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Macromineral and trace element concentrations in conventional and organic milk and plant-based beverages in the UK: implications for population intakes

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ABSTRACT

This study compared the minerals concentrations of milk (conventional $n = 20$; organic $n = 19$) to almond (conventional $n = 18$; organic $n = 7$) and oat (conventional $n = 19$; organic $n = 13$) plant-based beverages (PBB). Milk contained more Ca, Mg, P, K, I and Zn than PBB and less Na than oat PBB. Minerals concentrations of conventional and organic milk did not differ but conventional PBBs contained more Ca, P and I than organic PBBs due to permitted fortification. Despite fortification in conventional PBBs, Ca and I concentrations were lower than in milk. No differences were found between conventional and organic PBBs in concentrations of minerals that are not fortified, Mg, K and Zn. Replacement of milk with fortified conventional and organic almond and oat PBB, without other dietary changes, could reduce intakes of Ca and I below recommended intakes in some demographics, and increase prevalence of insufficiency for Mg, K, and Zn.

1. Introduction

A considerable global evidence base has established that there are differences between, and within, the mineral composition of milk and plant based beverages (PBB) (Antunes et al., 2023) marketed as 'alternatives' to milk, and that substitution of milk for PBB may increase the risk of inadequacy of some minerals in diets across different age- or sex-based demographics (Clegg et al., 2021; Glover et al., 2022; Medici et al., 2023; Zhang et al., 2020).

Milk contains a wide spectrum and varied concentrations of intrinsic micronutrients, including calcium, iodine, potassium, magnesium and zinc (Finglas., 2015), and higher consumption of milk and dairy is associated with micronutrient adequacy (Hobbs et al., 2020). Indeed, the contribution of milk to dietary intakes of calcium and iodine is particularly important as milk currently provides between 17 and 38 % of calcium and between 20 and 47 % of iodine in UK diets, depending on age. For iodine, other dietary sources are inadequately consumed to meet requirements (Nicol et al., 2024; SACN, 2014), and the National Diet and Nutrition Survey (NDNS) demonstrates that recommended intakes of calcium or iodine are not met without the contribution of milk (Bates et al., 2020). This is particularly important because of the increased risk of osteoporosis from calcium deficiency and potential for birth defects in babies born to mothers with iodine deficiency (Prentice, 2004; SACN, 2014).

Conversely, PBBs are not intrinsically rich in the same micronutrients found in milk (Moore et al., 2023). As a result, some are fortified with calcium so that their gross concentration is similar to that of milk (Astolfi et al., 2020; Martínez-Padilla et al., 2020; Sethi et al., 2016; Vanga & Raghavan, 2018), and iodine, although typically fortified at concentrations lower than those found in milk (Nicol et al., 2024). However, current public health dietary advice is that calcium-fortified plant-based dairy alternatives are suitable alternatives to dairy (NHS, 2024).

Consumers choose PBB for a variety of reasons. These include allergy or intolerance to the intrinsic components within milk, exclusion of milk for religious or cultural reasons, as well as a more significant and growing proportion of adult populations with ideological concerns for the environmental footprint of dairy production and/or animal welfare in intensive dairy production, and those who perceive dietary health benefits in PBB compared with milk (Euromonitor International, 2022b). To that end, research suggests that concerns for the environment and personal health are also driving disproportionate demand for

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organically produced products (Statista, 2023). Recent data shows that 10 % of PBB sold are organically produced, compared to only 5 % of total milk sales in the UK (Euromonitor International, 2024).

Organic and conventional production systems have different implications for environmental impacts (Linehan et al., 2024), unit cost (Linehan et al., 2024) and the nutritional quality of milk (Linehan et al., 2024; Qin et al., 2021) and PBB (Angelino et al., 2020; Marques et al., 2022). Most notably, organic PBB may not be fortified under European regulations (European Commission, 2018).

Studies globally have noted the variation in values found for concentrations of different minerals in PBB, both between and across plant families or individual plant bases (Chalupa-Krebzdak et al., 2018; Clegg et al., 2021; Medici et al., 2023; Vanga & Raghavan, 2018), but few have examined the relationships between the plant ingredient, production and processing characteristics that contribute to such diversity. This is especially important where such characteristics can variably affect dietary health. Additionally, in the UK, there is an absence of comprehensive, analytically determined data on the composition of PPB of different types and production and processing characteristics, including analysis of minerals that may be intrinsically present as a result of the interaction between the plant base and production system or added through fortification. To date, UK studies comparing the composition of milk to PBB are limited by reliance upon the nutrient content declared on product labels, where only minerals added through fortification are listed and therefore only differences in the concentrations of these minerals can be compared, or by focus on a single nutrient such as iodine (Bath et al., 2017). The dietary implications for minerals, including those not added through fortification, are uncertain.

In addition, a recurring observation in critical comparisons of milk to PBB is the contrasting relationship between the higher cost and lower nutrient density of PBB compared with milk (Clegg et al., 2021; Scholz-Ahrens et al., 2020). In the UK, Clegg et al. (2021) found that direct replacement of milk for PBB could approximately double the cost of consumption, while reducing micronutrient intakes, particularly among vulnerable groups. Given the price premium on organic products, the relationship between price and nutrient density is likely more divergent for organic milk and organic PBB.

The ability to determine how different PBBs, with different production characteristics, compare to milk and how effectively these products support nutrient adequacy, is key to providing relevant and more specific public health guidance. Recent work demonstrates that fortification practices of conventional PBB continue to evolve, with a higher proportion being fortified with calcium and iodine (Wall et al., 2023). In addition, as health remains a significant driver of PBB (Euromonitor International, 2022b) and organic PBB consumption, (Statista, 2023) and organic PBB are deemed to be a growing sector of the 'milk alternative' market (Euromonitor International, 2024), the implications for population mineral intakes must be clarified. In order to address this, larger-scale lab-based analyses including more representative brands within each plant type and assessment of all minerals of public health importance, rather than only nutrients listed on the label, are essential.

This is the first UK study (i) to analytically determine and compare the mineral concentrations of semi-skimmed milk and almond and oat PBB within conventional and organic production sectors and (ii) to consider the implications for UK population mineral intakes. In addition, given the price premium placed on organic products, this study (iii) calculated and compared the cost of consuming conventional and organic milk with conventional and organic PBB.

2. Materials and methods

2.1. Experimental design

This study analysed conventional and organic pasteurised semi-skimmed milk ($n = 39$; 20 conventional, 19 organic) and conventional and organic UHT almond beverages ($n = 25$; 18 conventional, 7 organic) and oat beverages ($n = 32$; 19 conventional, 13 organic), available from major UK supermarkets (Tesco, Sainsbury's, Asda, Aldi, Morrisons, Lidl, Coop, Waitrose, Ocado). In the absence of consumption data for PBB, and to maximise public health relevance, the experimental design and sampling protocol were based on products identified via an online retail survey of the websites of major UK supermarkets (representing 94 % retail market share (Kantar Worldpanel, 2024)). The retail survey was conducted between March to May 2023 to identify and record the price, nutrient composition and thermal processing characteristics of available PBBs, following a similar method described by Clegg et al. (2021). These specific products were selected because the survey demonstrated that almond and oat drinks were most widely available in both organic and conventional formats (organic were only available as UHT products), and published sales data for the UK showed that oat and almond were the most popularly consumed PBB (Euromonitor International, 2022c). Semi-skimmed milk is the most consumed of all milk types in the UK (Bates et al., 2020) and represents 66 % of liquid milk sales (Euromonitor International, 2022a). In addition, fresh pasteurised milk is sold in significantly greater volumes than UHT milk: 95 % vs 5 % respectively (Euromonitor International, 2022a), and organic semi-skimmed milks were largely only available as fresh, pasteurised products. Given that retail milk mineral concentrations vary by season (Newton, Pétursdóttir, et al., 2023), samples were collected during summer and winter (the two seasons with the greatest difference in milk minerals) so that the effect of this variation was accounted for in the study. Therefore, individual brands of pasteurised, conventional and organic semi-skimmed milk and UHT, conventional and organic almond and oat were purchased in Summer (June/July 2023), and the same products were purchased again in winter (January/February 2024). Where the same product was unavailable, they were replaced with an alternative with the same characteristics, where possible. The major private label brands and supermarket own label brands, representing approximately 68.8 % and 71.4 % of the milk and PBB market share, respectively, (Euromonitor International, 2022a) were included in the experimental design.

2.2. Milk and PBB analysis

After purchase, all samples were aliquoted into 7 mL sterile polypropylene tubes and stored in a freezer at −20 °C at the University of Reading. Samples were defrosted overnight at 4 °C before further analysis.

Mineral analysis was performed at the University of Reading. Samples were analysed 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). It was not possible to measure iron (Fe), selenium (Se) or mercury (Hg). In addition, lead (Pb), aluminium (Al) and tin (Sn) were below the limit of quantification (0.44 μg/kg; 1.08 μg/kg; 0.25 μg/kg, respectively), so results are not presented. Mineral concentrations were determined using a protocol for microwave-assisted acid digestion, using inductively coupled plasma-optical emission spectrometry (ICP-OES) (for macro minerals) and inductively coupled plasma and mass spectrometry (ICP-MS) (for trace elements and heavy metals) based on the method described by Newton, Theodoridou, et al. (2023). Briefly, 1 mL of milk or PBB was digested in 7.5 mL 67 % trace analysis grade HNO_3 and 2.5 mL 37 % HCL using an Ethos Easy Microwave Digestion system. The solution was heated to 180 °C over a ramp period of 15 min and then held at the same temperature for a further 10 min before cooling to ambient temperature. The filtrate was diluted to 50 g with ultra-pure water and then further diluted at a ratio of 1:4. For each analysis, the ICP-MS (Agilent 7900, Agilent Technologies, Singapore) and ICP-OES (Avio 500, Perkin Elmer, USA) were calibrated via single standards and multi-standard stock solutions. Calibration curves were prepared using 6 different concentrations between 0.5 and 50 μg/L for trace elements and 4 different concentrations between 1 and 20 mg/L for macro elements. Standards for Ca, Mg, P, K, 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 and 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 samples. Correlation coefficients demonstrated excellent linearity (R^2 = 0.998–0.999) for all calibration curves. Each analytical batch contained a minimum of 2 procedural blanks and 2 certified reference materials (CRM). Analyte recovery was verified using ERM-BD150 certified reference material, skim milk powder. 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 milk and PBB samples chosen at random from the dataset were analysed in duplicate, and all duplicate measures were within ±5 %. Operating conditions for the ICP-MS, ICP-OES, including limits of detection and quantification, can be found in tables S1 and S2.

2.3. Changes in mineral intakes and implications for meeting reference nutrient intakes through substitution of conventional milk for organic milk and conventional and organic PBBs

Calculation of changes in minerals intakes, comparison of the proportion of nutrient requirements met by each experimentally determined product, and estimated changes in reference nutrient intakes (RNI) through substitution of experimentally determined products in place of milk, by age group, was conducted for minerals of significant public health concern: Ca, Mg, K, Na, I and Zn. These are minerals for which there is both a UK government daily dietary reference value (DRV) (PHE, 2016) and where population intakes are monitored through the National Diet and Nutrition Survey (Bates et al., 2020). Reference Nutrient Intake (RNI) is a term encompassed by DRV that refers to the amount of a nutrient that is enough for almost every individual, even those who have high requirements for the nutrient. This level of intake is generally higher than most people need. If individuals are consuming the RNI of a nutrient, they are unlikely to be deficient in that nutrient. Calculation of changes in intakes of other minerals (not included because the risk of deficiency is low) analysed in this study, including P, Co, Cu, and Mn, and daily exposure to heavy metals, including Cd, Cr, and Ni, may be found in Supplemental Materials table S3. Calculations used the nutrient values that were analytically determined in this study and assumed that existing mean volumes of milk consumed by age group were 100 % replaced by equivalent volumes of conventional or organic milk and conventional and organic PBB. Volumes of milk consumed by age group were extracted from SACN (2024) therefore the intakes per age group applied in this study were: 1–1.5 years 286 mL/day, 1.5–4 years 246 mL/day, 5–10 years 174 mL/day, 11–18 years 136 mL/day, 19–49 years 118 mL/day, 50–64 years 170 mL/day, 65–74 years 156 mL/day and 75+ years 220 mL/day.

2.3.1. Daily contribution of minerals from product substitution to intakes in mg or µg per day by age group

To estimate the change in daily contributions to minerals intakes through substitution of conventional milk for organic milk and for conventional and organic almond and oat, mean volumes of milk consumed by age group per day (which included all whole, semi-skimmed and skimmed milk) (SACN, 2024) were multiplied by experimental values of minerals concentrations found in conventional and organic milk and conventional and organic almond and oat (Table 2).

2.3.2. Percentage contribution from product substitution to daily RNI

The proportion of daily recommended minerals intakes (%RNI) satisfied by each of conventional and organic milk and conventional and organic PBB by age group was calculated using the experimentally derived contribution to mineral intakes for each respective product, divided by government DRVs outlined in PHE (2016). UK Government DRVs are based on age and sex demographics that do not neatly fit within the same (milk consumption) age groups reported in SACN (2024). For this study, where DRVs straddled two age groups for milk consumption, a mid-point for the two DRVs was calculated. For example, SACN (2024) reports volumes of milk consumed for 5- to 10-year-olds, where the DRV for calcium differs for 4- to 6-year-olds (450 mg/day) and for 7- to 10-year-olds (550 mg/day). In this case, a mid-point of 500 mg/day DRV was used to calculate the % RNI for the age group of 5–10 years. Where DRVS vary by sex within the same age group, the higher DRV for males was applied.

2.3.3. Satisfaction of daily RNI, including product substitution, at whole diet level

The relative importance of milk as a contributor of minerals and the effect of substitution of conventional milk for organic milk or conventional or organic PBB was then considered in the context of other sources of minerals in the diet to estimate population-level dietary change. First dietary intakes of minerals without the contribution of milk were established. The contribution of milk to individual minerals intakes in mg or µg/day by age group was calculated by applying the percentage contribution of milk by age group to total minerals intakes per day (Bates et al., 2020; Lennox et al., 2013) and then subtracting from whole diet intakes per day (Bates et al., 2020; Lennox et al., 2013). Secondly, total dietary intakes of minerals, using experimentally measured mineral concentrations in the present study for conventional and organic milk, and conventional and organic PBB, were established by adding together total dietary mineral intakes without milk, plus the contribution to intakes from each experimental primary ingredient and production system. Finally, the total dietary intakes of minerals were expressed as a proportion of the total RNI for each age group.

2.4. Statistical analysis

Statistical analysis was carried out using Minitab®22.1. Data were analysed with linear mixed effects models using ingredient (milk, almond, oat), production system (conventional, organic), season (summer, winter), and their 2-way and 3-way interactions as fixed factors, and brand ID (nested within production system and ingredient) as a random factor. Normality of the residuals was visually assessed; no variables showed deviation from normality, and they were all analysed untransformed. Where the effect of fixed factors, or their interactions, 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 ($P < 0.05$).

3. Results

Conventionally produced pasteurised milk ($n = 20$), UHT almond ($n = 18$), UHT oat ($n = 19$), and organically produced pasteurised milk ($n = 19$), UHT almond ($n = 7$) and UHT oat ($n = 13$) were analysed. Of the conventionally produced PBBs, all were fortified with calcium ($n = 37$) and 37 % ($n = 14$) were fortified with iodine. Salt was also listed as an ingredient in all conventional PBBs. Organic PBBs were not fortified with any minerals, but the majority (almond $n = 5$; oat $n = 13$) listed sea salt, and few contained potassium carbonate as an ingredient (oat $n = 2$).

3.1. Effect of main ingredient

All macrominerals concentrations differed significantly by main ingredient (Table 1). Milk contained more than double the concentrations of Ca, P, and K than was found in almond (Ca + 754 mg/kg; P + 634 mg/kg; K + 964 mg/kg) and oat (Ca + 711 mg/kg; P + 677 mg/kg;

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

	Ingredient					Production System				Season			
	Cow	Almond	Oat	SE	P-Value[a]	Conventional	Organic	SE	P-Value[a]	Summer	Winter	SE	P-Value[a]
Parameters	$n = 39$	$n = 25$	$n = 32$			$n = 57$	$n = 39$			$n = 50$	$n = 46$		
Price (GBP/L)	1.26^{B}	1.80^{A}	1.77^{A}	0.122	**<0.001**	1.38^{B}	1.84^{A}	0.059	**<0.001**	1.62	1.60	0.046	0.638
Macrominerals (mg/kg)													
Calcium (Ca)	1242^{A}	488^{B}	531^{B}	86.6	**<0.001**	1059^{A}	448^{B}	41.9	**<0.001**	821^{A}	686^{B}	39.0	**0.008**
Magnesium (Mg)	112.5^{A}	61.8^{B}	31.1^{C}	3.46	**<0.001**	67.8	69.2	1.68	0.563	68.3	68.6	1.71	0.886
Phosphorus (P)	1038^{A}	404^{B}	361^{B}	70.0	**<0.001**	714^{A}	488^{B}	33.9	**<0.001**	623	579	30.5	0.221
Potassium (K)	1602^{A}	638^{B}	466^{B}	145.5	**<0.001**	860	944	70.4	0.417	833	971	62.0	*0.051*
Sodium (Na)	362^{B}	308^{B}	462^{A}	34.2	**<0.001**	396	358	16.6	0.122	406^{A}	348^{B}	15.3	**0.004**
Trace elements (µg/kg unless otherwise stated)													
Cobalt (Co)	3.18	3.05	1.77	1.302	0.346	3.40	1.93	0.631	0.116	4.27^{A}	1.07^{B}	0.641	**0.001**
Copper (Cu, mg/kg)	0.05^{C}	0.27^{A}	0.19^{B}	0.030	**<0.001**	0.11^{B}	0.23^{A}	0.014	**<0.001**	0.16	0.18	0.014	0.468
Iodine (I)	261.3^{A}	37.1^{B}	48.2^{B}	23.63	**<0.001**	142.3^{A}	88.7^{B}	11.44	**0.002**	75.5^{B}	155.6^{A}	10.15	**<0.001**
Manganese (Mn, mg/kg)	0.04^{B}	0.41^{A}	0.45^{A}	0.079	**<0.001**	0.28	0.32	0.038	0.405	0.30	0.29	0.031	0.752
Molybdenum (Mo)	26.9^{B}	25.0^{B}	82.5^{A}	7.22	**<0.001**	32.0^{B}	57.6^{A}	3.50	**<0.001**	32.2^{B}	57.4^{A}	3.55	**<0.001**
Zinc (Zn, mg/kg)	4.04^{A}	0.81^{B}	0.47^{B}	0.176	**<0.001**	1.74	1.81	0.085	0.563	1.74	1.81	0.084	0.549
Heavy metals (µg/kg)													
Cadmium (Cd)	0.03^{B}	0.38^{AB}	0.72^{A}	0.186	**<0.001**	0.57^{A}	0.18^{B}	0.090	**0.005**	0.36	0.40	0.088	0.729
Chromium (Cr)	42.7	16.0	57.2	18.57	*0.063*	51.2	26.1	9.00	*0.059*	18.3^{B}	59.0^{A}	9.15	**0.002**
Nickel (Ni)	45.9^{B}	78.1^{B}	157.9^{A}	23.01	**<0.001**	68.6^{B}	119.4^{A}	11.15	**0.003**	89.7	98.3	10.37	0.508

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 ($P < 0.05$).

K + 1136 mg/kg), and 45 % more Mg than almond (+50.7 mg/kg) and 73 % more Mg than oat (+81.4 mg/kg) ($P < 0.001$). Oat contained approximately half as much Mg as almond (−30.7 mg/kg; $P < 0.001$). Oat contained the most Na, which was 50 % higher than almond (+154 mg/kg) and 27 % higher than milk (+100 mg/kg) ($P < 0.001$). Trace elements differed substantially by main ingredient. Almond contained the highest concentration of Cu, which was 30 % greater than the amount found in oat (+0.08 mg/kg) and five times greater than concentrations found in milk (+0.22 mg/kg) ($P < 0.001$). Oat and almond both contained around 10 times more Mn than milk (+0.37 mg/kg and + 0.41 mg/kg; $P < 0.001$), respectively. Oat contained three times more Mo than milk and almond (+55.6 µg/kg and + 57.5 µg/kg, respectively; $P < 0.001$). Conversely milk was found to contain approximately seven times the amount of I compared to almond (+224 µg/kg) and more than five times the amount of I compared to oat (+213 µg/kg) and similarly contained almost five times as much Zn as almond (+3.23 mg/kg) and more than eight times as much Zn as oat (+3.57 mg/kg) ($P < 0.001$). Concentrations of Cd and Ni were greatest in oat, and these were significantly different from milk (+0.69 µg/kg and + 112 µg/kg, respectively). Although Cd and Ni were found to be lower in almond than oat, only Ni was significantly lower (−79.8 µg/kg) ($P < 0.001$). Milk was 32 % cheaper than almond (−£0.54/L) and 29 % cheaper than oat (−£0.51/L) ($P < 0.001$).

3.2. Effect of production system

The effect of production system was statistically significant for Ca, P, Cu, I, Mo, Cd and Ni ($P < 0.01$) (Table 1). Concentrations of Ca and P were found to be significantly higher in conventional products (Ca +611 mg/kg; P + 226 mg/kg) than in organic products. Cu and Mo were found to be around twice as high in organic products (+0.12 mg/kg; +25.6 µg/kg, respectively) compared to conventional products ($P < 0.001$). I was found to be 60 % greater in conventional products (+53.6 µg/kg) ($P = 0.002$). Concentrations of Cd were three times greater in conventional products (+0.39 µg/kg) compared to organic ($P = 0.005$), where Ni was found to be 74 % greater in organic products (+50.8 µg/kg) ($P = 0.003$). Organic products were significantly more expensive (+£0.46/L; $P < 0.001$) than conventional products.

3.3. Effect of season

The effect of season was statistically significant for Ca, Na, Co, I, Mo, and Cr (P < 0.01) (Table 1). Concentrations of Ca (+135 mg/kg; $P = 0.008$) and Na (+58 mg/kg; $P = 0.004$) were found to be higher in summer than in winter. Co, I and Mo differed according to season. Concentrations of I (+80 µg/kg; $P < 0.001$) and Mo (+25 µg/kg; $P < 0.001$) were found to be greater in winter, where concentrations of Co were approximately four times higher in summer (+3.2 µg/kg; $P < 0.001$). Cr was significantly higher in winter than in summer (+40.7 µg/kg; $P = 0.002$). The cost of milk and PBB did not vary by season.

3.4. Significant interactions between main ingredient, production system and season

The interaction between milk and production system did not produce any significant differences in mineral composition. However, the interaction between almond and oat and production system significantly affected concentrations of Ca ($P < 0.001$), P ($P = 0.003$), Cu ($P < 0.001$), I ($P = 0.016$), Mo ($P = 0.019$), Cd ($P = 0.040$) and Ni ($P = 0.002$) (Table 2). Concentrations of Ca and P were higher, by an order of magnitude, in conventionally produced almond (+895.4 mg/kg) and oat (+986 mg/kg) than in organically produced almond and oat. Additionally, concentrations of I were higher in conventional almond (+72.46 µg/kg) and oat (+95.44 µg/kg) than in organic, although the difference only reached significance for oat drinks, where no iodine was detected in organic versions. Organic almond and oat both contained significantly more Cu (+0.27 mg/kg and + 0.13 mg/kg, respectively) than their conventional equivalents, and organic oat contained more Mo (+43.4 mg/kg) than conventional oat. Conventional oat was higher in Cd (+0.76 µg/kg), where organic almond was higher in Ni (+139.68 µg/kg).

The interaction between ingredient and season (Table 3) was significant for almond and macrominerals, including Ca ($P < 0.001$), Mg ($P < 0.001$), K ($P = 0.036$) and Na ($P < 0.001$). Almond contained greater concentrations of Ca (+464 mg/kg), Mg (+16.6 mg/kg) and NA (+196 mg/kg) in summer than in winter, while it contained more K (+429 mg/kg) in winter. Unlike almond, milk contained more magnesium in winter (+15.2 mg/kg) than in summer. Concentrations of I (+224 µg/kg; $P < 0.001$), Mo (+41.84 µg/kg; $P = 0.046$) and Zn (+0.92 mg/kg; $P < 0.001$)

Table 2
Means and standard errors for the effect of the interaction between ingredient and production system on price and mineral profiles of milk and plant-based beverages.

	Conventional			Organic				
	Cow	Almond	Oat	Cow	Almond	Oat	SE	P-Value[a]
Parameters	$n = 20$	$n = 18$	$n = 19$	$n = 19$	$n = 7$	$n = 13$		
Price (GBP/L)	1.13	1.50	1.52	1.39	2.10	2.01	0.124	0.276
Macrominerals (mg/kg)								
Calcium (Ca)	1218.5^{A}	935.5^{B}	1023.6^{AB}	1265.2^{A}	40.1^{C}	37.6^{C}	87.49	**<0.001**
Magnesium (Mg)	112.9	61.1	29.2	112.1	62.5	33.0	3.50	0.704
Phosphorus (P)	1034^{A}	558^{B}	549^{B}	1041^{A}	$249B^{C}$	174^{C}	70.8	**0.003**
Potassium (K)	1594	433	553	1611	844	378	147.1	0.102
Sodium (Na)	346	406	466	377	210	458	32.4	0.225
Trace elements (μg/kg unless otherwise stated)								
Cobalt (Co)	4.62	2.68	2.91	1.75	3.42	0.64	1.315	0.286
Copper (Cu, mg/kg)	0.06^{CD}	0.13^{CD}	$0.14B^{C}$	0.04^{D}	0.40^{A}	0.24^{B}	0.030	**<0.001**
Iodine (I)	256.39^{A}	74.10^{BC}	95.44^{B}	266.45^{A}	1.64^{BC}	0.00^{C}	23.964	**0.016**
Manganese (Mn, mg/kg)	0.06	0.39	0.37	0.02	0.42	0.52	0.080	0.292
Molybdenum (Mo)	21.4^{C}	13.8^{C}	60.8^{B}	32.4^{C}	36.2^{BC}	104.2^{A}	7.29	**0.019**
Zinc (Zn, mg/kg)	4.17	0.59	0.45	3.92	1.02	0.48	0.18	0.107
Heavy metals (μg/kg)								
Cadmium (Cd)	0.03^{B}	0.58^{AB}	1.10^{A}	0.02^{B}	0.19^{B}	0.34^{B}	0.188	**0.040**
Chromium (Cr)	51.1	19.4	83.2	34.3	12.6	31.2	18.76	0.342
Nickel (Ni)	54.35^{BC}	8.26^{C}	143.16^{A}	37.50^{C}	147.94^{AB}	172.73^{A}	23.26	**0.002**

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 ($P < 0.05$).

Table 3
Means and standard errors for the effect of the interaction between ingredient and season on price and mineral profiles of milk and plant-based beverages.

	Summer			Winter				
	Cow	Almond	Oat	Cow	Almond	Oat	SE	P-Value[a]
Parameters	$n = 20$	$n = 14$	$n = 16$	$n = 19$	$n = 11$	$n = 16$		
Price (GBP/L)	1.29	1.84	1.72	1.23	1.76	1.81	0.077	*0.053*
Macrominerals (mg/kg)								
Calcium (Ca)	1168^{A}	720^{B}	575^{BC}	1316^{A}	256^{C}	486^{BC}	65.7	**<0.001**
Magnesium (Mg)	104.9^{B}	70.1^{C}	29.8^{E}	120.1^{A}	53.5^{D}	32.3^{E}	2.88	**<0.001**
Phosphorus (P)	1000^{A}	483^{B}	385^{B}	1075^{A}	324^{B}	338^{B}	51.3	**0.038**
Potassium (K)	1593^{A}	424^{C}	482^{BC}	1611^{A}	853^{B}	450^{BC}	104.2	**0.036**
Sodium (Na)	346^{B}	406^{AB}	466^{A}	377^{AB}	210^{C}	458^{A}	25.8	**<0.001**
Trace elements (μg/kg unless otherwise stated)								
Cobalt (Co)	5.33	5.17	2.30	1.04	0.93	1.24	1.081	0.234
Copper (Cu, mg/kg)	0.04	0.26	0.18	0.0	0.27	0.20	0.023	0.986
Iodine (I)	149.0^{B}	32.1^{C}	45.3^{C}	373.6^{A}	42.1^{C}	51.1^{C}	17.08	**<0.001**
Manganese (Mn, mg/kg)	0.06	0.41	0.44	0.03	0.40	0.45	0.052	0.759
Molybdenum (Mo)	5.96^{E}	18.37^{DE}	72.14^{AB}	47.80^{BC}	31.64^{CD}	92.88^{A}	5.993	**0.046**
Zinc (Zn, mg/kg)	3.58^{B}	1.15^{C}	0.48^{D}	4.50^{A}	0.46^{CD}	0.46^{CD}	0.142	**<0.001**
Heavy Metals (μg/kg)								
Cadmium (Cd)	0.00	0.46	0.61	0.05	0.31	0.83	0.149	0.497
Chromium (Cr)	0.13^{C}	6.17^{BC}	48.52^{ABC}	85.29^{A}	25.84^{ABC}	65.90^{AB}	15.422	**0.034**
Nickel (Ni)	36.5	71.0	161.5	55.3	85.2	154.3	17.45	0.659

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 ($P < 0.05$).

were significantly greater in winter milk than summer milk. Chromium was also found to be greater in milk in winter (+85.16 μg/kg; $P = 0.034$). There were no significant seasonal variations in the concentrations of minerals in oat.

The interaction between production system and season was also significant for Ca ($P = 0.006$), Na ($P = 0.007$), Mo ($P = 0.002$), Zn ($P = 0.023$) and Cd ($P = 0.021$) (Table 4). Conventional products purchased in the summer were found to be 25 % higher in Ca than conventional products purchased in winter (+232 mg/kg) and contained more than twice the concentration of Ca than organic products, irrespective of season (summer: +737 mg/kg; winter: +700 mg/kg). Conventional products purchased in summer contained the most Na, compared to conventional winter (+96 mg/kg) and organic summer products (+88 mg/kg). Although organic winter products were also lower in Na than conventional summer, the difference was not significant. Organically produced products purchased in the winter were highest in Mo compared to organic summer (+ 45.6 μg/kg), conventional winter (+42.5 μg/kg) and conventional summer (+56.1 μg/kg).

Significant variations in the concentrations of Ca ($P = 0.014$), Na ($P < 0.001$), I ($P = 0.017$) and Mo ($P = 0.037$)were found as a result of three-way interactions between ingredient, season and production system (Table 5). Ca concentrations in all milk, irrespective of season and production system, conventional oat in both seasons and conventional almond, purchased in summer, were found to be similar. Conventional almond purchased in winter was found to contain about 56 % less Ca than was determined in conventional winter milk (−732 mg/kg) and about 40 % less than was determined in conventional oat in winter (−384 mg/kg). Organic almond in summer contained 94 % less Ca (−1213 mg/kg) and in winter 92 % less Ca (−520 mg/kg) than in conventional almond products during the same seasons. Organic oat

Table 4
Means and standard errors for the effect of the interaction between production system and season on price and mineral profiles of milk and plant-based beverages.

	Summer		Winter			
	Conventional	Organic	Conventional	Organic	SE	P-Value[a]
Parameters	$n = 30$	$n = 20$	$n = 27$	$n = 19$		
Price (GBP/L)	1.38	1.86	1.39	1.81	0.063	0.282
Macrominerals (mg/kg)						
Calcium (Ca)	1173^{A}	436^{C}	941^{B}	473^{C}	52.3	**0.006**
Magnesium (Mg)	67.6	69.0	67.9	69.3	2.39	0.995
Phosphorus (P)	752	482	673	499	42.1	0.203
Potassium (K)	802	854	915	1038	86.0	0.629
Sodium (Na)	443^{A}	355^{B}	347^{B}	364^{AB}	20.5	**0.007**
Trace elements (µg/kg unless otherwise stated)						
Cobalt (Co)	5.53	2.61	1.20	1.39	0.884	*0.097*
Copper (Cu, mg/kg)	0.10	0.23	0.12	0.23	0.019	0.494
Iodine (I)	106.3	41.6	177.7	137.1	14.05	0.318
Manganese (Mn, mg/kg)	0.30^{A}	0.28^{A}	0.24^{A}	0.37^{A}	0.042	**0.009**
Molybdenum (Mo)	24.9^{B}	35.4^{B}	38.5^{B}	81.0^{A}	4.69	**0.002**
Zinc (Zn, mg/kg)	1.79^{A}	1.62^{A}	1.67^{A}	2.02^{A}	0.115	**0.023**
Heavy metals (µg/kg)						
Cadmium (Cd)	0.64^{A}	0.00^{B}	0.48^{A}	0.39^{AB}	0.120	**0.021**
Chromium (Cr)	34.11	0.09	67.95	52.80	12.758	0.478
Nickel (Ni)	64.9	114.2	72.2	124.9	14.45	0.903

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).

contained about 97 % less Ca (summer: −1061 mg/kg; winter: −920 mg/kg) than was found in conventional oat products during the same seasons. Compared with organic milk in the same seasons, organic almond contained between 93 % less Ca (summer: −1121 mg/kg) and 96 % less Ca (winter: −1288 mg/kg) and oat contained about 98 % less Ca (summer: −1171 mg/kg and winter: −1303 mg/kg).

Na concentrations did not vary significantly for milk and oat across production systems and seasons. Conversely, conventional almond purchased in summer contained the most Na and was significantly higher than conventional almond in winter and organic almond in both seasons. Conventional winter almond and organic almond contained similar levels of Na, and these were lower than levels found in milk and oat.

I concentrations were highest in winter milk (conventional and organic), and these were significantly higher than summer milk and all oat and almond. When compared to the same production system in summer, I concentrations in winter milk were two times greater than conventional and three times greater than organic milk (CON: +166 µg/kg; ORG: +283 µg/kg). Organic summer milk contained the least I of all the milk samples, and although greater than concentrations found in conventional almond (+66 µg/kg) and oat (+37 µg/kg) was not found to be significantly different. When comparing I concentrations in conventional milk to conventional almond, conventional almond contained 66 % less I in summer (−115 µg/kg) and 77 % less I in winter (−250 µg/kg). Similarly, conventional oat contained 49 % less I in summer (−86 µg/kg) and 70 % less I in winter (−236 µg/kg) than conventional milk in the same seasons. Concentrations of I did not vary significantly between almond and oat or by season, but the effect of production system was significant, where I was not detected in organic products.

Mo was highest in organic winter oat, and this was significantly higher than all other products. Although concentrations of Mo found in different products show a wide range of variation, differences were not found to be significant.

4. Discussion

This is the first large-scale UK study to analytically derive and compare a broad range of mineral concentrations in milk and PBB, and the first global study to the author's knowledge, to compare samples of semi-skimmed milk and types of PBB, controlling for the variables of ingredient, production system, and season.

4.1. Effect of main ingredient in milk and PBB

Mineral concentrations varied according to the primary ingredient. Milk contained higher concentrations of Ca, Mg, P, K, I and Zn and lower concentrations of Na than PBBs. Almond PBB contained higher concentrations of Mg and Cu than oat. Oat PBB contained more Na, Mo and Ni than almond PBB and milk. Other studies have also found significant differences in mineral concentrations between milk and different PBBs, with higher concentrations of Ca, P, K, I and Zn and lower Na in milk (Astolfi et al., 2020; Moore et al., 2023; Smith, Dave, Hill, & McNabb, 2022).

The composition and nutritional density of animal milk are fundamentally aligned to its purpose: to nourish growing infants (Thorning et al., 2016). The broad composition of milk and its major components, including minerals, varies, but within a limited range (Pereira, 2014). Variation in milk minerals has been well researched, and they are affected by dairy production system, cows' diet, animal breed and season (Newton, Pétursdóttir, et al., 2023; Qin et al., 2021; Toscano et al., 2023). A significant modifiable factor includes cows' dietary intake of minerals, which are provided to ensure optimum milk production and animal health and metabolism to maximise resource use and minimise excretions to the environment (Oliveira & Soares, 2024). Feed ingredients can also largely affect feed intakes with Qin et al. (2021) showing that cereals, forage and mineral supplements are ingredients that can impact concentrations of several minerals in milk, such as Ca, P, K, Cu and Zn. In addition to dietary management, researchers have also observed positive correlations between concentrations of Ca, Mg, P and Zn and milk protein (specifically casein which binds minerals such as Ca and P (Pereira, 2014)), lactose and fat; that may explain variation in minerals density in milk compared with PBBs, that also do not contain casein or lactose (Klop et al., 2014; Newton, Theodoridou, et al., 2023; Oliveira & Soares, 2024; Toscano et al., 2023). Seasonal effects have also been observed previously for milk minerals, with winter milk containing more Cu, I, Mn, Mo and Zn than summer milk (Newton, Pétursdóttir, et al., 2023), whilst the effect of alternative breeds (non-Holstein) has also been found to affect the concentrations of Ca, P, K and Na (Qin et al., 2021).

PBBs are not biological fluids but formulations of ingredients, based on different plant extracts, so nutritional variation between plant types and differences compared to milk are inevitable (McClements et al., 2019). However, raw almonds contain much of the same minerals

Table 5
Means and standard errors for the effect of the interactions between ingredient, season and production system on price and mineral profiles of milk and plant-based beverages.

	Cow				Almond				Oat				SE	P-Value[a]
	Summer		Winter		Summer		Winter		Summer		Winter			
	Con	Org	Con	Org	Con	Org	Con	Org	Con	Org	Con	Org		
Parameters	$n = 10$	$n = 10$	$n = 10$	$n = 9$	$n = 10$	$n = 4$	$n = 8$	$n = 3$	$n = 10$	$n = 6$	$n = 9$	$n = 7$		
Price (GBP/L)	1.12	1.46	1.13	1.32	1.50	2.19	1.50	2.00	1.51	1.94	1.53	2.09	0.176	*0.072*
Macrominerals (mg/kg)														
Calcium (Ca)	1136.7^{A}	1199.6^{A}	1300.3^{A}	1336.5^{A}	1291.7^{A}	78.7^{CD}	568.9^{BC}	48.2^{CD}	1089.3^{A}	28.3^{D}	952.9^{AB}	33.4^{D}	145.00	**0.014**
Magnesium (Mg)	105.1	104.8	120.7	119.4	71.2	69.1	51.1	55.9	26.5	33.2	32.0	32.7	6.61	0.619
Phosphorus (P)	991	1010	1078	1074	676	267	435	248	588	170	507	173	116.6	0.414
Potassium (K)	1578	1608	1609	1615	261	568	601	1133	568	387	537	366	238.5	0.784
Sodium (Na)	339^{CD}	353^{CD}	366^{BCD}	390^{ABCD}	523^{A}	262^{DE}	165^{E}	292^{BCDE}	467^{ABC}	451^{ABCD}	509^{AB}	411^{ABCD}	56.7	**<0.001**
Trace elements (µg/kg unless otherwise stated)														
Cobalt (Co)	7.82	2.84	1.42	0.71	4.54	5.00	0.69	2.30	4.24	0.00	1.51	1.14	2.448	0.782
Copper (Cu, mg/kg)	0.05	0.04	0.07	0.04	0.10	0.43	0.15	0.38	0.15	0.22	0.14	0.26	0.053	0.378
Iodine (I)	173.21^{B}	124.77^{BC}	339.58^{A}	408.14^{A}	58.17^{CD}	0.00^{CD}	90.03^{BCD}	0.00^{CD}	87.51^{BCD}	0.00^{D}	103.37^{BCD}	0.00^{D}	38.980	**0.017**
Manganese (Mn, mg/kg)	0.10	0.02	0.03	0.03	0.42	0.37	0.36	0.51	0.39	0.47	0.35	0.57	0.118	0.614
Molybdenum (Mo)	0.06^{E}	11.85^{DE}	42.73^{BCD}	53.60^{BC}	13.43^{DE}	15.04^{CDE}	12.84^{DE}	61.79^{BCD}	61.17^{B}	79.38^{B}	59.80^{BC}	127.67^{A}	12.987	**0.037**
Zinc (Zn, mg/kg)	3.72	3.45	4.61	4.40	1.12	1.06	0.04	1.08	0.54	0.35	0.36	0.58	0.318	0.194
Heavy metals (µg/kg)														
Cadmium (Cd)	0.00	0.00	0.05	0.06	0.78	0.00	0.35	0.46	1.15	0.00	1.03	0.65	0.333	0.202
Chromium (Cr)	0.00	0.27	102.24	68.70	7.46	0.00	30.49	27.97	94.88	0.00	71.11	61.71	35.353	0.125
Nickel (Ni)	35.57	37.50	73.12	37.62	14.62	126.63	1.72	169.97	144.38	178.41	141.85	166.97	40.037	0.393

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 ($P < 0.05$).

present in milk, and on a weight equivalent basis are a richer source of macrominerals and trace elements (except for iodine) than liquid milk (Finglas., 2015). Relative to almond and milk, raw oats contain significantly less Ca and do not contain any iodine, but contain higher concentrations of K, Mg, P and Mn than liquid milk (Finglas., 2015). Yet the significantly higher mineral density of milk compared to PBB and few significant differences between almond and oat in the present study, suggest that the nutritional value of the originating plant ingredient does not necessarily reflect on the nutritional value of the final PBB. This may be related to a number of factors, perhaps most importantly, the small proportion of the originating plant material contained in PBBs. Quantitative ingredient information on the labels showed that the almond PBBs analysed contained between 2 and 6 % of almonds while oat PBBs contained 10–13 % oats, which correspond to approximately to 20–60 almonds and 8–11 tablespoons of rolled oats per 1 L of commercial product (typical carton found in UK supermarkets), respectively. Other studies noting wide nutritional disparities between milk and PBBs have also noted the small proportions of the originating plant base in PBBs as a key driver (Scholz-Ahrens et al., 2020; Smith et al., 2022; Walther et al., 2022; Zhang et al., 2020). In addition, the minerals composition of the plant extracts in PBBs such as almonds and oats may also vary according to country of origin, growing region and conditions, variety and storage (Barreca et al., 2020; Greenfield and Southgate, 2003) although at a retail survey level it is challenging to speculate on the relative impact of each of these parameters on the final concentration due to the lack of the available information in the product label.

Na is found intrinsically within milk in higher concentrations than found in raw almonds, which also contain more Na than oats (Finglas., 2015). However, sea salt and salt are commonly added to PBB formulations to improve palatability (Sousa & Kopf-Bolanz, 2017). In the present study, salt was a quantified ingredient in all oat and almost all almond PBB, at similar concentrations to milk. The lower concentration of Na found in almond PBB was in line with its lower concentrations declared on product labelling. In contrast, the higher concentration determined in the present study in oat PBB contradicted the labelled quantity of added salt in oat PBB. The comparatively higher concentration of Na in oat PBB may reflect the sum of endogenous and added Na. The difference found in this study between analytical values and labelled values for Na is important to note, as it highlights the limitations of previous research based solely on comparison of labelled quantities of added ingredients (Clegg et al., 2021; Glover et al., 2022; Medici et al., 2023).

Comparing the interactions between primary ingredient and conventional (typically fortified cows' diets and PBBs) and organic (typically unfortified cows' diets and PBBs) production systems, as designated by the product label, allows the identification of within-system characteristics that affect nutrient composition and a clearer exploration of nutritional implications of consuming PBB or different plant varieties of PBB instead of milk.

4.2. *Effect of conventional and organic production systems on the mineral concentration of milk and PBB*

In line with other recent studies comparing variation in retail milk minerals' concentration between organic and conventional production systems, this study found no differences (Marques et al., 2022; Newton et al., 2023). However, previous studies have observed marginally lower mineral concentrations of I (Średnicka-Tober et al., 2016) and K and Mg (Manuelian et al., 2022) in organic milk. Under both production systems, milk contained significantly higher concentrations of Ca, P, and I than conventional and organic PBBs. Unlike milk, concentrations of these minerals varied in PBBs according to production system, where Ca, P and I were simultaneously higher in conventional and lower in organic products, mainly because organic PBBs are unfortified according to organic food regulations (European Commission, 2018). Consequently, greater differences were found between organic milk and organic PBBs than for conventional products.

Higher concentrations of Ca, I and P in conventional PBBs are associated with fortification during production. In the present study, 100 % of conventional PBBs were calcium-fortified, and 37 % were also fortified with I. Conventional PBBs contained about 50 % of the P found in conventional milk. Higher concentrations of P in conventional PBBs compared to organic, may also be associated with calcium fortification. In the current work, calcium phosphate or tricalcium phosphate was listed as an ingredient in fortified PBB, consistent with other studies reporting their use to increase Ca concentrations (Craig & Fresán, 2021; Medici et al., 2023; Redan et al., 2023; Sethi et al., 2016). Conversely, concentrations of some trace elements and potentially toxic elements also varied according to production system, but these differences may be associated with different agricultural practices and cultivation conditions. Organic almond and oat contained more Cu and Mo than conventional, both of which may be associated with organic agricultural practices. The use of copper-based fungicides is highly prevalent in organic farming (Burandt et al., 2024), and their use is particularly notable in the protection of European organic almond crops from fungal diseases (Tamm et al., 2022). Mo is found in soil (Kaiser et al., 2005), and therefore in nearly all foods in trace amounts (EFSA Panel on Dietetic Products & Allergies, 2013). Mo concentrations in plant foods are highly correlated to the properties of the soil in which the food is grown (EFSA Panel on Dietetic Products & Allergies, 2013) and organic farming relies upon manure as an organic fertilizer, which increases soil pH (Howe et al., 2024) and this facilitates optimum conditions for Mo absorption in crops (Kaiser et al., 2005).

Organic almond was significantly higher in Ni than conventional almond, and this difference was not observed in either milk or oat, which may suggest that the increased concentration is associated with differences in the cultivation conditions of organic almonds. Ni is an environmental contaminant found in air, groundwater, soil and plants (COT, 2003; EFSA, 2025) and is found in cereals, nuts and milk (DEFRA, 2015). Ni is believed to contribute to biological functions such as energy metabolism (COT, 2003). However, excess dietary exposure to Ni can have adverse health effects (COT, 2003; EFSA, 2025). Monitoring of the food supply (DEFRA, 2015) and risk (COT, 2003) and exposure assessments (COT, 2024) suggest that dietary intakes in the UK do not pose health risks. Although values for Ni concentrations are not available for independent types of PBB and are instead reported for 'alternatives to milk' in previous UK reports (DEFRA, 2015), the results of this study were broadly within the previously reported range for this category.

Conventional oat contained higher concentrations of Cd than organic oat. The same was numerically true for conventional almond and milk compared to organic, but differences were not statistically significant. Cd is an environmental contaminant, which may be toxic to human health if consumed in high quantities and is found in some foods like cereals and nuts, both through natural occurrence as well as from industrial sources during processing (EFSA, 2025). Few studies have measured the presence of environmental contaminants in PBB; no other studies have compared contamination in different production systems. In the UK, permitted concentrations of Cd in foods are regulated, and maximum limits are set for foods including cereals (0.1 mg/kg) and tree nuts (0.2 mg/kg) to prevent excessive dietary exposure, however, there is no maximum limit set for milk or PBB currently (European Commission, 2021).

4.2.1. *Effect of the primary ingredient within conventional production system on the mineral concentration of PBB*

When fortified in conventional products, Ca is most frequently added in amounts to provide similarity to milk (Medici et al., 2023; Pérez-Rodríguez et al., 2023), and this concentration also enables products to make nutrition claims regarding the Ca content (Pérez-Rodríguez et al., 2023). In the present study, all conventional PBB were equally Ca-fortified, so similarity between oat and almond PBBs, and between PBBs and milk, was in line with expectations raised from product labelling. However, despite similar fortification, conventional almond contained less Ca (77 % of the Ca contained in conventional milk) than oat (which contained 84 % of the Ca found in conventional milk). The differences found between conventional milk and PBBs and between conventional oat and almond may reflect a challenge observed in measuring extrinsically fortified minerals in the PBB matrix, where Ca salts are not evenly dispersed in the beverage and form a sediment on the bottom of the container (Smith et al., 2022); an aspect that can also affect their intake by consumers. Smith et al. (2022) reported that Ca values could vary by up to 18 % in almond and 97 % in oat PBBs if products were not well mixed before analysis. Samples in the present study were thoroughly mixed, but the fact that PBBs do not represent a homogeneous mixture or emulsion may still introduce variation to the final measured Ca concentrations. Others have also noted variation between labelled nutrients and those derived analytically in PBB, which may also be due to the interaction between the matrix and the form of minerals added to improve the nutrient content (Redan et al., 2023; Sevillano Pires et al., 2023). Similar added concentrations of phosphate-containing Ca fortification in conventional almond and oat would also explain the lack of significant difference in P concentrations between PBBs in the conventional sector.

While conventional PBBs are typically fortified to Ca concentrations similar to milk, the same is not true for I (Nicol et al., 2023) In the present study, mean I in conventional almond PBB was only 28 % of the I in conventional milk, while mean I in oat PBB was only 37 % of the I found in conventional milk. I concentration in PBBs is not as frequently compared as Ca, perhaps because it is not frequently added in fortification, despite the prevalence of iodine deficiency worldwide (de Benoist et al., 2003), and in the UK (Bath et al., 2017). Earlier research demonstrated that I is not frequently fortified in PBB; in the UK Clegg et al. (2021) reported no I fortification in either nuts- or grains- based PBBs; whilst across eleven European countries including the UK, Medici et al. (2023) reported only 6 % of almond and 22 % of oat PBBs were fortified with I. As in the present study, previous work also found lower concentrations in conventional almond and oat PBBs and PBBs based on other ingredients (including legumes and coconut) than in milk (Clegg et al., 2021; Glover et al., 2022; Medici et al., 2023; Smith et al., 2022; Walther et al., 2022; Zhang et al., 2020). Moreover, where I is fortified in PBB, reported median and range concentrations suggest I is not consistently added in concentrations equivalent to milk (Glover et al., 2022; Medici et al., 2023; Smith et al., 2022; Walther et al., 2022; Zhang et al., 2020). The comparatively higher concentrations of I in the present study reflect a higher frequency of I fortification in the UK in 2023 compared to 2020 (Clegg et al., 2021; Wall et al., 2023). Conventional oat contained more Mo, Cd and Ni than almond PBB or milk. As noted previously, these elements may be present naturally in soils or as a result of industrial pollution (COT, 2003; EFSA, 2025); Kaiser et al. (2005). The higher concentrations of such minerals in oat PBBs may reflect absorption from soil-based cultivation conditions (Butovskaya et al., 2025).

4.2.2. *Effect of the primary ingredient within organic production system on mineral concentration of PBB*

In the present study, organic PBBs contained 0–4 % of Ca and I concentrations, and 31–44 % of P found in conventional PBBs. Unlike conventionally produced PBBs, which may be fortified, organically produced and marketed PBBs may not be fortified to improve concentrations of minerals under European regulations (European Commission, 2018). Additionally, organic PBBs typically contain fewer ingredients; for example, in the present study, organic almond and oat PBBs contained on average 3.8 and 4.1 ingredients, respectively, while the conventional equivalents contained 10.1 and 11.8 ingredients, respectively. Recent consumer research (Euromonitor International, 2024) alluded to 'clean labelling' approaches from manufacturers to underline the 'natural' formulations of organic PBBs, and appeal to consumers valuing these practices, thus potentially further reinforcing the drive towards organic PBB containing fewer ingredients. Therefore, the lower mineral

Table 6
Estimated daily minerals intakes, contribution to reference nutrient intakes (RNI)[a] and percentage satisfaction of RNI from the total diet for conventional and organic milk by age group in the UK population and change in minerals intakes, contribution to RNIs and percentage satisfaction of RNI met when the mean intakes of milk for each demographic[b] is substituted for plant-based beverages based on almond and oat.

	Conventional									Organic								
	Milk			Almond			Oat			Milk			Almond			Oat		
Age (Years)	Mineral intakes (mg/day)	% RNI milk	% RNI total diet	Mineral intakes (mg/day)	% RNI ALM	% RNI total diet	Mineral intakes (mg/day)	% RNI OAT	% RNI total diet	Mineral intakes (mg/day)	% RNI milk	% RNI total diet	Mineral intakes (mg/day)	% RNI ALM	% RNI total diet	Mineral intakes (mg/day)	% RNI OAT	% RNI total diet
Calcium (Ca)																		
1–1.5	348	100	240	268	76	216	293	84	224	362	103	243	11	3	143	11	3	143
1.5–4	300	86	213	230	66	193	252	72	199	311	89	216	10	3	130	9	3	130
5–10	212	42	150	163	33	140	178	36	144	220	44	152	7	1	109	7	1	109
11–18	166	17	77	127	13	73	139	14	75	172	17	78	5	1	61	5	1	61
19–49	144	21	116	110	16	111	121	17	112	149	21	117	5	1	**96**	4	1	**96**
50–64	207	30	118	159	23	111	174	25	113	215	31	119	7	1	**89**	6	1	**89**
65–74	190	27	115	146	21	108	160	23	110	197	28	116	6	1	**88**	6	1	**88**
75+	268	38	121	206	29	112	225	32	115	278	40	123	9	1	**84**	8	1	**84**
Magnesium (Mg)																		
1–1.5	32	38	165	17	21	148	8	10	137	32	38	165	18	21	148	9	11	138
1.5–4	28	33	177	15	18	162	7	8	153	28	32	177	15	18	162	8	10	154
5–10	20	12	117	11	7	111	5	3	108	20	12	117	11	7	111	6	4	108
11–18	15	5	73	8	3	71	4	1	69	15	5	73	8	3	71	4	2	70
19–49	13	4	91	7	2	89	3	1	87	13	4	91	7	2	89	4	1	87
50–64	19	6	91	10	3	88	5	2	86	19	6	91	11	4	88	6	2	86
65–74	18	6	90	10	3	87	5	2	86	17	6	90	10	3	88	5	2	86
75+	25	8	78	13	4	74	6	2	72	25	8	78	14	5	74	7	2	72
Potassium (K)																		
1–1.5	456	57	205	124	15	163	158	20	168	461	58	205	241	30	178	108	14	161
1.5–4	392	49	212	107	13	177	136	17	180	396	50	213	208	26	189	93	12	175
5–10	277	18	134	75	5	121	96	6	122	280	18	134	147	9	126	66	4	120
11–18	217	7	68	59	2	64	75	2	64	219	7	68	115	3	65	51	2	63
19–49	188	5	81	51	1	77	65	2	77	190	5	81	100	3	78	45	1	77
50–64	271	8	81	74	2	76	94	3	76	274	8	82	143	4	78	64	2	76
65–74	249	7	82	68	2	77	86	2	77	251	7	82	132	4	78	59	2	76
75+	351	10	76	95	3	68	122	3	69	354	10	76	186	5	71	83	2	68
Sodium (Na)[c]																		
1–1.5	99	20	176	116	23	179	133	27	183	108	22	178	60	12	168	131	26	182
1.5–4	85	17	*	100	20	*	115	23	*	93	19	*	52	10	*	113	23	*
5–10	60	4	*	71	4	*	81	5	*	66	4	*	36	2	*	80	5	*
11–18	47	2	*	55	2	*	63	3	*	51	2	*	29	1	*	62	3	*
19–49	41	2	123	48	2	123	55	2	124	44	2	123	25	1	122	54	2	124
50–64	54	2	124	63	3	124	73	3	124	59	2	124	33	1	123	71	3	124
65–74	59	2	124	69	3	124	79	3	125	64	3	124	36	1	123	78	3	124
75+	76	3	124	89	4	125	102	4	126	83	3	125	46	2	123	101	4	125
Iodine (I)[d]																		
1–1.5	73.3	105	229	21.2	30	155	27.3	39	163	76.2	109	233	0.5	1	125	0.0	0	124
1.5–4	63.1	90	186	18.2	26	121	23.5	34	129	65.5	94	189	0.4	1	96	0.0	0	95
5–10	44.6	42	119	12.9	12	89	16.6	16	93	46.4	44	121	0.3	0	77	0.0	0	77
11–18	34.9	26	89	10.1	7	71	13.0	10	73	36.2	27	90	0.2	0	63	0.0	0	63
19–49	30.3	22	110	8.7	6	94	11.3	8	96	31.4	22	110	0.2	0	**88**	0.0	0	**88**
50–64	43.6	31	113	12.6	9	90	16.2	12	93	45.3	32	114	0.3	0	**82**	0.0	0	**81**
65–74	40.0	29	124	11.6	8	103	14.9	11	106	41.6	30	125	0.3	0	**95**	0.0	0	**95**
75+	56.4	40	124	16.3	12	**95**	21.0	15	**98**	58.6	42	125	0.4	0	**84**	0.0	0	**83**
Zinc (Zn)																		

(*continued on next page*)

Table 6 (*continued*)

	Conventional									Organic								
	Milk			Almond			Oat			Milk			Almond			Oat		
1–1.5	1.19	24	107	0.17	3	**87**	0.13	3	**86**	1.12	22	106	0.29	6	**89**	0.14	3	**86**
1.5–4	1.02	20	98	0.15	3	81	0.11	2	80	0.96	19	97	0.25	5	83	0.12	2	80
5–10	0.72	11	89	0.10	2	79	0.08	1	79	0.68	10	88	0.18	3	80	0.08	1	79
11–18	0.57	6	79	0.08	1	73	0.06	1	73	0.53	6	78	0.14	2	74	0.07	1	73
19–49	0.49	5	90	0.07	1	86	0.05	1	86	0.46	5	90	0.12	1	86	0.06	1	86
50–64	0.71	7	90	0.10	1	83	0.08	1	83	0.67	7	89	0.17	2	84	0.08	1	83
65–74	0.65	7	84	0.09	1	78	0.07	1	78	0.61	6	84	0.16	2	79	0.08	1	78
75+	0.92	10	74	0.13	1	65	0.10	1	65	0.86	9	73	0.23	2	66	0.11	1	65

Numbers in bold = indicates change, based on current volumes of conventional milk consumed, from meeting RNI to falling below the RNI.

Data sources: Government Dietary Recommendations (PHE, 2016); volumes of milk consumed by age group, (SACN, 2024); current minerals intakes, contribution of milk and % total RNIs children 1.5- adults 75+ for all minerals intakes except Na (Bates et al., 2020); Na intakes in adults (PHE, 2020); minerals intakes in children 12–18 months (Lennox et al., 2013).

[a] Reference nutrient intake. The RNI is an amount of a nutrient that is enough for almost every individual, even those who have high requirements for the nutrient. This level of intake is, therefore, generally higher than most people need. If individuals are consuming the RNI for a mineral, they are most unlikely to be deficient in that mineral.

[b] Mean intakes are based on volumes of milk consumed by age group. 1–1.5 years 286 mL/day, 1.5–4 years 246 mL/day, 5–10 years 174 mL/day, 11–18 years 136 mL/day, 19–49 years 118 mL/day, 50–64 years 170 mL/day, 65–74 years 156 mL/day and 75+ years 220 mL/day.

[c] Sodium intakes are not reported in children (Bates et al., 2020) and therefore change in intakes as a proportion of total diet could not be estimated.

[d] Daily mineral intakes for iodine are presented as μg/day.

concentrations of Ca, P and I in organic PBB compared with milk are also a reflection of the lower endogenous mineral concentrations of the extract of the originating plant. This hypothesis is further supported by the absence of significant differences in Mg, K, Mn, Zn (which are typically not fortified) between conventional and organic almond and conventional and organic oat, suggesting that cultivation conditions of the production system have little effect on endogenous minerals, and significant differences are most likely due to subsequent fortification in the production process. Higher concentrations of Cu in organic almond PBBs and Mo and Ni in organic oat PBBs were previously discussed and may be associated with organic cultivation and agricultural practices (Burandt et al., 2024; Kaiser et al., 2005).

4.3. *Effect of the interaction between ingredient, production system and season*

Seasonal variation in milk I concentration is well researched, and the higher concentrations of milk I in winter are consistent with other studies (Newton, Pétursdóttir Á, et al., 2023) as a result of changes in feeding practices for herds between summer and winter months (particularly the increase of pasture intake in summer) (Newton, Pétursdóttir Á, et al., 2023; Qin et al., 2021). The higher concentrations of Mo in winter in this study are also consistent with other research with milk collected at farm level (Qin et al., 2021). Seasonal variation in minerals in organic milk may result from the higher differences in diet composition in organic herds, as they are required to be provided access to grazing throughout the grazing season (Linehan et al., 2024), a practice that is optional to conventional herds that may feed a similar total mixed ration based on conserved forage and concentrates throughout the year, or provide less access to grazing than organic herds.

To the authors' knowledge, seasonal variation in PBB has not yet been examined. The present study found conventional winter almond PBB contained less Ca and Na than conventional summer almond PBB, and organic winter oat PBB was higher in Mo than organic summer oat PBB. All samples of conventional almond were labelled as Ca-fortified, and labelled quantities for summer and winter products suggest no obvious source of variation for either Ca or Na as a result of fortification. However, Ca and Na concentrations in the primary source may vary in different batches of almonds used to produce PBB, as a result of differences in cultivars, soil conditions and processing. Variation between labelled and analytically derived minerals has also been reported before (Redan et al., 2023; Sevillano Pires et al., 2023; Smith et al., 2022), which may also be partly explained by the challenges facing the accurate quantification of extrinsically fortified additives (Smith et al., 2022).

There is currently little evidence on the presence or concentrations of Mo, an essential trace element found in nearly all foods, in PBBs. Consistent with the results of the present study, Astolfi et al. (2020) found that Mo concentrations were of a similar magnitude in winter (January) and higher Mo concentrations in oat PBB than in milk or almond PBB. There is no frame of reference for the combined effect of season and production system on Mo concentrations in PBB; however, increased concentrations because of the interaction between season and production season have been observed in milk, as noted previously (Qin et al., 2021). It should also be noted that because of the longer shelf-life of PBBs (being UHT-treated), recorded sample dates in retail studies may reflect different production batches but not necessarily represent the production season in which samples are purchased.

4.4. *Implications for population dietary intakes*

There is an absence of consumption data for PBB in the UK (SACN, 2024), and the effect of substitution of milk on dietary intakes is currently unclear. To date, two UK studies have compared and modelled differences in the proportion of the daily reference values met by milk and PBB (Clegg et al., 2021; Glover et al., 2022), which may be indicative of potential dietary changes, but the total dietary intakes of minerals and the relative importance of milk to meeting daily requirements were not fully considered. In addition, in the absence of analytical data, dietary changes have been modelled for a narrow subset of minerals which are mentioned in the product label because they are added for fortification, while this study showed that analytical values may differ (i.e. for Ca, I and Na) from what is presented on the label, or sourced from food composition tables (Clegg et al., 2021; Glover et al., 2022; Nicol et al., 2024; SACN, 2024). Impact on other mineral intakes of public health concern (Mg, K, Zn) have also not been considered in the absence of composition data on product labels. Lastly, a lack of standardisation in the fortification practices for conventionally produced PBB, and an evolving increase in fortification (Wall et al., 2023) suggests that the nutritional differences between organic (unfortified) and conventionally (fortified) produced PBB may be greater compared to previous work, so the varied implications of choosing products from different production systems is not well represented in literature. This study modelled differences in nutrient intakes for all minerals of public health interest, based on substitution of conventional and organic milk for conventional and organic oat and almond PBBs, while also considering the potential risk from the resulting changes in mineral intakes, within the context of the background diet (Table 6).

Based on existing consumption patterns, this study suggests that consumption of organic milk instead of conventional milk is unlikely to impact population mineral intakes. However, replacing milk with either almond or oat PBBs could reduce population intakes of Ca, Mg, P, K, I and Zn and increase intakes of Na. Consideration of the background diet and other dietary sources of minerals suggests that not all reductions in intakes will result in nutritional consequences for different population age groups.

Substitution of milk with conventional almond and oat could reduce intakes of Ca across the population, but mean intakes, from all dietary sources, including other dairy, are currently sufficiently above the RNI for most of the UK population, even when intakes are reduced through substitution of milk with PBB. While milk is an important source of Ca in diets across the population, contributing between 19 and 38 % of dietary intakes, the presence of significant concentrations of Ca in other highly consumed food groups, such as cereals, mitigates the nutritional risk from the lower Ca concentrations in PBB. However, mean Ca intakes are currently below the RNI for 11–18-year-olds, and mean intakes for 15 % of the population fall below the lower reference nutrient intake level (LRNI), suggesting current mean dietary intakes in this age group are inadequate. LRNI is the amount of a nutrient that is enough for very few people with low needs; most of the population will require more than the LRNI, and if individuals habitually consume less than the LRNI, they will almost certainly be deficient. As conventional almond and oat contain less Ca than milk, with substitution, a higher proportion of this population may fall below the LRNI. In addition, the current model is based only on gross Ca content and does not include any adjustment for the lower bioavailability of Ca in fortified conventional PBB (Angelino et al., 2020; Pérez-Rodríguez et al., 2023; Scholz-Ahrens et al., 2020; Sousa & Kopf-Bolanz, 2017). Some studies have noted that compared to the bioavailability of Ca in milk, tri-calcium phosphate (which was most frequently observed for Ca fortification in the retail study for this work) is lower (Craig & Fresán, 2021; Muleya, F. Bailey, & H. Bailey, 2024; Sethi et al., 2016; Zhang et al., 2020). Calcium carbonate, less frequently observed as an ingredient in this study, is reported to have higher bioavailability than tri-calcium phosphate (Craig et al., 2021; Sethi et al., 2016) but lower stability in the PBB matrix (Sethi et al., 2016). While it remains to be examined whether differences determined in vitro for Ca bioavailability in PBBs could be clinically significant within the context of population dietary intakes (Medici et al., 2023), the greater difference between gross Ca content and bioavailable Ca, compared with milk (Muleya et al., 2024) could also increase the prevalence of low Ca among adults 19–75+ years when milk is substituted with PBBs in diets. Studies also note that the significant presence of insoluble fibre, phytates and oxalates present in PBB may further inhibit the absorption of Ca from PBB (Craig et al., 2021; Muleya et al., 2024; Pérez-Rodríguez et al., 2023; Zhang et al., 2020).

Substitution of milk with organic, and therefore unfortified, almond or oat would more drastically affect the ability to meet Ca RNIs set for different age groups and would render currently adequate dietary intakes inadequate for most of the population, children and adults 11–75 years+. It should be noted that current dietary advice in the UK suggests that where PBBs are consumed as alternatives to milk, they should be Ca-fortified (NHS, 2024). Inadequate intakes of calcium, especially in 11–18-year-olds, could have long-term clinical implications, by preventing achievement of optimal bone mass density during puberty and increasing the risk of osteoporosis in later life (Hanafy et al., 2022). Low intakes in adults, and particularly older post-menopausal women, may contribute to loss of bone mass density and increased risk for osteoporosis (Prentice, 2004).

Choosing to consume almond or oat PBBs (either conventional or organic) will affect population dietary intakes of Mg and K. Current dietary intakes of Mg and K are below the RNIs for children and adults 11–75 years+. Additionally, NDNS estimates that intakes of Mg for 40 % of adolescents aged 11–18 and 16 % of adults over 75 years are below the LRNI, and intakes of K for 30 % of adolescents aged 11–18, 17 % of adults 19–64 and 19 % of adults over 75 years are below the LRNI. Therefore, lower concentrations of Mg and K in PBB could further reduce intakes and compound an existing high prevalence of inadequate intakes across these populations. However, Mg and K are found in relative abundance in both plant and animal sources, and milk is not a major source of Mg and K in the diets of children and adults 11–74 years (contributing between 5 and 7 % of Mg and 7–9 % K) so the effect of lower concentrations of Mg and K in almond and oat PBB has a proportionately limited effect on total dietary intakes.

Choosing conventional almond or conventional or organic oat PBBs over milk will increase population intakes of Na. Available data for adult intakes (PHE, 2020) shows that current dietary intakes already exceed the RNI, and recommendations are that Na should be reduced in the diet. Milk, however, is not a significant source of Na in diets across most of the population (contributing between 3 and 5 % in children 5 years to adults 75+ years), and the increase in Na intake from PBBs would be relatively small. However, the increase in Na intakes would be greater for young children 12 months to 4 years, due to their higher consumption of milk. Higher salt intakes in childhood can influence long-term dietary habits by increasing preference for salt (Strazzullo et al., 2012). High salt intakes in children have been associated with increased blood pressure (Leyvraz et al., 2018), which may track into adulthood (Leyvraz et al., 2018), and elevated blood pressure is a risk factor for cardiovascular disease (SACN, 2003). Na intakes for children are not monitored through the NDNS, so the effect on total intakes could not be estimated.

Consuming any conventional almond or oat PBB will substantially affect population intakes of I. Milk is the main source of dietary iodine in the UK, contributing between 20 and 47 % of iodine in the diets of the population (Bates et al., 2020), and conventional PBB are currently not sufficiently fortified to avoid lower intakes. Mean dietary intakes of iodine are generally adequate across the population, except in the case of adolescents 11–18 years, and girls in particular, where mean intakes are only 88 % of the RNI and 28 % fall below the LRNI (Bates et al., 2020). NDNS does not currently provide estimated nutrient intakes for pregnant women, although 12 % of women 19–64 also fall below the LRNI (Bates et al., 2020). Substitution of milk with conventional almond or oat would make the currently adequate intakes for children 5–10 years, adults 19–64 and older adults 75+ inadequate. Choosing organic almond and oat would more drastically affect population intakes of I, rendering currently sufficient intakes inadequate across all age ranges except for children 12–18 months. Iodine deficiency can have a range of clinical consequences, and is especially significant for pregnant women, where recommended intakes are higher (SACN, 2014). Severely inadequate intakes can result in birth defects and neurodevelopmental impairment in babies and children (SACN, 2014).

Choosing to consume conventional or organic almond or oat PBBs will also affect population dietary intakes of Zn. Estimated mean intakes of Zn are around or below the RNI across most of the population. Lower concentrations of Zn in almond and oat PBB could considerably reduce mean intakes across the population, especially for young children 12 months to 4 years, for whom milk contributes 23 and 19 % of dietary Zn, respectively (Bates et al., 2020; Lennox A, 2013). Currently sufficient intakes in adolescents 11–18 years could fall short of the RNI, and prevalence of low intakes will be increased across the population, particularly among older adults, for whom milk contributes 12 % of current intakes. Zinc is involved in multiple core biological processes, and deficiency can therefore affect dermatological, gastrointestinal, skeletal, reproductive and central nervous systems (Knez & Stangoulis, 2023). In children, mild to moderate deficiency is also associated with impaired linear growth and in older adults, it has been reported to impair immune system response (Knez et al., 2023). Additionally, Zn absorption is reported to be limited by the same dietary components that limit Ca absorption, found in high concentrations in plant-based foods, including phytates and oxalates (Knez et al., 2023). This also means that children and adults with diets that contain only, or high proportions, of plant-sourced foods will have higher requirements for dietary Zn (Knez et al., 2023), and the impact from the substitution of milk with PBBs may be greater than the current study reports.

4.5. *Implications for household expenditure*

In line with UK studies, (Clegg et al., 2021; Glover et al., 2022) the present research found that both organic and conventional PBB were more expensive than the corresponding milk. Based on an average family with two adults (19–49) and one child (1.5–4 years), and the prices recorded in the present study between March 2023 and February 2024, it would cost £196 per year to consume conventional milk at the current reported consumption per age group. If instead the same family consumed conventional almond or oat, the cost would increase by 34 % to £263 or by 36 % to £268 per year, respectively. If the same family chose to consume organic almond or oat, then costs would further increase to £370 per year for organic almond or £354 per year for organic oat, representing an increase in expenditure of 81 to 88 % over conventional milk, or 35–41 % over organic milk. In 2023, the average household spent £3302 annually on food and non-alcoholic beverages (Office for National Statistics, 2025). Current conventional milk consumption would represent 6 % of that budget, which would increase to 8 % of the budget for conventional PBB or around 10 % for organic PBB.

Organic milk typically attracts a price premium over conventional milk, (KPMG, 2019) attributed to increased costs of production and decreased yield (Linehan et al., 2024). The current study, in line with others (Newton, Pétursdóttir, et al., 2023; Qin et al., 2021), found that conventional and organic milk have similar concentrations of macrominerals and trace elements. Conversely, for PBBs, the price premium for the organic products comes with a reduction in mineral density, in particular Ca, P, and I. The results for mineral concentrations in the present study contradict consumer perceptions that organic products are nutritionally superior and better for health, (Statista, 2023) although mineral concentrations represent only one dimension of the nutritional value of a food.

5. Conclusions

Milk plays an important and varied role in the delivery of micronutrients to diets in the UK. In this study, the presence and concentration of minerals in milk did not differ significantly between organic and conventional production systems. Conversely, while functional replacement of milk is underlined in consumer perceptions and, particularly at the point of sale for PBB, the present study showed that neither fortified conventional nor unfortified organic PBB products can be regarded as nutritionally equivalent, and yet both would increase household food costs. Without standardized fortification of conventional PBBs, with at least equivalent concentrations of minerals that are sometimes added like Ca and I, and the inclusion of other minerals found in milk, including Mg, K and Zn, there is potential for currently adequate I intakes to become insufficient and for prevalence of low intakes of Mg, K, and Zn to increase across the population. However, the bioavailability of fortified and unfortified minerals in PBB, compared to milk, is not yet strongly evidenced, and additional fortification may further increase the price difference between milk and PBBs by increasing the production costs of the latter. While it is possible for most minerals to be obtained through varied animal and plant-based dietary sources, substitution of milk for conventional or organic PBB would require significant dietary change to meet requirements. Dietary changes should be facilitated by clarity in the nutritional differences between milk and conventional and organic PBBs, to minimise increased risk of potential deficiencies, in particular for Ca and I, and also for Mg, K and Zn. In addition, considering the increasing popularity of organic PBBs and their corresponding increase in cost, it should be noted that neither their organic nature nor their price premium equates to improved concentrations of macrominerals and trace elements.

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, 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 authors declare the following financial interests/personal relationships which may be considered as potential competing interests: 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 the 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 organisations did not contribute to the funding of this research, or to the conceptualisation, methodology, validation, data collection and analysis, writing or reviewing of 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.foodchem.2025.145083.

Data availability

Data will be made available on request.

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