was also higher in winter (+11 mg/kg), whereas concentrations of Mn (+0.25 mg/kg), Cd (+0.73 μg/kg), and Cr (+96.3 μg/kg) were higher in summer. For almond, the concentrations of P (+ 271 mg/kg) and Zn (+ 1.5 mg/kg) were also significantly higher in summer than in winter. Oat was higher in Cr in summer (+63.1 μg/kg). The mean Na concentration was lower in summer UHT milk and plant-based drinks compared to summer pasteurised drinks (−48 mg/kg). However, the individual means of interactions were not found to differ according to Tukey's honestly significant difference test (Table A3 in Supplement 1).

3.2. Mineral concentrations in yoghurt and plant-based yoghurt imitations

A total of 80 yoghurt samples and 49 PBYIs were included in the analysis. The PBYIs were based on two different primary ingredients: coconut and soya. In the PBYI sample set, $n = 41$ were fortified with Ca (calcium phosphate, tricalcium phosphate, tricalcium citrate, calcium carbonate) and $n = 6$ were fortified with iodine (form not listed). In addition, $n = 36$ PBYI contained added sea salt. Sodium citrate was also listed as an acidity regulator in yoghurts ($n = 14$) and PBYI ($n = 18$).

3.2.1. Effect of yoghurt or PBYI main ingredient

Yoghurt was higher in Ca, P and K than coconut (Ca +751 mg/kg; P + 603 mg/kg; K + 651 mg/kg, respectively) and soya (Ca +312 mg/kg; P + 371 mg/kg; K + 900 mg/kg, respectively) ($P < 0.001$) (Table 2). Soya was significantly higher in Na than yoghurt (+276 mg/kg) and Coconut (+260 mg/kg; $P = 0.006$). Soya contained significantly more Cu than coconut (+0.49 mg/kg) and yoghurt (+1.23 mg/kg), and more Mo (+185.7 μg/kg and + 178.5 μg/kg, respectively) ($P < 0.001$). Yoghurt was significantly higher in I than coconut (+150.8 μg/kg) and soya (+97 μg/kg). Yoghurt also contained more Zn than both coconut (+2.94 mg/kg) and soya (+1.23 mg/kg) ($P < 0.001$). Coconut and soya contained similar levels of Mn; both of which were found to be higher than yoghurt (+2.4 mg/kg and + 2.15 mg/kg, respectively) ($P < 0.001$). Soya was significantly higher in Cd than both coconut (+3.36 μg/kg) and yoghurt (+4.44 μg/kg) ($P < 0.001$). Coconut was significantly more expensive than soya (+£2.75/kg) and yoghurt (+£3.59/kg) ($P < 0.001$). Although soya was more expensive than yoghurt (+£0.84/kg), the difference was not statistically significant.

3.2.2. Effect of yoghurt and PBYI style

Greek-style yoghurt was significantly higher than standard yoghurt in Na (+195 mg/kg; $P = 0.013$), Cu (+0.21 mg/kg; $P < 0.001$) and Cd (+1.23 μg/kg; $P < 0.001$) (Table 2). Greek-style yoghurt was also significantly more expensive (+£1.50/kg; $P = 0.012$) than standard yoghurt.

3.2.3. Effect of season

The concentration of Mg was found to be significantly higher in yoghurts purchased in winter (+11 mg/kg; $P = 0.001$) than those purchased in summer (Table 2). Conversely, yoghurts purchased in summer were found to be higher in K (+92 mg/kg) than those purchased in winter ($P < 0.001$). Co (+6.6 μg/kg; $P = 0.033$) was found to be higher in summer than winter yoghurts, where concentrations of Mo (+45.2 μg/kg; $P = 0.003$) and Zn (+1.2 mg/kg; $P < 0.001$) were found to be significantly higher in winter. There was no significant difference in the

Table 2
Means and standard errors for the effect of ingredient, style and season on price and mineral profiles of yoghurt and plant-based imitations.

	Ingredient			SE	P-value[a]	Style		SE	P-value[a]	Season		SE	P-value[a]
	Cow	Coconut	Soya			Greek-style	Standard			Summer	Winter		
Parameters	n = 80	n = 22	n = 27			$n = 54$	$n = 75$			$n = 65$	$n = 64$		
Price (GBP/Kg)	4.07^{B}	7.66 ^{A}	4.91^{B}	0.415	**<0.001**	6.30	4.80	0.401	**0.012**	5.61	5.48	0.302	0.453
Macrominerals (mg/kg)													
Calcium (Ca)	1627 ^{A}	876^{B}	1315^{AB}	98.8	**<0.001**	1243	1303	95.6	0.667	1238	1307	72.8	0.138
Magnesium (Mg)	153	166	179	9.38	0.198	169	163	165.5	0.664	160	171	6.72	**0.001**
Phosphorus (P)	1369 ^{A}	766^{B}	998^{B}	74.1	**<0.001**	1052	1026	71.7	0.804	1067	1011	54.5	0.104
Potassium (K)	2052 ^{A}	1401^{B}	1152^{B}	103.0	**<0.001**	1526	1544	99.6	0.898	1581	1489	73.2	**0.001**
Sodium (Na)	505^{B}	521^{B}	781 ^{A}	54.5	**0.006**	700	505	52.7	**0.013**	589	616	39.5	0.197
Trace elements (μg/kg unless otherwise stated)													
Cobalt (Co)	4.49	1.78	3.63	2.125	0.736	3.62	2.98	2.08	0.832	6.60	0.00	2.138	**0.033**
Copper (Cu, mg/kg)	0.08^{C}	0.82^{B}	1.31 ^{A}	0.045	**<0.001**	0.84	0.63	0.044	**0.001**	0.72	0.76	0.038	0.354
Iodine (I)	152.0 ^{A}	1.20^{B}	55.0^{B}	19.56	**<0.001**	78.8	60.1	19.06	0.500	74.8	64.0	14.49	0.231
Manganese (Mn, mg/kg)	0.21^{B}	2.61 ^{A}	2.36 ^{A}	0.142	**<0.001**	1.80	1.65	0.138	0.447	1.72	1.73	0.110	0.982
Molybdenum (Mo)	56.4^{B}	49.2^{B}	234.9 ^{A}	15.54	**<0.001**	97.4	129.6	15.17	0.148	90.9	136.1	13.16	**0.003**
Zinc (Zn, mg/kg)	4.12 ^{A}	1.18^{C}	2.89^{B}	0.242	**<0.001**	2.79	2.68	0.235	0.745	2.33	3.13	0.190	**<0.001**
Heavy metals (μg/kg)													
Cadmium (Cd)	0.25^{C}	1.33^{B}	4.69 ^{A}	0.191	**<0.001**	2.70	1.47	0.187	**<0.001**	2.23	1.95	0.163	0.133
Chromium (Cr)	133	112	153	18.9	0.556	127	138	18.5	0.691	152	112	19.0	0.141
Nickel (Ni)	114	147	175	16.9	***0.057***	125	165	16.5	***0.097***	122	169	16.9	***0.053***

SE = standard error, n = number of samples, GBP = pounds sterling.

[a] Significances were declared at $P < 0.05$ and trends at $0.05 < P < 0.10$. Means within a row and variable with different upper-case superscript letters are significantly different according to Tukey's Honestly Significant Difference test ($P < 0.05$).

mean price of yoghurts between summer 2023 and winter 2024.

3.2.4. Significant interactions between main ingredient, style and season

There was significant variation in the concentration of some minerals as a result of the interaction between ingredient and season (Fig. 2; Table A5 in Supplement 1). Yoghurts were higher in Ca (+224 mg/kg; $P = 0.006$), Mg (+22 mg/kg; $P < 0.001$) and Zn (+1.41 mg/kg) in winter. The same seasonal effect was observed in increased concentrations of Ca, Mg, P and Zn in soya (Ca +113 mg/kg; Mg +20 mg/kg; P + 26 mg/kg, and Zn +0.5 mg/kg respectively). Soya contained more Cd and Cr in summer (+1.37 μg/kg and + 153.7 μg/kg), and the same seasonal effect was observed for the concentrations of Cr in yoghurts (+55.6 μg/kg). Unlike soya and yoghurt, coconut contained more Cr in winter (+89.7 μg/kg) and was higher in P in summer (+255 mg/kg).

The interaction between ingredient and style was statistically significant for some minerals (Fig. 3; Table A6 in Supplement 1). Soya Greek style was significantly higher in Na (+543 mg/kg; $P = 0.003$) than soya standard, milk-based standard, Greek-style, and coconut standard. Soya Greek style was higher in Cu (+0.33 mg/kg) and Cd (+2.53 μg/kg) than all standard versions. Milk standard yoghurt was significantly higher than milk Greek-style yoghurts for both Cr (+93.4 μg/kg) and Ni (+114.3 μg/kg). The interaction between ingredient and style did not demonstrate a statistically significant impact on price ($P > 0.05$), although the price of Greek-style soya was substantially higher (+ £3.28/kg) than standard soya yoghurt.

The interaction between style and season affected the concentration of some minerals (Fig. 4; Table A7 in Supplement 1). There was a seasonal increase in the Ca content of standard yoghurts in winter (+ 166 mg/kg; $P = 0.032$), but this effect was not observed for Greek-style yoghurts. There was a statistically significant decrease in the I content of standard yoghurts in winter (−31.7 μg/kg; $P = 0.022$). Standard yoghurts were significantly higher in Cr in summer (+139.5 μg/kg; $P <$

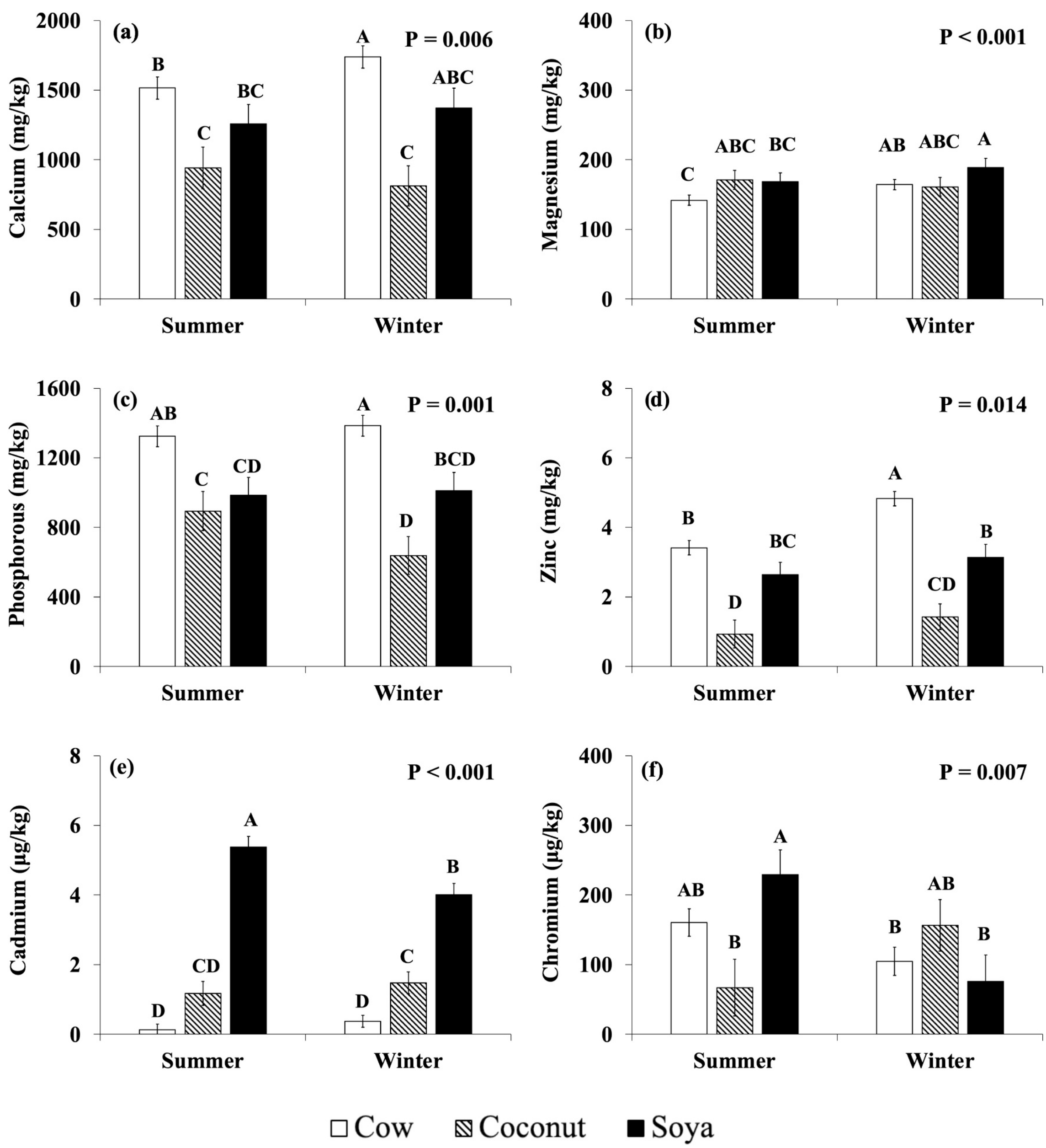

Fig. 2. Interaction means (bars) ± SE (standard error bars) for the effects of ingredient (Cow, Coconut, Soya) and season (summer, winter) on mineral profiles of yoghurt and plant-based yoghurt imitations. P represents the P-value for the interaction. Means with different upper-case letters are significantly different according to Tukey's Honestly Significant Difference test ($P < 0.05$).

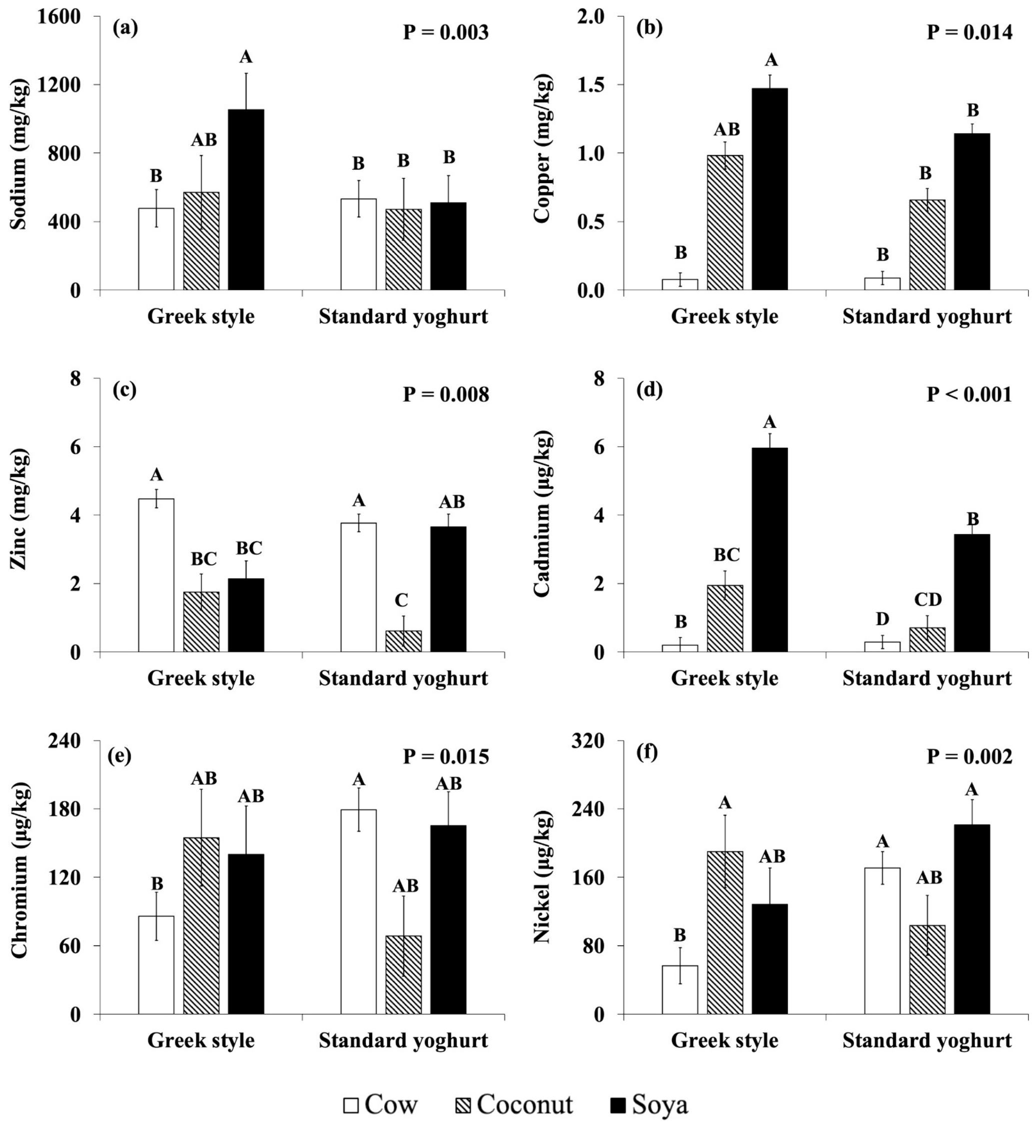

Fig. 3. Interaction means (bars) ± SE (standard error bars) for the effects of ingredient (cow, coconut, soya) and style (Greek style, standard style yoghurt) on mineral profiles of yoghurt and their plant-based imitations. P represents the P-value for the interaction. Means with different upper-case letters are significantly different according to Tukey's Honestly Significant Difference test (P < 0.05).

0.001). Greek-style yoghurts were higher in Zn (+1.49 mg/kg; $P <$ 0.001) and Ni in winter (+101.1 µg/kg; $P = 0.026$).

3.3. Macrominerals concentrations in cheese and plant-based cheese imitations

A total of 52 cheeses and 40 PBCI were analysed. The primary ingredient for the PBCI was coconut oil. Of the PBCI, $n = 34$ were fortified with Ca (in the forms of calcium phosphates, tricalcium phosphate, calcium citrate, tricalcium citrate, calcium carbonate) and $n = 8$ were fortified with I (in the form of potassium iodide). Salt was listed as an ingredient in some cheeses ($n = 14$), and all PBCI contained salt or sea salt.

3.3.1. Effect of cheese and PBCI main ingredient

There were significant differences between cheese and coconut for all macrominerals (Table 3). Cheese contained significantly more Ca (+3007 mg/kg), Mg (+108 mg/kg), P (+3206 mg/kg), K (+288 mg/kg) and significantly less Na (−1318 mg/kg) than coconut. There were also significant differences between the primary ingredients for all trace elements. Cheese contained more Cu (+0.01 mg/kg), I (+111 µg/kg), Mo (+43 µg/kg) and Zn (+22.46 mg/kg) than coconut, and coconut contained more Mn (+0.8 mg/kg) and Cr (+45 µg/kg). Cheese was cheaper than PBCI (−£2.90 /kg).

3.3.2. Effect of cheese and PBCI style

Concentrations of some macrominerals varied according to style (Table 3). Cheddar and mozzarella were both higher in Ca (+3210 mg/kg; +2546 mg/kg; $P < 0.001$), P (1920 mg/kg; +1785 mg/kg; $P <$ 0.001) and Na than spreadable cream cheese (+3993 mg/kg; +2484 mg/kg; $P = 0.001$). Spreadable cream cheese contained more K than cheddar (+316 mg/kg) and mozzarella (+480 mg/kg) ($P = 0.003$). Cheddar contained more I than mozzarella and spreadable cream cheese, although only spreadable cream cheese reached statistical significance (+196 µg/kg; $P = 0.05$). Cheddar also contained more Zn than mozzarella (+1.67 mg/kg) and spreadable cheese (+13.89 mg/kg) ($P <$ 0.001).

3.3.3. Effect of season

The effect of season was statistically significant for K and Cr ($P <$ 0.05), where both were higher in the winter (K + 60 mg/kg; Cr +0.01 µg/kg) than in summer (Table 3).

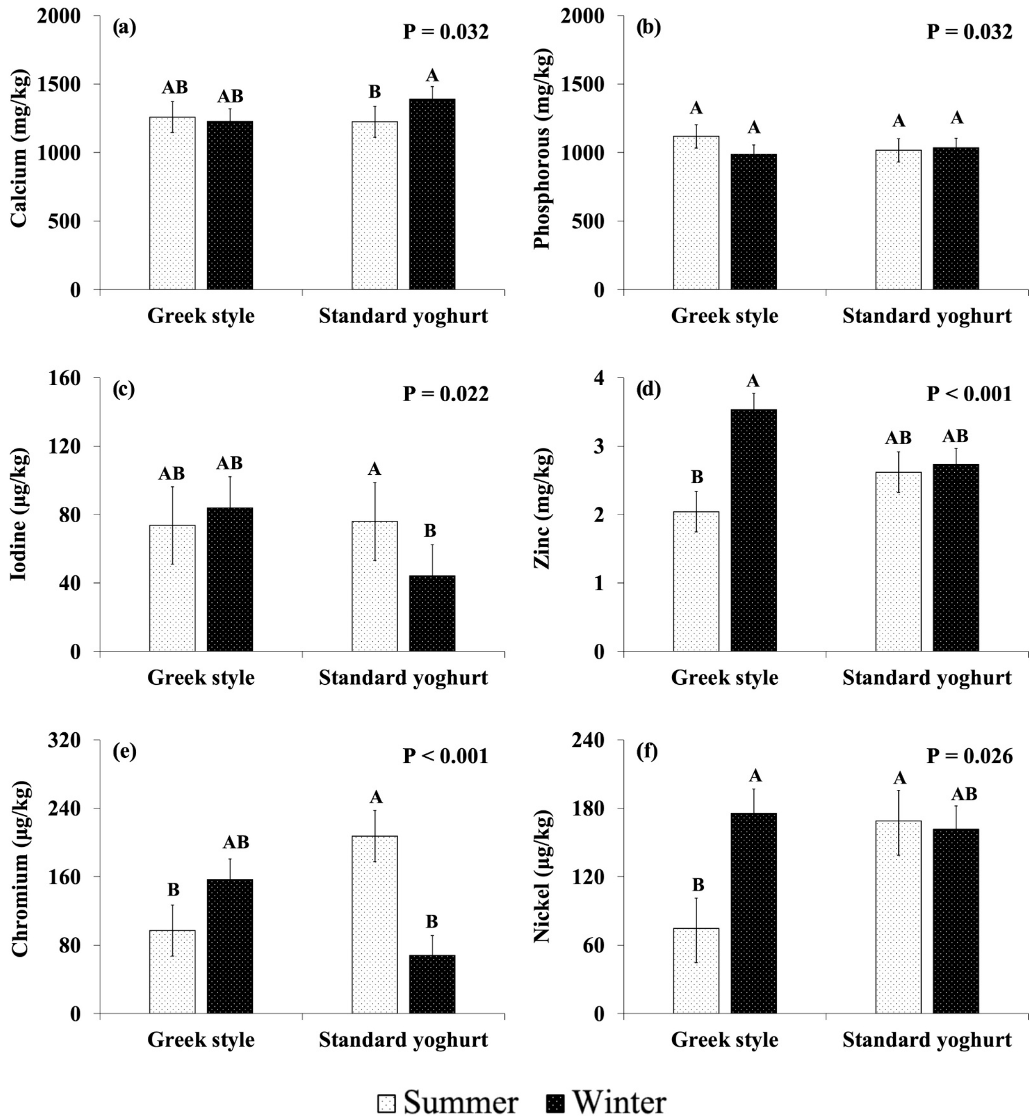

Fig. 4. Interaction means (bars) ± SE (standard error bars) for the effects of style (Greek style, Standard) and season (summer, winter) on mineral profiles of yoghurt and their plant-based imitations. P represents the *P*-value for the interaction. Means with different upper-case letters are significantly different according to Tukey's Honestly Significant Difference test (P < 0.05).

3.3.4. *Significant interactions between main ingredient, style and season*

The interaction between main ingredient and style produced significant interactions for most macrominerals and trace elements (Fig. 5; Table A10 in Supplement 1). Compared to coconut cheddar-style and coconut mozarella-style, cheddar and mozzarella contained more Ca (+5814 mg/kg; +4317 mg/kg, respectively), Mg (+234 mg/kg; +204 mg/kg, respectively) and P (+4672 mg/kg; +4586 mg/kg, respectively) ($P < 0.001$). Coconut cheddar-style contained the most Na, although this was not significantly different from cheddar but was significantly different from both mozzarella and coconut mozzarella-style (≥ 1999 mg/kg; ≥ 3425 mg/kg, respectively) and spreadable-style cheeses ($P = 0.04$). Cu concentrations were highest in coconut spreadable-style cheese, cheddar and mozzarella, which were all significantly higher than their dairy or plant-based counterparts. Cheddar and mozzarella contained the highest concentrations of I, although not significantly different from coconut cheddar-style (+233 μg/kg) and mozzarella-style (+174 μg/kg). Coconut spreadable contained more I (+76 μg/kg) than cows' milk spreadable. Mn was highest in spreadable coconut, which was significantly higher (≥2.07 mg/kg; $P = 0.001$) than all other dairy and coconut-based cheeses. Zn was significantly higher in cheddar, mozzarella and spreadable than their plant-based counterparts (+33.48 mg/kg; +30.98 mg/kg; 2.94 mg/kg, respectively) ($P < 0.001$). The interaction between style and season was significant for K ($P = 0.017$) and Mo ($P = 0.007$), where both were highest in spreadable cheeses in winter (Fig. 6; Table A11 in Supplement 1).

4. Discussion

This is the first large-scale UK study to measure and compare the mineral concentrations of highly consumed dairy products ($n = 172$), including semi-skimmed milk, standard and Greek-style yoghurt and cheeses with plant-based imitations ($n = 227$).

4.1. *The effect of primary ingredient on minerals concentrations of milk, yoghurt and cheese and PBDI*

Mineral concentrations in milk are influenced by many factors, including dairy management, cows' diet and season (Newton, Pétursdóttir, et al., 2023) and the nutritional composition of dairy products is significantly influenced by the nutritional composition of milk used (Manuelian et al., 2017; Montemurro et al., 2021; van der Reijden et al., 2019; Wang et al., 2024). Milk is the sole ingredient in

Table 3
Means and standard errors for the effect of ingredient, style and season on price and mineral profiles of cheese and plant-based imitations.

	Ingredient		SE	P-value[a]	Style			SE	P-value[a]	Season		SE	P-value[a]
	Cow	Coconut			Cheddar	Mozzarella	Spreadable			Summer	Winter		
Parameters	n = 52	n = 40			n = 36	n = 27	*n* = 29			*n* = 47	*n* = 45		
Price (GBP/Kg)	9.20^{B}	12.10 ^{A}	0.050	**<0.001**	10.50	11.10	10.40	0.061	0.789	10.80	10.50	0.370	0.199
Macrominerals (mg/kg)													
Calcium (Ca)	5014 ^{A}	2007^{B}	207.6	**<0.001**	4802 ^{A}	4138 ^{A}	1592^{B}	254.6	**<0.001**	3391	3630	175.3	0.208
Magnesium (Mg)	200.24 ^{A}	92.58^{B}	7.47	**<0.001**	160	132	148	9.15	0.100	140	153	7.54	0.256
Phosphorus (P)	3670 ^{A}	464^{B}	65.1	**<0.001**	2752 ^{A}	2617 ^{A}	832^{B}	79.8	**<0.001**	2080	2055	52.6	0.617
Potassium (K)	1045 ^{A}	757^{B}	76.9	**0.012**	853^{B}	680^{B}	1169 ^{A}	94.3	**0.003**	871^{B}	931 ^{A}	56.6	**0.038**
Sodium (Na)	5047^{B}	6365 ^{A}	223.8	**<0.001**	7540 ^{A}	6031^{B}	3547^{C}	274.3	**<0.001**	5658	5754	178.4	0.549
Trace elements (μg/kg unless otherwise stated)													
Cobalt (Co)	1.00	4.82	0.262	**<0.001**	2.89	1.85	4.00	0.321	0.131	3.09	2.73	0.265	0.655
Copper (Cu, mg/kg)	0.26 ^{A}	0.25^{B}	0.029	**0.020**	0.23	0.22	0.31	0.04	0.712	0.24	0.27	0.029	0.563
Iodine (I)	318 ^{A}	207^{B}	33.8	**0.027**	358 ^{A}	267^{AB}	162^{B}	41.39	**0.005**	264	261	26.14	0.887
Manganese (Mn, mg/kg)	0.22^{B}	1.02 ^{A}	0.138	**<0.001**	0.32	0.28	1.25	0.169	0.764	0.46	0.77	0.106	0.263
Molybdenum (Mo)	98.6 ^{A}	55.6^{B}	11.17	**<0.001**	65.49^{AB}	49.01^{B}	116.74 ^{A}	13.700	**0.023**	70.83	83.33	8.304	0.643
Zinc (Zn, mg/kg)	23.29 ^{A}	0.83^{B}	0.245	**<0.001**	17.25 ^{A}	15.58^{B}	3.36^{C}	0.301	**<0.001**	12.09	12.03	0.226	0.821
Heavy metals (μg/kg)													
Cadmium (Cd)	0.08	4.25	0.531	**<0.001**	1.45	1.62	3.43	0.651	0.489	1.44	2.89	0.413	0.521
Chromium (Cr)	31.10^{B}	76.77 ^{A}	6.262	**<0.001**	55.23	55.25	51.33	7.677	0.919	46.29^{B}	61.59 ^{A}	5.638	**0.031**
Nickel (Ni)	41.94	84.14	33.217	*0.057*	41.24	33.20	114.67	40.727	0.114	53.42	72.66	25.187	0.476

SE = standard error, n = number of samples, GBP = pounds sterling.
[a] Significances were declared at P < 0.05 and trends at 0.05 < P < 0.10. Means within a row and ingredient with different upper-case superscript letters are significantly different according to Tukey's Honestly Significant Difference test (P < 0.05).

liquid milk, plain yoghurt and plain cheese, but additional ingredients in flavoured yoghurts and spreadable cheeses, including fruits, nuts, herbs, salt and additives, may also affect mineral concentrations (Finglas, 2015).

Similarly, it has been suggested that the nutritional value of PBB (McClements et al., 2019; Scholz-Ahrens et al., 2020) and PBYI (Montemurro et al., 2021) is associated primarily with the raw materials included in the formulations. Imitations of milk, yoghurt and cheese are based on different plant sources and ingredients, depending on the targeted taste, texture, appearance, nutritional composition and functionality of the product (Grasso et al., 2020; Grasso et al., 2024; McClements et al., 2019). Water is listed as the first or second ingredient for all products, which reflects the relative proportions of the plant-water solutions upon which all PBDIs are based (McClements et al., 2019). All PBDIs contain more ingredients than their dairy counterparts. In the present study, PBB contained 10–12 ingredients, depending on the plant base; PBYI contained 11–13 ingredients, depending on the plant base and style; and PBCI contained 14–15 ingredients, depending on the style. The individual impact of the plant base is difficult to isolate from other ingredients in the final product.

4.1.1. Calcium (ca)

In the present study, semi-skimmed milk, yoghurt and cheese contained more Ca than their PBDI. However, unlike PBYI and PBCI, all PBBs contained statistically similar concentrations to semi-skimmed milk, and this is consistent with other research analysing Ca-fortified PBBs (Astolfi et al., 2020). In the UK, Ca-fortified PBBs contain around 120–130 mg/100 g, which is similar to semi-skimmed milk (Finglas, 2015) and the results of the present study. In the current study, any contribution of the primary plant ingredient cannot be extricated from the total concentrations achieved through Ca fortification (where studies analysing and comparing unfortified PBB across different plant bases have demonstrated differences in endogenous Ca concentrations (Marques et al., 2022; Moore et al., 2023; Wall et al., 2025).

Conversely, for PBYI, Ca concentrations differed by plant base. Soya contained significantly more Ca than coconut, as all soya PBYI were Ca fortified, compared with only 64 % of coconut yoghurts. Unfortified PBYI contain only 10 % of the Ca found in fortified versions (Rebellato et al., 2023), which would support the lower Ca content of coconut PBYI in this study. A similar frequency of fortification in PBYI was reported in an earlier study by Clegg et al. (2021), so unlike PBB (Wall et al., 2023), there is no evidence of improvement in fortification frequency. Moreover, while gross Ca concentrations are consistently added to PBBs at a level similar to milk, fortification practices for PBYI remain inconsistent between plant bases (Clegg et al., 2021; D'Andrea et al., 2023; Medici et al., 2023), perhaps reflecting greater variability within the yoghurt category compared with milk (Finglas, 2015).

Coconut PBCI contained only 40 % of the Ca found in cheese, despite 85 % of the PBCI being Ca-fortified. Other studies comparing Ca in cheese with PBCI based on their product labels have consistently found lower concentrations of Ca in PBCI, suggesting that Ca fortification is not matched to equivalent levels found in cheese (Clegg et al., 2021; Glover et al., 2022; Majhenič et al., 2025). The functional and nutritional objectives for Ca in PBCI may be more challenging to achieve than for other PBDI because of the role Ca salts play in cheese coagulation: higher concentrations of Ca impair texture and reduce meltability (Grasso et al., 2024; McMahon et al., 2005), so lower levels of Ca in PBCI may reflect nutritional compromise for functional performance.

4.1.2. Magnesium (Mg)

Soya PBB contained more Mg than milk > almond > coconut > and oat, consistent with some studies (Antunes et al., 2025; Walther et al., 2022), while others report different patterns in the relative concentrations of plant bases (Astolfi et al., 2020; Moore et al., 2023). As Mg is not declared as an added ingredient or quantified on PBDI product labels, concentrations may reflect both endogenous presence in the plant base and the proportionate contribution of the plant base to the overall product. On a dry weight equivalent basis, almonds contain more Mg than oats, soya beans, and coconut (Finglas, 2015). However, almonds represented only 2–3 % of the total product, whereas soya PBB contained between 6 and 12 % of soya. Indeed, the lower Mg and mineral content of almond PBB may be due to the small proportion of the plant material in the final product (Smith et al., 2022).

Unlike PBB, soya and coconut PBYI contained similar concentrations of Mg to yoghurt, which differs from recent work where yoghurts contained more Mg than PBYI (Rebellato et al., 2023). In the present study,

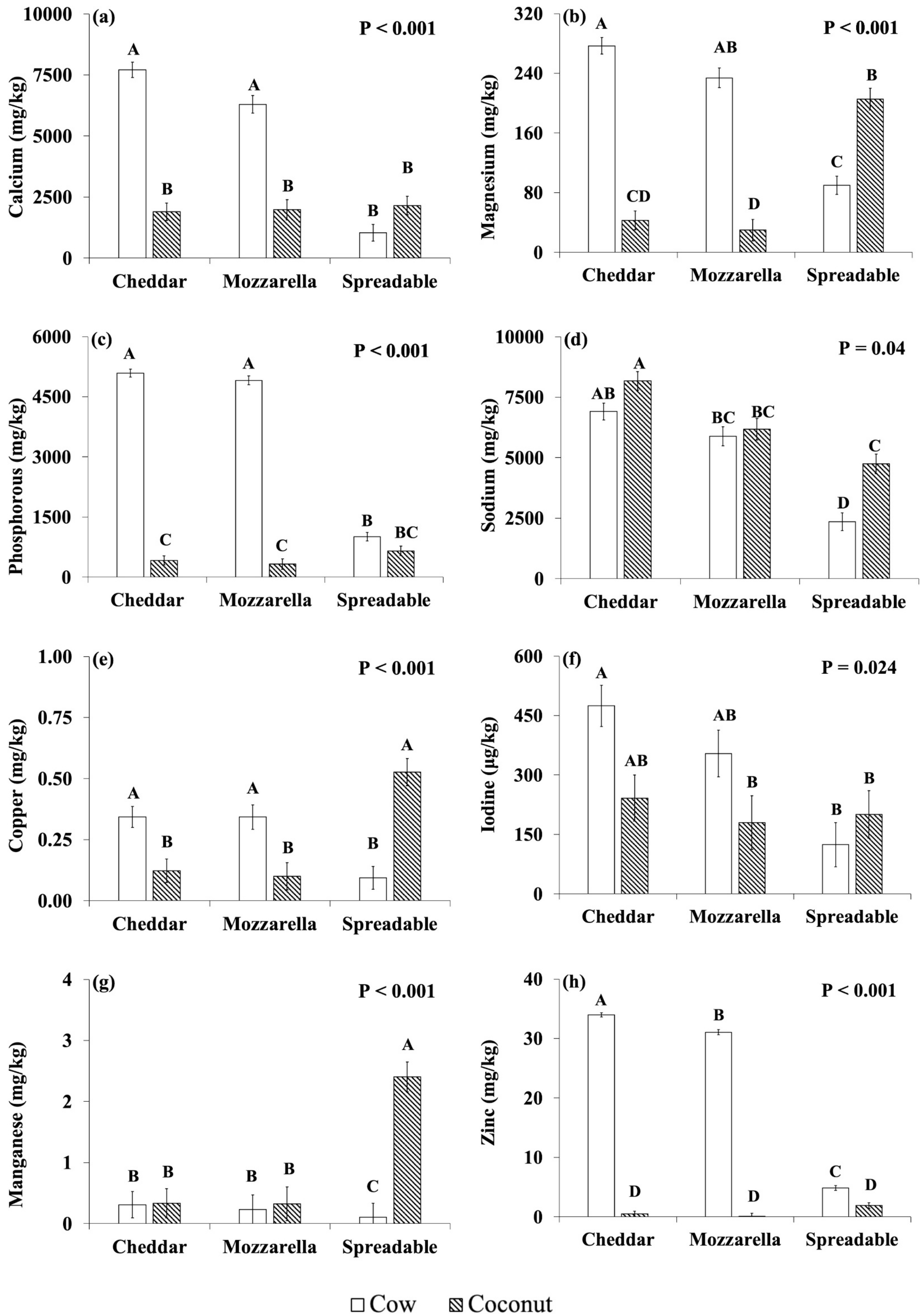

Fig. 5. Interaction means (bars) ± SE (standard error bars) for the effects of ingredient (Cow, Coconut) and style (cheddar, mozzarella, spreadable) on mineral profiles of cheese and plant-based imitations. P represents the P-value for the interaction. Means with different upper-case letters are significantly different according to Tukey's Honestly Significant Difference test ($P < 0.05$).

the soya bean solution represented between 7 and 16 % of the PBYI product, whereas solutions of coconut milk or coconut cream ranged between 17 and 85 % of the final product. However, the presence of unquantified additives such as starches and flours, absent from PBB, may contribute to similar concentrations of Mg across different plant bases and their higher concentrations compared to PBB made from the same plant bases.

For PBCI, coconut oil is not a source of Mg (Finglas, 2015); therefore, the lower levels of Mg in comparison to milk were consistent with expectations. Concentrations of Mg in PBCI in the present study likely reflect the varied presence and volume contribution of soya protein concentrate (which contains endogenous Mg), an ingredient primarily added to improve the textural characteristics (including gelation, elasticity, stretchability and softness) in addition to improving the protein

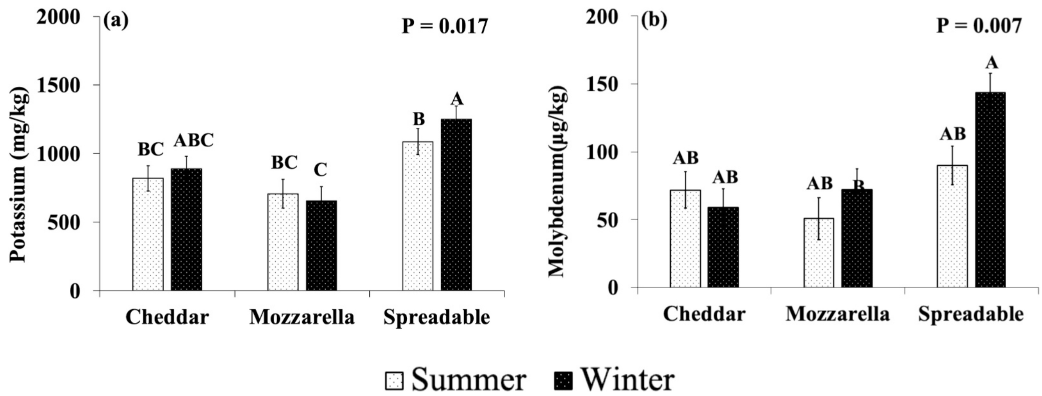

Fig. 6. Interaction means (bars) ± SE (standard error bars) for the effects of style (cheddar, mozzarella, spreadable) and season (summer, winter) on mineral profiles of cheese and plant-based imitations. P represents the P-value for the interaction. Means with different upper-case letters are significantly different according to Tukey's Honestly Significant Difference test ($P < 0.05$).

content of PBCI (Sözeri Atik & Huppertz, 2025).

4.1.3. Phosphorus (P)

Concentrations of P were greater in all dairy products than PBDI, consistent with previous studies (Astolfi et al., 2020; Marques et al., 2022; Moore et al., 2023; Pointke & Pawelzik, 2022; Rebellato et al., 2023). Ca- fortified PBB and PBYI contain more P than unfortified products (Marques et al., 2022; Rebellato et al., 2023), because Ca phosphates are most frequently used to improve Ca content (Craig & Fresán, 2021; Sethi et al., 2016). In the present study, Ca phosphates were used in 85 % of Ca-fortified PBB, 76 % of Ca-fortified PBYI, and 35 % of Ca-fortified PBCI. P concentrations were lowest in PBCI, consistent with the lower use of Ca phosphates. Studies comparing P concentrations in unfortified PBB have also found the same relative order of concentrations for the plant sources as in the present study (soya> oat, almond, coconut) (Marques et al., 2022; Moore et al., 2023). Differing concentrations of P for types of PBB and PBYI in the present study may therefore reflect the aggregate combination of varied endogenous P and added Ca phosphates for fortification.

4.1.4. Potassium (K)

Concentrations of K were greater in all dairy products than PBDI, which is in close agreement with other studies (Astolfi et al., 2020; Marques et al., 2022; Moore et al., 2023; Pointke & Pawelzik, 2022; Rebellato et al., 2023) and reflects the naturally high concentration of K in milk, yoghurt and cheese.

Concentrations of K varied by plant base in PBB. Soya was similar to milk, while oat >coconut, and almond PBB contained significantly less. This ranking is consistent with studies quantifying K in unfortified PBB (Marques et al., 2022; Moore et al., 2023). As unfortified PBB typically contain fewer than five ingredients (Wall et al., 2025), these studies likely reflect endogenous differences in plant bases. In the present study 45 % of PBB were fortified with potassium iodide. The parallel ranking of both K (soya> oat> coconut> almond) and I (soya >oat > almond> coconut) suggest that a higher frequency of iodine fortification resulted in improved K and I content of PBB.

Unlike PBB, coconut-based and soya-based PBYI contained similar concentrations of K, despite a higher frequency of fortification with potassium iodide for soya PBYI. However, many of the PBYI in the present study contained fruits and fruit purees, associated with increased concentrations of K (Rebellato et al., 2023). For PBCI, as coconut oil is not a source of minerals (Finglas, 2015), and frequency of fortification with potassium iodide was low, the relatively high concentration of K is likely related to the significant contribution of additional plant ingredients such as potato and maize starches oat and bamboo fibres and soya protein concentrate, the raw ingredients for which also contain significant concentrations of K (Finglas, 2015).

4.1.5. Sodium (Na)

Concentrations of Na found in milk, yoghurt, and cheese in the present study were consistent with those reported in UK food composition data (Finglas, 2015) and other analytical studies (Astolfi et al., 2020; Marques et al., 2022; Rebellato et al., 2023). In the present study, the concentrations of Na in milk, yoghurt and cheese were lower than in PBDI. Experimentally determined evidence for Na in PBCI is limited but consistent with the present study finding higher Na in PBCI than in cheese (Majhenič et al., 2025; Pointke & Pawelzik, 2022).

Variation in Na in PBDI across plant bases is largely due to formulation, as plant ingredients contain low or trace levels of Na (Finglas, 2015). In the present study, salt was an ingredient in all PBB, PBCI and 75 % of all PBYI. Concentrations in PBDI (PBCI > PBYI > PBB) followed the same order across dairy products, suggesting manufacturers target levels typical of dairy products to match taste attributes. Differences between plant bases within categories may relate to the varied functional roles of salt in balancing flavour, texture and pH (Aydar et al., 2020; McClements & Grossmann, 2021). In cheese-making, salt also acts as a preservative, reduces moisture, and contributes to meltability and plasticity, which have been challenging to reproduce in PBCI (Majhenič et al., 2025; Sözeri Atik & Huppertz, 2025). Consequently, salt reduction in PBCI may be challenging (Alehosseini et al., 2025; Majhenič et al., 2025). Indeed, Pointke and Pawelzik (2022) reported an increase in salt in PBCI since 2019, when they had been closer to concentrations found in dairy. It is possible, therefore, that variations in findings over time also reflect reformulation as products are redesigned to improve both taste and textural aspects of PBCI.

4.1.6. Iodine (I)

I values for semi-skimmed milk were in close agreement with recently analysed milk samples reported by OHID, which were lower than previously analysed in 1996 (OHID, 2025b). Mean levels for cheese in the present study were in line with published values, while those analytically determined for yoghurt were lower (Finglas, 2015) but broadly in line with a recent UK study (Alzahrani et al., 2023). Contrary to I values for yoghurt in UK food composition data (Finglas, 2015) and consistent with the findings in Alzahrani et al. (2023), I values in yoghurt were lower than those determined for semi-skimmed milk.

I concentrations in dairy products such as cheese and yoghurt have been correlated with originating milk I content, (van der Reijden et al., 2019), which can be highly variable as a result of numerous factors along the production line including country of origin, breed, diet, and season (Niero et al., 2023; Tattersall et al., 2024) and lower I concentrations have been reported in European milk compared with British milk (Tattersall et al., 2024). Unlike the milk and the majority of cheeses sampled, at least 25 % of the yoghurts analysed in the present study were made from milk of European origin.

Iodine concentrations in PBDIs are rarely analysed in the literature, and this is an important gap because milk and dairy are important contributors to dietary intakes, and iodine deficiency is of global concern (de Benoist et al., 2003). In line with the present study, other works have demonstrated lower mean concentrations in PBB compared with milk (Alzahrani et al., 2023; Bath et al., 2017; Walther et al., 2022). This reflects the low endogenous I content of plant bases (Finglas, 2015) and the low frequency of I fortification in the UK (Wall et al., 2023). In the current study, only 45 % of Ca-fortified PBB were also fortified with I. Higher concentrations of I were determined in soya PBB (39 % of the I concentration found in milk) followed by oat > almond > coconut (22 % of the concentration found in milk), and this order was in line with frequency of fortification: Soya, 50 %, compared to oat, 40 %; almond, 30 %; coconut, 21 %. Even in fortified PBB, I concentrations were lower relative to endogenous levels found in milk in the present work, consistent with other work (Alzahrani et al., 2023).

I was lower in PBYI than in yoghurt. Soya-based PBYI contained approximately 36 % of the I found in yoghurt, which was greater than the coconut-based PBYI (<1 %), although this difference was not statistically significant, likely due to the low frequency of I fortification in PBYI overall. In the present study, only 12 % of the total sample set (15 % of Ca-fortified PBYI) were fortified with I. The higher concentration of I in soya-based compared to coconut-based PBYI was supported by product labelling, which rarely declared I fortification for coconut-based PBYI. Interestingly, soya-based PBYI contained a similar proportion of I relative to yoghurt, as soya-based PBB contained relative to milk, despite a lower frequency of fortification in PBYI, perhaps indicating that concentrations of I in PBDI are limited by design. However, there is little evidence in the functional design or nutritional literature on the distinct difference in frequency of I fortification between PBB and PBYI, or indeed, reasons for the broader discrepancy between Ca and I fortification across all PBDI.

In the present study, PBCI contained 65 % of the I found in cheese, despite the low frequency of I fortification, which was 20 % of the total PBCI sample set. Certain commonly used ingredients like sea salt (Dellavalle & Barbano, 1984), carrageenan, agar or other algal derivatives (Aakre et al., 2021; Sözeri Atik & Huppertz, 2025), may elevate I concentrations as a side effect of improving texture and meltability in PBCI (Alehosseini et al., 2025; Walther et al., 2022). In the present study, 56 % of PBCI contained combinations of sea salt and carrageenan and agar, and 50 % of cheddar-style PBCI also contained yeast extract, which is richer in I than milk on a weight-equivalent basis (Finglas, 2015). Although quantities of these additives were not reported on product labels (hydrocolloids might represent up to 4 % by mass in PBCI, with higher amounts used in hard cheeses (Ferawati et al., 2021)), this may explain the comparatively elevated I concentrations found in PBCI, compared with PBYI and PBB, in the present study.

4.1.7. Zinc (Zn)

Concentrations of Zn were greater in all dairy products than PBDI, and soya ranked above all other plant sources for all PBDI, which is in line with other studies (Pointke & Pawelzik, 2022; Rebellato et al., 2023; Smith et al., 2022; Walther et al., 2022). Zinc is not typically fortified in PBDI, and therefore the presence and concentrations found in the present study in PBB and PBYI likely reflect both the density of endogenous concentrations within the different plant bases, as well as the proportionate contribution of the plant base to the overall formulation (between 2 and 11 % for PBB and 9–85 % for PBYI). On a weight-equivalent basis, milk and yoghurt contain relatively less Zn than the unprocessed plant bases, soya> almond> coconut and oat (Finglas, 2015). However, the plant bases typically represent a small proportion of the final products, and this is reflected in the comparatively lower concentrations found (Walther et al., 2022; Zhang et al., 2020). Cheese contained substantially more Zn than PBCI, as coconut oil is not a source of minerals (Finglas, 2015). The low concentration of Zn found in PBCI is therefore more likely a result of contamination from the use of metallic instruments during processing (Manuelian et al., 2017).

4.1.8. Heavy metals

Heavy metals were consistently higher in PBDI than in dairy, and soya was consistently higher in Cd and Cr across both PBB and PBYI, and these results were consistent with other studies comparing concentrations in milk and PBB and yoghurt and PBYI (Astolfi et al., 2020; Llorent-Martínez et al., 2012; Redan et al., 2023). Evidence for PBCI is lacking in the extant literature.

Cd is an environmental contaminant found in foods through industrial and agricultural sources (EFSA, 2025), and is classified as a human carcinogen (EFSA, 2009). The tolerable weekly intake for Cd is set at 7 μg/kg of body weight (EFSA, 2009). However, UK children aged 1.5–3 years, who have the highest average consumption of milk across the population, and who would have the lowest average body weight (estimated to be 15 kg) compared to other age groups, would need to consume around 25 kg of soya PBB (and higher volumes of other PBDI) per week to reach tolerable intake limits. Therefore, the comparatively higher concentration of Cd in PBDI poses no health risk.

Trivalent Cr is ubiquitous in diets, and milk and dairy products are a primary source, along with oils, fats, breads, cereals and pulses (EFSA Panel on Dietetic Products and Allergies, 2014). There is no evidence of beneficial effect associated with intakes of Cr and no evidence of adverse effects for intakes up to 1 mg/day, and the tolerable daily intake is 300 μg/kg bodyweight (EFSA Panel on Dietetic Products and Allergies, 2014). At current consumption levels across the population, the concentrations found in PBDI would fall far short of meeting the daily tolerable intake level (around 10 %), again suggesting that higher Cr in PBDI poses no health risks.

4.2. The effect of the product style and interactions with ingredient on mineral concentrations in milk, yoghurt and cheese and their PBDI

There were no significant differences in mineral concentrations between pasteurised and ultra-heat-treated (UHT) milk and PBB. In previous studies on milk, thermal treatment has shown minimal or no effect on the concentrations of Ca, K, Mg, P, Na, and Zn, as these inorganic compounds are not affected by heat (Lalwani et al., 2024; Niero et al., 2023).

Similarly, there were few significant interactions between ingredient and style for yoghurts and PBYI. Soya Greek-style contained more Na, Cu and Cd than Soya standard-style PBYI; but the same was not observed for Greek and standard yoghurts, where Na and Cu were mostly, or wholly, endogenous. Studies analysing the mineral composition of yoghurts and PBYI are scarce, but the role of salt as a flavour enhancer in PBDI is frequently acknowledged, as is the undesirable beany flavour from soya-based products (Alehosseini et al., 2025; Majhenič et al., 2025; McClements & Grossmann, 2021). As Greek-style PBYI contained a higher proportion of the soya plant base (13.1 %) than standard-style (9.7 %), the higher Na content in Greek-style may improve the flavour and increase consumer appeal. Similarly, higher concentrations of Cu and Cd may also be associated with the higher proportion of plant base in Greek-style soya PBYI compared to standard-style.

Unlike milk and yoghurt, the effect of the interaction between primary ingredient and style produced significant differences in the mineral concentrations of most macrominerals and trace elements in cheese and PBCI. Mineral concentrations are higher in cheese than in the milk used to make it, on a weight-equivalent basis, due to the reduction in moisture content, which increases mineral concentrations (Manuelian et al., 2017). Similarly, hard cheeses with a low moisture content, such as cheddar, typically contain more minerals than semi-hard cheeses with higher moisture content, like mozzarella or spreadable cheeses. This relationship explains the differences found in the present study between cheddar and mozzarella, as well as soft cheese, despite the same ingredients for cheddar and mozzarella, and the primary ingredient for spreadable cheese.

Conversely, mineral concentrations in coconut oil-based PBCI do not follow the same order evident in cheese, related to the moisture content for each style, and interestingly, concentrations of Ca, P, I and Zn did not differ by style. As coconut oil is not a source of minerals (Finglas, 2015), the presence and concentrations of minerals are wholly related to additional ingredients and their proportions included in formulations. Indeed, Ca, P and I are all minerals associated with the use of Ca phosphates and potassium iodide, fortificants used to improve mineral concentrations in PBDI, as noted previously. However, similar Ca and I concentrations across different styles of PBCI may not be intended to replicate the comparatively varied concentrations found in the same styles of cheese. Indeed, limiting Ca fortification in PBCI may be necessary to optimise appearance and meltability, which may reduce consumer appeal (Grasso et al., 2024).

Higher concentrations of Mg, Cu and Mn were found in spreadable PBCI, compared to cheddar-style and Mozzarella-style imitations. These minerals are not typically associated with compounds used in fortification and likely relate to the varied presence and proportions of other ingredients. Spreadable PBCI contained more ingredients than either cheddar-style or mozzarella-style, and in particular, 67 % of samples contained soya protein concentrate, which was also associated with higher levels of Mg in PBYI and soya-based PBB. Unlike cheddar-style and mozzarella-style PBCI, spreadable PBCI also included ingredients such as garlic, garlic powder, parsley, chives and olive extract, which are all sources of Mn and Cu (Finglas, 2015), and could explain their presence in higher concentrations.

4.3. Implications for population dietary intakes

There is limited evidence on the impact of increased consumption of PBDI on dietary intakes and nutritional status in the UK. Consumer research indicates the growing popularity of PBDI in the order of milk >

Table 4

Estimated minerals intakes, percentage contribution to reference nutrient intakes (RNI)[a] and percentage satisfaction of RNI from the whole diet when including dairy milk, yoghurt and cheese in the UK, by age group, and differences when dairy imitations are substituted into the diet.

Age (Years)	Dairy milk, yoghurt, cheese			Coconut imitations			Soya imitations			Almond PBB + Soya PBYI + PBCI			Oat PBB + Coconut PBYI + PBCI		
	Mineral intakes mg/day	% RNI	% RNI whole diet	Mineral intakes mg/day	% RNI	% RNI whole diet	Mineral intakes mg/day	% RNI	% RNI whole diet	Mineral intakes mg/day	% RNI	% RNI whole diet	Mineral intakes mg/day	% RNI	% RNI whole diet
Calcium (Ca)															
1.5–3	413	118	202	322	92	176	345	98	182	364	104	188	302	86	170
4–10	332	66	146	245	49	128	268	54	133	282	56	136	231	46	126
11–18	248	25	**75**	177	18	**68**	189	19	**69**	199	20	**70**	167	17	**67**
19–64	285	41	115	195	28	102	213	30	104	222	32	106	185	26	100
65–74	316	45	112	218	31	**98**	239	34	101	250	36	102	207	30	**96**
75+	379	54	118	278	40	104	301	43	107	317	45	109	262	37	102
Magnesium (Mg)															
1.5–3	36	42	172	17	20	150	42	50	180	25	30	160	14	17	147
4–10	28	17	115	15	10	107	33	20	118	21	13	111	13	8	106
11–18	19	7	**72**	10	3	**69**	22	8	**73**	14	5	**70**	8	3	**69**
19–64	22	7	**91**	12	4	**87**	25	8	**92**	16	5	**89**	11	4	**87**
65–74	25	8	**90**	14	5	**86**	28	9	**91**	18	6	**88**	12	4	**85**
75+	31	10	**77**	17	6	**72**	36	12	**79**	23	8	**75**	14	5	**72**
Potassium (K)															
1.5–3	483	60	207	145	18	164	374	47	193	99	12	159	228	28	175
4–10	374	24	132	128	8	116	281	18	126	92	6	114	185	12	120
11–18	252	8	**68**	81	2	**63**	193	6	**66**	58	2	**62**	122	4	**64**
19–64	282	8	**81**	102	3	**76**	210	6	**79**	76	2	**75**	143	4	**77**
65–74	319	9	**82**	116	3	**76**	238	7	**80**	86	2	**75**	162	5	**78**
75+	414	12	**76**	139	4	**68**	314	9	**73**	100	3	**67**	204	6	**70**
Sodium (Na)[b]															
1.5–3	155	31	*	184	37	*	206	41	*	232	46	*	200	40	*
4–10	135	8	*	160	10	*	180	11	*	197	12	*	171	11	*
11–18	119	5	*	144	6	*	155	6	*	168	7	*	152	6	*
19–64	141	6	125	171	7	126	185	8	127	198	8	127	178	7	127
65–74	152	6	125	183	8	126	200	8	127	214	9	128	192	8	127
75+	161	7	125	193	8	126	214	9	127	234	10	128	205	9	127
Iodine (I)[c]															
1.5–3	73	104	180	16	23	**99**	29	41	118	21	30	106	23	33	109
4–10	54	51	118	12	11	**78**	22	21	**87**	16	15	**82**	17	16	**83**
11–18	39	29	**87**	10	7	**65**	16	12	**70**	12	9	**67**	13	10	**68**
19–64	42	30	110	10	7	**88**	17	12	**93**	13	10	**90**	14	10	**90**
65–74	47	33	125	11	8	100	19	14	105	15	11	102	15	11	102
75+	61	44	124	14	10	**91**	25	18	**98**	18	13	**94**	19	14	**95**
Zinc (Zn)															
1.5–3	1.4	28	**96**	0.2	4	**72**	0.8	16	**84**	0.4	7	**75**	0.2	3	**71**
4–10	1.1	17	**87**	0.2	2	**73**	0.6	9	**80**	0.3	4	**75**	0.1	2	**73**
11–18	0.9	10	**78**	0.1	1	**69**	0.4	4	**73**	0.2	2	**70**	0.1	1	**69**
19–64	1.0	11	**91**	0.1	1	**81**	0.4	5	**84**	0.2	2	**82**	0.1	1	**81**
65–74	1.1	12	**84**	0.1	1	**74**	0.5	5	**78**	0.3	3	**75**	0.1	1	**74**
75+	1.3	14	**79**	0.2	2	**67**	0.7	7	**72**	0.3	3	**69**	0.1	2	**67**

Numbers in bold = highlight where population total dietary intakes fall below the RNI.

[a] RNI = reference nutrient intake. The RNI is an mount of a nutrient that is enough for almost every individual, even those with high requirements. If individuals are consuming 100% of the RNI of a nutrient they are unlikely to be deficient in that mineral.

[b] Sodium intakes are not reported in children and therefore change in intakes as a proportion of total diet could not be estimated.

[c] Daily mineral intakes for iodine are presented as μg/day. Data sources: Government dietary recommendations (PHE, 2016); volumes of milk, cheese and yoghurt, total dietary intakes of minerals and % contribution from milk, cheese and yoghurt from NDNS (Bates et al., 2020); Na intakes in adults (PHE, 2020).

yoghurt> cheese, but it is unclear how this translates into changes in dietary intakes and nutritional status in the short or long term.

Previous studies have compared proportions of DRVs met through equivalent volumes of PBDI (Clegg et al., 2021; Glover et al., 2022), and the UK government has also considered potential nutritional risks to public health when substituting milk for PBBs (SACN-COT, 2025). However, the risk assessment was based on nutritional profiles of PBBs from market data collected between 2019 and 2020, and there is evidence of reformulation (Wall et al., 2023). The present work, unlike earlier studies, models dietary impact based on laboratory quantification of minerals using an extensive sample set of the most popular PBB, PBYI and PBCI in the UK. In addition, it includes all minerals of public health importance, including Mg, K, and Zn, which are not currently included in fortification schemes for PBDI and are therefore not reported on product labels.

Based on existing consumption patterns, this study demonstrates that replacing dairy with PBDI can reduce intakes of Ca, Mg, K, I and Zn and increase intakes of Na, however consideration of the current background diet in the UK population, and the relative contributions of milk, yoghurt and cheese to delivering these nutrients, demonstrates that not all changes may be nutritionally consequential for different population age groups (Table 4, and Tables S4, S5, S6).

Replacing dairy with PBDI could reduce Ca intakes in all age groups. Milk, yoghurt, and cheese contribute between 31 and 53 % of Ca to diets, with higher contributions in the diets of children 1.5–3 years and older adults, both 65–74 years and 75+ years (Bates et al., 2020). Indeed, without milk and dairy, Ca requirements would not be met in any age-based population (Bates et al., 2020). However, as milk contributes more Ca to diets than yoghurt and cheese, and all PBB were Ca-fortified at a similar concentration to milk, replacement of milk and dairy with Ca-fortified PBDI would not detrimentally affect the ability to meet nutrient requirements in most age groups.

Nevertheless, if adults 65–74 years chose exclusively coconut-based PBDI, or a higher proportion of coconut-based PBDI (including both yoghurt and cheese imitations), there is a possibility that Ca intakes for this group would fall below the RNI. Additionally, mean Ca intakes for adolescents 11–18 years (who are also the lowest consumers of dairy products) are already inadequate, with mean intakes falling significantly below (−25 %) the RNI, and 15 % of this age group fall below the lower reference nutrient intake (LRNI). The LRNI is the amount of a nutrient that is only sufficient for a very small proportion of individuals with very low needs, and habitual intakes at this level may indicate deficiency. Therefore, the prevalence of low Ca intakes in this group would likely increase if they switched to PBDI. Sufficient Ca intake is critical during adolescence to achieve peak bone mass density, 95 % of which is acquired by the age of 16 years (Hanafy et al., 2022; Weaver, 2014), and to reduce the risk of osteoporosis in later life (Prentice, 2004).

Ca bioavailability from milk, yoghurt, and cheese is similar (Melse-Boonstra, 2020), which is around 30 % of the gross content, and this is high compared with most plant foods (Weaver et al., 1999). Conversely, studies analysing nutritional differences between dairy and PBDI have noted the lower bioavailability of Ca from compounds frequently used to improve the gross Ca content of PBB (Craig & Fresán, 2021; Sethi et al., 2016; Zhang et al., 2020), which suggests that the potential risk of Ca inadequacy is further increased when the potentially lower Ca bioavailability is taken into consideration.

Replacing dairy with soya-based PBB and PBYI could marginally improve intakes of Mg, while replacement with coconut or mixed plant bases could reduce Mg intakes in all age groups. Milk, cheese, and yoghurt contribute between 9 and 22 % of Mg to diets, with the highest contributions in the diets of children 1.5–3 years (Bates et al., 2020). For the youngest age groups, the increase in Mg when consuming soya PBDI, or the reduction when consuming coconut or mixed PBDI, is largely nutritionally inconsequential, as background dietary intakes for Mg from other sources, excluding dairy, currently exceed their requirements. Notably, it is also recommended that young children (1.5–5 years) should vary their sources of plant protein in diets due to a small but increased risk of endocrine-modifying effects associated with increased consumption of soya phytoestrogens (SACN-COT, 2025).

For older populations, including adolescents 11–18 years and all adults, there is an existing high prevalence of low Mg intakes from all dietary sources, including dairy (Bates et al., 2020). Additionally, a particularly high proportion (40 %) of adolescents have intakes that fall below the LRNI, compared with adult populations (12–16 %) (Bates et al., 2020). Therefore, lower levels of Mg found in almond, coconut, and oat PBB, as well as in PBCI, would further reduce the ability to meet Mg requirements and likely increase the prevalence of intakes below the LRNI. Adequate supply of Mg is important for bone health and may affect bone formation, growth, and bone mass density (Bonjour et al., 2009). Wide-scale population insufficiency (particularly among adolescents who have a narrow window to achieve optimum bone mass density (Hanafy et al., 2022)) is a concern given the increasing prevalence of osteoporosis in the UK (OHID, 2025a), and an annual cost to the NHS of more than £4.4bn due to associated fractures. This finding further provides support for the pragmatic, at least equivalent to dairy, fortification of PBDI (Drewnowski et al., 2021) with Mg.

Replacing dairy with PBDI could reduce K intakes in all age groups. Milk and dairy products contribute between 10 and 27 % of K to diets, with higher contributions in the diets of children 1.5–10 years and older adults 75 years+ (Bates et al., 2020). For the youngest age groups, the reduction when consuming coconut, soya or mixed plant-based PBDI is currently largely inconsequential as background dietary intakes from other sources, excluding dairy, currently exceed requirements. However, there is a significant prevalence of low intakes across adolescent and all adult populations, and 30 % of adolescents (11–18 years), 17 % adults (19–64 years), and 19 % of adults (75+ years) have mean intakes below the LRNI (Bates et al., 2020). The lack of equivalent K in PBDI contributes to the increased prevalence of low K intakes across these populations. Despite evidence of low dietary intakes of K in the UK, there is limited evidence for the clinical effects of deficiency (SACN-COT, 2017). However, low intakes of K have been associated with high blood pressure, and increased dietary intakes have been linked to a lower incidence of hypertension (Zacchia et al., 2016) and stroke (SACN-COT, 2017).

Replacement of dairy with coconut, soya, and mixed PBDI could result in small increases in Na intakes in all age groups. The government recommends limiting salt intake (PHE, 2016a) to reduce the risk of hypertension and cardiovascular disease (SACN, 2003), yet dietary intakes already exceed the guidance (PHE, 2020). Although PBDI contain more Na, their impact on adult Na intakes is small because dairy foods contribute only 9 to 11 % of total Na in diets. Yoghurt and cheese contain more Na than milk on a weight-equivalent basis and similarly PBYI and PBCI contain more Na per gram than PBB. However, most dairy consumption, and therefore potential for change in intakes through substitution, comes from milk, while yoghurt and cheese are consumed in smaller amounts. The effect on Na intakes in children 1.5–18 years could not be estimated as current intakes are not reported in NDNS. However, higher salt intakes in children's diets can increase their preference for salty foods (Strazzullo et al., 2012), which may contribute to increased blood pressure in adulthood (Leyvraz et al., 2018).

Milk, yoghurt and cheese contribute between 32 and 58 % of I to diets, with higher contributions in the diets of children 1.5–10 years and older adults 75+ (Bates et al., 2020). There are few other highly consumed dietary sources of I in the background diet of the UK population, so requirements are not met without the contribution of milk and dairy. Therefore, low I concentrations and unequal and infrequent I fortification across PBDI have a significant impact on I intakes when they are replacing milk and dairy in the diet. Intakes of I would be reduced in all population age groups, and currently adequate intakes (for children 1.5–10 years; and adults 19–64 and 75+) may become inadequate across all plant-based consumption scenarios, but especially so for coconut PBDI. Mean I intakes for adolescents 11–18 years are already insufficient, and 28 % of adolescent females have intakes below the LRNI (Bates et al., 2020); therefore, switching from milk and dairy to PBDI would likely exacerbate the prevalence of low intakes. The clinical consequences of I deficiency are particularly significant for women of childbearing age (16–49 years), and pregnant women who have higher requirements to support foetal brain development, and where inadequate intakes can lead to congenital disabilities and long-term cognitive impairment in babies and children (SACN, 2014). This finding provides further support for standardising I fortification across PBDI, targeting equivalent concentrations to milk, yoghurt, and cheese, to prevent lower intakes across the population.

Replacement of dairy with PBDI could reduce Zn intakes in all age groups. Milk and dairy products contribute between 13 and 30 % of Zn to diets, with higher contributions in the diets of children 1.5–10 years and older adults 75 years+ (Bates et al., 2020). Current intakes of Zn are at or below the RNI for all age groups when dairy is included in diets. Consequently, the significantly lower concentrations of Zn in all plant-based dairy imitations (due to the absence of fortification) could have a detrimental effect, increasing the prevalence of inadequate intakes in the UK population. Zinc deficiencies can have wide-ranging and detrimental effects on various organ systems, including the integumentary, gastrointestinal, reproductive, skeletal, and nervous systems (Knez & Stangoulis, 2023). Additionally, deficiency can variably affect different age-based populations and has been associated with lower linear growth in children and impaired immune system response in older adults (Knez & Stangoulis, 2023).

In summary, switching from milk, cheese, and yoghurt to PBDIs could reduce dietary intakes of Ca, Mg, K, I, and Zn across the population. Existing adequate intakes of I may become inadequate for all age groups except children 1.5–3 years, and currently adequate intakes of Ca for adults 65–74 years may become inadequate if coconut-based products (which currently have a lower frequency of fortification) are included in their diets. Existing inadequate intakes of Ca for adolescents 11–18 years, Mg and K for adolescents 11–18 years and all adult populations, and Zn for all age groups could be exacerbated.

A limitation of this dataset, and indeed a gap in the evidence base in this area of research, is the relatively limited *in-vivo* understanding of the bioavailability of minerals within the PBDI matrix compared with dairy. Bioavailability can be influenced by various factors, including an individual's health and nutritional status, as well as interactions between nutrients or other components in food (Melse-Boonstra, 2020). Notably, insoluble dietary fibres, phytate and oxalate, which are present in unprocessed plant foods, can limit absorption of minerals, including Ca and Mg (Melse-Boonstra, 2020). Few *in vitro* studies have examined mineral bioaccessibility (the fraction released through digestion that becomes available (bioavailable) for biological processes) for PBDI, and estimates of bioaccessible fractions vary widely and are not entirely consistent (Muleya et al., 2024; Rebellato et al., 2023; Silva et al., 2020). These studies, based on a small number of samples, provide evidence that further, larger-scale *in vivo* assessments of bioavailability for all minerals of public health interest are essential. This will enable the potential impact on dietary intakes and nutritional status from consuming dairy and PBDI to be more accurately considered for different population age groups.

4.4. Implications for household expenditure

Milk, yoghurt, and cheese were cheaper on a volume/weight equivalent basis than all PBDI, which is consistent with other studies comparing the costs of dairy and PBDI in the UK (Clegg et al., 2021; Glover et al., 2022). If consumed at the same volume and weight as milk, cheese, and yoghurt, choosing PBDI could significantly increase household food expenditure (supplementary tables S7, S8, S9). Based on an average family of two adults (19–49) and one child (1.5–3 years), it would cost £518.67 per year to consume milk, yoghurt and cheese at the current reported daily consumption for these age groups, and this represents about 16 % of the annual food budget (Office for National Statistics, 2025). If the same family chose to consume coconut-based PBDI, the cost would increase by 57 % to £816.56 per year (25 % of annual budget), and if soya PBDI were chosen, the cost would increase by 23 % to £635.48 (19 % of annual budget). Consuming a mixture of different plant bases instead of dairy could also increase costs by up to 51 %, based on the consumption of oat PBB, coconut PBYI, and PBCI. However, these increased household costs assume functional replacement of like-for-like volumes and weights, and do not reflect the potential differences in mineral intakes demonstrated through modelling. To replace the mineral content (Ca, Mg, K, I, Zn) provided by the currently consumed volumes and weights of milk, yoghurt, and cheese, substantially greater volumes of PBDI would need to be consumed, which would incur additional costs (supplementary tables S10, S11, S12). Adolescents 11–18 years and adults 19–64 years, who currently consume the least milk across the different age groups, about 121 mL per day, for a cost of £0.14, would need to consume more than a litre of almond or oat PBB to provide the same minerals, at a substantially greater cost of between £1.51 and £1.90, respectively. For adolescents 11–18 years, who also consume the least yoghurt per day (22 g), the volume required and cost to meet the same mineral concentrations with coconut PBYI are prohibitive, at 2.7 kg for £21.07. This calculation is relevant to all age groups because existing shortfall nutrients are also the limiting nutrients in PBDI, such as K, I and Zn in PBB; I in PBYI, and Zn in PBCI. The scale of difference between the volumes and weights of dairy and PBDI required to provide the same mineral concentrations highlights the disparity in mineral density and cost efficiency in meeting mineral requirements between dairy and PBDI. Moreover, the volumes and weights required for PBDI to replace the mineral content of dairy are largely unrealistic (except perhaps for soya-based PBDI), providing further evidence that unless these minerals are fortified in PBDI, there is a risk that existing low intakes of minerals will be further exacerbated. In comparison to PBDI, milk, yoghurt, and cheese are cheaper and more highly concentrated sources of minerals, including shortfall minerals, in the UK, and therefore provide a more cost-efficient way for families and individuals to meet mineral requirements.

5. Conclusions

In comparison to PBDI, milk, yoghurt, and cheese are cheaper and more highly concentrated sources of minerals, including shortfall minerals in the UK and therefore provide a more cost-efficient way for families and individuals to meet mineral requirements.

Nutritional replacement of dairy with PBDI requires an unfeasible change in the volume of food required and would also be prohibitively expensive. Functional replacement of dairy with PBDI would increase the risk of inadequate intakes of Ca, Mg, K, I, and Zn. The present study found that Ca-fortified plant-based beverages (PBBs) contained similar amounts of Ca to milk. However, yoghurt and cheese imitations contained less Ca than dairy, despite a high level of Ca fortification, suggesting current fortified concentrations are inadequate. All PBDIs are also inadequately fortified with I. In PBCI, despite low levels of declared fortification, I concentrations suggest that other ingredients within the formulation improve the total concentration. Zn, K, and Mg, which are not fortified in PBDI and therefore not represented on product nutrition labels, are low (except for Mg and K in soya PBB) compared to dairy. As there is evidence of low intakes of these minerals across the UK population, it is recommended that PBDIs be fortified, while their bioaccessibility is also determined and compared with dairy products in future research.

Finally, it is not evident from consumer research that consumers who limit dairy are aware of the differences in mineral concentrations between dairy and PBDI. In the absence of equivalent fortification of PBDI and variable composition, providing age- and sex-specific dietary guidance on meeting nutrient requirements while incorporating different types of plant-based foods into diets could help different populations, particularly vulnerable groups such as adolescents and women of childbearing age, to optimise dietary choices aligned with their requirements. In the near term, general population guidance should clarify the nutritional differences between milk and dairy and PBDI, and advise consumers who may choose to replace milk and dairy in their diets with plant-based imitations to consume Ca- and I-fortified PBDI to reduce the risk of potential deficiency.

CRediT authorship contribution statement

Rachael J. Wall: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Miriam Clegg:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Yiran Zou:** Writing – review & editing, Validation, Supervision, Methodology, Data curation. **Sokratis Stergiadis:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The PhD scholarship for RJW was funded by the University of Reading and Arla Foods. Arla Foods is a dairy cooperative that produces both dairy and plant-source products. Arla Foods did not contribute to conceptualisation, methodology, validation, data collection and analysis, or writing or reviewing the manuscript. RJW reports a relationship with Joint SACN (Scientific Advisory Committee on Nutrition) - COT (Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment) Group on Plant-Based Drinks that includes: consulting or advisory. SS reports a relationship with Dairy UK, which includes speaking and lecture fees; the Dairy Council for Northern Ireland, which includes speaking and lecture fees; and the Dutch Dairy Association, which includes speaking and lecture fees and travel reimbursement. These organizations did not contribute to the funding of this research, or to the conceptualization, methodology, validation, data collection and analysis, writing or reviewing the manuscript. The other 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.foodres.2025.117741.

Data availability

Data will be made available on request.

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