REVIEW

A Scoping Review of the Environmental Impacts and Nutrient Composition of Plant-Based Milks

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ABSTRACT

Dairy milk is a ubiquitous nutrient-dense beverage and ingredient, especially in Western diets. However, consumers are increasingly seeking alternatives to dairy, called plant-based milks (PBMs), to avoid allergens, pursue a plant-based diet, or reduce their environmental impacts. The base ingredients used in PBMs have a wide range of environmental impacts, which may translate to substantial variation across the impacts associated with PBMs themselves. To assess the state of the literature on this topic, we performed a scoping review of the environmental impacts of PBMs, following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews. Recent growth in the variety of PBMs available means that there is unlikely yet enough data for conclusive statements regarding environmental impacts of all PBM types, which makes this topic appropriate for a scoping review. We included all relevant documents found through searching scholarly databases. We found 20 studies covering 6 types of PBMs, but the literature does not examine many other types of PBMs. All studies examined use the life cycle assessment methodology. The most data regarding environmental impacts were available for soy- and almond-based milks, and the most common impact quantified was greenhouse gas emissions. We also examined the nutrient composition of PBMs compared with dairy using data from the USDA. PBMs attempt to replicate the organoleptic properties of dairy but often do not exactly match the nutrient profile of dairy. We identified a need for the application of a standardized methodology to facilitate more comprehensive assessment of environmental impacts of the wide variety of PBMs available, which are presented as environmentally preferable to dairy. *Adv Nutr* 2022;13:2559–2572.

Statement of Significance: To the authors' knowledge, this is the first scoping review to explore the literature regarding the environmental impacts of plant-based milks. This review aggregates all such known literature and identifies important knowledge gaps to prioritize for future research to fill. Such research would help identify the most sustainable choices for plant-based milks as well as potential instances where impacts would be comparable to or exceed those of dairy milks.

Keywords: scoping review, plant-based milks, life cycle assessment, dairy alternatives, vegan diet, environmental impacts, sustainability

Introduction

Dairy milk was the third most consumed packaged beverage globally in 2020, following water and alcohol, and just ahead of carbonated soft drinks (1). In addition to drinking it directly, milk is often added to coffee, tea, and breakfast cereal, and it is used in many recipes for its organoleptic properties. Milk is a nutrient-rich beverage with components that may promote health such as calcium (2), although there are no nutrients exclusive to milk, and some purported health benefits of milk are not supported by the evidence (3). In addition, three-fourths of adults globally and one-fourth of adults in the United States are unable to properly digest lactose, a natural sugar found in milk (2). For the purposes of this article, *dairy milk* typically refers to milk from domesticated cows.

For those who want to avoid dairy milk but replicate its sensory experience, there is a rapidly growing market meeting this demand with so-called plant-based "milks" (PBMs), which are beverages marketed as alternatives to

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Supplemental Tables 1–4 are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/advances/.

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Abbreviations used: GHGE, greenhouse gas emission; GWP, global warming potential; ISO, International Organization for Standardization; LCA, life cycle assessment; m^2a, meters squared per annum; PBM, plant-based milk.

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milk. The market for PBMs is expected to reach $14 billion (4). PBM manufacturers attempt to match the sensory characteristics of dairy milk by creating a product that has a similar viscosity and is white and creamy (5). They also attempt to match prominent nutrient characteristics of dairy milk by fortifying and promoting the calcium and protein content of some PBMs, although there is a wide variation in nutrients provided by different PBM types (5). Assessment of various PBMs found that although some met consumer expectations for sensory attributes but had undesirable nutritional characteristics, others with superior health values were less preferred by consumers due to bitterness and astringency (6). Some new manufacturing technologies for PBMs are being explored, including alternatives to thermal pasteurization treatments, which may also influence sensory characteristics in positive or negative ways depending on the technology applied (7).

Various government bodies such as the US FDA and the European Union restrict the terminology used in describing these beverages that compete with dairy milk, with some arguing that *milk* is an inaccurate and misleading term because they are not mammary secretions (4). There is also some concern that consumers will assume that plant-based milks are appropriate nutritional replacements for dairy milk (8). Despite this, most consumers understand that plant-based “milks” do not contain dairy; in fact, a higher proportion of consumers does not understand that lactose-free milk contains dairy milk (9). Therefore, for simplicity and to avoid confusion with other plant-based beverages such as juices, the term *PBM* is used here to refer to beverages made from plants and marketed as alternatives to dairy milk.

PBMs are often positioned as an environmentally friendly alternative to dairy milk that can help lower consumers’ environmental impacts. For example, Silk brand PBMs advertise that their beverages have a lower carbon footprint than US conventional dairy milk (10). The sustainability of PBMs compared with dairy milk has been investigated using life cycle assessment (LCA), a quantitative method that estimates the embodied environmental impacts of products based on the inputs and outputs throughout the life cycle of that product. LCAs of foods consistently show that animal-based foods have higher environmental impacts than plant-based foods (11–13). However, many LCA studies examine foods that have not undergone extensive processing, which has the potential to increase associated environmental impacts (14). Therefore, examinations of specific products are the only way to ensure an accurate representation of the consequences of consumer choices.

The objective was to evaluate the current state of knowledge in assessing the environmental impacts of PBMs, and this scoping review explores the available literature on the topic, with a focus on the context, methods used, and findings presented. Although LCA is the primary method by which environmental impacts of foods are assessed, this review includes all relevant literature regardless of examination method. This scoping review also provides a summary of PBM nutrient compositions based on USDA data for context.

Methods

Protocol and registration

This review followed the PRISMA extension for scoping reviews guidelines. The review protocol was registered on the Open Science Framework at https://osf.io/pf3m2. The registration digital object identifier is https://doi.org/10.17605/OSF.IO/PF3M2. The protocol page provides relevant methodologic details such as search strategy, including databases selected and exact search terms (15).

Eligibility criteria

Inclusion.

Studies were eligible if they included data on the environmental impacts of any plant-based milks, which typically include greenhouse gas emissions (GHGEs), land use, water consumption, and other quantifiable emissions to the environment or depletion of resources. Documents in all languages, if they included an English-language abstract, and from all geographic regions were included. If necessary, translators were sought for the data extraction of articles in languages not spoken within the research team.

Exclusion.

Studies were excluded if they were not relevant to the objective, lacked quantitative data for PBMs, or used only aggregate data from previous studies.

Information, selection of sources of evidence, and search strategy

Two reviewers independently searched PubMed (https://pubmed.ncbi.nlm.nih.gov/) and EMBASE (https://www.embase.com/) databases in the fall of 2021. They screened sources for eligibility and collected data including study characteristics and findings, with discrepancies being resolved through consultation with a third researcher. The search strategy used key terms related to nondairy and dairy milk and environmental impacts. Search terms for PubMed were (oat∗[tiab] OR soy∗[tiab] OR almond∗[tiab] OR coconut∗[tiab] OR bean∗[tiab] OR lentil∗[tiab] OR macadamia∗[tiab] OR cashew∗[tiab] OR pea∗[tiab] OR rice∗[tiab] OR cow∗[tiab] OR buffalo∗[tiab] OR non-dairy∗[tiab] OR plant-based∗[tiab] OR dairy∗[tiab]) AND (land use∗[tiab] OR water use∗[tiab] OR CO2∗[tiab] OR global warming potential∗[tiab] OR GWP OR environmental impact∗[tiab] OR life cycle assessment∗[tiab]). Search terms for EMBASE were (oat: ab, ti OR soy: ab, ti OR almond: ab, ti OR coconut: ab, ti OR bean: ab, ti OR lentil: ab, ti OR macadamia: ab, ti OR cashew: ab, ti OR pea: ab, ti OR rice: ab, ti OR cow: ab, ti OR buffalo: ab, ti OR “non-dairy”: ab, ti OR “plant based”: ab, ti OR dairy: ab, ti) AND (“land use”: ab, ti OR “water use”: ab, ti OR co2: ab, ti OR “global warming potential”: ab, ti OR gwp: ab, ti OR “environmental impact”: ab, ti OR “lifecycle assessment”: ab, ti). No language limits were set in either case. Reviewers also manually searched references in relevant articles that were identified during screening. The protocol registration describes additional methodological details: https://osf.io/pf3m2.

Data charting process

Investigators MR-G and AJB manually and independently reviewed the relevance of search results based on study titles, then abstracts, and finally full-text documents. Discrepancies in relevance were discussed and resolved between investigators. If any discrepancies were not resolved, a third researcher, JS, was consulted.

Data items

Data extraction was independently conducted by two researchers (AJB and MR-G). Extracted data were reviewed independently by JS. Data were sought for bibliographic variables including authors, year of publication, type of document (e.g., journal article, thesis, or commissioned report), and publisher, if relevant. Study characteristic variables including type(s) of PBMs examined (including brand if stated), country or geographic region, system boundaries, functional unit, and specific environmental outcomes presented with corresponding impact units used were also recorded.

Data synthesis

The data were presented in a tabular format and calculations were performed to convert them to a common functional unit to facilitate comparison between studies. Simple descriptive statistics were also provided if there were sufficient values in comparable studies for comparable PBMs examined. The means of the environmental outcomes were calculated as the arithmetic mean of the outcomes reported in the individual studies that met the eligibility criteria, after conversion to a common functional unit basis. The units chosen were kg CO_2-eq per liter of PBMs for GHGEs, m^2 per liter of PBMs for land use, and liter per liter of PBMs for water consumption.

Results

Selection of sources of evidence

As shown in **Figure 1**, 6282 records from 2 databases were screened for relevance. After eliminating 1897 duplicates and excluding 4262 by title, 106 by abstract, and 12 by full text, 5 studies remained for inclusion. An additional 18 studies were found through examining citations of the 5 included studies and targeted searching, of which 3 were excluded for not providing new data. In total, 20 studies were included in this scoping review.

Results of individual sources of evidence

A study by Ernstoff et al. (16) examining healthy and sustainable diets in Switzerland included consideration of soy-, rice-, and coconut-based milks' GHGEs. Calculations for GHGEs of these milks, available in the article's supplementary material, were based on 100% allocation to the base ingredients of soy, rice, and coconut, excluding other ingredients. This assumption likely led to overestimating the environmental impacts, as water has comparatively low impacts on these ingredients, which use water in their production and therefore have embodied water, and water is typically a high proportion of PBMs. Therefore, the study by Ernstoff et al. (16) is excluded from aggregated data reporting, although it is still included in the summary table, which notes that it is data for the base ingredient, not the PBMs.

An International Organization for Standardization (ISO) 14040- and 14044-compliant LCA by Winans et al. (17), focused on California unsweetened almond milk, provided the global warming potential (GWP) and freshwater consumption associated based on system boundaries from cradle to factory gate, including packaging. Packaging accounted for a significant portion (45%) of the GWP reported, but freshwater consumption was primarily from production of the almonds themselves.

A study by Poore and Nemecek (18) on reducing environmental impacts of foods reported a range of midpoint indicators (characterized environmental impacts based on life cycle inventory data) for soy milk, including land use, GHGEs, acidification, eutrophication, freshwater withdrawals, and stress-weighted water use based on consolidated data from a variety of sources, including >300 different farms. Another study (5) reported land use, GHGEs, eutrophication, and water use for soy milk, almond milk, oat milk, and rice milk and cited Poore and Nemecek (18) for these values.

A study by Grant and Hicks (19) comparing milk- and plant-based alternatives reported GWP, eutrophication, ecotoxicity, fossil fuel depletion, water intake, and cumulative energy demand values for dairy, almond, and soy milks. Grant and Hicks (19) examined production from cradle to gate but also added transportation to retail and electricity at retail, which accounted for a substantial portion of the total impacts of almond and soy milks in several categories.

A study by Seves et al. (20) examining nutritional adequacy of sustainable diets included GHGEs and land-use impacts estimates for 2 types of soy drinks. The LCA data used in calculating environmental impacts were from Blonk Consultants using a 2012 data set for cradle-to-grave LCA, although some foods required data extrapolation, and it is not clear what data category soy milk was in.

A study of GHGEs associated with different dietary patterns in the United Kingdom by Scarborough et al. (21) included estimates for soy milk based on the primary ingredient of soybeans, adjusted for change in weight between production and consumption. The authors assumed that the weight adjustment for soy milk was a factor of 0.1, based on a homemade soy milk recipe. Therefore, Scarborough et al. (21) determined the environmental impact of soy milk to be equivalent to one-tenth of the environmental impact of soybeans, assuming that soybeans account for 10% of the weight of soy milk and that the environmental impact of the added water and processing is negligible.

A study by Meier and Christen (22) regarding the environmental impacts of dietary recommendations and

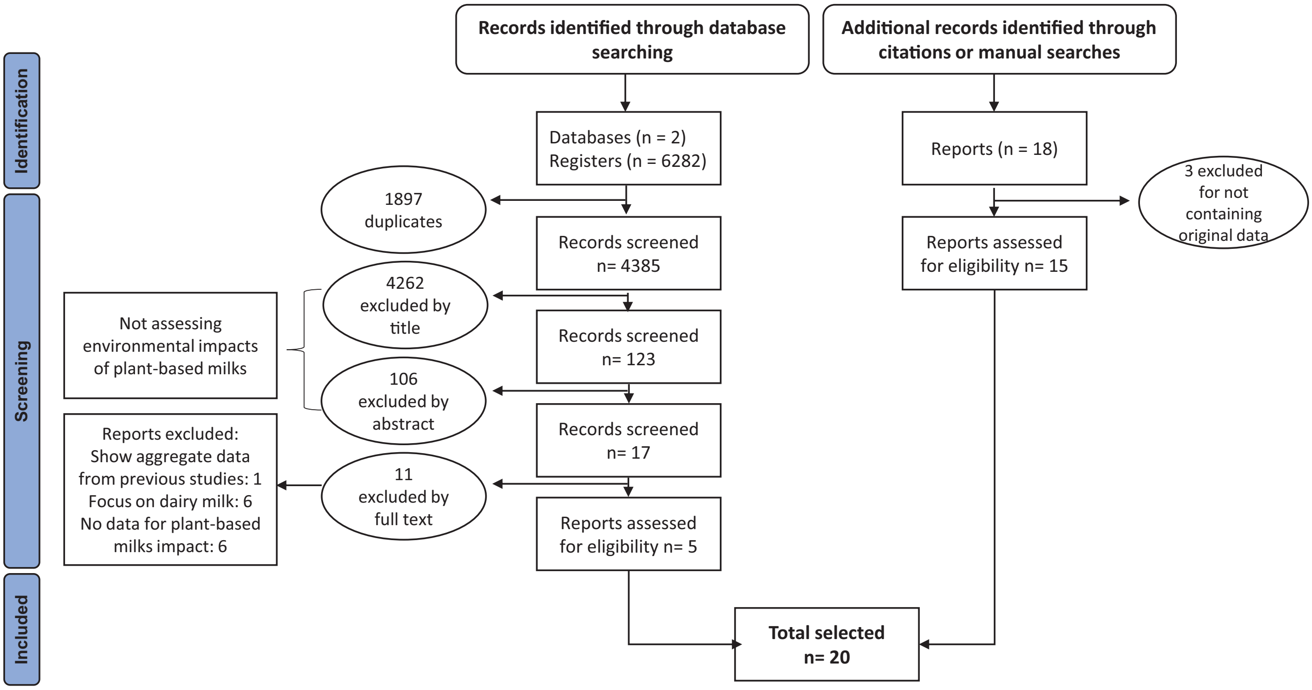

Figure 1. PRISMA flow diagram of the included studies of plant-based milks.

styles in Germany reported the GHGEs, land use, and blue water use for PBMs but did not distinguish between types of vegan milk or elaborate on the exact method used in calculating these impacts.

A study by Temme et al. (23) examining the land-use, iron, and saturated fat impacts of replacing meat and dairy with plant-based foods in young Dutch adult women included a land-use estimate for soy milk. Land-use estimates were derived from a conversion model that translated foods consumed into primary agricultural products, so soy milk land use was estimated based on the amount of land required to grow a certain amount of soybeans.

An examination of the water footprint of soy and equivalent animal products by Ercin et al. (24) reported the water footprint of soy milk produced in Belgium. The authors found 99.7% of the water footprint was from the supply chain, mostly from soybeans, when considering a cradle to manufacturing system boundary.

Results from a thesis by Dahllöv and Gustafsson (25), reported in a journal article by Mäkinen et al. (26), examined the GHGEs for Oatly brand oat milk. The thesis itself also included acidification and eutrophication potential, as well as photochemical oxidant creation impacts. The largest variations in impacts observed in the thesis were from the type of cultivation, the success of the harvest, and transportation distances, although most impacts come from the processing of oats into oat milk.

A study by Wenzel and Jungbluth (27), presented as a poster, reported eco-points (an endpoint indicator aggregating impacts into a single score) associated with almond, oat, rice, soy, and whole dairy milks. The highest impacts were for whole milk, and agriculture was the primary source of impacts for every type of milk.

A study by Mikkola and Risku-Norja (28) reported GHGEs associated with soy- and oat-based milks compared with conventional and organic dairy milks, with consideration of domestic or imported feed and ingredients. Dairy milk displayed the highest GHGEs in the study, followed by imported soy and domestic oat bases for plant-based milks.

Two commissioned reports and 1 conference paper were reported in 1 university center report assessing dairy and dairy alternatives in sustainable diets (29). Unfortunately, the direct sources could not be found for these studies. Kerkhof and Terlouw (30) reported results from a life cycle assessment of soy milk, UHT milk (milk that has been ultra-pasteurized by heating at an ultra high temperature of at least 135°C), and fresh dairy in a European context commissioned by Alpro, with a wide variety of environmental impacts, including climate change, ozone depletion, human toxicity, particulate matter, ionizing radiation, photochemical ozone formation, acidification, eutrophication, land transformation, water depletion, and resource depletion. Results from a 2012 Tesco product carbon footprint summary included carbon footprints for 6 varieties of Tesco brand soy drinks (31). Finally, an LCA by Feraldi et al. (32) reported the energy demand, global warming, ozone depletion, water consumption, and acidification associated with coconut, almond, and soy milks.

Henderson and Unnasch (33) prepared a report for Ripple to compare the GWP and water use of almond, pea, and soy milk. For the PBMs considered, impacts were derived primarily from processing, whereas for the dairy milk, farming was the main driver of impacts.

An internal study for Granarolo brand soy milk (34) examined the global warming, ozone-creating, acidification, and eutrophication potentials associated with the product through an LCA with cradle-to-grave system boundaries.

Floren et al. (35) completed a commissioned report for Oatly, assessing fresh and aseptic Oatly brand oat milk compared with semiskimmed dairy milk, finding that both had a lower impact in most considered categories, except freshwater eutrophication and water consumption. Other impacts considered included GHGEs, energy use, soil and marine eutrophication, acidification, tropospheric ozone, and land use.

A class project by Ho et al. (36) examined the impacts of almond milk compared with dairy milk using hybrid LCA (including economic input–output LCA) in terms of GHGEs and water use. They found trade-offs between the lower GHGEs of almond milk and the lower water use of dairy milk.

A class project by Birgersson et al. (37) examined the environmental impacts of soy milk in terms of land use, energy use, eutrophication, acidification, climate change, and ozone depletion. The authors found that the farming and manufacturing phases dominated the impacts, except for ozone layer depletion, which was primarily from packaging.

Synthesis of results

Table 1 provides a summary of the main characteristics of studies examined.

Studies collected included 9 journal articles (16–24), all published within the past 10 y. Studies were primarily published in a European context (16, 20–24), although 2 were set in the United States (17, 19) and 1 had a global context (18).

Eleven additional studies were gathered in 9 references (25, 27–29, 33–37), since 1 reference reported the results from 3 other studies, for which the original source was not available (29). These studies consisted of a conference paper (28), a poster (27), commissioned reports (29, 33–35), class projects (36, 37), and a master's thesis (25) reported in a journal article (26). Again, most studies had a primarily European context (25, 27, 28, 34, 35, 37), whereas the remaining studies were set in the United States (33, 36) or not specified (29). Seven of these 11 additional studies were for specific PBM brands or companies (26, 29, 33–35, 37). In contrast, none of the 9 journal articles specified a brand of PBM or company for their studies.

All studies reviewed containing quantitative data reported the results of LCA using a weight-based functional unit, which facilitates comparison across alternatives. However, system boundaries were not always specified (16, 23, 29), and those reported varied substantially in the ending cutoff point. Twelve studies focused on 1 type of PBM per study (17, 20, 21, 23, 24, 26, 29, 34, 36, 37), 7 studies included multiple PBM types (5, 16, 19, 27–29, 33), and 1 did not specify PBM type beyond "vegan milk products" (22), which suggests more than 1 was considered in the study. All but 2 studies reported at least GHGEs, often combined with land and/or water use, and the 2 studies that did not report GHGEs instead reported land or water use (23, 24).

Results for GHGEs, land use, and water consumption were collected and converted to a common functional unit of 1 L of PBMs for easier comparison across sources. The resulting scatterplots are shown in **Figure 2**. These data, as well as the original data they were derived from, are also available in **Supplemental Table 1** and **Supplemental Table 2**.

Each of the 3 scatterplots displayed has its own y-axis corresponding to the environmental impact portrayed. The black squares are data points from studies that included multiple different types of PBMs, whereas the orange triangles are from studies that only assessed 1 type of PBM each. Although there is some variation in GHGEs and very little variation in land use, water consumption has a large range, particularly for almond milk.

To better understand the distribution of environmental impacts presented, the same data used to make Figure 2 were used to make box-and-whisker plots for **Figure 3**.

The box-and-whisker plots show the interquartile range as the box, the mean as an X, the median as a line across the box, the range as the whiskers extending from the box, and outliers as dots. PBM types shown without boxes had only 1 data point available per environmental impact category presented. The box-and-whisker plot for water consumption uses a split y-axis to better show the variation in all PBM types, because almond milk has such a large range of values that it compresses the appearance of the other PBMs when using a continuous y-axis.

Most of the studies reviewed found that the PBM types considered had GWP values <1 kg CO_2-eq/L of PBMs and land use <1 m^2a/L (meters squared per annum per liter). Water use of the PBM types reported in these studies varied more substantially, with a range between 3 and 6938 liters/L, depending on the source and variety of PBMs. The highest overall impacts for PBMs came from a study that found GWP values >3 kg CO_2-eq/L for soy and almond milk and water use above 6000 liters/L for almond milk (19). The lowest impacts reported for PBMs were 0.22 kg CO_2-eq GWP and 0.4 m^2a/L land use for soy milk and 3 liters/L water use for coconut milk. Within references examining multiple types of PBMs, almond milk consistently had the highest water use.

Nutrient composition

Nutrient information was sought for those PBMs for which we obtained environmental impact data, including soy-, almond-, oat-, rice-, coconut-, and pea-based milks, as well as for whole, reduced-fat, low-fat, and fat-free dairy milk. Nutrient composition of different PBMs and dairy milk was evaluated based on the method from a previous study comparing nutrient density and nutritional value of PBMs and dairy milk (8). Nutrient content was compiled using data obtained from searching the USDA "FoodData Central" website in the fall of 2021 (38). The terms used for the search were *soy milk*, *soy plant–based*, *almond milk*, *almond*

Table 1. Main characteristics of the 20 studies included in this scoping review of plant-based milks

Author(s), year (citation)	Document type	Country/geographic region	Available plant-based milks (brand, if stated)	Environmental outcome (impact unit)	Functional unit	System boundaries
Ernstoff et al., 2020 (16)	Journal article	Switzerland	Coconut, rice, soy	Greenhouse gas emissions (kg CO_2-eq)	1 kg of base ingredient (not plant-based milk)	Not reported
Winans et al., 2019 (17)	Journal article	California	Almond	Greenhouse gas emissions (kg CO_2-eq) and water use (kg)	48 oz milk	Cradle to gate
Poore and Nemecek, 2018 (18), reported in McClements, 2019 (5)	Journal article citing another journal article	Global	Almond, rice, oat, soy	Greenhouse gas emissions (kg CO_2-eq), land use (m^2/y), terrestrial acidification (g SO_2-eq), eutrophication (g $PO_4{}^{3-}$-eq), and scarcity-weighted freshwater withdrawals (kL eq.).	1 L of milk	Cradle to retailer
Grant and Hicks, 2018 (19)	Journal article	United States, including sale in Chicago	Almond, soy	Greenhouse gas emissions (kg CO_2-eq) and water use (L)	1 L of milk	Cradle to retailer, including refrigeration until purchase
Seves et al., 2017 (20)	Journal article	The Netherlands	Soy	Greenhouse gas emissions (kg CO_2-eq) and land use (m^2)	1 kg of soy milk	Cradle to grave
Scarborough et al., 2014 (21)	Journal article	United Kingdom	Soy	Greenhouse gas emissions (kg CO_2-eq)	100 g of food	Cradle to farm gate
Meier and Christen, 2013 (22)	Journal article	Germany	Vegan milk products	Greenhouse gas emissions (kg CO_2-eq), land use (m^2), and water use (L)	1 kg	Cradle to store
Temme et al., 2013 (23)	Journal article	The Netherlands	Soy	Land use (m^2)	1 kg	Not reported
Ercin et al., 2012 (24)	Journal article	Belgium	Soy	Water use (L)	1 L of soy milk	Cradle to manufacturing gate

(*Continued*)

Table 1. (*Continued*)

Author(s), year (citation)	Document type	Country/geographic region	Available plant-based milks (brand, if stated)	Environmental outcome (impact unit)	Functional unit	System boundaries
Dahllöv and Gustafsson, 2008 (25), reported in Mäkinen et al., 2016 (26)	Thesis, reported in journal article	Sweden	Oat (Oatly)	Greenhouse gas emissions (kg CO_2-eq)	1000 L of packed oat drink	Cradle to grave: Cultivation of oat, production of container, processing in Oatly factory, storage in supermarket, and consumption of oat drink
Wenzel and Jungbluth, 2017 (27)	Poster presentation	Switzerland	Almond, rice, oat, soy	Greenhouse gas emissions (ecopoints)	1 L of beverage	Cradle to retailer
Mikkola and Risku-Norja, 2008 (28)	Conference paper	Finland	Oat, soy	Greenhouse gas emissions (mg CO_2-eq)	2100 million kg milk	Cradle to farm gate
Kerkhof and Terlouw, 2015 (30), reported in Röös et al., 2018 (29)	Report from university center citing a commissioned report	Belgium, Germany, the Netherlands, and United Kingdom	Soy (Alpro)	Greenhouse gas emissions (kg CO_2-eq) and water use (m^3)	1 L of drink	Not reported
Tesco, 2012 (31), reported in Röös et al., 2018 (29)	Report from university center citing a commissioned report	United Kingdom, reported by Tesco Products	Soy (Tesco)	Greenhouse gas emissions (kg CO_2-eq)	1 L unsweetened soya alternative to dairy	Not reported
Feraldi et al. 2012 (32), reported in Röös et al., 2018 (29)	Report from university center citing a conference paper	Not reported	Almond, coconut, soy	Greenhouse gas emissions (kg CO_2-eq) and water use (L)	0.5 gal (2.27 L)	Not reported
Henderson and Unnasch, 2017 (33)	Commissioned report	United States	Almond, pea (Ripple), soy	Greenhouse gas emissions (g CO_2-eq) and water use (gal)	Protein/L of milk (weight basis also reported)	Global warming potential: Cradle to retailer plus packaging disposal Water: Cradle to farm gate

(*Continued*)

Table 1. (*Continued*)

Author(s), year (citation)	Document type	Country/geographic region	Available plant-based milks (brand, if stated)	Environmental outcome (impact unit)	Functional unit	System boundaries
Granarolo, 2014 (34)	Commissioned report	Italy	Soy (Granarolo)	Greenhouse gas emissions (kg CO_2-eq) and water use (L)	0.5 or 1 L soy drinks	Cradle to grave, except transport from retail to consumer
Floren et al., 2013 (35)	Commissioned report	Sweden	Oat (Oatly)	Greenhouse gas emissions (kg CO_2-eq), land use (m^2), and water use (m^3)	1 L oat drink (fresh with cold storage compared with aseptic at room temperature)	Cradle to grave
Ho et al., 2016 (36)	Class project report	United States, specifically California	Almond	Greenhouse gas emissions (kg CO_2-eq) and water use (gal)	1 L of almond	Cradle to gate
Birgersson et al., 2009 (37)	Class project report	Sweden/Europe, with Brazilian soybean production	Soy (Alpro)	Greenhouse gas emissions (g CO_2-eq) and land use (m^2)	1 L of milk or soy milk	Cradle to grave

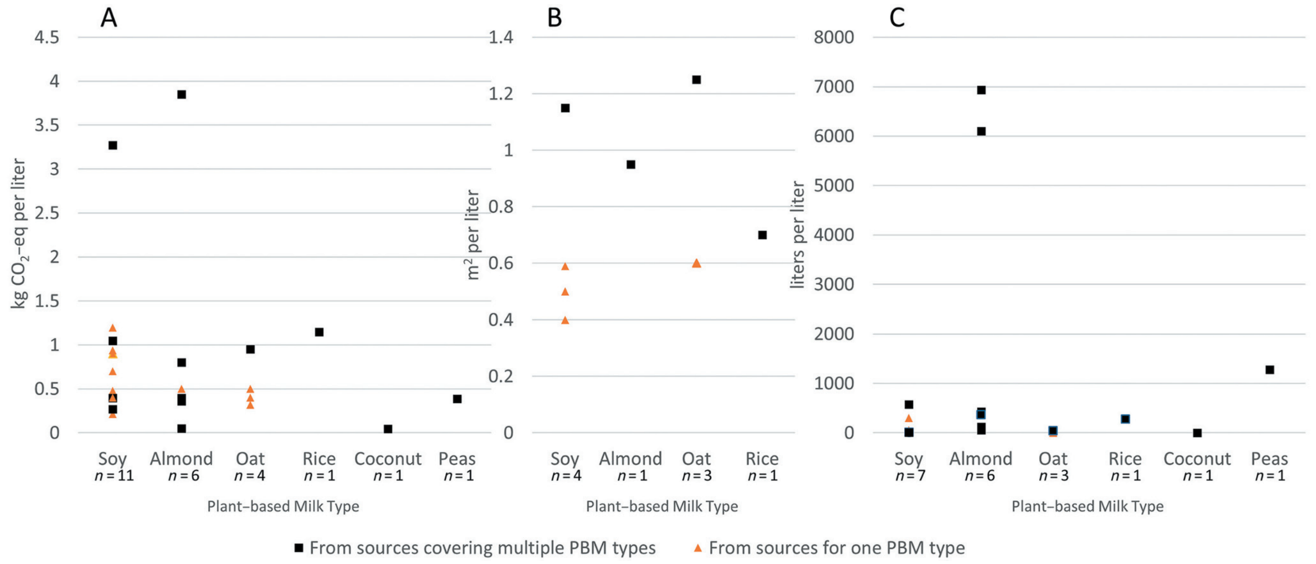

Figure 2. Scatterplots of harmonized mean values of environmental impacts of plant-based milks. (A) Global warming potential. (B) Land use. (C) Water consumption. Each orange triangle displayed represents a value taken from a source specifically for a single plant-based milk (PBM) type, whereas black squares represent sources that included values for multiple PBM types.

plant-based, *oat milk*, *oat plant-based*, *rice milk*, *rice plant-based*, *coconut milk*, *coconut plant-based*, *pea milk*, and *pea plant-based*. If a "Foundation Foods" entry was available, this was used to be representative of the nutrient content for that type of PBM. If only "Branded Foods" were available, PBMs without added flavor and sugar were selected. If there were >1 of the same PBM brands meeting these criteria, the one reporting more nutritional components was selected. A summary of nutrition data for the various milk types is available in **Supplemental Table 3**, with a more detailed

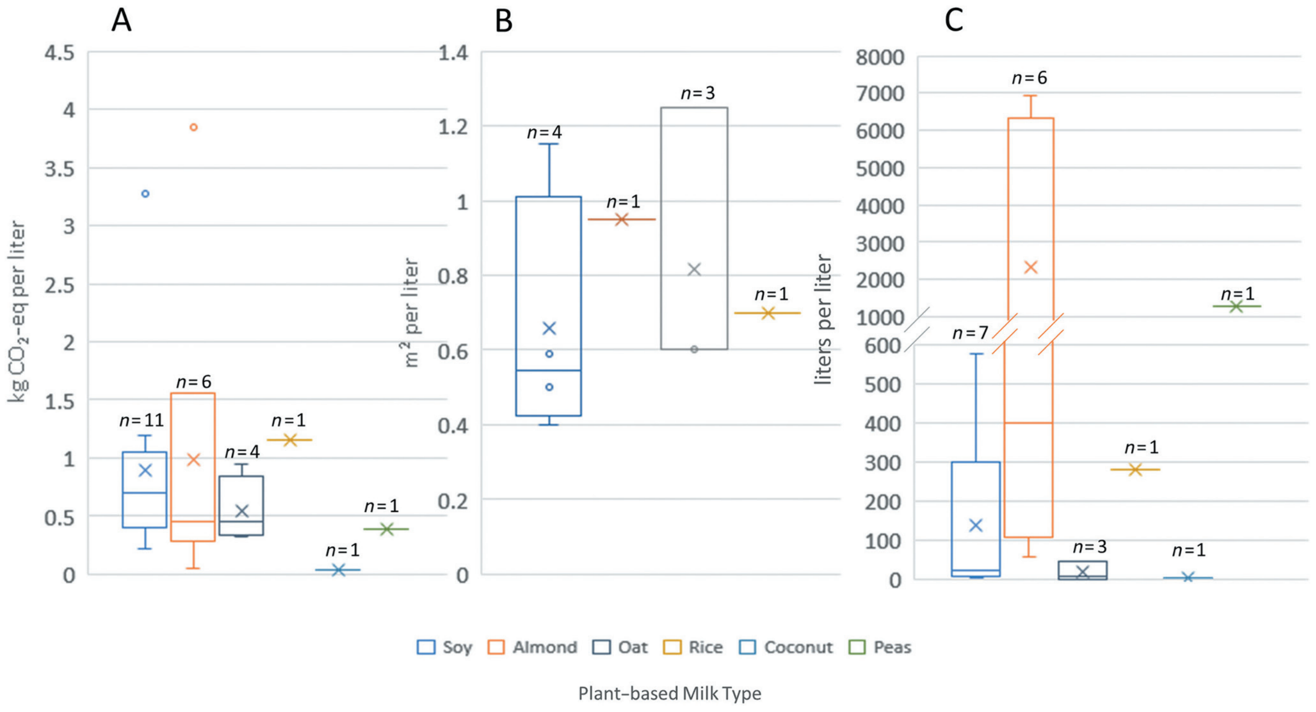

Figure 3. Box-and-whisker plots of harmonized mean environmental impacts of plant-based milks. (A) Global warming potential. (B) Land use. (C) Water consumption.

comparison of nutrients provided in **Supplemental Table 4**. The mean, standard deviation, and number of entries used for a variety of relevant nutrients are summarized in **Table 2**.

Foundation Foods data were available for soy and almond milk and are presented alongside Branded Foods data. Other PBMs only had Branded Foods data available. Additional methodologic details are explained on the FoodData Central website (38). Nutrients in 4 types of dairy milk, based on fat percentage, are provided for comparison purposes.

As seen in Table 2, PBMs are less energy dense than the different varieties of dairy milks, with the exception of coconut milk. This is because dairy milk has a higher content in carbohydrates (although below oat milk and rice milk) and fat (although below coconut milk and depending on the type of dairy milk). The carbohydrates present in dairy milk are mostly sugar (lactose), but PBMs have a lower amount of sugar in relation to the total carbohydrate content. Unlike dairy milk, PBMs contain fiber. In terms of fats, coconut and dairy milks have a higher content of saturated fat in relation to the total fat content, whereas the other PBMs have a higher content of mono- and polyunsaturated fatty acids. Cholesterol is present only in dairy milk.

Soy and pea milks have a similar amount of protein as dairy milk, whereas the rest of the PBMs have less. The protein in soy and pea milks contains the highest concentration of essential amino acids, which makes them more complete sources of protein compared with the other PBMs (39). Although dairy milk is usually richer in calcium than PBMs, when enriched with calcium carbonate (which has better absorption than tricalcium phosphate), PBMs are equivalent to dairy milk (40).

Dairy milk does not contain iron, but the PBMs reviewed here do. Only soy and coconut milks have a higher magnesium content than dairy milk. Potassium is lower in PBMs than in dairy milk, with the exception of soy milk. Many PBMs include salt among their ingredients. However, soy and coconut milks have a lower sodium content. All PBMs reviewed except oat milk have less zinc than dairy milk. All milks reviewed have about the same amount of selenium, except oat milk, which is lower.

Data were more limited for vitamin content. Soy and almond milks contain more folate and vitamin E than dairy milk. Vitamin A varies greatly between different PBMs but also between different types of dairy milk. PBMs are generally less rich in vitamin B-12 (with the exception of coconut milk) and vitamin D than dairy milk. Despite the above, it has been shown that when the PBMs were fortified, the amounts of vitamins were equivalent to those of dairy milk (41).

Discussion

The growth in popularity of PBMs as alternatives to dairy milk inspired 2 related questions, both of which facilitate comparison between these choices: are PBMs better for the environment, and do PBMs provide the same nutrients as dairy milk? The need to understand environmental impacts of PBMs was based on the common motivation of consumers shifting to PBMs to pursue a more sustainable diet, and a complementary examination of nutritional characteristics was due to concern for nutritional adequacy. Nutrient profiles of PBMs compared with dairy milk provide an important context for consumers considering a shift to PBMs to pursue a more sustainable diet. Manufacturers of PBMs might also consider fortification to more closely match the nutrient profile of dairy milk to meet the expectations of consumers expecting PBMs to provide a functional replacement for dairy milk.

PBMs were found to primarily have low GHGEs, land use, and water consumption in comparison to dairy milk, although almond milk had a very high range of water consumption values. The lowest reported GWP was from almond milk, whereas the lowest reported land use and water consumption were from soy milk. The highest reported GWP and water consumption were from almond milk, whereas the highest reported land use was from oat milk. The range of values for environmental impacts was by far the highest for water consumption, whereas both GWP and land use had fairly low ranges.

In terms of nutrient content, PBMs were not found to be equivalent to dairy milk and have significant variation based on their base ingredient. This aligns with the conclusions of previous research that PBMs have a wide range of nutrient content across different sources of the "milk" (8) and that nondairy milks should not be considered nutritionally equivalent to dairy milk (41–43). However, other research states that the lack of some vitamins and minerals could be solved by fortifying the PBMs (40) and choosing varieties with a more complete amino acid content (39). Dairy milk itself is typically fortified with added vitamins and minerals, and the exact same profile could be provided through fortification of PBMs. Therefore, it is fair to make a comparison of environmental considerations that excludes the added impact associated with fortification of both types of milks. It is also worth mentioning that PBMs can be interesting in terms of offering other components that are not present in dairy milk. Some of these have bioactive compounds, such as isoflavones and phytosterols in soy milk, α-tocopherol and arabinose in almond milk, and β-glucan in oat milk. But they also present other substances such as phytate and oxalate that, in some cases, may affect the bioavailability of some vitamins and minerals (44). In addition, the added nutrients are not always as bioavailable as if they were naturally present, although more and more innovations are being made to improve bioavailability, with one example being the use of probiotic bacteria (45).

However, it is important to note that consumers are not necessarily choosing PBMs based on nutritional equivalency but may be instead looking for a product with similar sensory aspects to milk in terms of color, texture, and, where possible, flavor (46). The choice of PBMs will depend on the characteristics that individual consumers are looking for, including those related to environmental impact. Therefore, it is important to take all these aspects into account when evaluating a substitute to dairy milk.

Table 2. Macro- and micro-nutrient composition of different plant-based milk alternatives and cow milk products standardized to a 100-mL serving[1]

	Soy milk				Almond milk				Oat milk		Rice milk		Coconut milk		Pea milk		Whole milk, 3.25% milk fat	Reduced-fat milk, 2% milk fat	Low-fat milk, 1% milk fat	Fat-free or skim milk
Characteristic	**Mean[2]**	***n***	**Mean ± SD[3]**	***n***	**Mean[2]**	***n***	**Mean ± SD[3]**	***n***	**Mean ± SD[3]**	***n***	**Mean ± SD[3]**	***n***	**Mean ± SD[3]**	***n***	**Mean ± SD[3]**	***n***				
Energy, kcal	38.0	8	37.4 ± 9.2	8	15.00	Calculated	21.8 ± 12.6	9	45 ± 8.43	5	54.0 ± 5.7	2	91.71 ± 76.84	7	31 ± 2.83	2	61	50	43	34
Protein, g	3.55	Calculated	3.4 ± 0.6	8	0.55	Calculated	0.8 ± 0.7	9	1.14 ± 0.35	5	0.4 ± 0.0	2	0.46 ± 0.66	7	2.5 ± 1.17	2	3.27	3.36	3.38	3.43
Carbohydrate, g	1.29	Calculated	2.2 ± 1.5	8	0.34	Calculated	1.0 ± 0.9	9	7.14 ± 1.07	5	10.2 ± 1.4	2	2.89 ± 2.78	7	0.84 ± 1.18	2	4.63	4.9	5.18	4.92
Sugars, total, g	0.56	Summed	1.0 ± 0.8	8	0.00	Summed	0.1 ± 0.2	8	2.61 ± 1.93	5	4.2 ± 2.3	—	1.30 ± 1.58	7	0.63 ± 0.88	2	4.81	4.89	4.96	5.05
Fiber, total, g	<0.45	8	0.4 ± 0.2	7	<0.45	8	0.3 ± 0.2	9	0.68 ± 0.38	5	0.0 ± —	1	0.42 ± 0.66	6	0.0 ± 0.0	2	—	—	—	—
Total lipids, g	2.12	8	1.7 ± 0.4	8	1.22	8	1.6 ± 1.2	9	1.38 ± 0.58	5	0.9 ± 0.1	2	8.66 ± 7.98	7	1.98 ± 0.14	2	3.2	1.9	0.95	0.008
Total saturated fatty acids, g	0.31	8	0.2 ± 0.1	8	0.10	8	0.1 ± 0.1	8	0.14 ± 0.17	5	0.0 ± —	1	8.74 ± 7.31	6	0.11 ± 0.15	2	1.86	1.11	0.568	0.049
Total monounsaturated fatty acids, g	0.42	8	0.4 ± 0.0	4	0.73	8	0.6 ± —	1	1.04 ± —	1	—	—	—	—	1.25 ± —	1	0.688	0.4	0.21	0.017
Total polyunsaturated fatty acids, g	1.15	8	1.1 ± 0.1	4	0.28	8	0.2 ± —	1	0.42 ± —	1	—	—	—	—	0.42 ± —	1	0.108	0.058	0.032	0.006
Cholesterol, mg	—	—	0.0 ± 0.0	5	—	—	0.0 ± 0.0	8	0.0 ± 0.0	5	0.0 ± —	1	0.0 ± 0.0	7	0.0 ± 0.0	2	12	8	5	3
Minerals																				
Calcium, mg	101.0	13	95.3 ± 67.4	8	173.0	14	86.5 ± 86.0	8	0.0 ± 0.0	2	146.0 ± —	1	34.0 ± 46.7	7	159.5 ± 40.31	2	123	126	126	132
Iron, mg	0.54	13	0.5 ± 0.1	7	0.29	14	0.2 ± 0.2	8	73.2 ± 62.4	5	0.3 ± —	1	0.07 ± 0.07	4	0.77 ± 0.49	2	0	0	0	0
Magnesium, mg	21.50	13	17. 0 ± 0.0	2	6.80	14	17.0 ± —	1	0.16 ± 0.18	5	—	—	15.00 ± —	1	0.0 ± —	1	11.9	12	12	12.5
Potassium, mg	158.00	13	152.1 ± 21.8	8	31.00	14	38.3 ± 31.7	7	—	—	56.0 ± 38.2	2	48.00 ± 36.83	4	119.5 ± 169.0	2	150	159	159	167
Sodium, mg	34.00	13	36.1 ± 22.4	8	60.00	14	44.6 ± 33.6	9	74.6 ± 51.2	5	52.0 ± 32.5	2	23.00 ± 19.26	7	64.5 ± 14.85	2	38	39	39	41
Zinc, mg	0.31	13	0.4 ± 0.1	2	0.17	14	0.3 ± —	1	33.2 ± 20.1	5	—	—	0.33 ± —	1	—	—	0.42	0.43	0.43	0.45
Selenium, μg	1.90	8	—	—	<2.5	8	2.0 ± —	1	0.42 ± —	1	—	—	3.00 ± —	1	—	—	1.9	1.8	2.1	2
Vitamins																				
Folate total, μg	20.00	8	17.0 ± —	1	<6	8	10.0 ± —	1	—	—	—	—	—	—	—	—	0	2	2	2
Vitamin B-12, μg	0.39	10	1.0 ± 0.4	3	0.34	10	1.3 ± —	1	—	—	—	—	1.04 ± 0.59	2	0.33 ± —	1	0.54	0.55	0.61	0.58
Vitamin A, μg	58.00	13	72.90 ± 78.7	4	41.00	13	41.90 ± 36.3	3	0.22 ± 0.18	3	—	—	31.20 ± 44.12	2	62.4 ± —	1	32	83	58	64
Vitamin D, D2 + D3, IU	27.20	Calculated	54.0 ± 5.7	3	37.10	Calculated	12.5 ± 25.0	4	10 ± 17.3	3	—	—	14.00 ± 24.25	3	50.0 ± —	1	38.4	45.2	42.4	44
Vitamin E, mg	0.16	8	—	—	3.32	14	2.0 ± —	1	—	—	—	—	—	—	—	—	0.05	0.03	0.02	0

[1] Source: USDA FoodData Central Database (38).

[2] Based on Foundation Foods. Only data for the count and mean were available, not for standard deviation.

[3] Based on Branded Foods. Data were sufficient to calculate the mean and standard deviation.

Characteristics of sources of evidence

We found 9 relevant peer-reviewed journal articles, 1 thesis, 1 poster, 1 conference paper, 3 reports from university centers, 3 commissioned reports, and 2 class projects in our searching. Two of the journal articles were from *Public Health Nutrition*, and no other journal had >1 article found in this scoping review. The wide variety of contexts for these sources is reflected in a lack of similarity in their method and content. The journal articles were published between 2008 and 2020, with 5 of the 10 published after 2017. The recent PBM market growth means that many brands and certain types of PBMs are not represented in these sources. The geographic regions for these studies were primarily Europe and North America, limiting the relevance of their findings for other geographic regions. Most studies examined GWP with a weight-based functional unit and cradle-to-gate system boundaries. Other environmental impacts examined included land use and water use. Soy and almond milks had the most available data, followed by oat milk. Therefore, the strongest conclusions can be made regarding the GWP of soy and almond milks.

Critical appraisal within sources of evidence

Many of the data sources used were in the context of studies examining dietary patterns or substitutions in general rather than being specifically focused on PBMs and therefore had limited methodologic explanations for the PBM component of diets examined (16, 18, 20–23). In some instances, proxies were used by either assuming similar impacts to the base ingredient of a PBM or applying a conversion factor for its weight to account for PBMs using a significant amount of water in their formulation (16, 21, 23). One study artificially extended the system boundary to also include transportation to retail and electricity for storage at retail (19). Some of the methodologic assumptions mentioned above were questionable, raising concerns of possible bias and doubts regarding accuracy of the results. The variety of contexts, goals, and LCA characteristics among the studies makes direct comparisons between their findings difficult. In particular, uniform system boundaries and consistent midpoint indicators based on a common functional unit would be ideal for comparison of results but are missing from most of the studies reviewed.

Limitations

This scoping review was limited to searching scholarly databases and therefore may have missed some gray literature such as preprints. Some of the studies included in this review were commissioned by PBM brands, which presents a potential conflict of interest. Some of the sources included also were not subject to peer review. The USDA FoodData Central Foundation Foods were not available for 4 of the 6 examined PBMs, so Branded Foods data with potentially lower data quality were used. Using the USDA database limits the ability to extrapolate nutritional results to a global level, as not all plant-based milks have consistent formulations across the world.

There are at least 20 different PBM bases derived from cereals, legumes, nuts, seeds, and pseudo-cereals (4). However, this review found environmental impact data only for 6 PBM base types. Environmental impacts of the remaining PBMs might vary based on the base chosen, its proportion of the final product, and the processing necessary to incorporate it in a PBM. Even within this review, water consumption in particular had drastic variations in impacts across different PBM bases, so it should not be assumed that other PBMs will all have similar environmental impacts to those described here. Data were also primarily for a European and North American context, so variations based on geographical context may change the results of LCAs performed for PBMs. Only 1 data point was found for GWP of rice, coconut, and pea milks; land use of almond and rice milks; and water consumption of rice, coconut, and pea milks. Therefore, there could be substantial additional variability in impacts for these underrepresented categories. Water consumption for almond milk provides an example where there is a very large range of reported values, and it may be reasonable to expect a large range for other plant-based milks using a base grown on trees, such as coconut milk.

Studies varied in their approach to water use, which may account for some of the large range in values for that impact compared with others reported. Unfortunately, methodologic details were insufficient to fully harmonize these data. Only 1 of the reviewed studies stated its compliance with ISO 14040 and 14044 guidelines (17). Adhering to such standardizations would greatly facilitate better comparisons and harmonization of data across sources, and the authors of this review recommend this approach for future LCA of PBMs.

In conclusion, this scoping review was primarily motivated by the desire to understand the environmental implications of choosing PBMs. However, as many consumers consider shifting from consuming dairy milk to PBM, it is also important to understand what potential consequences on nutrition such a change would have. Overall, PBMs were found to have fairly low environmental impacts compared with those of dairy milk, and the nutritional characteristics of PBMs were found to have trade-offs in comparison to those of dairy milk, with soy milk having the most similar nutrient profile. However, this scoping review found that there is a paucity of data regarding the environmental impacts of PBMs. The objectives of studies included in this scoping review were primarily to examine questions about broader dietary patterns and substitutions rather than having a focus on a straightforward assessment of PBM environmental impacts. The most reported impact was GHGEs, and several studies included water use and/or land use. A couple of studies reported a broad range of midpoint indicators. System boundaries were mostly from cradle to farm or manufacturing gate. Most studies found that PBMs were environmentally preferable to dairy milk, although there were some exceptions to this finding. Environmental impacts of many modern PBMs had no representation at all in the literature. Endpoint indicators were also not seen in this review. Only 1 study stated compliance with ISO LCA standards, whereas several made dramatic simplifying assumptions such as base ingredients being equivalent in impacts to the PBM itself. Studies were fairly consistent in finding that PBMs were lower in the considered environmental impacts than dairy milk. Future work should seek to expand the literature examining PBM environmental impacts directly and extend the range of indicators reported. Examination of nutritional characteristics should also be included, especially when comparing multiple PBMs and/or comparing with dairy milk. Greater knowledge of the impacts and nutrient profiles of more PBMs from high-quality studies with consistent framing and methods will allow stakeholders, including researchers, policymakers, producers, and consumers, to make better decisions when choosing these products.

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