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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Advancing methods for comparative nutritional LCA of milk and plant-based milk substitutes

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Abstract

Purpose The contribution of milk on the environmental and nutritional impacts of diets is substantial especially in countries with high consumption rates of dairy products, such as in the Nordic countries. Due to environmental and health reasons, plant-based drinks (PBDs) are gaining popularity among consumers, but the nutritional composition of PBDs varies depending on their base ingredients and possible fortification. This study develops product group-specific nutrient indices to be used as functional units (nFU) in life cycle assessments (LCA) of milks and PBDs.

Methods Here, we formed three product group–specific nutrient indices for milk and PBDs: (i) based on our previous development of product group–specific indices considering the current dietary role of milk in Finnish diets, (ii) based on the potential nutritional benefits of PBDs compared to milk, and (iii) as combination of the two abovementioned indices. The new indices were then applied as a nFUs in a case study comparing selection of 46 drinks from the Finnish food composition database including milks and fortified and unfortified PBDs. The environmental impacts were assessed in five different impact categories utilizing data from LCA databases.

Results and discussion The index based on current consumption led to the highest nutrient index scores for cow's milks and consequently lower environmental impacts when used as a nFU, whereas the index based on nutrients obtained from PBDs as nFU led to higher environmental impacts for milk and lower for PBDs. Cow's milk had the highest climate impact when the impacts were allocated per unit of mass, but in nFU-based comparison, some PBDs had higher impacts than cow's milk. The results showed notable difference between fortified and unfortified PBDs, as the environmental impacts of unfortified PBDs were higher than impacts of milk when the comparison was based on nutrient content, while the environmental impacts of fortified drinks were lower than those of milk.

Conclusions The index based on nutrients currently obtained from milk is the most suitable one for capturing the nutritional consequences of substituting milk with PBDs in the current diets. However, the other indices can bring additional information on the possible nutritional benefits in another decision-making situation. As nutrient fortification has substantial impact on the results, the role of fortification in sustainable foods should be further evaluated and the methodological approaches to consider fortification in nLCA advanced.

Keywords Nutritional Life Cycle Assessment · Functional unit · Environmental impact · Nutrient index

1 Introduction

Food production is responsible of a third of all human-induced greenhouse gas emissions (Crippa et al. 2021) and over 80% of biodiversity loss, fresh water use, and emissions of nitrogen and phosphorus (Campbell et al. 2017), with the majority of the impacts caused by animal production (Poore & Nemecek 2018; Willett et al. 2019). Shifting to a more plant-based diet is essential, especially

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in Western countries, for both human health and environment (Harwatt et al. 2024; Willett et al. 2019).

Milk production contributes significantly to the environmental impact of food production, as this food group along with meat has the heaviest burden on the environment (Carvalho et al. 2023; Halpern et al. 2022; Irz et al. 2024a, b; Poore & Nemecek 2018). On a global scale, the Nordic countries stand out as one of the leading consumers of milk products, making this food group a pivotal factor in the total environmental footprint of the diet in the Nordics (Harwatt et al. 2024). It has been estimated that milk accounts for 20% of climate impacts and 10% of biodiversity impacts associated with the Finnish dietary pattern (Kyttä et al. 2023a; Saarinen et al. 2019). Considering the nutritional aspects when identifying solutions to reduce the environmental impacts of food consumption is important, especially when the food group under study has a significant nutritional role. Finland is among the countries with the highest milk consumption per capita globally (Mäkelä & Rautavirta 2018), making it an important component of the Finnish food culture and agriculture as well as a significant source of many nutrients (Valsta et al. 2018). The latest Nordic Nutrition Recommendations (NNR 2023) (Blomhoff et al. 2023) address this issue highlighting the importance of moderation of consumption in dairy products to improve the environmental sustainability of the Nordic dietary patterns. The NNR 2023 recommends intakes of 350–500 ml of low-fat milk products daily or fortified plant-based drinks (PBDs) if the daily consumption of milk is lower than 350 ml (Blomhoff et al. 2023).

Dairy foods are a staple part of most food-based dietary guidelines globally (Comerford et al. 2021). The recommendations are often based on the protein content and quality of dairy products, as well as relatively high contents of calcium, vitamin D, iodine, and other micronutrients essential to human health (Comerford et al. 2021; White & Gleason 2023). A selection of PBDs with a varying raw material base has been developed as a substitute for milk to enable and speed up the transition to more sustainable diets and to accommodate dietary restrictions. PBDs are gaining increasing popularity among consumers due to health concerns such as lactose intolerance and milk allergy, as well as growing awareness of environmental impacts of foods (Bridges 2018; Ramsing et al. 2023; Su et al. 2024). However, the nutrient content of PBDs varies and is highly dependent on the base ingredient and fortification of micronutrients (Plamada et al. 2023; Ramsing et al. 2023). PBDs are often fortified with calcium, vitamin D, vitamin B12, and vitamin A to better match the nutritional composition of cow's milk. On the other hand, PBDs usually naturally contain fiber, polyunsaturated fatty acids, and iron, which are not found in milk (Berardy et al. 2022). Substituting milk with PBDs in the diet could therefore result in very different outcomes in nutrient intake, depending on the selected PBD and overall diet.

Life cycle assessment (LCA) has been widely used to define the environmental impacts of food products (McLaren et al. 2021). In recent years, many advances have been made to assess environmental impacts and nutritional aspects of food products simultaneously using different methods (Grigoriadis et al. 2021; McLaren et al. 2021). A common approach is to use a nutrient index as a nutritional functional unit (nFU) in life cycle assessment (Fulgoni et al. 2009; Green 2022; Grigoriadis et al. 2021; McLaren et al. 2021; Saarinen et al. 2017). The development of product group–specific metrics has been identified as one of the topics of further research in the development of nLCA methodology (McLaren et al. 2021). Previous development has mostly been focused on protein-rich foods (Green et al. 2021; Kyttä et al. 2023b; McAuliffe et al. 2018; Saarinen et al. 2017), but recently, the protocol to develop product group specific indices has been introduced also to product groups of sources of carbohydrates as well as vegetables, fruits, and berries (Kyttä et al. 2023c). The product group–specific indices previously developed by Kyttä et al. (2023b; 2023c) consider the nutritional consequences of changes in the food intake in the dietary context of the target population, incorporating nutrients relevant to each product group into the functional units. However, the role of beverages in this context has not been studied.

Regarding specifically milk and PBDs, relatively few studies have been done to evaluate the environmental impact and nutritional properties in parallel. Many studies have utilized a mass or volume-based FU in LCA regarding milk and PBDs (Geburt et al. 2022; Grant & Hicks 2018). Nutritional aspects have been included in the form of protein quantity (Geburt et al. 2022; Grant & Hicks 2018), protein quality (Singh-Povel et al. 2022), and across the board nutrient indices, which have been formed based on priority micronutrients (Katz-Rosene et al. 2023) and all recommended micronutrients (Smedman et al. 2010). Nutritional properties of milk have also been taken into account by forming a separate impact category for human health (Stylianou et al. 2016). To our knowledge, product group–specific FUs have not been previously applied in nLCA for milks and PBDs. This approach provides valuable information on the environmental and nutritional trade-offs of substituting milk with plant-based options, especially relevant in diets where milk heavily influences both environmental impact and nutrition.

The aim of this study was to develop a nutrient index to be used as nFU when comparing the environmental impacts of milk and PBDs. The index was developed following the approach for creating product group–specific nFUs presented by Saarinen et al. (2017) and further defined by Kyttä et al. (2023b), considering the role of milk in Finnish diets. Using the developed nFUs, the environmental impacts of substituting milk with PBDs were then assessed, considering the nutritional needs of different population groups. To explore the emerging, possibly different role of PBDs in the diet, two additional indices were formed to assess the potential nutritional contribution these drinks could provide to the diet.

2 Materials and methods

The nutrient indices were formed following the approach for product group–specific nFUs introduced by Saarinen et al. (2017) and Kyttä et al. (2023b, 2023c), where the indices were formed to include nutrients, which are relevant for the product group under study in current diets. The indices were calculated according to the formula previously composed by (Fulgoni et al. 2009):

$$\text{Index} = \sum \frac{NUTRIENTi}{DRIi} \times 100/\text{number of nutrients in the index}$$

Nutrient_i is the amount of nutrient per 100 g of a product, and DRI_i is the daily recommended intake of the nutrient according to the nutrition recommendation used. A higher index score indicates that 100 g of the product contains greater amounts of the selected nutrient, whereas a lower score indicates lesser quantities of the selected nutrient.

The nutrient indices in this study were calculated individually for different age groups according to the Finnish nutrition recommendations (VRN 2014). The groups were men and women aged 10–13, 14–17, 18–30, 31–60, 61–74, and < 75 and children aged 12–23 months, 2–5 and 6–9 years. Specific recommendations for each age group are presented in the supplementary material. Since recommendations for macronutrients in the Finnish nutrition recommendations are given in energy percentages (E%), the recommended amounts of macronutrients in grams were calculated as follows: protein and carbohydrate energy values were set at 4 kcal/g and fat at 9 kcal/g. The recommended energy intake for the sedentary population (VRN 2014) was used to calculate the amount of protein and carbohydrates in grams, except for the age groups of 12–23 months and ≥ 75-year-olds. The recommended energy intake for 12–23-month-old children was set to 900 kcal (Hollis et al. 2020), and food recommendations for the elderly (Council & Welfare (THL), 2020) were used to determine energy intakes for ≥ 75-year-olds, which were set to 1887 kcal for men and 1815 kcal for women.

2.1 Selected drinks and their nutritional information

Nutritional content of different dairy milks and PBDs was identified from the food composition database Fineli® by the National Institute for Health and Welfare (THL). Nutrient data was obtained for skimmed milk ($n = 4$); semi-skimmed milk ($n = 6$); full-fat milk ($n = 5$); and hazelnut ($n = 1$), cashew ($n = 1$), coconut ($n = 1$), oat ($n = 6$), rice ($n = 5$), almond ($n = 2$), and soy ($n = 15$)-based drinks. Nutritional composition information of both fortified and unfortified drinks was included when available. Nutritional content of assessed foods is presented in the supplementary material.

2.2 *Product group–specific nutrient indices*

By selecting nutrients currently obtained from milk in significant amounts in the context of a Finnish diet, the index can be used to evaluate the nutritional effects of substituting milk with plant-based drinks. However, PBDs include many beneficial nutrients which are absent in milk, thus providing other nutritional functions (Reyes-Jurado et al. 2023) which might be substantially beneficial in the context of altered diets, for example, much more plant-based diets. Therefore, three different nutritional functional units (nFUs) were formed for milk and PBDs: $\text{NR-FI}_{\text{milk}}$ index based on nutrients obtained from milk following the approaches presented in the previous studies and $\text{NR-FI}_{\text{PBD}}$ index based on nutrients obtained from PBDs, and $\text{NR-FI}_{\text{milk+PBD,}}$ which is a combination of both $\text{NR-FI}_{\text{milk}}$ and $\text{NR-FI}_{\text{PBD}}$ indices, including all nutrients used in these indexes. The $\text{NR-FI}_{\text{milk+PBD}}$ index was formed to include the nutritional properties of both milk and PBDs to enable a more comprehensive assessment of the nutritional profiles. Nutrients for the $\text{NR-FI}_{\text{Imilk}}$ were selected based on food consumption of the Finnish population. Based on the information from the National FinDiet Survey (Valsta et al. 2018), the nutrients for which milk was among the first or second most important dietary sources selected for the $\text{NR-FI}_{\text{milk}}$ following the principles of selecting nutrients for the "baseline nutrient index" according to Kyttä et al. (2023b). The nutrients selected based on this criterion were protein, monounsaturated fatty acids (MUFAs), vitamin D, riboflavin, niacin, vitamin B12, iodine, phosphorus, calcium, selenium, zinc, and potassium.

To explore whether substituting milk with PBDs would result in any beneficial changes in nutrient intake among the Finnish population, $\text{NR-FI}_{\text{pbd}}$ index was developed. In the FinDiet Survey (Valsta et al. 2018), the consumption of PBDs was included in the category "beverages" and subcategory "vegetable-juices and vegetable-based drinks." The subcategory includes oat-, almond-, rice- and soy-based drinks, as well as carrot and tomato juices. Therefore, the consumption volumes and nutritional role of PBDs alone could not be determined. For this index, the daily consumption volume of fluid milk was determined from the FinDiet-study (Valsta et al. 2018) (subcategories "milks, skimmed," "milks (0.1–2% fat)," and "milks (> 2% fat and cream), which was 266 g for men and 171 g for women. Based on this, we calculated the amount of each recommended nutrient (VRN 2014) obtained from the amount of fluid milk consumed daily, or alternatively PBDs if used in similar quantities (Table 1). The nutritional content of milk and PBD was an average amount of each nutrient calculated from all milks ($n = 15$) and all PBDs ($n = 31$) previously identified from the Fineli® database. Average amounts of nutrients PBDs in this case include both fortified and unfortified drinks since the database did not provide sufficient information on the fortification measures. PBDs include higher content of PUFA, fiber, and vitamin nutrient intake (%) from the amount of liquid milk (Valsta et al. 2018) consumed daily in relation to the DRI:s for 31–60-year-old sedentary population (VRN 2014) in comparison to theoretical nutrient intake from PBDs calculated as average amounts from previously listed products, if consumed in similar quantities as milk. The nutritional content of PBDs in this comparison is the average amount of nutrient from all drinks included in this study.

2.3 Environmental impact data

Based on the planetary boundaries framework (Rockström et al. 2009; Steffen et al. 2015), we selected to assess the environmental impact categories relevant to agricultural production, i.e., climate impact, water consumption, land use, marine eutrophication, and freshwater eutrophication (McLaren et al. 2021; Willett et al. 2019). Published LCA studies of milk and PBDs have used different methods and cover only a limited number of products and impact categories (Khanpit et al. 2024). To have comparable data on all the studied products, the climate impact (CO2 eq), water consumption (m3), land use (m2a), marine eutrophication (N eq), and freshwater eutrophication (P eq) of the studied products were obtained from the French Agribalyse 3.1 database (Asselin-Balençon et al. 2022), using ReCiPe 2016 midpoint (H) impact assessment method (Huijbregts et al. 2017). The environmental impacts of cashew and hazelnut PBDs were assessed by switching the almonds used as ingredient in producing almond PBD to the same amount of cashew or hazelnuts. The environmental impacts were then assessed in relation to the nutrient densities of different drinks. Nutrient indices were used as a functional unit by dividing the environmental impact of 100 g of a product by the nutrient indices, which were also calculated per 100 g of product.

Table 1 Nutrient intake (%) from the amount of liquid milk (Valsta et al. 2018) consumed daily in relation to the DRI:s for 31–60-year-old sedentary population (VRN 2014) in comparison to theoretical nutrient intake from PBDs calculated as average amounts from previously listed products, if consumed in similar quantities as milk. Nutritional content of PBDs in this comparison is the average amount of nutrient from all PBDs included in this study

	Men (266 g)		Women (171 g)	
Nutrient	Milk (%)	PBD (%)	Milk (%)	PBD (%)
Carb. (g)	3.73	3.17	2.87	2.54
Protein (g)[a]	9.13	5.19	7.61	4.17
Fiber (g)[b]	0.00	6.61	0.00	5.31
MUFA (g)[a]	1.83	2.25	1.43	1.81
PUFA (g)[b]	0.46	8.23	0.00	6.62
Calcium (mg)[a]	46.50	30.99	31.25	19.92
Iron (mg)[b]	1.11	15.84	0.67	6.11
Iodine (μg)[a]	28.47	1.34	19.33	0.86
Potassium (mg)[a]	14.29	6.52	9.68	4.73
Magnesium (mg)[b]	8.57	11.63	7.14	9.35
Phosphorus (mg)[a]	45.50	15.45	30.83	9.93
Selenium (μg)[a]	13.83	6.93	11.40	5.35
Zinc (mg)[a]	13.33	6.50	12.86	5.37
Folate (μg)[b]	4.33	16.01	2.67	10.29
Niacin (mg, NE)[a]	14.44	9.43	12.86	7.80
Pyridoxine (B6) (mg)[b]	5.33	9.48	5.00	7.61
Riboflavin (mg)[a]	38.00	24.59	31.67	19.76
Thiamine (mg)[b]	6.92	14.53	4.55	11.04
Vitamin A (μg, RE)	3.56	2.40	3.00	1.98
Vitamin B12 (μg)[a]	55.00	21.38	45.00	13.74
Vitamin C (mg)	4.0	0.00	2.67	0.00
Vitamin D (μg)[a]	31.0	8.93	21.00	5.74
Vitamin E (mg)[b]	0.00	18.40	0.00	14.79

[a]Nutrient is included in NR-FI$_{milk}$ index

[b]Nutrient is included in NR-FI$_{PBD}$ index

3 Results

3.1 Nutrient indices

The index scores varied considerably between different drinks and across indices (Fig. 1). The highest index scores in every index group occurred for small children (aged 12–23 months, 2–5 years, and 6–9 years) due to the lowest DRI-values. Cashew, unfortified oat, and unfortified rice drinks had consistently low index scores across all indices.

When using the NR-FI$_{milk}$ index, dairy milks (skimmed, semi-skimmed, whole) had the highest index score among both unfortified and fortified versions compared to PBDs (Fig. 1A) Cashew, oat (unfortified), and rice (unfortified) drinks had the lowest index scores in this category. Among PBDs, hazelnut, oat, almond, and soy drinks had the highest

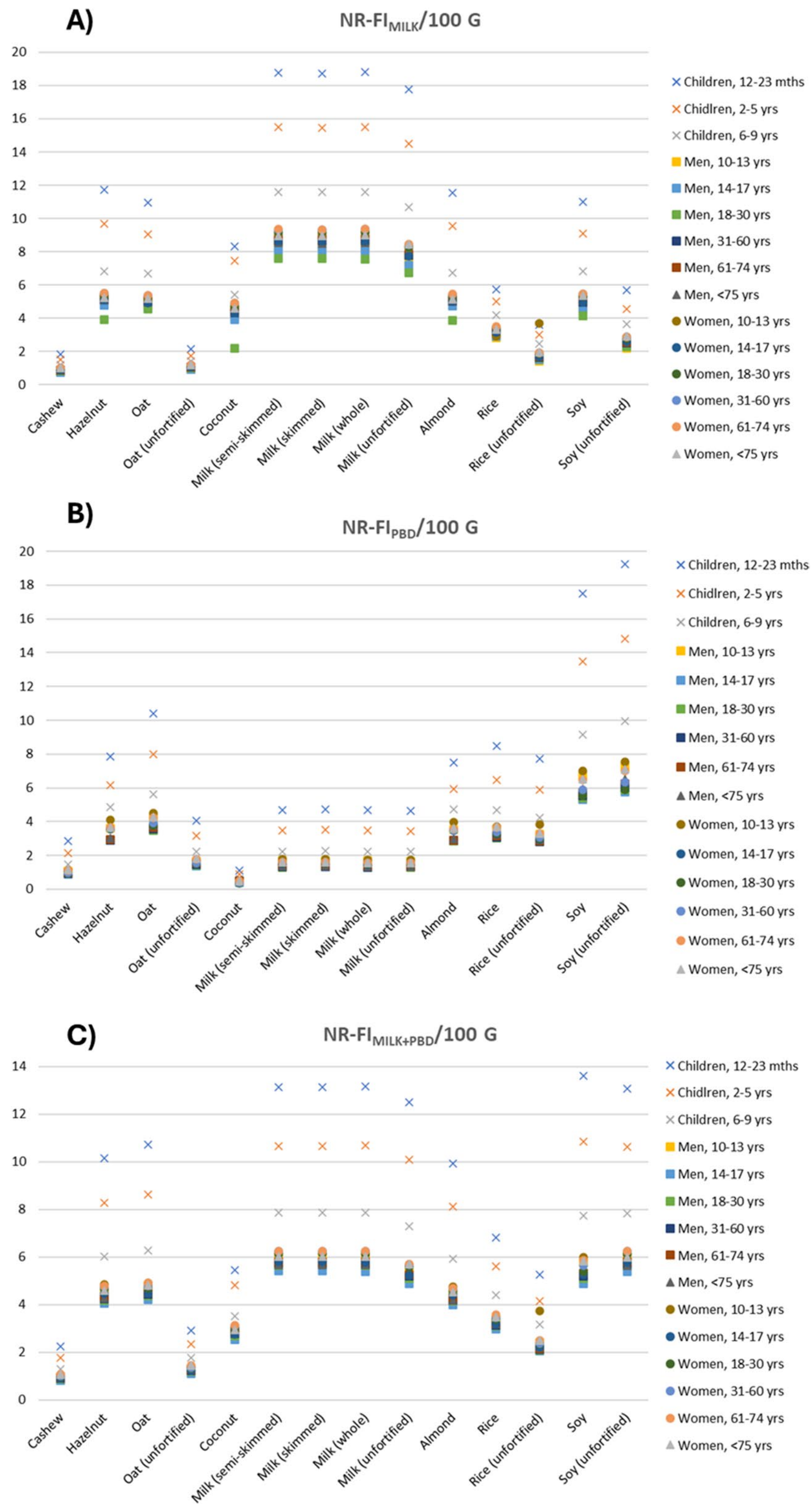

Fig. 1 Nutrient index scores per 100 g of a product calculated for different population groups. **A** The NR-FI$_{milk}$ index, **B** the NR-FI$_{pbd}$ index, **C** NR-FI$_{milk+pbd}$ index. A higher score indicates higher amounts of the nutrients selected for the index in relation to recommended intake

index scores when using the NR-FI$_{milk}$. The index scores varied from 0.76 (cashew drink) to 18.82 (whole milk).

When using the NR-FI$_{PBD}$ index, the highest scores occurred in the group of unfortified soy drinks (Fig. 1B). Coconut drink had the lowest index scores in every age group. In this category, index scores varied between 0.37 (coconut drink) and 19.26 (unfortified soy drink).

Within the NR-FI$_{milk+PBD}$ index, the index scores varied from 0.81 (cashew drink) to 13.61 (fortified soy drink) (Fig. 1C) Milks and soy drinks had the highest index scores, with the differences between average scores varying in between 6.31 and 6.83.

3.2 Environmental impacts of different drinks

The environmental impacts per 100 g of a product varied between different drinks (Figs. 2, 3, 4, and 5a). Note that contrary to nutrient indices, higher scores for environmental impact indicate increased environmental impacts. Across all impact categories, coconut drink was among the three drinks with the highest environmental impact and had the highest impact in land use (m2a eq/100 g), freshwater eutrophication (kg P eq/100 g), and water consumption (m3/100 g). Dairy milks had the highest climate impact (kg CO2 eq/100 g) and the second highest impact in land use (m2a eq/100 g). Oat drink had the highest marine eutrophication impact (kg N eq/100 g). Rice and almond drinks had the lowest environmental impacts in land use and global warming but had the second and third highest impacts in water consumption. Soy drink had the lowest impacts in water use and both eutrophication categories (kg P eq/100 g, kg N eq/100 g). On average, almond and rice drinks scored lowest across environmental impacts despite having higher water use impact, whereas coconut drink and milks scored the highest.

Using the nutrient indices as a functional unit changed the ranking of the products in terms of environmental impacts. The results differed depending on the nutrient index used in the calculation. Across categories and indices, fortified soy drink remained among the drinks with the lowest impact, whereas cashew, unfortified oat, and coconut drink were consistently among the drinks with higher impact (Figs. 2, 3, 4, and 5b). When using the NR-FI_{pbd}

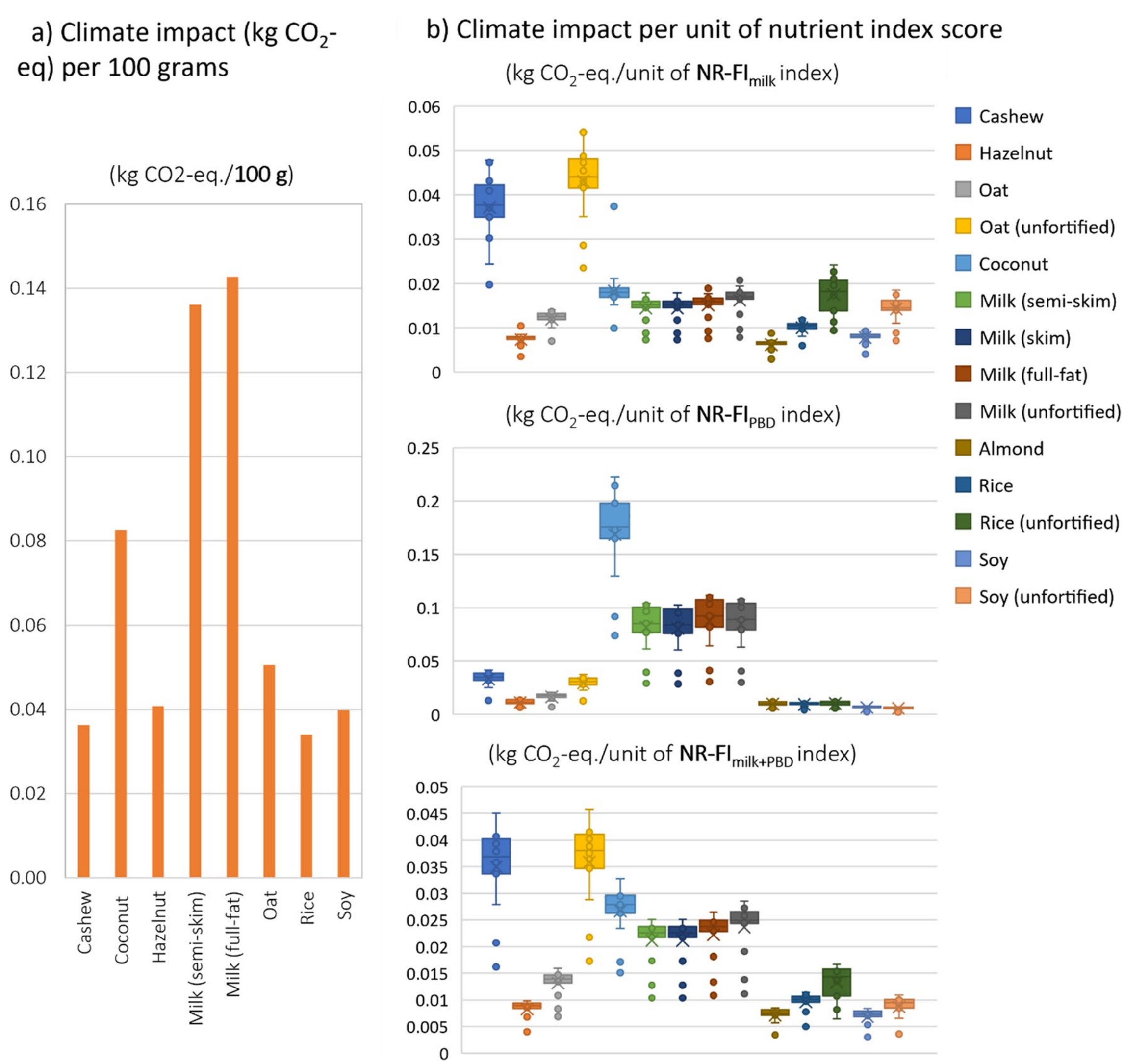

Fig. 2 **a** Climate impact (kg CO2-eq) per 100 g of a product. **b** Climate impact per unit of nutrient index score for NR-FI_{milk}, NR-FI_{pbd}, and NR-$FI_{milk+pbd}$.

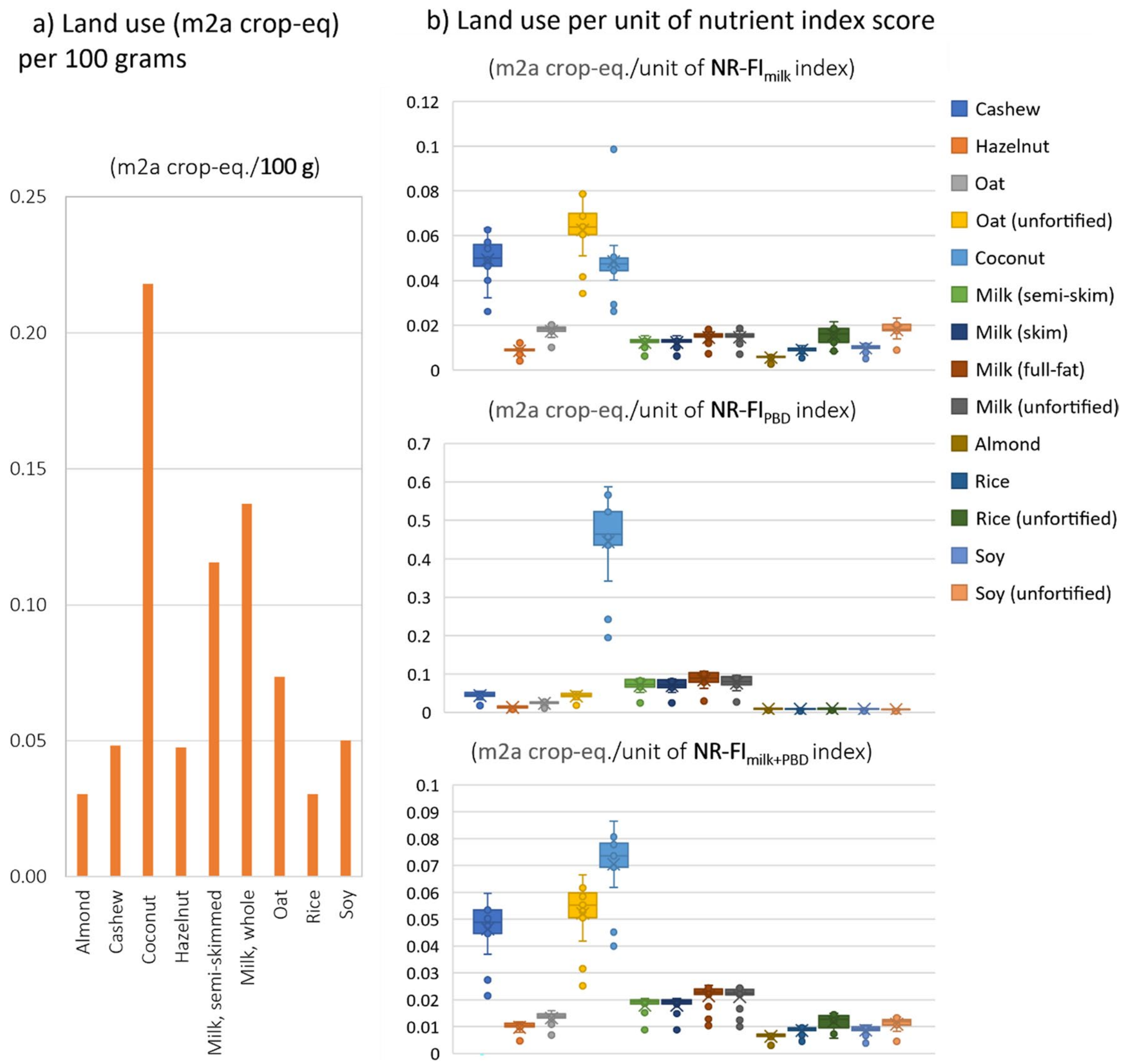

Fig. 3 **a** Land use (m2a crop-eq) per 100 g of a product. **b** Land use per unit of nutrient index score for NR-FI$_{milk}$, NR-FI$_{pbd}$, and NR-FI$_{milk+pbd}$.

index, coconut drink had the highest impact in every impact category. Fortified and unfortified soy drinks had the lowest impact score across impact categories when using the NR-FI$_{pbd}$ index. With the NR-FI$_{milk}$ index as a FU, dairy milks had the lowest impacts in freshwater use (m3) and freshwater eutrophication (kg P eq), whereas almond and fortified soy drink had the lowest climate impact (kg CO2 eq), land use (m2a), and marine eutrophication (kg N eq). When using the NR-FI$_{milk+pbd}$ index, cashew and unfortified oat drink had relatively high environmental impacts across impact categories, whereas fortified soy drink consistently had low impact scores (Fig. 6).

4 Discussion

In this study, we formed three product group–specific nFUs for milk and PBDs which were then used in a demonstrative nLCA for the selected products. This study contributes to the developmental work of product group–specific metrics in nLCA and examines the possible environmental and nutritional trade-offs of replacing milk with PBDs in a dietary context where milk currently provides many essential nutrients. To our knowledge, product group–specific nutrient indices specifically for milk and PBDs have not been developed in previous nLCA studies.

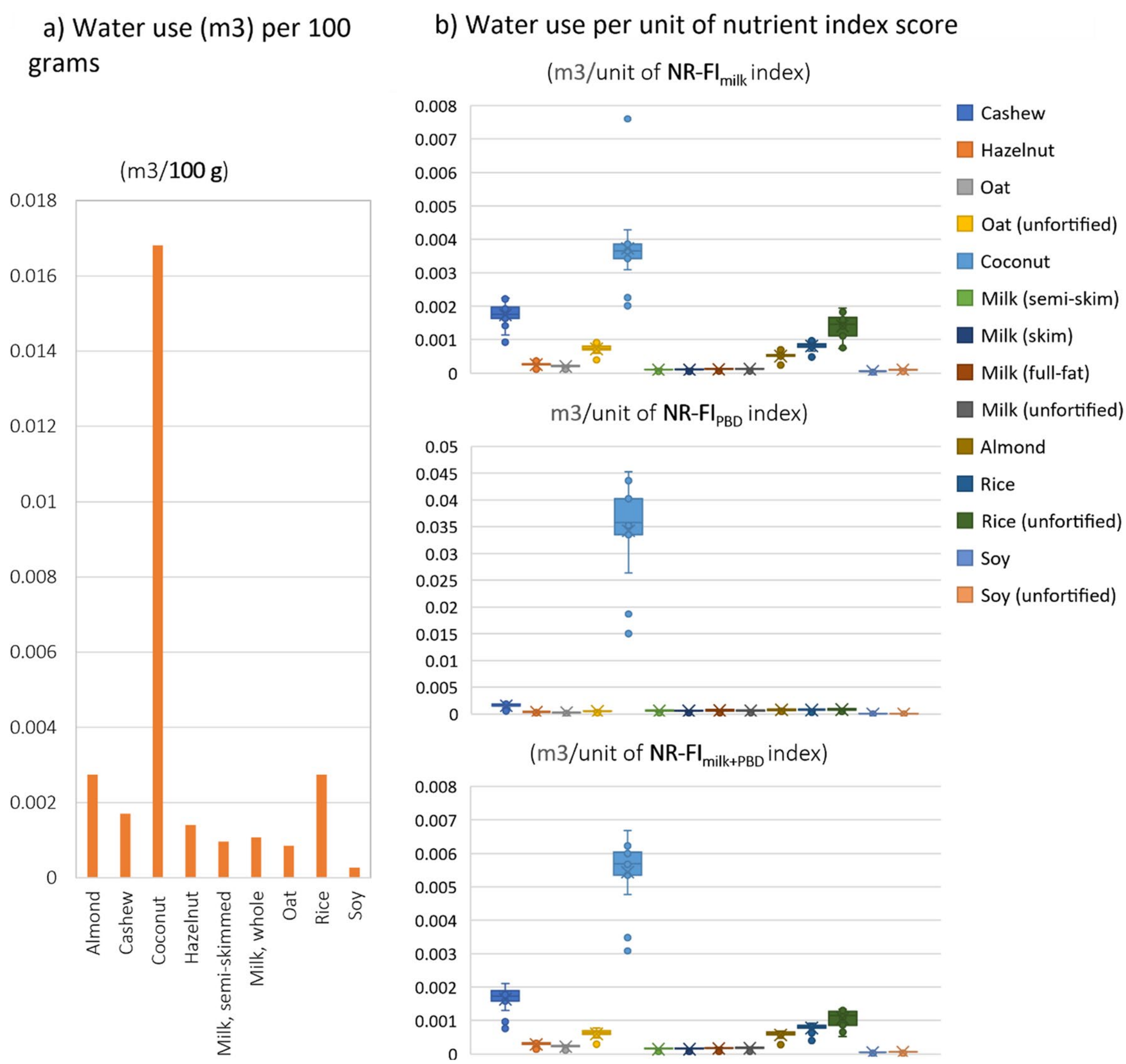

Fig. 4 **a** Water use (m3) per 100 g of a product. **b** Water use per unit of nutrient index score for NR-FI_{milk}, NR-FI_{pbd}, and NR-$FI_{milk+pbd}$.

4.1 Environmental impacts using different FUs

This study considered five environmental impact categories to acknowledge the trade-offs in environmental impacts for the same products across different indicators. Some previous studies on milk and PBDs have focused on the climate impact of the products (Singh-Povel et al. 2022; Smedman et al. 2010), which these studies have found to be higher for milk than PBDs when measured per mass. While in this study milk also has higher climate impact per 100 g than any PBD, in all the other environmental impact categories, one or more PBDs surpass the impacts of milk. This underscores the importance of assessing multiple environmental indicators for a more thorough understanding of the overall impacts.

On average, almond and rice drinks had the lowest environmental impacts of all assessed drinks, despite having higher water use impact compared to other drinks. Coconut drink and milk had the highest impact on average. However, the ranking changed when environmental impacts were assessed per nutrient indices, resulting in coconut, cashew, or unfortified oat drinks having the highest impacts across categories. Especially for cashew and unfortified oat drink, the poor nutrient content resulted in higher environmental impacts especially when NR-FI_{milk} or NR-$FI_{milk+pbd}$ was used as nFU. For instance, cashew drink was among the three products with the lowest climate impact, but when using the NR-FI_{milk} as a FU, the climate impact of cashew drink was among the two highest. Coconut drink exhibited relatively high impacts across

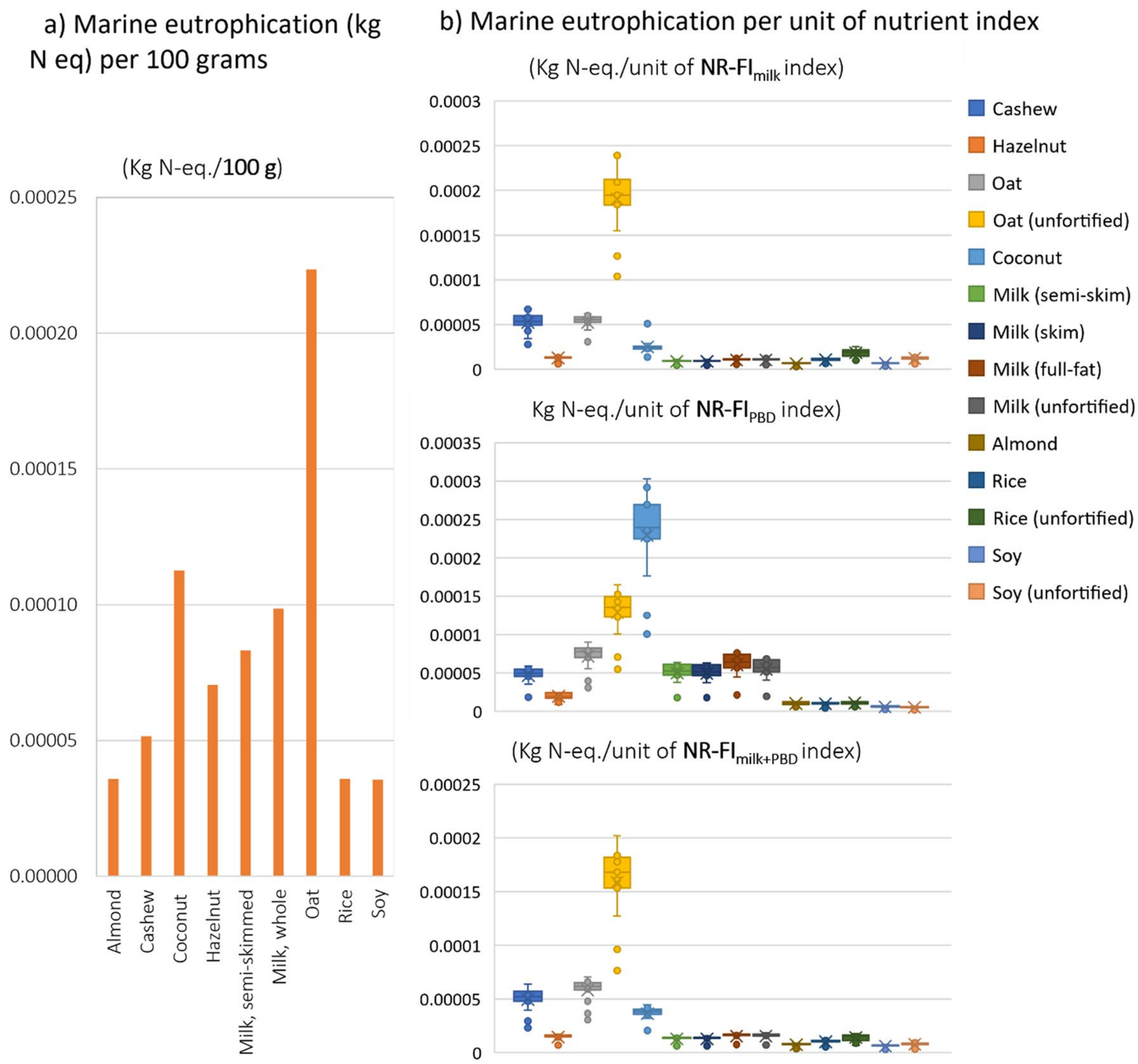

Fig. 5 **a** Marine eutrophication (kg N-eq) per 100 g of a product. **b** Marine eutrophication per unit of nutrient index score for NR-FI_{milk}, NR-FI_{pbd}, and NR-$FI_{milk+pbd}$.

environmental categories, and its average nutritional content did not notably affect the impact evaluation when measured per nutrient index. In contrast, milk mostly demonstrated lower environmental impacts per NR-FI_{milk} or NR-$FI_{milk+pbd}$ due to its better nutritional profile.

Because the aim of this study was to develop a nutrient index to be used as nFU when comparing the environmental impacts of milk and PBDs, the environmental impact data used in this study was derived from LCA database. Since the environmental impacts of agricultural products can have high variation (Poore & Nemecek 2018), the impacts presented in this study might not fully represent the impacts of products typically consumed in Finland, but rather in Central Europe. The variability in the environmental impacts of milks and PBDs are high (Khanpit et al. 2024; Ramsing et al. 2023), and thus, more value chain–specific information is needed in the future.

4.2 The choice of nutrients for the indices

This study shows that the choice of nFUs can greatly affect the environmental impacts for same drinks in nLCA, which is in line with previous findings (Grant & Hicks 2018; Kyttä et al. 2023b; McLaren et al. 2021). The NR-FI_{milk} index included nutrients that are currently obtained from milk in the average Finnish diet, making it the most valid index for assessing which PBDs would be nutritionally comparable as a milk substitute. This index was formed based on previously

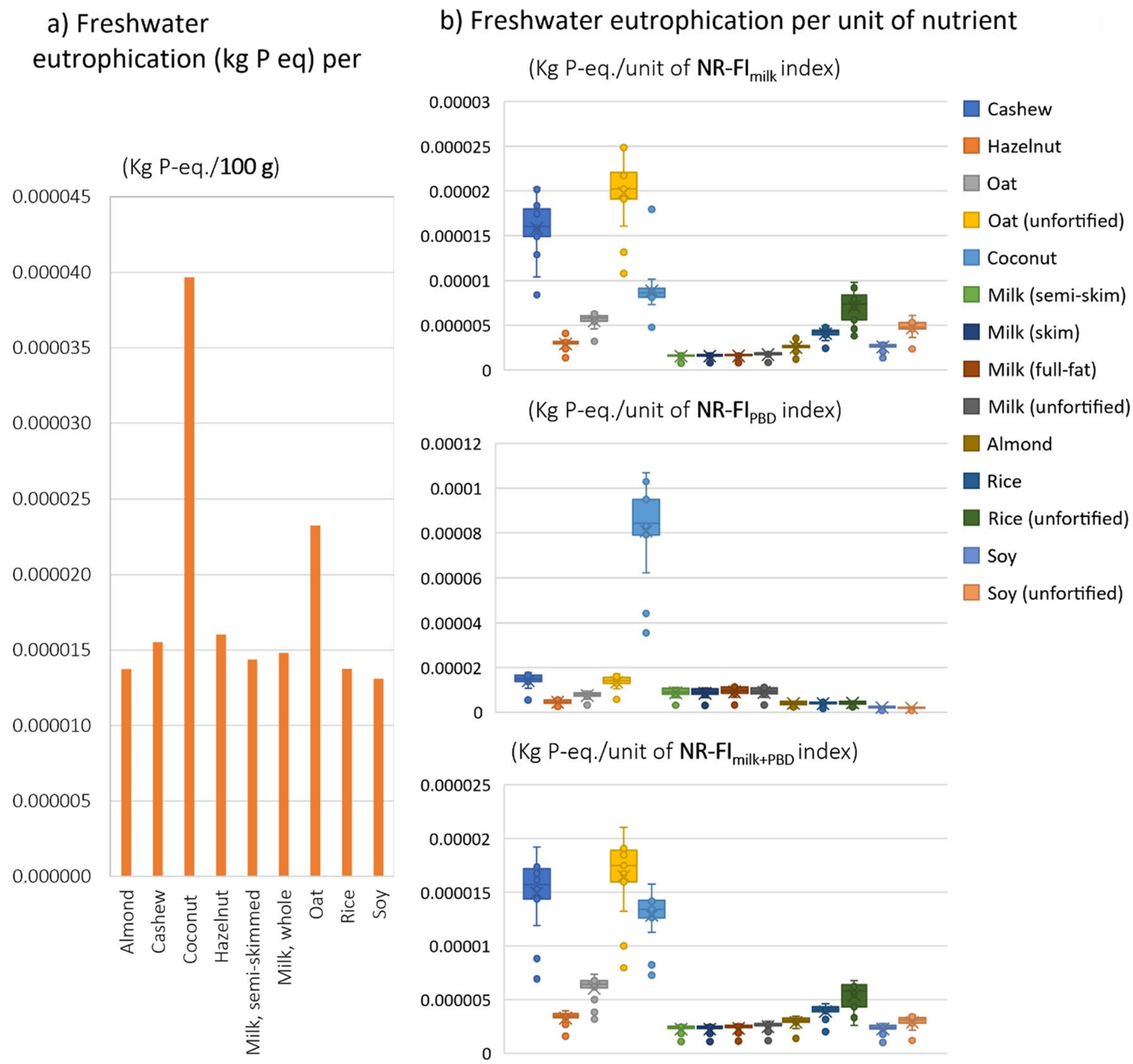

Fig. 6. **a** Freshwater eutrophication (kg P-eq) per 100 g of a product. **b** Freshwater eutrophication per unit of nutrient index score for NR-FI_{milk}, NR-FI_{pbd}, and NR-$FI_{milk+pbd}$.

used methods (Kyttä, et al. 2023b, 2023c; Saarinen et al. 2017), and taking into account that milk has traditionally been the most common drink consumed with meals in Finland.

The NR-FI_{pbd} index contained nutrients that would be obtained in greater quantities if PBDs were used instead of milk. The intake of iron, folate, thiamine, and PUFA from current Finnish average diets is not optimal (Valsta et al. 2018). Given that many plant-based foods are rich in these nutrients, moving towards a more plant-based diet in general would result in increased intakes of these nutrients. Additionally, the NR-FI_{pbd} index illustrates the challenges of making valid comparisons between PBDs, since the raw material substantially affects the nutritional content.

As discussed in previous research (Berardy et al. 2022; Drewnowski et al. 2021) and demonstrated in our study, PBDs are not a coherent group in neither their nutritional quality nor environmental impact. Consumer awareness on the nutritional variation of PBDs should be emphasized, as many may have misconceptions of all PBDs being nutritionally equivalent to milk (Khandpur et al. 2021; Su et al. 2024).

The NR-$FI_{milk+pbd}$ index considered the nutritional advantages of both milk and most PBDs. This nutrient index resulted in the highest scores for dairy milks and soy drinks, suggesting that these drinks could provide the most, although slightly different nutritional advantages to the diet considering the environmental impact.

4.3 The role of nutrient fortification

Nutrient fortifications considerably contribute to the nutritional content of PBDs. In this study, fortifications in PBDs resulted in higher NR-FI$_{milk}$ and NR-FI$_{milk+pbd}$ scores compared to unfortified drinks of the same base ingredient. This, in turn, resulted in, e.g., unfortified oat and rice drinks having higher environmental impacts per nutrient index compared to those of fortified versions of the same drinks. Unfortified PBDs (cashew, oat and rice) included in this study were poor source of nutrients even on the NR-FI$_{pbd}$ index, raising the question whether these drinks provide any nutritional benefits to the diet. An exception to this was unfortified soy drink that received the highest NR-FI$_{pbd}$ scores among all drinks. However, unfortified soy drink received lower scores than fortified PBDs when measured using the NR-FI$_{milk}$ index, indicating that it would not be nutritionally adequate substitute for milk. The variation in nutrient content has sparked a discussion on whether PBDs intended to be used as milk substitutes should have specific nutrition standards according to which they should be fortified (Drewnowski et al. 2021), or if PBDs should be considered as a milk analogue at all due to their different nutritional benefits and shortfalls in comparison to milk (Pérez-Rodríguez et al. 2023; Reyes-Jurado et al. 2023; Smith et al. 2022).

Fortification measures are an important point of discussion in the transition towards sustainable food systems, as they are seen as a potential enabler in achieving nutritionally adequate sustainable diets (Drewnowski et al. 2021, 2022; Grasso et al. 2023). On the other hand, fortification practices raise questions for instance regarding the health effects of processed foods (Beal et al. 2023) and bioavailability of fortified nutrients (Bunge et al. 2024). From a methodological standpoint, fortifications should be reported in nLCA studies (McLaren et al. 2021). However, in practice, this might be challenging because the nutrient composition databases, such as the one used in this study, might not provide information on whether nutrients were fortified or in what quantities.

4.4 Possible nutritional consequences of substituting milk with PBD

Fortified soy drink is usually recommended as the best substitute for dairy milk due to its high protein content and balanced amino acid composition (Brusati et al. 2023; Escobar-Sáez et al. 2022). In this study, the NR-FI$_{milk}$ index provides the most accurate information on assessing the nutritional value of PBDs as milk substitutes, focusing on key nutrients currently obtained from milk. Among PBDs examined, hazelnut, almond, and fortified soy drinks scored closest to dairy milks on the NR-FI$_{milk}$ index, indicating they are the most nutritionally comparable alternatives to dairy milk. When substituting dairy products with plant-based alternatives, the overall diet should be considered to make sure no deficiencies occur as a result (Brusati et al. 2023; Escobar-Sáez et al. 2022; Walther et al. 2022). Nutrient indices are usually calculated for the nutritional needs of a healthy adult population. However, to move towards an overall sustainable food system, considering vulnerable groups and different age stages is crucial (Beal et al. 2023). Therefore, it is important to note the differences in micro- and macronutrient compositions of different drinks especially within population groups with increased needs for certain nutrients, i.e., children (over the age of 12 months), the elderly, and people who consume none or little animal-based foods (Singh-Povel et al. 2022). Currently, the NNR 2023 as well as the Finnish Nutrition recommendation state that dairy products can be substituted with fortified PBDs. While PBDs may be fortified with nutrients such as calcium, vitamin B12, and vitamin D, the contents of other nutrients, i.e., protein, vary based on the base ingredient. This should be considered especially when making recommendations for different population groups. For instance, the lower amount of protein in some PBDs would not necessarily risk the overall protein intake of the healthy adult population in Finland, whose protein intake is often sufficient or even above the recommended amount (Valsta et al. 2018), yet could have detrimental effects on the elderly population who are often at risk of under and malnutrition and protein deficiency (Jyväkorpi et al. 2016; Rautakallio-Järvinen et al. 2022).

Some of the possibly beneficial health effects of PBDs are related to their bioactive compounds, such as isoflavones and phytosterols (Aydar et al. 2020; Berardy et al. 2022; Sethi et al. 2016). However, PBDs contain compounds that can negatively affect the bioavailability of nutrients, i.e., phytates and protein inhibitors (Sethi et al. 2016). Information on antinutrients is often scarce in food composition databases, making it difficult to include them in nutritional assessments. For example, PBDs included in this study on average included more iron compared to milk (Table 1), yet bioavailability of nutrients was not assessed, making it challenging to draw conclusions on the actual nutritional benefit.

The NNR 2023 advice that 350 ml of low fat dairy products paired with sufficient amounts of legumes, dark green vegetables, and fish should provide enough calcium, iodine, and vitamin B12 to the diet (Blomhoff et al. 2023). In the dietary sustainability shift, it is indeed important to consider the whole diet as a source of critical nutrients; thus, in the NNR2023, dark green vegetables and legumes will contribute to calcium intake instead of just dairy products. The NR-FI$_{milk+pbd}$ index enables comparisons from a broader perspective that includes the beneficial nutritional characteristics of PBDs, considering them not only as substitutes for milk but also food products with potentially different nutritional functions in the future diets. However, dietary shifts happen slowly and many obstacles, such as acceptability and financial aspects, hinder the process (Erkkola et al. 2022; Irz et al. 2024a, b; Meltzer et al. 2024), positioning the NR-FI_{milk} probably the most accurate indicator for the present circumstances and dietary patterns. While nutritional guidelines are increasingly incorporating environmental considerations alongside health recommendations, they often remain separate entities in practice. The development of nLCA methodologies like those presented in this study could create a basis for integrating these two aspects, possibly enabling more comprehensive approaches in nutrition counseling and the development of dietary guidelines in the future.

5 Conclusions

The results of this study show that the application of nFUs in LCA of milk and PBDs affects the relative differences and ranking of the products' environmental impacts in contrast to a volumetric FU. The choice of nFU can also significantly impact the results of LCA. From the three different indices formed in this study, NR-FI_{milk} is the most useful in assessing the nutritional trade-offs of substituting milk with PBDs. NR-$FI_{milk+pbd}$ provides additional insight about the different beneficial changes PBDs could bring to the diet, while also considering the nutrients that are currently obtained from milk. The NR-FI_{pbd} index brings to light some previously discovered issues with the grouping of PBDs due to their varying nutritional content, resulting in difficulties in comparing these products.

We found that many of the PBDs are not nutritionally adequate substitutes for milk. Considering the varying nutritional content of PBDs is crucial when forming recommendations to reduce environmental impacts for different population groups. Consumer awareness of the differences between products should be further emphasized to help make more informed decisions based on individual dietary needs.

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Declarations

Competing interests The authors declare no competing interests

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