



Review on milk substitutes from an environmental and nutritional point of view

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ABSTRACT

Milk consumption in humans lasts longer than in other mammals species. Today consumers' awareness of the environmental burden that some products carry, like milk, keeps growing. Consequently, they are looking for alternatives that are more environmentally friendly and well as nutritionally similar. This review explores the data available in the literature and compares the nutritional profile and the environmental impact of several milk alternatives with the profile of milk from different mammals. Overall plant-based beverages available on the market shelves appear to be nutritionally richer than animal milk: their profile shows a possible fortification in some nutrients, which is a normal practice during the processing step of these products. On the environmental impact of these products, a lot of data is missing, making it impossible to make a full comparison across environmental categories. Overall, the environmental impact of plant-based milk is lower than milk, with exceptions in some categories. This study has many limitations since the available data for the different products is limited, for both nutritional profile and environmental impact. For example, while mammals' milk is very well characterised, the biggest occurrence of missing data is found in the nutritional profile of plant-based beverages, where some products only have available information on macronutrients.

1. Introduction

Milk has a very important role in mammals' diets: it is used as a source of nourishment for babies and this can go on for different periods, depending on the animal (Chalupa-Krebzdak et al., 2018; Stuart-Macadam, 2017). This is a very important food since it is the first food that mammals come in contact with right after being born, and it supplies all the required nutrients for their growth and development (Chalupa-Krebzdak et al., 2018; Pereira, 2014). Except for humans, all mammals stop consuming milk after the weaning period, since they substitute it with other foods that ensure their survival and development (Pereira, 2014). In the case of the human diet, after the weaning period, milk comes from different animals, being cow milk the most consumed one (Pereira, 2014) which results in the development of many different products from it.

Today, beverages (including milk) are seen as more than just thirst-quenchers. The nutritional profile of the beverages became important to the consumer (Sethi et al., 2016), as well as their environmental and animal-welfare impacts (Grunert et al., 2018). Consumers have turned to plant-based beverages for different reasons: allergies (cow milk al-

lergy is one of the most widespread allergies among infants (Vanga & Raghavan, 2018) and intolerances (lactose intolerance is estimated to affect almost 100% of the population of some countries (Vanga & Raghavan, 2018), calorie concern and prevalence of high cholesterol (Aydar et al., 2020; Chalupa-Krebzdak et al., 2018; Mäkinen et al., 2016), diet selection – veganism, vegetarianism, flexitarian and others (Aydar et al., 2020; Haas et al., 2019; Paul et al., 2020) or fears over growth hormones or antibiotic residues in cow's milk (Mäkinen et al., 2016). Another reason that incentives the development and production of plant-based beverages is that milk production has a considerable environmental impact (aan den Toorn et al., 2020). This is because most of the calorific energy consumed by an animal is utilised for metabolic processes and only a small part is transformed into meat, eggs, or milk (Paul et al., 2020).

The substitutes for animal milk are known as plant-based or non-dairy milk alternatives. These beverages are emulsions that result from the homogenization of plant components and water (Mäkinen et al., 2016; Rösös et al., 2016; Sethi et al., 2016), and mimic the consistency and appearance of cow milk (Haas et al., 2019). Depending on the base plant, it is possible to distribute these beverages in five general cate-

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gories: cereal-based (e.g., oat milk), legume-based (e.g., soy milk), nut-based (e.g., almond milk), seed-based (e.g., sesame milk), and pseudo-cereal based (e.g., quinoa milk). The final product's nutritional profile heavily relies on the chosen plant as well as the processing and fortification, and legumes appear as a favourite choice due to their rich nutritional profile (Mäkinen et al., 2016; Paul et al., 2020). For some products, fortification may be a necessary step, as some end up with low values of some minerals and vitamins (Mäkinen et al., 2016), or the presence of certain anti-nutrients that can interfere with the absorption of some compounds (Aydar et al., 2020; Tangyu et al., 2019).

The fact that one of the aims of the development of these types of beverages is the resemblance with cow milk (both nutritionally and organoleptically) creates some challenges during manufacturing (Tanguy et al., 2019). Milk is a natural emulsion and plant-based beverages must ensure good homogenization and emulsion-stable properties when reaching the consumer.

Following the description of (Mäkinen et al., 2016), the production process of all plant-based milk analogues is quite similar: it starts by milling the raw material into a slurry and removal of bigger particles – this can be done to both dry and soaked plant material. Then other ingredients such as sugar, oil, flavourings, and stabilisers may be added followed by homogenisation and pasteurisation/UHT treatment as a way of improvement of the suspension and microbial stability. In the end, there is the opportunity to spray dry these extracts to produce powders and store them for extended periods. (Paul et al., 2020) shows that the process can vary slightly, e.g., some beverages can go through fermentation processes for different reasons: to enhance their properties, help remove some anti-nutrients or increase the presence of some bioactive compounds.

The consumption of plant-based beverages appears to have health benefits (Aydar et al., 2020; Paul et al., 2020; Sethi et al., 2016): helps strengthen the immune system, has possible antimicrobial effects, helps reduce the risk of cardiovascular, gastrointestinal, and neurodegenerative disorders, reduce the risk of low bone mass, protection against oxidative damage, and others. Nevertheless, the substitution of milk consumption with plant-based beverages should be done as a part of a balanced diet to eliminate certain nutritional deficiencies that are created by substitution. Carvalho et al. (2001) report protein, vitamin D, and calcium deficiency in different toddlers whose diets had incorporated such products. Besides severe malnutrition deficiencies, other health problems can be associated with this careless substitution: obesity and reduced insulin sensitivity, increased liver, muscle, and visceral fat content, increased blood pressure, high concentrations of triglyceride and cholesterol, among other long-term health issues (Thorning et al., 2016).

The overall popularity of plant-based products has been increasing with passing time with their sales accounting for around 13% of the total milk sales in the US and 8% in the UK (Paul et al., 2020). The most popular beverage is soy-based, but its share has been decreasing with time because of the appearance of coconut, oat, and almond-based products (McClements et al., 2019; Sethi et al., 2016; Tangyu et al., 2019). The range of these beverages is very wide: plain, flavoured (mainly with vanilla and chocolate), sweetened, and unsweetened (Paul et al., 2020). The rapid growth in sales is said to be a result of mainstreaming of certain diet types – from the normal diet to vegetarianism, veganism, or flexitarianism. Additional popularity was added by proclaiming 2019 as “the year of the vegan” (Clay et al., 2020; McCarthy et al., 2017). Some consumers are still hesitant to use these beverages because of the “beany” flavour (McClements et al., 2019; Tangyu et al., 2019) or lack of processing and cooking performance e.g., for hot beverages (McClements et al., 2019).

Available reviews often compare the nutritional profile of some available plant-based beverages, with bovine milk (Chalupa-Krebzdak et al., 2018), as well as their popularity against animal-based milk or acceptance of these by the consumer (McCarthy et al., 2017). The environmental impact of these novel beverages is also often among the researched problems. Some researchers aim to the compari-

son against bovine milk (Ho et al., 2016), while others just analyse the impact of bovine milk (Batalla et al., 2015; Broekema & Kramer, 2014) or plant-based beverages (CarbonCloud Ab, 2018). The studies are sporadic and do not allow for consolidated conclusions on the overall performance of plant-based milk substitutes in combined environmental and nutritional perspectives. Besides this, some studies do not have available complete data. For example, life cycle assessment (LCA) studies often include only separate indicators like global warming potential (Clune et al., 2017; Ho et al., 2016), but it does not provide the full picture of the different impacts on the environment. Besides this, all available products are different – both nutritionally and in their environmental impact. Therefore, the objective of this review was to perform a critical comparative review of recent literature on nutrient composition and environmental impact of animal milks and plant-based milk alternatives to define further key research areas around animal product substitution potentially leading to sustainable food systems.

2. Material and methods

The review was conducted using the Google Scholar database. The search of the papers was structured into two phases using two different sets of keywords. The first was aimed at LCA and the second was for the nutritional properties of the beverages. For the life cycle assessment data collection, the keywords used were “xxx milk LCA”, “mylk vs milk LCA”, “milk vs plant-based milk LCA”, “plant-based milk LCA”, “xxx beverage LCA”, “milk substitutes LCA” and “environmental impact of milk substitutes”. For the nutritional value of these products the used keywords were “xxx milk”, “xxx mylk”, “plant beverages”, and “nutritional profile of plant beverages”. In these, the “xxx” term was substituted by different terms depending on the source of the beverage: bovine/cow, goat, human, sheep, or buffalo (for animal milk) and almond, cashew, coconut, hazelnut, hemp, oat, peanut, quinoa, rice, sesame, soy, tiger nut or walnut (for plant-based beverages). The term “mylk” is used in this search since it is used to refer to plant-based beverages (Clay et al., 2020; Zhang et al., 2020) due to pressure from the dairy industry to differentiate the products. The review was limited to studies published in scientific journals from the last 10 years and available in English. The initial search yielded more than 239 articles. Further title, abstract and results sections of the articles were analysed for the availability of quantified data on nutrients and environmental impact. The analysis narrowed down the articles used in this review to 74. The information was then retrieved for further analysis in the review.

3. Results and discussion

3.1. Nutritional comparison of plant-based beverages with animal milk

3.1.1. Macronutrients

The available plant-based substitutes in the market have advantages and disadvantages going for them, as explained by Vanga & Raghavan, 2018). This article shows an analysis of their nutritional content, from the plant used to produce the beverage to the nutritional profile of the product sold. It is possible to see the change in the nutritional profile from the plant (almond, soy, rice, and coconut) to the final product (plant-based beverage). Paul et al. (2020) also provide a comparison between bovine milk and plant beverages, aiming additionally at the comparison of oat, cocoa, kidney bean, peanut, and hemp beverages. Both studies agree that soy milk is the best alternative since it has a nutritional profile that is closer to cow milk, but they also highlight that many consumers complain about its “beany” flavour. This, together with the presence of some anti-nutrients, forced the industry to look for other plant alternatives such as almonds. One more study (Paul et al., 2020) shows that no plant-based beverage can be a perfect substitute for standard cow milk due to a reduced nutrient diversity. The authors also

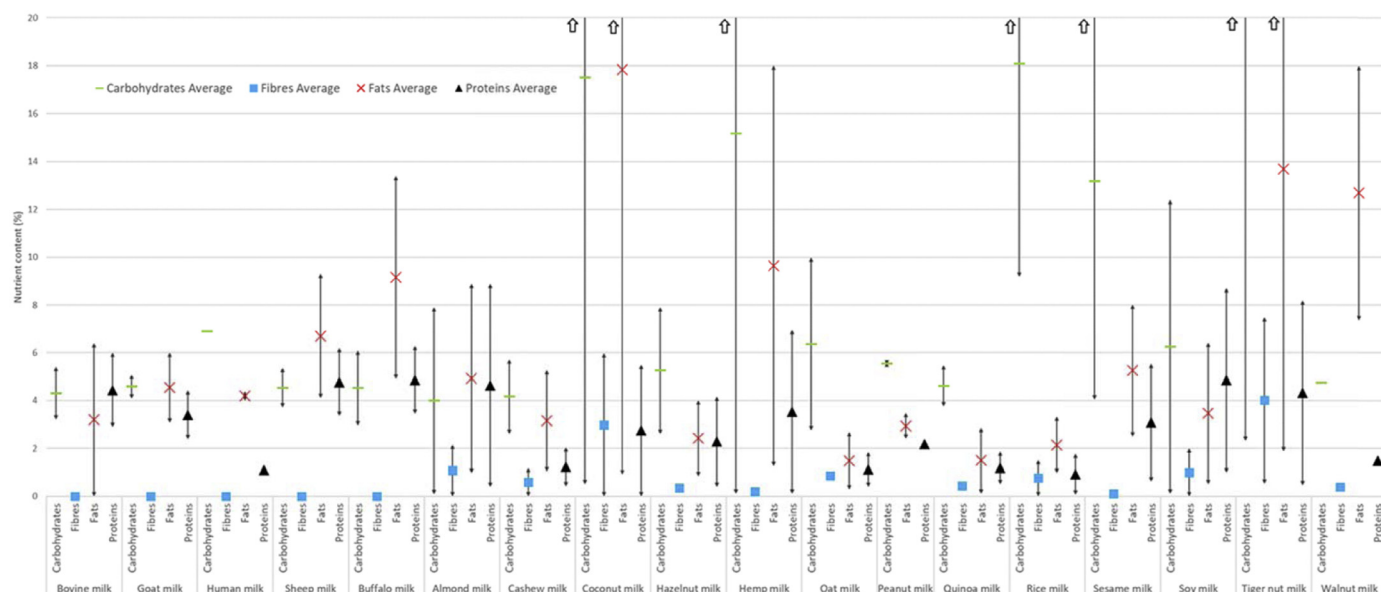


Fig. 1. Figure 1 - Nutritional information (carbohydrates, fibres, fat, and protein content) for different milks and plant-based beverages per 100 g of product. For detailed data see Supplementary material: Table 3. Sources: (Aydar et al., 2020; Barłowska et al., 2011; Bawalan & Chapman, 2006; Chalupa-Krebzdak et al., 2018; Fructuoso et al., 2021; Maduka & S. Ire, 2018; Manzoor et al., 2017; McClements et al., 2019; Paul et al., 2020; Pereira, 2014; Rasika et al., 2021; Scholz-Ahrens et al., 2020; Sethi et al., 2016; Silva et al., 2020; Singhal et al., 2017; U.S. Department of Agriculture, 2019; Vanga & Raghavan, 2018; Verduci et al., 2019; Zhang et al., 2020).

remind that, when drinking any of these alternative-based products, it is important that consumers have a balanced diet to accommodate for the absence of different nutrients from these products.

3.1.1.1. Proteins. The profiles of animal-derived milk, as well as plant-based alternatives, vary considerably in their nutritional profiles (Fig. 1 with details in Supplementary material: Table 3). Starting with the protein content (g / 100 g of product), the highest value comes from almond milk, followed by soy milk, tiger nut milk, hemp milk, buffalo milk and sheep milk. This shows that plant-based beverages can have a higher protein concentration than the equivalent animal-based beverage. Values in this category range from 0 g / 100 g (coconut milk) to 8.89 % (soy milk). With the lowest values coming from plant-based beverages: coconut milk (0 g / 100 g), rice milk (0.07 g / 100 g), hemp milk (0.1 g / 100 g) almond, hazelnut and oat milk (0.4 g / 100 g), cashew milk (0.42 g / 100 g), tiger nut milk (0.47 g / 100 g) and quinoa milk (0.5 g / 100 g). All other analysed products fall between these two points, from lowest concentration to highest: sesame milk (0.625 - 5.55 g / 100 g), soy milk (0.99 - 8.71 g / 100 g), human milk (1 - 1.20 g / 100 g), walnut milk (1.3 - 1.70 g / 100 g), peanut milk (2.05 - 2.33 g / 100 g), goat milk (2.38 - 4.43 g / 100 g), bovine milk (2.9 - 6.00 g / 100 g), sheep milk (3.35 g / 100 g) and finally buffalo milk (3.44 - 6.29 g / 100 g).

It is important to remind that the proteins in animal and plant-based products are very different and behave differently when consumed. They also have different amino acid content, with plant proteins lower amino acid content and are deficient in other essential amino acids (e.g. lysine or sulphur amino acids) (Berrazaga et al., 2019).

3.1.1.2. Fat. The fat concentration varies very little in animal milk, and can go from very close to 0 with cow milk – fat removal is a normal procedure in the industry to be used for other products such as butter or creams (Lubary et al., 2011) – to the highest value in this group with buffalo milk (close to 13.5 %). The overall highest value comes from coconut milk, with values close to 35 g of fat per 100 g of beverage. Plant-based beverages overall have a lower fat content than the equivalent animal products, except for tiger nut milk, walnut milk, and some

sesame-based products. As said previously, these products are artificial emulsions where some extra oil may be added during processing to help with emulsification – which may explain some of the high values. Also, contrary to plant-based products, animal-based milk is a natural emulsion, containing no added fat. The remaining products have fat concentration values in the same range.

This category can be further divided and defined into saturated, monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA). (Hooper et al., 2020) explain that dietary saturated fat is bad for people's health since it increases serum cholesterol and so increases cardiovascular risk. On the other hand, they explain that the consumption of polyunsaturated fats reduces the risk of both.

This way, bovine milk has (per 100 mL of product) between 0 and 2.3 g of saturated fats, 0.021 and 1.06 g of MUFA and 0.003 and 0.195 g of PUFA (Chalupa-Krebzdak et al., 2018; McClements et al., 2019; Vanga & Raghavan, 2018; Zhang et al., 2020). Comparatively to this, almond milk (0.000 - 0.080 g / 100 mL), cashew milk (0.000 - 0.880 g / 100 mL), hemp milk (0.000 g / 100 mL), rice milk (0.000 - 0.48 g / 100 mL) and soy milk (0.210 - 1.320 g / 100 mL) have smaller ranges of saturated fatty acids (Chalupa-Krebzdak et al., 2018; McClements et al., 2019; Vanga & Raghavan, 2018; Zhang et al., 2020). The only exception is coconut milk whose values range from 0.000 to 5.000 g / 100 mL (Chalupa-Krebzdak et al., 2018; McClements et al., 2019; Vanga & Raghavan, 2018; Zhang et al., 2020).

Comparing the amount of MUFA present in the plant-based beverages, some products have smaller ranges compared with cow milk (cashew milk, 0.620 g / 100 mL and soy milk, 0.210 - 1 g / 100 mL), whereas others achieve higher values in the maximum point of the scale (almond 0.620 - 2 g / 100 mL, rice milk 0.48 - 1.5 g / 100 mL) (Chalupa-Krebzdak et al., 2018; McClements et al., 2019; Vanga & Raghavan, 2018).

Lastly, the amount of PUFA in these alternative beverages is higher in all products that had data available, when compared with bovine milk: almond milk 0.210 - 1 g / 100 mL, cashew milk 0.000 - 0.880 g / 100 mL, rice milk 0.3 - 1.68 g / 100 mL and soy milk 0.830 - 3 g / 100 mL (Chalupa-Krebzdak et al., 2018; McClements et al., 2019; Vanga & Raghavan, 2018).

3.1.1.3. Fibres. Animal milk does not have fibres in its composition – 0 g / 100 g of product – while the concentration in plant-based products goes from low (hazelnut 0.3 g, quinoa 0.43 and oat 0.8 g) or null values (almond, cashew, coconut, hemp, rice, sesame and soy) in some plant-based products, to almost 6% in coconut milk and 7.5 % in tiger nut milk. Dietary fibre is very important for humans, with many studies associating it with some health benefits (e.g.: (Kendall et al., 2010)), but the current average consumption is lower than recommended (Li & Komarek, 2017). The consumption of plant-based products may help increase the average consumption (Brownlee et al., 2017) and thus often is indicated as a nutritionally and healthy beneficial aspect.

3.1.1.4. Carbohydrates. Carbohydrates are not considered essential nutrients, but they have a central role in energy obtention in current diets (Sjöblad, 2019). This way, it is important to study the composition of these molecules due to the potential excess of dietary energy and high glycaemic index. Studies have shown that plant-based beverages have a higher glycaemic index than bovine milk, with values ranging from 47 for bovine milk to 100 in rice-based beverages (Jeske et al., 2017, 2018).

Such is confirmed by the fact that carbohydrates' presence in the analysed plant products is overall higher than in animal products, with the highest value coming from some tiger nut products with 58.01 g / 100 g. This occurs possibly because, in its majority, plant-based products are sweetened to appeal more to the consumer (Paul et al., 2020). Other than this, the base plants already have high carbohydrate concentrations, ranging from 1.8 % for almond beverages to almost 80 % for those based on rice (Supplementary material: Table 4). In terms of the animal milks, the range of concentrations goes from 2.95 g / 100 g in buffalo milk to 6.90 g / 100 g in human milk. In these, lactose (a disaccharide) is the primary sugar, whereas in plant-based beverages different types of sugars can be added by the manufacturer, adding to the ones that are naturally occurring in the product. These can be, for example, glucose or fructose (monosaccharides) or sucrose (disaccharide) (Sumner & Burbridge, 2021).

3.1.2. Micronutrients

Looking at the mineral composition of the different products, there are distinctive differences between the products (see Fig. 2). First, minerals are present in animal products without antinutrients. Plant-based products, on the other hand, can contain antinutrients, which reduce the bioavailability of other nutrients (Aydar et al., 2020; Guyomarc'h et al., 2021; Mäkinen et al., 2016; Melse-Boonstra, 2020). Common antinutrients found in these plants are phytic acid, oxalate, phytate, trypsin, protease and amylase inhibitors, saponins, tannins, gossypol, lectins, and goitrogens (Aydar et al., 2020; Samtiya et al., 2020, Fig. 2).

3.1.2.1. Minerals. Calcium is one of the minerals that is mostly associated with milk consumption (Melse-Boonstra, 2020). In animal products, the highest concentration comes from sheep milk with close to 200 mg per 100 g, whilst the lowest comes from human milk close to 32 mg / 100g of product. Plant-based beverages usually do not contain high calcium amounts and thus are often fortified with this mineral (Mäkinen et al., 2016). This fortification can be seen through the comparison of Tables 3 and 4, presenting the nutritional profiles of plant and animal-based beverages. For this mineral, cashew, coconut, hazelnut, rice, and tiger nut milk are most likely fortified – from 28 - 52 mg to 8 - 188 mg in cashew milk, from 20 mg to 0 - 495 mg in coconut milk, 114 - 264 mg to 120 - 125 mg in hazelnut milk, 0.54 - 54.60 mg to 0-330 mg in rice milk, and 19.09 - 155 mg was kept almost the same with 152 mg in tiger nut milk.

Iron is one mineral that is present in extremely low values both in animal and plant milk. The overall concentration of this nutrient is not very high: the highest concentration was 0.0065 % (6.58 mg / 100 g) in some hemp milk products, followed by 4.01 mg / 100 g in some coconut products, 2.60 mg / 100 g in some soy products and 1.80 mg / 100 g in

some almond drinks. All other beverages, both from animal and plant sources have their maximum values of this mineral under 1 mg / 100 g.

Magnesium's concentration ranges from 0.542 mg / 100 g in cashew milk to close to 70 mg / 100 g in soy milk. While animal milk ranges from 3 mg (human milk) to 31 mg (buffalo milk) per 100 g, plant-based beverages range from 0.542 mg (cashew milk) to 70 mg (soy milk) per 100 g of product, but no product appears to have been fortified in this mineral. It is important to note that this category has approximately 33 % of missing values and all of them belong to the group of plant-based beverages.

Phosphorus's presence in the beverages ranges from 2 - 256.35 mg / 100 g. The high values come from the fact that these plant-based beverages are most likely fortified (from 174 mg / 100 g in the fruit to 2 - 256.35 mg / 100 g in coconut-based beverages). This category has a high percentage of missing values (close to 39 %) and, once again, all these belong to the group of plant-based beverages.

Potassium concentration varies from 12.5 mg in cashew milk to 639.02 mg in coconut milk, per 100 g of product. There is one product in this range that appears to be fortified, and that is coconut milk. This is because the concentration of this mineral in the fruit is around 565 mg / 100 g and in the beverages is between 14.58 - 639.02 mg / 100 g – so not all products may be fortified, but the ones that achieve the highest values appear to be. Animal products' potassium concentration ranges between 51 mg (on human milk) and 204 mg (on goat milk) per 100 g of product. In this category, the percentage of missing values is once again, around 33 % and all of them belong to plant-based beverages.

Sodium presence is higher in plant-based products than in animal products. This is most likely due to the addition of this mineral during processing to help make the product more flavourful to the consumer. However, there are exceptions to this as most plant-based products also have products with very low concentrations of this mineral. In the analysed products, there is the possibility of some rice and soy-based products had some sodium added through processing since their values are higher than the ones found in the base plants. Missing values in this category belong to plant-based products and are around 28 %.

Zinc has the highest percentage of missing values in the group of minerals, with more than 44 % of the values missing, and all belonging to the group of plant-based beverages. No product appears to have been fortified, and the concentrations in the products are all under 1 mg of zinc per 100 g. The range goes from 0.059 mg (goat milk) to 0.94 mg (almond milk, coconut milk, rice milk and soy milk).

3.1.2.2. Vitamins. Table 1 shows the vitamin concentration of the different beverages. Human milk is the beverage that has the highest vitamin C concentration with 5 mg / 100 g, followed by sheep milk with 4.6 mg / 100 g. Most plant-based beverages have null concentrations of this vitamin, like almond, cashew, some coconut products, hazelnut, oat, some rice products and soy milk.

Vitamin B1 (or thiamine) concentration varies from 0 mg / 100 g in almond milk to 0.10 mg / 100 g in soy milk. Around 50% of the analysed plant beverages have missing values for this category while animal milk's values fall within this range.

In the case of vitamin B2 (riboflavin), its concentration varies between 0 mg (in coconut milk) and 0.376 mg (in sheep milk). Very close to sheep milk there are almond, rice, and soy milk with their maximum concentration of this vitamin marking 0.33 mg / 100 g. However, there are products based on these plants that have lower values: the lower limit is 0.01 mg for almond milk, 0.07 mg for soy milk and 0.142 mg for rice milk, and null values can be found in coconut milk. Products based on cashew, hazelnut and rice are most probably are fortified with this vitamin (considering the concentration of the vitamin in source materials).

The concentration of vitamin B3 (niacin) for these beverages varies from 0.07 mg (in almond milk) to 0.637 mg (in coconut milk). This category has one of the highest percentages of missing values, all found

Table 1

Vitamin concentration of different milk and plant-based beverages. Vitamin C, Thiamine, Riboflavin, Niacin, Vitamin B6, Folate, Vitamin B12, Vitamin A and Vitamin D content per 100g of product.

Milk source	Vitamins										Sources
	Vit. C (mg)	Vit. B1 (mg)	Vit. B2 (mg)	Vit. B3 (mg)	Vit. B6 (mg)	Vit. E (mg)	Vit. B9 (μ g)	Vit. B12 (μ g)	Vit. A (μ g)	Vit. D (μ g)	
Bovine	0-1.50	0.04-0.05	0.00016-0.172	0.08-0.17	0.011-0.042	0.0625-0.08	5-8.5	0.357-0.8	0-59000.00	0.02-1.2917	(Barłowska et al., 2011; McClements et al., 2019; Pereira, 2014; Scholz-Ahrens et al., 2020; Sethi et al., 2016; Singhal et al., 2017; U.S. Department of Agriculture, 2019; Verduci et al., 2019; Zhang et al., 2020)
Goat	1.1-1.30	0.048-0.068	0.13-0.21	0.24-0.277	0.046-0.05	0-0.50	1.00	0-0.07	55-55.50	0.0575-1.30	(Barłowska et al., 2011; Pereira, 2014; U.S. Department of Agriculture, 2019; Verduci et al., 2019)
Human	5.00	0.01-0.017	0.02-0.04	0.177-0.18	0.011	0-0.08	5.00	0.03-0.05	57-61.00	0.035-0.42	(Barłowska et al., 2011; Pereira, 2014; U.S. Department of Agriculture, 2019; Verduci et al., 2019)
Sheep	4.16-4.60	0.065-0.080	0.34-0.376	0.41-0.417	0.06-0.08	0.11	6-7.00	0.66-0.712	43.8-64.00	0.18-1.18	(Barłowska et al., 2011; Pereira, 2014; U.S. Department of Agriculture, 2019; Verduci et al., 2019)
Buffalo	2.3-2.50	0.05-0.052	0.11-0.135	0.091-0.17	0.023-0.33	0.19	0.6-6.00	0.36-0.4	53-69.00	n.d.	(Barłowska et al., 2011; U.S. Department of Agriculture, 2019; Verduci et al., 2019)
Almond	0.00	0.00	0.01-0.33	0.07	0-3.84	1.20-19.2	1-19.20	0-77.14	0-180.00	0.45-3.30	(McClements et al., 2019; Scholz-Ahrens et al., 2020; Sethi et al., 2016; Singhal et al., 2017; U.S. Department of Agriculture, 2019; Vanga & Raghavan, 2018; Verduci et al., 2019)
Cashew	0.00	n.d.	0.125	n.d.	n.d.	n.d.	n.d.	0.417	n.d.	1.563	(Singhal et al., 2017)
Coconut	0-1.00	0.02-0.022	0.00-0.166	0.3-0.637	0.028-0.030	n.d.	14-19.20	0.00-1.25	0.00-60.00	0-3.33	(Barłowska et al., 2011; McClements et al., 2019; Scholz-Ahrens et al., 2020; Sethi et al., 2016; Singhal et al., 2017; U.S. Department of Agriculture, 2019; Vanga & Raghavan, 2018; Verduci et al., 2019; Zhang et al., 2020)
Hazelnut	0.00	n.d.	0.125	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.563	(Singhal et al., 2017)
Hemp	0.00	n.d.	0.1125	n.d.	n.d.	n.d.	n.d.	n.d.	0-37.50	1.563	(Sethi et al., 2016; Singhal et al., 2017)
Oat	0.00	n.d.	0.125-0.3	n.d.	n.d.	n.d.	n.d.	n.d.	37.50	1.563	(Sethi et al., 2016; Singhal et al., 2017)
Rice	0-0.50	0.027	0.142-0.33	0.39	0.039-0.04	0.13-3.00	2.00	0.63-1.00	0-150.00	0-3.33	(McClements, 2020; Scholz-Ahrens et al., 2020; Sethi et al., 2016; Singhal et al., 2017; U.S. Department of Agriculture, 2019; Vanga & Raghavan, 2018; Verduci et al., 2019)
Soy	0.00	0.06-0.10	0.07-0.33	0.11-0.44	0.07-0.12	4.00	19-48.00	0.30-1.00	0-77.14	0.45-2.50	(McClements, 2020; Scholz-Ahrens et al., 2020; Sethi et al., 2016; Singhal et al., 2017; Vanga & Raghavan, 2018; Verduci et al., 2019)

Note: n.d. – no data

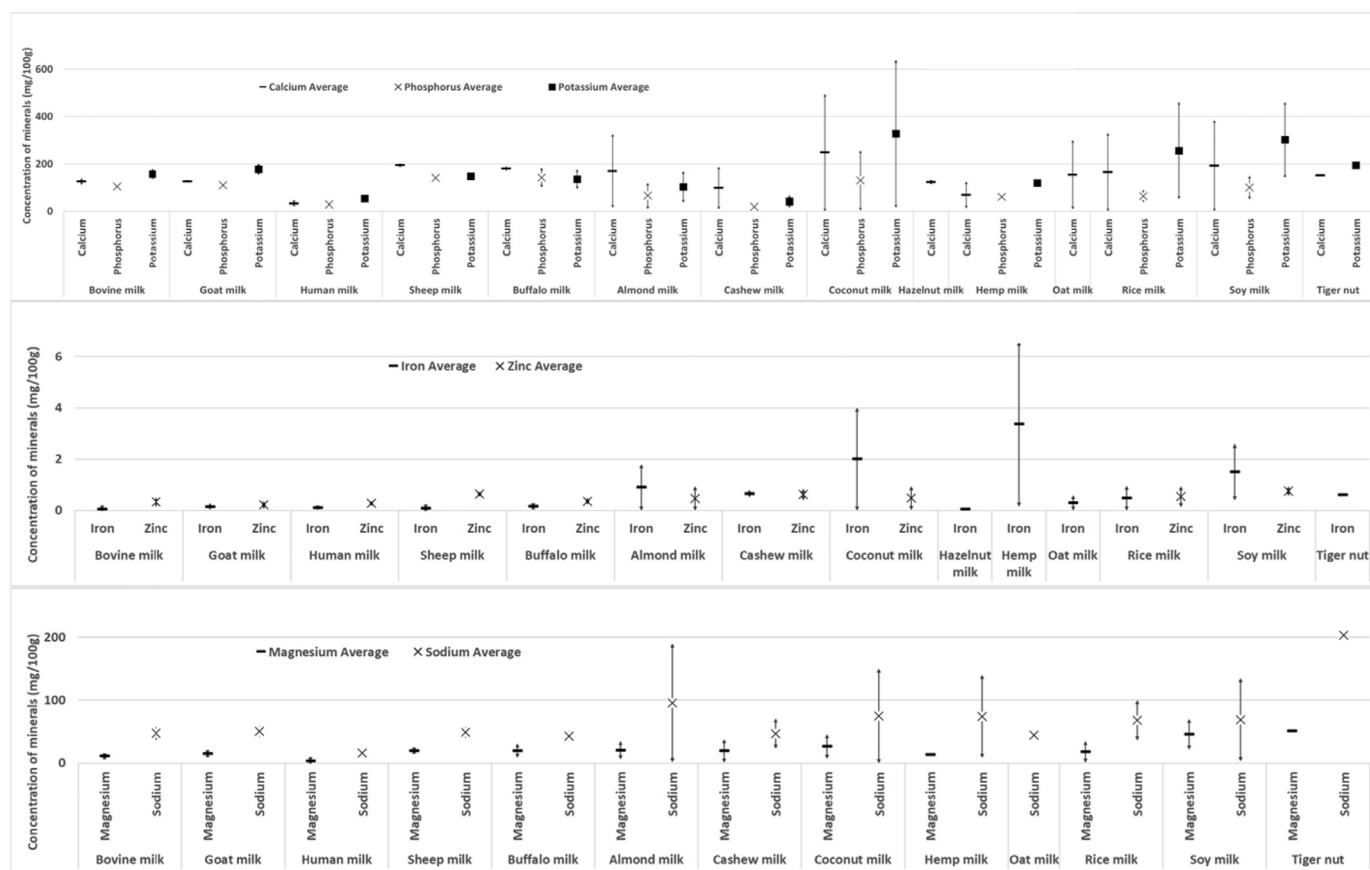


Fig. 2. Mineral composition (Calcium, Iron, Magnesium, Phosphorus, Potassium, Sodium, and Zinc content) of different milks and plant-based beverages per 100g of product.

For detailed data see Supplementary material: Table 3. Sources: (Barłowska et al., 2011; Bawalan & Chapman, 2006; Chalupa-Krebsdzak et al., 2018; Fructuoso et al., 2021; Maduka & S. Ire, 2018; Manzoor et al., 2017; McClements et al., 2019; Paul et al., 2020; Pereira, 2014; Scholz-Ahrens et al., 2020; Sethi et al., 2016; Silva et al., 2020; Singhal et al., 2017; U.S. Department of Agriculture, 2019; Vanga & Raghavan, 2018; Verduci et al., 2019; Zhang et al., 2020).

in the group of plant-based beverages, and reaching 50 % of all products. No products appear to have been fortified in this vitamin.

Vitamin B6 is present in amounts between 0 mg and 3.84 mg, both values for almond milk and all the other products fall between these two values. The second highest value comes from buffalo milk, with 0.023 - 0.33 mg / 100 g. Almond-based products may have been fortified with this vitamin during processing since their values in almonds are 0.08 - 0.16 mg / 100 g, and for almond-based milk are 0 - 3.84 mg / 100 g. This category, as well as the previous has 50 % of missing data for the available and analysed products, once again all a part of the group of plant-based beverages.

Vitamin E concentration in plant-based beverages ranges from 0.13 to 19.2 mg / 100 g of plant-based products whereas animal-based products' values range from null (goat and human milk) to 0.19 mg / 100 g (buffalo milk). This category has the highest percentage of missing values, reaching almost 56 %, all belonging to the group of plant-based beverages. The three plant-based beverages whose values are available for analysis (almond, rice and soy) are most likely fortified.

For vitamin B9, also known as folate, its concentration in these products ranges from 1 to 48 µg / 100 g in plant milk and from 0.6 to 8.5 µg / 100 g in animal milk. Some plant-based products are possibly fortified with this vitamin, such as almond-based milk (from 0.044 - 0.13 µg of folate in almonds to 1 - 19.20 µg in almond-based milk). Missing values in this category belong to plant-based beverages and are around 44%.

Vitamin B12's concentration in these products goes from 0 µg to 77.14 µg per 100 g of product and some products are possibly fortified in this vitamin, such as rice or soy-based beverages (the plant has

0 µg, and the beverage has 0.63 - 1 µg of vitamin B12), or cashew milk (from 0 - 0.111 µg to 0.417 µg / 100 g). Missing values in this category belong to plant-based beverages and are, once again, around 44%.

The highest concentration of vitamin A is found in cow milk with 59000 µg, followed by almond milk, with almost 33 times less vitamin (180 µg), and the range of concentration of this vitamin in these products ranges from null values (cow milk, almond milk, coconut milk, hemp milk, rice milk and soy milk) to 59000 µg / 100g. Some plant products appear to have been fortified with vitamin A, such as almond, coconut, hemp, oat and rice milk. The percentage of missing data is close to 39% and these are, once again, from the group of plant-based beverages.

Lastly, the highest value found for vitamin D is presented by both coconut and rice-based beverages (3.30 µg and 3.33 µg / 100 g, respectively) and these, together with cashew, coconut, hazelnut, hemp and soy are products that appear to have been fortified. Missing values in this category lower to close to 28%, and this time includes values missing from the animal milk group as well (buffalo milk).

3.1.3. Recommended daily dose (RDD)

The consumption of 100 g of these animal products or plant-based products can provide different percentages of the recommended daily doses of the different minerals and vitamins, as shown in Table 2. Overall, the products that provide the highest percentages of the recommended daily dose of different vitamins and minerals are in the plant-based beverages group. All available minerals and vitamins are important for humans, and there is extensive evidence in the literature that ex-

Table 2

Recommended daily dose and per cent of the daily value of animal-based milk and plant-based milk per 100g of product. M – Male; F – Female. Data for pregnant and lactating women are not present.

	Gender	RDD for adults	Animal milk	Plant milk	Sources for RDD
Calcium	M / F	1000-1200 mg	2.67-20.00 %	0.00-49.50 %	(NIH, 2021i)
Iron	M	8 mg	0.09-3.75 %	0.00-82.25 %	(NIH, 2021l)
	F	8-18 mg	0.04-3.75 %	0.00-82.25 %	
Magnesium	M	400-420 mg	1.90-7.75 %	0.13-17.50 %	(NIH, 2021k)
	F	310-320 mg	2.50-10.00 %	0.17-22.58 %	
Phosphorus	M / F	700 mg	2.00-26.43 %	0.29-36.62 %	(NIH, 2021c)
Potassium	M	3400 mg	1.50-6.00 %	0.77-18.79 %	(NIH, 2021d)
	F	2600 mg	1.96-7.85 %	1.01-24.58 %	
Sodium	M / F	2300 mg	0.65-2.58 %	0.00-8.83 %	(FDA, 2017)
Zinc	M	11 mg	0.54-6.79 %	0.00-8.55 %	(NIH, 2021a)
	F	8-9 mg	0.66-9.34 %	0.00-11.75 %	
Vitamin C	M	90 mg	0.00-5.56 %	0.00-1.11 %	(Farhan Aslam et al., 2017; Pacier & Martirosyan, 2015)
	F	75 mg	0.00-6.67 %	0.00-1.33 %	
Vitamin B1	M	1.2-1.5 mg	0.67-56.67 %	0.00-8.33 %	(Fattal-Valevski, 2011)
	F	1.0-1.1 mg	0.91-68.00 %	0.00-10.00 %	
Vitamin B2	M	0.9-1.1 mg	0.01-41.78 %	0.00-36.67 %	(Pinto & Zempleni, 2016)
	F	1.1-1.3 mg	0.01-34.18 %	0.00-30.00 %	
Vitamin B3	M	16 mg	0.50-2.61 %	0.44-3.98 %	(NIH, 2021b)
	F	14 mg	0.57-2.98 %	0.50-4.55 %	
Vitamin B6	M	1.3-1.7 mg	0.65-3.85 %	0.00-295.38 %	(NIH, 2021f; Parra et al., 2018)
	F	1.3-1.5 mg	0.73-3.85 %	0.00-295.38 %	
Vitamin E	M / F	15 mg	0.00-0.53 %	0.87-128.00 %	(Farhan Aslam et al., 2017; NIH, 2021h)
Vitamin B9	M / F	400 µg	0.15-2.13 %	0.25-12.00 %	(Farhan Aslam et al., 2017; NIH, 2021j)
Vitamin B12	M / F	2.4 µg	0.00-33.33 %	0.25-3214.17 %	(Farhan Aslam et al., 2017; NIH, 2021m)
Vitamin A	M	900 µg	0.00-7.67 %	0.00-20.00 %	(NIH, 2021e)
	F	700 µg	0.00-9.86 %	0.00-25.71 %	
Vitamin D	M / F	15-20 µg	0.10-8.67 %	0.00-22.20 %	(Farhan Aslam et al., 2017; NIH, 2021g)

plains their role in the humans' organism as well as the nefarious effects of their absence. This review does not provide a complete review of all the potential possible variations of available minerals or vitamins in these products, but rather the most common ones in them. The analysed minerals (calcium, iron, magnesium, phosphorus, potassium, sodium, and zinc) and vitamins (vitamin C, B1, B2, B3, B6, E, B9, B12, A, and D) together with many others that are not analysed in this review, are important micronutrients for humans. Their absence can cause many disturbances in the organism, for example, low values of iron cause different imbalances in the body (see (Camaschella, 2019)), or magnesium's absence disturbs the normal functioning of more than 300 enzymes (DiNicolantonio et al., 2018), and (Farhan Aslam et al., 2017) explains how many vitamins are involved in boosting up the immune response. But their presence in excess also can cause problems. For example, excess sodium causes high blood pressure and is associated with a higher risk of cardiovascular diseases (FDA, 2017). The products analysed in this review are not the best sources for the consumption of these micronutrients. (Pacier & Martirosyan, 2015), for example, present a list of food products with the highest presence of vitamin C.

3.2. Environmental impact

The food system has a great deal of influence on the environment, including accelerating climate change, creating eco-toxicity, increasing water and land usage, eutrophication as well as loss of biodiversity (Aydar et al., 2020). The environmental damage of the food system is shown in several recent studies: (Poore & Nemecek, 2018) show that this industry, in particular, has big greenhouse gas, land, and water footprints. The same authors show that greenhouse gas and land use of dairy cattle are 36 and 6 times greater than the ones produced by pea production. (Springmann et al., 2018) have similar findings and show that environmental pressures caused by animal products are very high, especially the greenhouse emissions – and the impacts tend to keep growing with time. These emissions are mostly due to low feed-conversion efficiencies, enteric fermentation in ruminants, and manure-related emissions. Alternative protein products often use the fact of the

high impact of animal-derived proteins as an advocate for a reduction in animal products consumption, mainly red meat and dairy (Clay et al., 2020; Haas et al., 2019).

(Haas et al., 2019) say that most environmental issues related to milk production are soil degradation, air and water pollution, and loss of biodiversity. (Rotz et al., 2010) show that milk production's environmental footprint can vary very easily with a couple of variables, e.g., the number of animals on the farm, the conditions where they are kept, and milk production level. The release of greenhouse gases (GHG) from this industry boils down to most of it being CO₂, CH₄, N₂O, and these are released from various points in the life cycle, as shown for example by (Poore & Nemecek, 2018; Potter & Röös, 2021; Rotz et al., 2010). Some studies compare the environmental impact of milk production with the production of plant-based alternatives through Life Cycle Assessment (LCA) (see (Grant & Hicks, 2018; Ho et al., 2016; Röös et al., 2016)), while others just look at the impact from one of the sides, either milk production (Berton et al., 2021; Thomassen et al., 2008) or plant-based beverage production (Winans et al., 2020).

When looking at the LCA of plant products, the part that differs the most among them is the base plant production, since the rest of the processes are quite similar (Aydar et al., 2020; Mäkinen et al., 2016). In terms of different technologies, (Aydar et al., 2020) report that some novel technologies like ultrasound (US), pulsed electric fields (PEF), ohmic heating, or high and ultra-high-pressure processing (HPP, UHPP) can be used to enhance the product's stability without the use of additives. The processing part of milk and plant-based drinks imitating milk in some parts could be similar (pasteurisation, homogenisation). At the same time plant-based drinks require additional roasting, hulling, blanching, soaking, sometimes cooking, milling, separation and filtration and fermentation) (Tangyu et al., 2019).

Figure 3 shows the overall environmental impact of the production of different products – animal milks and plant-based beverages (complete data in Supplementary material: Table 5). The production of one litre of milk can release to the environment between 0.089 and 72.70 kg CO₂ eq. for animal-based milk and between 0.021 and 3.85 kg CO₂ eq. for plant-based beverages, almost 19 times less CO₂ than the same volume of animal-based milk.



Fig. 3. Environmental footprint of different animal-based and plant-based beverages per litre: A – Global warming potential (kg CO₂ eq.), B – Energy consumption (MJ), C – Water consumption (L of water), D – Ozone depletion potential (kg CFC11 eq.), E – Marine eutrophication (kg N eq.), F – Acidification potential (kg SO₂ eq.), G – Freshwater eutrophication (kg P eq.); H – Land use (m²) per litre of milk. For detailed data see Supplementary material: Table 5. Sources: (Batalla et al., 2015; Berton et al., 2021; Bhandari et al., 2021; Broekema & Kramer, 2014; Cabral et al., 2020; CarbonCloud Ab, 2018; Clune et al., 2017; Ernstoff et al., 2020; Grant & Hicks, 2018; Health Care Without Harm, 2017; Heller et al., 2020; Ho et al., 2016; Pirlo et al., 2014; Ritchie & Roser, 2020; Robertson et al., 2015; Thomassen et al., 2008; Winans et al., 2020; Zucali et al., 2020).

Energy use comparison is not that straightforward. The highest and lowest energy consumption (both renewable and non-renewable energy consumption) comes from rice milk production (1.04–47.60 MJ / L of milk), whilst almond milk production consumes 1.53 – 36.90 MJ and cow milk production 2.7 – 36.30 MJ per litre of milk produced.

Water consumption reaches very high volumes with almond milk production (59 – 6100 L / L of milk), followed by cow milk production (11.7 – 1030 L / L of milk). During almond milk production, a big part of the impacts come from almond production, as shown by Winans et al. (2020).

Depletion of the ozone layer can be caused by many factors, and during LCA is weighted through kg CFC11 eq. released to the environment. The highest impact on ozone layer depletion is associated with goat milk (8.78E-8 to 9.82E-7 kg CFC11 eq.), while plant-based beverages have a 10 times lower impact in this category.

Water eutrophication is divided into marine eutrophication (kg N eq.) and freshwater eutrophication (kg P eq.). In the first, once again animal milk has the highest impact on this category, 0.001 – 0.346 kg N eq., whilst plant-based milk varies between 0.000267 – 0.0062 kg N eq. On freshwater eutrophication the highest impact comes from cow milk

0.00035 - 10.65 kg P eq. / L milk, followed by rice milk (4.69 kg P eq.), oat milk (1.62 kg P eq.).

The highest acidification potential comes again from animal milk production, most precisely buffalo milk (0.065 kg SO₂ eq.). Almond and cow milk follow, but with less than half the emissions: 0.0029-0.0268 kg SO₂ eq. and 0.0109-0.0268 kg SO₂ eq., respectively.

Land use for the production of these products varies a lot, with the highest values coming from animal products, more specifically cow milk (1.18 – 54 m² / L of milk), as there is no data for the other animal milks. In the group of plant-based milk, the highest value of land use comes from oat milk (0.66 m²), followed by soy milk (0.66 m²), almond milk (0.50 m²) and lastly rice milk (0.34 m²).

Currently, other types of biomass can be used to produce another possible milk substitute. (Tello et al., 2021) studied the possibility of using *Tenebrio molitor* larvae as a biomass source to produce different milk alternatives. In the comparable categories, this prototype showed lower ozone depletion potential (5.063E-08 kg CFC11 eq.) than the lowest value found for this category in milk alternatives (1.48E-07 kg CFC11 eq. in almond milk). In the other categories, the prototype's values were still higher than the lowest values found for this review.

4. Limitations of the study

To the authors' knowledge, there is no LCA data on human milk in the animal-based milk category, or cashew, coconut, hazelnut, hemp, peanut, quinoa, sesame, tiger nut, and walnut-based beverages. Even on the available data for the other products (cow, buffalo, goat, sheep, oat, almond, rice, and soy), there is missing data that does not allow to make a complete comparison of the available data. The only category that has data available for the mentioned beverages is global warming potential. This is an important category for the life cycle assessment, however, a comparison of products or services in this sole category does not show the real impact of the product.

In, the nutritional analysis of the beverages, some of the characterized products did not have a lot of information for a complete comparison. The biggest occurrence of missing data is found in the plant-based beverages where the lowest amount of data found (14%) was for peanut-based milk, followed by quinoa, sesame and walnut milk (19 %) and hazelnut and tiger nut milk (43%). These beverages had more than 50% of the data necessary for the characterization missing. This way, it is very complicated to compare the products with each other nutritionally to see which has the most complete nutritional profile and how they would function when being part of a given diet. More research must be done in this direction to accompany new product development in this area, as more and different products are developed.

Conclusions

Plant-based beverages on the market, imitating milk, appear to be nutritionally richer than animal milk. It is often achieved with the nutrient fortification of plant-based milks. At the same time, the amount of carbohydrates and sodium content in the plant beverages is high and these are two of the most concerning points in current diets, which are often being recommended for reduction. This happens because plant-based milk has higher concentrations of these two nutrients caused by the addition of sugar and salt during processing to appeal to the consumer. The antinutrients present in these alternative beverages can hinder the absorption of the nutrients in these beverages. However, it is possible to reduce the number of antinutrients during the processing stage of the product, as explained in (Tangyu et al., 2019).

The overall environmental impact of plant-based milk is lower than bovine milk. At the same time, the water footprint for some plant milks is much higher. It is especially obvious for almond milk production. Energy consumption could also be high for plant-based milks: it is higher for rice milk production than almond or cow milk.

There is still a lot of data lacking, especially related to plant-based beverages – both on the nutritional profiles and their environmental impact. This can be seen through the reduced number of sources that were used for this review (74 articles) for the analysis of both LCA and nutritional aspects of these products. This makes comparison and analysis quite limited and thin. For example, no data was found for vitamin presence in peanut, quinoa, sesame, tiger nut, and walnut-based milk products. For other products such as cashew, hazelnut, hemp or oat milk, only 30 or 40 % of the information was available for the vitamin presence in these products. While analysing the mineral profile of these beverages, while animal milk was once again very well characterised, plant-based products were either completely uncharacterised (peanut, quinoa, sesame and walnut milk), or the available information was very scarce (hazelnut and oat milk).

Many categories are used to assess and compare the environmental impact of both animal and plant-based milk. Overall, there was a lot of data missing, even though there was usually a good balance between both animal and plant milks. It is important to note, however, that there are a lot of missing values concerning the environmental impact of animal milk. The least characterised product is sheep milk, as the only data found concerns global warming potential, followed by buffalo milk, which in addition to this category, has data on acidification potential and freshwater eutrophication as well. Oat milk has missing data on energy consumption, ozone depletion potential, marine eutrophication and acidification potential. All the other products are either completely characterised for the analysed parameters (cow and almond milk) or have more than 50 % of the values available.

Ethics statement

The authors confirm that the current study does not involve

- the use of human subjects
- animal experiments:
- data collected from social media platforms:

Declaration of Competing Interest

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

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.afres.2022.100105](https://doi.org/10.1016/j.afres.2022.100105).

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