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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Life cycle assessment of California unsweetened almond milk

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Abstract

Purpose Plant-based alternatives to dairy milk have grown in popularity over the last decade. Almond milk comprises the largest share of plant-based milk in the US market and, as with so many food products, stakeholders in the supply chain are increasingly interested in understanding the environmental impacts of its production, particularly its carbon footprint and water consumption. This study undertakes a life cycle assessment (LCA) of a California unsweetened almond milk.

Methods The scope of this LCA includes the production of almond milk in primary packaging at the factory gate. California produces all US almonds, which are grown under irrigated conditions. Spatially resolved modeling of almond cultivation and primary data collection from one almond milk supply chain were used to develop the LCA model. While the environmental indicators of greatest interest are global warming potential (GWP) and freshwater consumption (FWC), additional impact categories from US EPA's TRACI assessment method are also calculated. Co-products are accounted for using economic allocation, but mass-based allocation and displacement are also tested to understand the effect of co-product allocation choices on results.

Results and discussion The GWP and FWC of one 48 oz. (1.42 L) bottle of unsweetened almond milk are 0.71 kg CO_2e and 175 kg of water. A total of 0.39 kg CO_2e (or 55%) of the GWP is attributable to the almond milk, with the remainder attributable to packaging. Almond cultivation alone is responsible for 95% of the FWC (167 kg H_2O), because of irrigation water demand. Total primary energy consumption (TPE) is estimated at 14.8 MJ. The 48 oz. (1.42 L) PET bottle containing the almond milk is the single largest contributor to TPE (42%) and GWP (35%). Using recycled PET instead of virgin PET for the bottle considerably reduces all impact indicators except for eutrophication potential.

Conclusions For the supply chain studied here, packaging choices provide the most immediate opportunities for reducing impacts related to GWP and TPE, but would not result in a significant reduction in FWC because irrigation water for almond cultivation is the dominant consumer. To provide context for interpretation, average US dairy milk appears to have about 4.5 times the GWP and 1.8 times the FWC of the studied almond milk on a volumetric basis.

Keywords Almond milk · Carbon footprint · Impact assessment · Life cycle assessment · Water footprint

1 Introduction

Stakeholders across the food production supply chain are growing more interested in understanding the environmental impacts of food choices. And increasingly, plant-based diets are being encouraged as environmentally preferable (e.g., Poore and Nemecek 2019; Hallström et al. 2015; Westhoek et al. 2014; Tilman and Clark 2014). The dairy alternatives market, including plant-based milks, is a rapidly growing segment of plant-based food alternatives; it is projected to grow by more than USD 12 billion between 2018 and 2023, with almond-based dairy alternatives constituting the fastest growing sector (PRNewswire 2019).

California-grown almonds constitute about 80% of the world's commercial almond production (CDFA 2017a). Almond cultivation occupies about 1% of California's total

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land area (0.40 million hectares (ha), or about 11% of irrigated cropland), and the total production area, as well as the value of almond products, is projected to increase over time (USDA/NASS 2018; CDFA 2017b). About half of almonds are retailed as pure almonds while the other half are processed into other food products, among them almond milk. As of 2013, 6.5% of all almond production in California went to almond milk (Sumner et al. 2014).

The environmental impact of agricultural products and foods can be characterized through a variety of analytical approaches and may focus on different impacts. Life cycle assessment (LCA) provides a comprehensive view of product environmental impact and has been increasingly used in scholarly studies (e.g., Clune et al. 2017; Notarnicola et al. 2017; Schau and Fet 2008), as well as business-to-business and consumer-facing communications such as environmental product declarations (EPDs).

The aim of this study is to characterize the life cycle impacts of almond milk production from almond cultivation through retail-ready primary packaging at the facility gate for a producer located in the Tulare Lake Basin region of California. The study reports results based on a 48 oz. (1.42 L) bottle of unsweetened almond milk.

A spatially explicit approach (at the regional scale for the Tulare Lake Basin in California) is used to model almond cultivation, with particular focus on irrigation water use and the embedded energy for delivering it from surface and groundwater sources. Scenario analysis is used to explore the effect of potentially influential choices, including co-product allocation methods and beverage packaging choices.

2 Methods

The ISO 14040 and 14044 LCA standards are used to guide methods, model development, and calculations conducted in this research (ISO 2006).

2.1 Goal and scope definition

The goal of this study is to develop a process-based attributional LCA to estimate the environmental impacts associated with unsweetened almond milk production from cradle-to-facility gate. The model therefore accounts for energy and resource inputs at every stage, from almond cultivation to packaged unsweetened almond milk, and the upstream environmental burdens associated with these inputs. The functional unit is a 48 oz. (1.42 L) bottle of unsweetened almond milk.

Impact categories considered in the study include 100-year global warming potential (GWP_{100}) (Myhre et al. 2013); renewable and non-renewable total primary energy use (TPE); freshwater consumption (FWC); and the following impact categories based on the US EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1: ozone depletion potential (ODP), eutrophication potential (EP), acidification potential (AP), human toxicity potential (HTP, cancer and non-cancer), Human Health Particulate Air (HHPA), smog formation potential (smog), and ecotoxicity potential (ETP) (Bare 2012).

2.2 System definition and system boundaries

Figure 1 illustrates a simplified process flow diagram. The system boundary includes almond cultivation, almond hulling and shelling, processing for almond meal, production of other almond milk ingredients, almond milk production, facility operations (e.g., equipment, lighting, climate control, etc.), and primary packaging. All facilities assessed in this supply chain produce multiple products, and in some cases, were initially built and used for other purposes. Because of this, impacts from facility construction and capital equipment are not included in the system boundaries.

Almond cultivation is modeled based on an updated version of an existing almond LCA model (Kendall et al. 2015; Marvinney et al. 2015). The updates of importance include changes to irrigation energy requirements for pumping surface water and groundwater that reflect improved modeling techniques and the effects of California's recent drought and updated life cycle inventory (LCI) datasets from the GaBi databases (service pack 32) (Thinkstep 2017) and Ecoinvent databases (Wernet et al. 2016). Primary data were collected as part of this study for each phase of the production process following cultivation and harvest (hulling and shelling, almond meal processing, and almond milk production). Primary data collection activities are described in greater detail in the following sections.

2.3 Inventory analysis

Inventory analysis is composed of two steps; first, the development of representative data for the foreground systems (almond production, almond processing, and almond milk production); and second, data collection to characterize the background systems, i.e., the inputs to and outputs from the foreground systems. The foreground systems were characterized using a combination of modeled data (almond production) and primary data (almond processing and almond milk production), and the background systems were characterized through the collection of reference LCIs or the development of new LCIs when needed.

2.4 Almond production

The almond production model includes spatial modeling for groundwater depth and other spatially dependent factors that affect the energy, water, and resource demands of almond production. The model is an update to the one described in Kendall et al. (2015). Annual crop production practices are

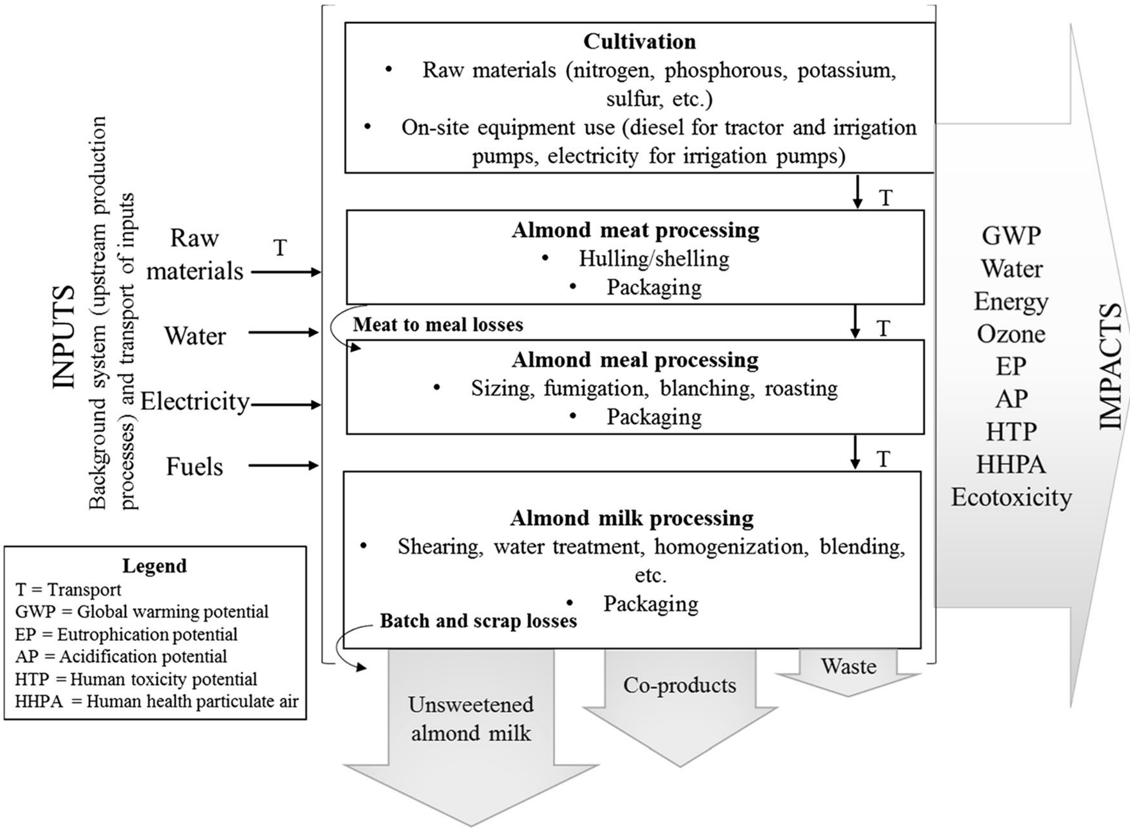

Fig. 1 Simplified process flow diagram

based on the University of California Cost-and-Return studies, including typical nutrient, pesticide, fuel, and water use, as well as monthly in-field operations such as tractor use (Yaghmour et al. 2016). Almond production processes accounted for in the model include nursery production of almond saplings, orchard establishment, field operations, production and transport of chemicals, material inputs to the orchard, pollination operations, nutrient cycles (e.g., nitrogen application and in-field emissions), transport, and use of co-products like pruning and orchard clearing biomass. The almond orchard system is assessed over a 26-year time period. Year 0 is for land preparation and orchard establishment; years 1 and 2 are used to grow the almond trees and have no yield. Years 3 through 6 assume increasing yields, prunings, and fertilizer and water inputs. Years 7 through 25 assume tree maturation, at which point steady-state yields are achieved, and maximum fertilizer and water are required. After harvest, in year 25, the orchard is removed, yielding 86% of all woody biomass generated by the orchard. There are a number of options for managing this end-of-life (EOL) biomass. Based on information provided by cooperating growers, 68% is removed and processed for electricity generation, (20%) is surface mulched, and 12% is burned on site.[1]

[1] [1]Data from growers were collected through a supplier who, based on a non-disclosure agreement, has elected to remain anonymous in all publications.

Some model parameter values relied on state-wide averages, e.g., for percent of groundwater versus surface water source, and these values were verified and modified based on direct feedback from almond growers in the Tulare Lake Basin region. The provision of surface and groundwater for irrigation requires energy-intensive processes to deliver water to orchards. Pumping is required for increasingly deep groundwater wells, and California has a highly engineered and energy-intensive surface water delivery network. LCIs for delivery of both of these water sources were developed using models. Groundwater pumping energy is estimated using groundwater table maps and calculations, and a GIS-based model combined with reported infrastructure energy use is used to estimate the energy intensity of surface water deliveries (Kendall et al. 2018).

2.5 Almond processing and milk production

Almond processing includes hulling and shelling as well as almond meal production. Hulling and shelling facility operations include seasonal equipment operation and transport of shelled almonds to an almond processing facility for further transformation to almond meal (along with other products). Data for the processing operations were provided under a non-disclosure agreement, and thus the primary data are not included in this article.

Almond milk production modeling is based on primary data collected at a facility that produces almond milk. These data include inputs of energy, water, and almond milk ingredients, as well as outputs of solid waste (Table 1), and the value and the quantity of all products and co-products from the facility. 'Almond milk ingredients' is a category that includes almond meal and other ingredients used to make the unsweetened almond milk. Some of the primary data collected for this study are subject to a non-disclosure agreement and are not provided in Table 1.

Packaging data for almond processing and almond milk facilities were collected for packaging of ingredients delivered to each facility (e.g., plastic bags, plastic containers, and containerboard), as well as packaging material used for the almond milk product (Table 1). A literature review was conducted when primary packing data were not sufficient, for example, to determine the mass of a packaging item.

LCIs for each flow were either taken directly from commercial databases, including the PE Professional Database or Ecoinvent or modified where necessary (GaBi 8.1 Thinkstep, Service Pack 34, 2017). Metadata on each LCI used, except for ingredients, is provided in the Electronic Supplementary Material S1.

2.6 Co-product allocation

Almond cultivation generates hulls, shells, and woody biomass in addition to the primary product of interest, almond meat, and facilities involved with almond processing and milk production all produce multiple product lines, as illustrated in

Table 1 Life cycle inventory data for unsweetened almond milk production in 2016 and 2017

	Year		
	2016[a]	2017[a]	Unit
Inputs			
Grid electricity	1.93×10^{-01}	1.85×10^{-01}	kWh/48 oz. (1.42 L)
Natural gas	3.25×10^{-02}	3.21×10^{-02}	m^3/48 oz. (1.42 L)
Propane	2.66×10^{-04}	6.11×10^{-05}	kg/48 oz. (1.42 L)
Water "In-Use"	5.81	6.03	kg/48 oz. (1.42 L)
Water consumed[b]	3.07	3.19	kg/48 oz. (1.42 L)
Ingredients[c] (almonds, calcium carbonate, sunflower lecithin, sea salt, potassium citrate, natural flavors, locust bean gum, gellan gum)	5.34×10^{-02}	5.10×10^{-02}	kg/48 oz. (1.42 L)
Cleaners[d]	8.77×10^{-04}	7.48×10^{-04}	kg/48 oz. (1.42 L)
Ingredients packaging[e]	2.27×10^{-03}	2.16×10^{-03}	kg/48 oz. (1.42 L)
Cleaners packaging[e]	3.10×10^{-06}	3.36×10^{-06}	kg/48 oz. (1.42 L)
48 oz. bottle (polyethylene terephthalate (PET) plastic)	6.41×10^{-02}	6.41×10^{-02}	kg/48 oz. (1.42 L)
Bottle cap (polypropylene (PP) plastic)	1.46×10^{-02}	1.46×10^{-02}	kg/48 oz. (1.42 L)
Bottle label (polystyrene film)	6.00×10^{-03}	6.00×10^{-03}	kg/48 oz. (1.42 L)
Heat seal (aluminum foil, polyethylene (PE) foam, PE)[f]	2.53×10^{-04}	2.53×10^{-04}	kg/48 oz. (1.42 L)
Transport (for all inputs)	4.93	4.69	kg km
Outputs			
lbs to landfill (trash)	5.94×10^{-03}	4.74×10^{-03}	kg/48 oz. (1.42 L)
lbs to recycling or reused	1.87×10^{-02}	1.57×10^{-02}	kg/48 oz. (1.42 L)

[a] Values account for unit conversions (e.g., lbs. to kg) on per functional unit (48 oz. unsweetened almond milk) basis, including economic allocation factors 0.1606 and 0.1769 for unsweetened almond milk for 2016 and 2017, respectively

[b] 2016 water consumed values assume the ratio of input to output water calculated for 2017 values because net water use values were not available for 2016

[c] Non-water ingredients. Ingredient water is accounted for in water consumption

[d] Cleaner estimates are based on total equivalent products (i.e., unsweetened almond milk and any other products produced at the facility within the respective year)

[e] Packaging assumes one-time use

[f] Sum of parts, excluding the bonding layer

Fig. 1. Thus, each production and processing site requires a co-product allocation step. In this study, an economic allocation is used as the baseline approach for the treatment of co-products at each stage. However, two other approaches are included as alternative scenarios for comparison: co-products from almond cultivation, hulling, and shelling are treated using the displacement approach, and mass-based allocation is tested for almond meal processing and almond milk production (Table 2).

This study uses economic allocation, rather than displacement or allocation based on other properties, as its baseline approach founded on the following rationale. This is an attributional LCA and displacement methods are a consequential approach; in addition, displacement methods cannot reasonably be applied to processing and milk production facilities, so displacement and value-based allocation would need to be combined. Finally, displacement calculations require modeling of the affected markets and products, which can introduce uncertainty and additional complexity, and which is avoided when using economic allocation.

In addition, using a value other than economic for allocation, such as mass or energy, cannot be reasonably applied across the life cycle stages. For example, almonds are not produced to generate hulls, shells, or EOL biomass, but they dominate the mass and energy of materials generated at an orchard. Economic value is a far better indicator of the purpose of the production system—producing almonds.

The economic allocation factors for unsweetened almond milk are calculated given the total output of all products produced at the facility, and their factory gate value using the customer pick-up price (without shipping costs). The prices at the factory gate and the relative masses of each product vary from year to year, for example, due to market variability and field conditions (e.g., physiological traits of the almonds), or different product line production volumes. Economic and mass-based allocation factors are shown for 2 years (2016 and 2017) of almond milk production to illustrate the potential for year-to-year variability.

When the baseline method of economic allocation is applied to almonds, almond hulls at the hulling and shelling facility gate are the only co-product included in the allocation calculation because they are the only co-product with economic value to the producer. However, other co-products are generated that have value, even if they have no selling price. Orchard biomass removed at EOL is one such product. One common disposal method for orchard EOL biomass is combustion in a biomass-fired power plant that produces electricity. Thus, when displacement methods are used, EOL orchard biomass is modeled as displacing the average electricity grid mix in California (see Kendall et al. (2015) for details on displacement credit calculations for orchard biomass).

Hulls are typically sold as dairy feed, so displacement credits for hulls are based on an equivalent mix of dairy feed ingredients as determined by the PC Dairy calculator, a nutritional content and price-based dairy feed optimization tool (Robinson and Ahmadi 2015). PC Dairy uses information on the nutritional content and price of every feed ingredient in the market to identify optimal feed rations. Scenarios are run with and without almond hulls to estimate the change in feed ration ingredients caused by almond hulls in the market. Although the use of almond hulls displaces some ingredients, it increases the use of others to maintain a nutritional balance (or avoid digestion problems), resulting in both avoided and increased demand for other feed ingredients. Thus, the displacement value of hulls includes both avoided impacts and induced impacts, though the net result is a displacement credit (net reduction in impacts) due to the inclusion of almond hulls in feed rations.

2.7 Impact assessment

Impact assessment translates the inventory data into indicators of environmental impact. The impact categories considered in this study include GWP_{100} (Myhre et al. 2013), total primary energy use (TPE), freshwater consumption (FWC), and the TRACI impact categories.

Table 2 Baseline and alternative allocation approaches for almond milk and almond milk precursors

Life cycle stage		Almond cultivation	Hulling and shelling facility	Almond processing facility	Almond milk production facility
Product		Whole almond fruit	Almond meat	Almond meal	Unsweetened almond milk
Baseline approach	Economic allocation factor	1.000	0.9752	0.3668	0.1606 (2016) 0.1769 (2017)
Alternative approach	Mass allocation factor	N/A	N/A	0.3331	0.1848 (2016) 0.2131 (2017)
	Co-product and its displacement use	68% of orchard biomass used in power generation	100% of hulls used in dairy feed ration	N/A	N/A

The TPE use from renewable and non-renewable sources is calculated and reported in MJ. The FWC includes surface water (lakes and rivers), groundwater use, and water used in processes (e.g., water used in turbines for electricity generation) minus all water returned to the watershed, reported in kg of water. Both upstream, as well as direct water use, are accounted for in this study. Direct water use for cultivation is calculated based on applied irrigation water, which is modeled as entirely consumptive use (i.e., no water is returned to the watershed) because there is little to no run off or infiltration to groundwater. FWC does not characterize the impacts of water consumption; rather, it is an inventory level indicator. Water impacts are highly heterogeneous over space and time, but especially space. Water consumed in water-scarce or water-stressed regions, such as California's Tulare Lake Basin region, is arguably more impactful than water consumed in water-rich regions, such as the US's Great Lakes region. Over the last decade, significant progress has been made in developing impact assessment methods for water use (e.g., Pfister et al. 2009; Boulay et al. 2018). However, because of a lack of information on the location of production for many inputs to the production systems, aside from almonds, process water, and electricity, reporting a water impact assessment result is challenging.

To address this challenge, the water stress impact indicator Available WAter REmanin (AWARE) (Boulay et al. 2018) is quantified and discussed in Sect. 3.4. The AWARE method is a recent consensus-based impact assessment method developed by the Water Use in Life Cycle Assessment (WULCA) organization, which was initiated under the auspices of the UNEP-SETAC Life Cycle Initiative (Boulay et al. 2018). The AWARE method is used here to characterize the water use impact of the FWC calculated for the assessed almond milk product.

3 Results

3.1 Total primary energy, freshwater consumption, and global warming potential

Producing one 48 oz. (1.42 L) bottle of unsweetened almond milk uses 14.8 MJ of TPE, consumes 175 kg of freshwater, and generates 0.71 kg of CO_2e. Packaging and transport of packaging materials contribute 0.325 kg CO_2e per bottle of unsweetened almond milk or 46% of the life cycle GWP. Primary packaging is responsible for 0.307 kg CO_2e (94% of all packaging and 43% of the total life cycle GWP impact). The breakdown of primary packaging is 81% for the PET bottle (0.249 kg CO_2e), 13% for the PP bottle cap (0.041 kg CO_2e), 5% for the PS label (0.016 kg CO_2e), and < 1% for the heat seal (0.01 kg CO_2e). Ingredient packaging, cleaner packaging, and transportation of packaging contribute a negligible amount to the total GWP impact or any other environmental impact category. The 48 oz. (1.42 L) PET bottle is the largest single contributor to TPE (42%) and GWP (35%).

Almond production is responsible for 95% of FWC, and almond milk ingredients as a whole comprise 97% of FWC. Almond milk ingredients are the second largest contributor to TPE (20%) and GWP (30%). Other significant contributors to these three impact categories include facility energy use, including both electricity and natural gas, as well as the polypropylene bottle cap.

Detailed values for 2016 and 2017 almond milk production impacts are reported in Table 3. Overall, the difference between the 2016 results and the 2017 results is less than 5%. This change is primarily due to a 5% reduction in batch loss between 2017 and 2016. The reduced loss resulted in less use of almond milk ingredients. Accordingly, all impacts were reduced, e.g., FWC decreased by 4.8% in 2017 compared to 2016.

3.2 Other impact categories

Almond milk ingredients are the most significant contributor to each TRACI impact category except AP, for which natural gas use is the largest contributor (Table 3). The contribution of the PET bottle is 24% for smog, 13% for AP, 12% for HHPA, and 10% for EP. Five inputs contributed over 90% to each TRACI impact category: almond milk ingredients, PET bottle, the bottle cap, and other primary packaging materials (e.g., heat seal and label), facility electricity use, and facility natural gas use (Fig. 2).

3.3 The effect of co-product allocation methods on almond production, processing, and almond milk impacts

As described in Table 2, an alternative allocation approach is tested to evaluate whether allocation methods have a significant effect on LCA outcomes. The alternative approach combines displacement calculations for almond orchard products (cultivation through hulling and shelling) and mass-based allocation for the processing and almond milk facilities. Two materials require displacement calculations; orchard removal biomass used in biomass power plants, and hulls used as dairy feed. Sixty-eight percent of the biomass is assumed to be used for electricity generation with the remaining either chipped and incorporated in soils or burned in the field. The PC Dairy calculator was used to estimate the effect of almond hulls in the California feed market by testing an identical market (based on costs and availability of feeds in the California market) with and

Table 3 LCIA results for 2016 and 2017

	Units	Year	Almond milk ingredients	48 oz. (1.42 L) PET bottle	Bottle cap and other primary packaging	Natural gas	Electricity	Other	Total
Ecotoxicity potential (ETP)	CTUe	2017	2.87	1.64×10^{-02}	5.68×10^{-03}	2.01×10^{-01}	1.87×10^{-03}	6.83×10^{-03}	3.10
		2016	3.00	1.64×10^{-02}	5.68×10^{-03}	2.03×10^{-01}	1.95×10^{-03}	7.78×10^{-03}	3.24
Human toxicity, potential, cancer (HTPc)	CTUh	2017	2.14×10^{-09}	1.02×10^{-10}	2.95×10^{-11}	2.32×10^{-10}	1.27×10^{-11}	1.19×10^{-10}	2.63×10^{-09}
		2016	2.24×10^{-09}	1.02×10^{-10}	2.95×10^{-11}	2.34×10^{-10}	1.33×10^{-11}	1.39×10^{-10}	2.76×10^{-09}
Human toxicity potential, non-cancer (HTPnc)	CTUh	2017	1.42×10^{-07}	4.72×10^{-09}	1.71×10^{-09}	8.38×10^{-09}	-4.30×10^{-10}	9.53×10^{-09}	1.66×10^{-07}
		2016	1.49×10^{-07}	4.72×10^{-09}	1.71×10^{-09}	8.47×10^{-09}	-4.49×10^{-10}	1.16×10^{-08}	1.75×10^{-07}
Human health particulate air (HHPA)	kg $PM_{2.5}e$	2017	8.69×10^{-05}	2.70×10^{-05}	8.88×10^{-06}	8.10×10^{-05}	8.21×10^{-06}	4.97×10^{-06}	2.17×10^{-04}
		2016	9.10×10^{-05}	2.70×10^{-05}	8.88×10^{-06}	8.19×10^{-05}	8.57×10^{-06}	5.22×10^{-06}	2.23×10^{-04}
Ozone depletion potential (ODP)	kg CF-C-11e	2017	1.41×10^{-08}	2.07×10^{-11}	1.01×10^{-11}	5.59×10^{-10}	2.22×10^{-11}	1.03×10^{-10}	1.48×10^{-08}
		2016	1.48×10^{-08}	2.07×10^{-11}	1.01×10^{-11}	5.65×10^{-10}	2.32×10^{-11}	1.21×10^{-10}	1.55×10^{-08}
Smog formation potential (Smog)	kg O_3e	2017	1.11×10^{-02}	5.83×10^{-03}	1.56×10^{-03}	1.85×10^{-03}	1.95×10^{-03}	1.69×10^{-03}	2.40×10^{-02}
		2016	1.17×10^{-02}	5.83×10^{-03}	1.56×10^{-03}	1.87×10^{-03}	2.03×10^{-03}	1.68×10^{-03}	2.46×10^{-02}
Acidification potential (AP)	kg SO_2e	2017	8.59×10^{-04}	3.74×10^{-04}	1.11×10^{-04}	1.28×10^{-03}	1.83×10^{-04}	9.95×10^{-05}	2.90×10^{-03}
		2016	9.00×10^{-04}	3.74×10^{-04}	1.11×10^{-04}	1.29×10^{-03}	1.91×10^{-04}	1.02×10^{-04}	2.97×10^{-03}
Eutrophication potential (EP)	kg N e	2017	1.94×10^{-04}	2.61×10^{-05}	6.92×10^{-06}	1.51×10^{-05}	9.91×10^{-06}	1.46×10^{-05}	2.67×10^{-04}
		2016	2.03×10^{-04}	2.61×10^{-05}	6.92×10^{-06}	1.53×10^{-05}	1.03×10^{-05}	1.58×10^{-05}	2.78×10^{-04}
Total primary energy (TPE)	MJ	2017	2.92	6.17	1.83	1.62	1.83	3.99×10^{-01}	$1.48 \times 10^{+01}$
		2016	3.06	6.17	1.83	1.63	1.91	3.79×10^{-01}	$1.50 \times 10^{+01}$
Freshwater consumption (FWC)	kg	2017	$1.69 \times 10^{+02}$	2.00	3.08×10^{-01}	9.99×10^{-03}	1.03	3.28	$1.75 \times 10^{+02}$
		2016	$1.77 \times 10^{+02}$	2.00	3.08×10^{-01}	1.01×10^{-02}	1.08	3.14	$1.83 \times 10^{+02}$
Global warming potential (GWP_{100})	CO_2e	2017	2.10×10^{-01}	2.49×10^{-01}	5.82×10^{-02}	9.15×10^{-02}	8.14×10^{-02}	2.11×10^{-02}	7.11×10^{-01}
		2016	2.20×10^{-01}	2.49×10^{-01}	5.82×10^{-02}	9.25×10^{-02}	8.50×10^{-02}	2.00×10^{-02}	7.24×10^{-01}

without almond hulls. The result is that 1 kg of almond hulls displaces 0.876 kg silage corn, 1.125 kg dried distillers grains and solubles (DDGS), and 0.0009 kg limestone flour, while requiring the addition of 0.198 kg corn gluten feed, 1.195 kg oat silage, 0.0034 kg salt, and 0.686 kg wheat. The LCA model uses reference LCIs for

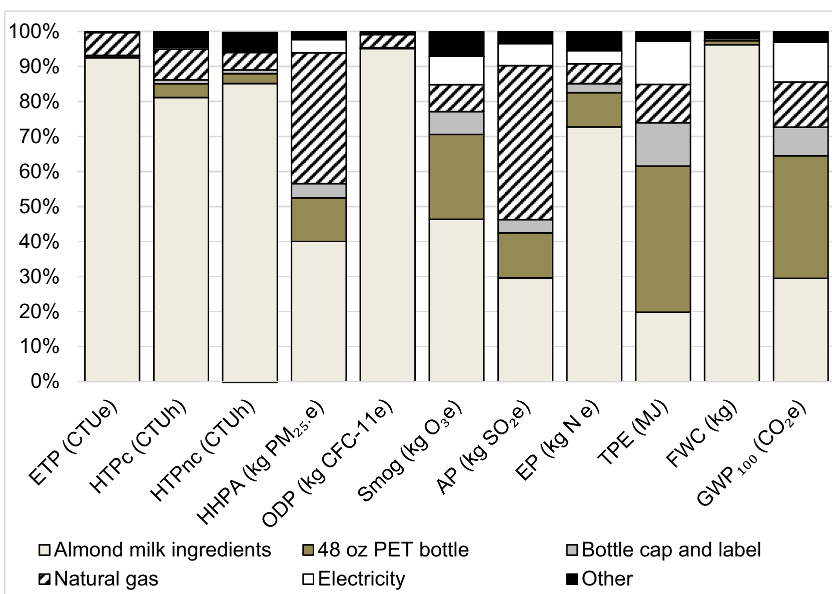

Fig. 2 Percent contribution to life cycle impacts of almond milk by process or input category for 2016 and 2017: ecotoxicity potential (ETP), human toxicity potential cancer (HTPc), human toxicity potential non-cancer (HTPnc)), Human Health Particulate Air (HHPA), ozone depletion potential (ODP), Smog formation potential (Smog), acidification potential (AP), eutrophication potential (EP), total primary energy (TPE), freshwater consumption (FWC), and 100-year global warming potential (GWP_{100})

these other feeds that are not California-based. This is appropriate for some feeds like DDGS, which are imported from the US Corn Belt, but not for other feeds like corn silage which is typically produced in-state. This potentially distorts the actual environmental value of avoided demand for feeds, particularly for water use due to California's uniquely high dependence on irrigation.

The combined displacement credit for orchard biomass and hulls is higher than the environmental value accorded by economic allocation for many, but not all impact categories. As illustrated in Table 4, the displacement approach more than halves the GWP of a kilogram of almonds, but leads to a slight increase in water use relative to economic allocation. However, the effect of the allocation method on the final milk product is just a modest increase in FWC and a decrease in GWP.

3.4 Applying a water scarcity method to the FWC estimate

While a lack of spatial information in reference LCIs prevents a complete application of water scarcity impact methods to the studied product system, irrigation water for almond cultivation is the dominant water consumer (167 kg H_2O/48 oz. (1.42 L), or 95% of FWC) and has a known water consumption region. AWARE, a recent consensus-based impact assessment method, is used here to characterize the irrigation water used for almond cultivation (Boulay et al. 2018). AWARE characterization factors are available for a number of scales, and here, the scale with an upper bound of 100 is used. California's semi-arid southern San Joaquin Valley, the region of almond production for this study, has an AWARE100 characterization factor of 88 L-equivalent/L (L-eq/L) for agricultural water use and reflects the relatively high "potential to deprive another user (human or ecosystem) when consuming water" in the region (Boulay et al. 2018, p. 370). The resulting AWARE value for irrigation water use per functional unit is 167 kg H_2O × 88 L-eq/L = 14,696 kg H_2O-eq.

4 Discussion

4.1 Comparing almond milk to other plant-based milks and dairy milk

Despite nearly 40 years of efforts to standardize LCAs, LCA practitioners must still make choices regarding data, modeling assumptions, and which impact methodology to use. Variations in LCA practitioners' interpretation of the standardized LCA methodology make comparisons between different LCAs challenging and often lead to varying results for LCAs of the same product (Baldini et al. 2017).

A literature review conducted to understand the scope, quality of analysis, and findings of other reports on dairy and non-dairy milk shows that used impact indicators and characterization models vary widely, and that most other studies only assessed GWP. The LCA results for GWP were extracted from selected publications and converted to the functional unit of this LCA (i.e., 48 oz. (1.42 L) of beverage). Table 5 shows study results for GWP of dairy and plant-based milk production only, i.e., without primary packaging. Processes downstream of the factory gate (i.e., distribution to retail, beverage storage, and use, and EOL) are not included as these processes were outside the scope of this study.

There is a lively debate about the best way to define functional units of food LCAs, especially comparative ones. It is not obvious on what basis food items should be compared, since their consumption or substitution value is frequently not driven by caloric or nutrient content. The aim of this study is not to contribute to this debate, but rather to report and benchmark the study results in a useful and transparent manner. As such, results in Table 5 are reported on a volumetric basis, with the caveat that these products do not provide identical

Table 4 The effect of co-product allocation approaches on almond milk life cycle stages (baseline refers to economic allocation at all stages. Alternative refers to displacement calculations for whole almond production (cultivation through hulling and shelling) and mass-based allocation for all other stages. Milk results include packaging)

Life cycle stage	Impact	Unit	Baseline	Alternative	% Change
Almond meat production (cradle-to-gate)	FWC	kg H_2O/kg almond	4520	4630	2%
	GWP_{100}	kg CO_2e/kg almond	2.77	1.03	− 169%
Processing to meal (gate-to-gate)	FWC	kg H_2O/kg meal	3.33	3.10	− 8%
	GWP_{100}	kg CO_2e/kg meal	2.39	2.18	− 10%
Milk production (gate-to-gate)	FWC	kg H_2O/48 oz. (1.42 L) milk	8.07	7.49	− 8%
	GWP_{100}	kg CO_2e/48 oz. (1.42 L) milk	0.520	0.537	3%
Almond milk (cradle-to-gate)	FWC	kg H_2O/48 oz. milk	175	180	3%
	GWP_{100}	kg CO_2e/48 oz. (1.42 L) milk	0.711	0.674	− 5%

Table 5 Global warming potential results in kg CO_2e per 48 oz. of milk produced (without packaging)

Source	Process stage	Milk type					
		Pea	Almond	Soy	Coconut	Oat	Dairy
This study (2017 results)	Farming	–	0.11	–	–	–	–
	Processing	–	0.28	–	–	–	–
	Total	–	0.39	–	–	–	–
Clune et al. (2017)	Total	–	0.58	1.21	0.58	–	1.90
Florén et al. (2013)	Farming	–	–	–	–	0.11	1.52
	Processing	–	–	–	–	0.42	0.18
	Total	–	–	–	–	0.54	1.70
Grant and Hick (2017)	Total	–	0.40	0.24	–	–	1.72
Henderson and Unnasch (2017)[a]	Farming	0.09	0.05	0.04	–	–	1.81
	Processing	0.35	0.34	0.37	–	–	0.16
	Total	0.44	0.39	0.42	–	–	1.97
Thoma et al. (2013a), Thoma et al. (2013b)[b]	Farming	–	–	–	–	–	1.67
	Processing	–	–	–	–	–	0.13
	Total	–	–	–	–	–	1.80
Granarolo (2016)	Farming	–	–	0.67	–	–	–
	Processing	–	–	0.38	–	–	–
	Total	–	–	1.05	–	–	–

[a] Co-product credits (− 0.14 kg CO_2e for pea and − 0.023 kg CO_2e for almond) are included in the processing stage

[b] Total value is derived from Thoma et al. (2013a), breakdown by life cycle stage based on Thoma et al. (2013b)

services to the consumer, insofar as they have different nutrient profiles. This means that a direct comparison between products should be avoided, and instead, the GWP of the other plant and dairy milks should be interpreted as providing context for interpreting almond milk results, and not as a direct comparison of substitutable products.

Grant and Hicks (2017) and Henderson and Unnasch (2017) report GWPs for almond milk very similar to this study. Henderson and Unnasch (2017) used inventory data from Kendall et al. (2015) and combined it with inventory data and models that are different from those in this study. Although overall GWP results are similar between this study and Henderson and Unnasch (2017), the main contributor to GWP in Henderson and Unnasch (2017) is processing, whereas in this study, the main contributors are packaging and almond milk ingredients. Henderson and Unnasch (2017) used proxy data from soy and pea milk production to estimate the processing stage for almond milk production.

Reported GWPs for an equal volume of dairy milk are consistently higher than that for almond milk, by a factor of 4–5. The Innovation Center for US Dairy funded a very detailed and relatively recent LCA of dairy products. GHG emission results from this LCA are published in Thoma et al. (2013a), which report a US average GWP for dairy milk that is 4.5 times the size of the GWP for almond milk presented here.

Comparing almond milk to other non-dairy milk is more challenging due to the large variability in study transparency,

Table 6 The absolute and percent changes of total primary energy, renewable and nonrenewable, (TPE), global warming potential (GWP), smog air, and eutrophication potential (EP), when switching to a 50% and 100% recycled content 48 oz. PET bottle

Impact category	No recycled content	50% recycled content		100% recycled content	
	Unsweetened almond milk impact	Unsweetened almond milk impact	Percent reduction	Unsweetened almond milk impact	Percent reduction
TPE (MJ)	14.9	12.7	− 14.4%	10.6	− 28.8%
GWP (kg CO_2e)	0.71	0.64	− 9.6%	0.58	− 19.0%
Smog (kg O_3eq)	2.46×10^{-2}	2.35×10^{-2}	− 4.6%	2.23×10^{-2}	− 9.3%
EP (kg Neq)	2.69×10^{-4}	3.10×10^{-4}	15.2%	3.51×10^{-4}	30.3%

quality, and results. There was only one LCA of pea milk and one of oat milk found in the literature, both of which have GWPs slightly higher than the unsweetened almond milk when excluding packaging. There was one LCA for coconut milk, which also reports a higher GWP than unsweetened almond milk. Finally, there were four LCAs of soy milk considered in this report, with varying GWP values.

Life cycle calculations of FWC include consumptive water use that occurs directly (i.e., in production processes such as irrigation for almond production) as well as indirectly (i.e., in connected supply chains such as for the generation of electricity used in the production system). Henderson et al. (2017) estimated freshwater consumption for dairy milk production, including careful spatial modeling of feed production (not represented by the acronym FWC to ensure it is not confused with the life cycle-based FWC accounting undertaken in this study). They found US average freshwater consumption of 307 L per 48 oz. of milk. This result is 1.8 times the FWC estimate for unsweetened almond milk from this study (175 L per 48 oz. of milk).

4.2 Evaluating the potential for reducing impacts through packaging choices

As evidenced in the results, primary packaging of almond milk accounted for more than half of the TPE and more than 40% of GWP, and of this, the PET bottle alone accounted for 35% of GWP and 42% of TPE of a 48 oz. bottle of almond milk. While there are a number of strategies for reducing packing-related impacts, substituting recycled materials in place of virgin ones can provide significant benefits. Here, scenarios testing bottles that use 50% and 100% recycled PET (RPET) in place of virgin PET are explored.

Significant reductions are achieved in TPE, GWP, and smog air when 50% or 100% recycled content is used in the bottle (Table 6). For context, reducing the mass of the PET bottle by 26% (16 g) or 55% (35 g) achieves the same decrease in GWP, a slightly larger decrease in smog air, and a slightly smaller decrease in TPE and all other impact categories. Section S2 of the online resource material provides additional information on the underlying data used in these calculations and additional packaging alternatives.

5 Conclusions

This cradle-to-gate LCA of unsweetened almond milk uses product-specific primary data to account for almond production, almond processing, and unsweetened almond milk production. The LCA examined two years of production, 2016 and 2017, and due to reduced batch losses in almond milk ingredients of 5% in 2017, attendant water use and other impacts associated with almond milk ingredients were also reduced. Almond milk ingredients, PET bottle, PP bottle cap, and the electricity and natural gas use of the almond milk processing facility make up over 90% of each environmental impact category. For consumptive freshwater use, almond milk ingredients are the overwhelming source, dominated by almond production. Results for other categories highlight the importance of primary packaging in determining the GWP and TPE attributable to almond milk. As such, scenario analysis showed significant opportunities for reducing these impact categories by adopting recycled bottle material or mass reductions in the bottle itself. Another scenario analysis included in this study tested alternative co-product allocation methods and found that LCA results for packaged almond milk changed only slightly, despite significant differences for almond production in many impact categories.

While comparison to other dairy and plant-based milks is challenging due to differences in study methods and indicators, on a volume basis, US average dairy milk appears to have about 4.5 times the GWP and about 1.8 times the FWC of unsweetened almond milk. Unsweetened almond milk has similar or lower GWP relative to most other plant-based milks and appears to have higher FWC compared to plant-based milks from largely rainfed crops.

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