



Comparing plant-based drink alternatives and cow's milk based on environmental burdens and a novel nutrient profiling system

Ashley Green^{1,2*}, Barbara Walther³, Alexander Mathys¹, Thomas Nemecek^{2*}

¹ Laboratory of Sustainable Food Processing, ETH Zurich

² Life Cycle Assessment Research Group, Agroscope

³ Human Nutrition, Sensory Analysis and Flavour Research Group, Agroscope, *Corresponding authors



Imprint

Publisher	Agroscope Schwarzenburgstrasse 161 3003 Bern www.agroscope.ch
Information	Thomas.nemecek@agroscope.admin.ch
Layout	Géraldine Zosso
Cover Photo	Gabriela Brändle
Download	www.agroscope.ch/science
Copyright	© Agroscope 2026
ISSN	2296-729X
DOI	https://doi.org/10.34776/as231e

Disclaimer

The information contained in this publication is intended solely for the information of readers. Agroscope endeavours to provide readers with correct, up-to-date and complete information, but accepts no liability in this regard. We disclaim all liability for any damages in connection with the implementation of the information contained herein. The laws and legal provisions currently in force in Switzerland apply to readers. Current Swiss jurisprudence is applicable.

Table of Contents

Summary	4
Zusammenfassung	4
Résumé	5
Riassunto	5
1 Introduction	6
2 Methods	7
2.1 Developing the Food Substitute Index 20 (FSI20) metric.....	7
2.2 Environmental assessment.....	7
3 Results	10
3.1 Nutrient profiles.....	10
3.1.1 Nutrient variability.....	12
3.2 Environmental impacts.....	13
3.2.1 Uncertainty analysis impacts for GWP.....	14
3.2.2 Nutritionally-invested environmental impacts compared to impacts on a volumetric basis.....	15
4 Discussion	16
4.1 Evaluating environmental and nutritional tradeoffs and synergies.....	16
4.2 Future areas of work.....	17
5 Conclusion	18
Acknowledgements	19
References	19
6 Supplementary material	23
6.1 Appendix A: Developing the FSI20 metric.....	23
6.2 Appendix B: Processing & uncertainty analysis methodology.....	24
6.3 Appendix C: Nutrient variability.....	26
Supplementary references	27

Summary

The purpose of this study is to compare the environmental sustainability and nutrient densities of various plant-based drinks from soy, oat, almond, rice, spelt, and cashew against cow's milk from different production systems (i.e., grass-fed, pasture-raised, and arable-land based). For the nutritional assessment, we developed the Food Substitution Index 20 to rank the substitution potential of plant-based drink for cow's milk. This nutrient algorithm is characterized by micronutrient deficiencies that exist in a specific dietary pattern. In addition to essential nutrients, we also included an analysis of amino acids, fatty acids, and disqualifying nutrients. For the environmental assessment, we performed a life cycle assessment to calculate cradle to factory gate impacts per one serving size of drink for seven impact categories; namely, global warming potential, deforestation, water scarcity, acidification, particulate matter, eutrophication, soil quality, and non-renewable energy use. Finally, we measured environmental impacts against the aforementioned nutrient density algorithm to calculate nutritionally-invested environmental impacts. Overall, plant-based drinks are environmentally favorable when compared to cow's milk but while these drinks may have lower climate impacts they can have higher impacts than cow's milk in other environmental categories such as deforestation or water scarcity, which underscores the importance of considering multiple impacts to avoid burden shifting. When the nutritional dimension is introduced, only soy drink systematically outperforms cow's milk, which complicates setting recommendations. Moreover, plant-based drinks must be fortified to compete with cow's milk on a micronutrient basis whereas for the other nutrition categories (e.g., fatty acids) there are tradeoffs across animal and plant drinks.

Zusammenfassung

Ziel dieser Untersuchung ist ein Vergleich von pflanzlichen Getränken aus Soja, Hafer, Mandeln, Reis, Dinkel und Cashew mit Kuhmilch aus unterschiedlichen Produktionssystemen (Grasfütterung, Weidehaltung, ackerlandbasiert) in Bezug auf die ökologische Nachhaltigkeit und die Nährstoffdichte. Zur Bewertung der Nährstoffe wurde der «Food Substitution Index 20» entwickelt, um das Substitutionspotenzial pflanzlicher Drinks gegenüber Kuhmilch einzustufen. Dieses Nährstoff-Bewertungsmodell ist dadurch gekennzeichnet, dass es Mikronährstoffdefizite in einem bestimmten Ernährungsmuster aufzeigt. Neben den essenziellen Nährstoffen wurden Aminosäuren, Fettsäuren und sogenannte disqualifizierende Nährstoffe in die Analyse einbezogen. Für die Umweltbewertung wurde eine Lebenszyklusanalyse durchgeführt, um die Auswirkungen von der Wiege bis zum Fabrikator pro Portionsgrösse eines Getränks in sieben Wirkungskategorien zu berechnen: globales Treibhauspotenzial, Entwaldung, Wasserknappheit, Versauerung, Feinstaubbelastung, Eutrophierung, Bodenqualität und Verbrauch nicht erneuerbarer Energieressourcen. Schliesslich setzten wir die Umweltwirkungen in Relation zum oben beschriebenen Nährstoffdichte-Modell, um ernährungsbezogen gewichtete Umweltwirkungen zu berechnen. Insgesamt sind pflanzliche Getränke im Vergleich zu Kuhmilch aus ökologischer Sicht vorteilhaft. Ihre Klimaauswirkungen sind generell geringer; allerdings können sie in anderen Umweltkategorien wie Entwaldung oder Wasserknappheit stärkere Auswirkungen verursachen. Daher ist es wichtig, mehrere Umweltwirkungen gleichzeitig zu berücksichtigen, um eine Verlagerung von Belastungen («burden shifting») zu vermeiden. Hinsichtlich der Nährstoffe schneidet nur Sojadrink systematisch besser ab als Kuhmilch, was die Formulierung von Empfehlungen erschwert. Zudem müssen pflanzliche Getränke angereichert werden, um hinsichtlich der Mikronährstoffe mit Kuhmilch konkurrenzfähig zu sein, während es in anderen Nährstoffkategorien (z. B. Fettsäuren) bei tierischen und pflanzlichen Getränken Vor- und Nachteile gibt.

Résumé

L'objectif de cette étude est de comparer la durabilité environnementale et la densité nutritionnelle de différentes boissons végétales à base de soja, d'avoine, d'amande, de riz, d'épeautre et de noix de cajou par rapport au lait de vache issu de divers systèmes de production (animaux nourris à l'herbe, élevés au pâturage ou sur des terres arables). L'évaluation nutritionnelle repose sur le développement de l'indice de substitution alimentaire 20 conçu pour classer le potentiel de substitution des boissons végétales par rapport au lait de vache. Cet algorithme nutritionnel prend en compte les carences en micronutriments caractéristiques d'un régime alimentaire spécifique. Outre les éléments nutritifs essentiels, l'analyse inclut également le profil en acides aminés, en acides gras ainsi que les éléments nutritifs dits défavorables. L'évaluation environnementale s'appuie sur une analyse du cycle de vie visant à quantifier les impacts d'une portion de boisson «du berceau à la porte de l'usine» dans sept catégories: potentiel de réchauffement global, déforestation, pénurie d'eau, acidification, émissions de particules fines, eutrophisation, qualité des sols et utilisation d'énergies non renouvelables. Les impacts environnementaux ont ensuite été rapportés à l'algorithme de densité nutritionnelle mentionné plus haut afin de calculer les impacts environnementaux par unité de valeur nutritionnelle. Dans l'ensemble, les boissons végétales présentent des performances environnementales plus favorables que le lait de vache. Toutefois, si elles génèrent généralement des impacts climatiques plus faibles, elles peuvent entraîner des impacts supérieurs dans d'autres catégories environnementales telles que la déforestation ou la pénurie d'eau, soulignant ainsi l'importance d'une approche multicritère afin d'éviter le transfert des impacts environnementaux. Lorsque la dimension nutritionnelle est intégrée à l'analyse, seule la boisson au soja surpasse systématiquement le lait de vache, ce qui complexifie l'élaboration de recommandations nutritionnelles. De plus, les boissons végétales doivent être enrichies pour rivaliser avec le lait de vache en termes de micronutriments, tandis que pour d'autres catégories nutritionnelles (p. ex. les acides gras), il existe des compromis entre les boissons d'origine animale et végétale.

Riassunto

Il presente studio mira a confrontare la sostenibilità ambientale e la densità nutrizionale di varie bevande vegetali a base di soia, avena, mandorle, riso, spelta e anacardi con il latte vaccino proveniente da diversi sistemi di produzione (ad es. alimentazione a base d'erba, al pascolo o basata su terreni coltivati). Per la valutazione nutrizionale abbiamo sviluppato il Food Substitution Index 20 (indice di sostituzione alimentare 20) per classificare il potenziale di sostituzione del latte vaccino con le bevande vegetali. Tale algoritmo nutrizionale è caratterizzato da carenze di micronutrienti presenti in un modello alimentare specifico. Oltre ai nutrienti essenziali, abbiamo incluso anche un'analisi degli aminoacidi, degli acidi grassi e dei nutrienti non essenziali. Per la valutazione ambientale abbiamo eseguito un'analisi del ciclo di vita volta a calcolare l'impatto di una porzione di bevanda dalla culla alla fabbrica in sette categorie: potenziale di riscaldamento globale, deforestazione, rarefazione delle risorse idriche, acidificazione, particolato, eutrofizzazione, qualità del suolo e impiego di energie non rinnovabili. Abbiamo infine misurato l'impatto ambientale rispetto all'algoritmo di densità nutritiva sopraccitato per calcolare gli impatti ambientali correlati al valore nutrizionale. Nel complesso, le bevande vegetali sono più rispettose dell'ambiente rispetto al latte vaccino. Tuttavia, se da un lato possono avere un impatto minore sul clima, dall'altro l'impatto risulta maggiore in altre categorie ambientali, come la deforestazione o la rarefazione delle risorse idriche. Ciò sottolinea l'importanza di considerare numerosi impatti per evitare lo spostamento dell'onere ambientale. Una volta introdotta la dimensione nutrizionale, solo le bevande a base di soia dimostrano sistematicamente un impatto migliore del latte vaccino, risultato che complica la definizione delle raccomandazioni. Inoltre, le bevande vegetali devono essere fortificate per poter competere con il latte vaccino in termini di apporto di micronutrienti mentre, per quanto riguarda le altre categorie nutrizionali (come gli acidi grassi), esistono compromessi tra bevande animali e vegetali.

1 Introduction

With increasing pressure on our planet's natural resources, agri-food production actors are looking toward alternative proteins such as plant-based milk alternatives, which we will refer to as plant-based drinks (PBD) in this study. The market share of PBD has, overall, continued to increase (BCG 2023) and consumer acceptance of PBD is growing because of their lower climate impacts, absence of lactose (an advantage for people with lactose intolerance), and perceived health benefits. However, many studies point to the varied (Drewnowski et al. 2021) and lower nutrient contents of PBD (Scholz-Ahrens et al. 2020); additionally, impacts other than climate change such as water scarcity and deforestation are also important to evaluate to avoid burden shifting. Consequently, we examine the environmental and nutritional sustainability dimensions of cow, cashew, almond, oat, rice, and spelt drinks found in Swiss supermarkets. We further differentiate between milk from grass-fed cows, arable-land based cows, and pasture-raised cows because the choice of production system can influence nutrient contents and environmental impacts.

As shown in other studies, understanding tradeoffs between nutritional and environmental sustainability dimensions is critical (Willett et al. 2019). Moreover, using nutritional and environmental data differentiated by region can reveal different results (Green et al. 2021), extolling the limitations of studies relying on globally-averaged data for implementing actions at more local scales. Additionally, results can vary across temporal scales, such as seasons or years (Bär et al. 2020), and even at more granular scales (Pedolin et al. 2021; Romeiko et al. 2020). Consequently, more context-specific studies are needed. Overall, however, the findings of this study are globally relevant.

With regards to the added-value of this study, most studies that assess PBD do not quantify tradeoffs between nutritional and environmental dimensions (Queiroz Silva and Smetana 2022). Additionally, to rank drinks based on their nutrient density, we developed the Food Substitute Index 20 (FSI20), which is a metric that ranks substitute food items (within a food group) based on their ability to address nutrient deficiencies of concern within a specific population and dietary pattern. Such nutrient algorithms are increasingly used in studies to understand the relative nutrient density of various products. However, there have been calls to make these nutritional profiling methods used in environmental analyses more standardized, robust, and adapted to context-specific cases (i.e., less generalized) (Green et al. 2023; Kytä et al. 2023; Mozaffarian et al. 2021a). Accordingly, we followed the points of differentiation framework (Green et al. 2023) to develop the FSI20. Additionally, we quantify (when possible) and explore the role of nutrient bioavailability. We also include nutrients that are commonly unlisted on PBD labels such as fatty acids, amino acids, and additional micronutrients (Walther et al. 2022). Finally, most papers only consider more common drinks (i.e., cow, almond, oat, soy) (Carlsson Kanyama et al. 2021; Ramsing et al. 2023), whereas we analyzed a wider range of relevant products.

As climate change becomes ever-present in our lives, one of the major drivers of PBD consumption are lower GHG emissions. However, this is only one impact category and measuring multiple environmental impacts to avoid burden shifting (i.e., optimizing one impact at the expense of another) is critical. Therefore, in this study, we included cradle to factory gate assessments for eight impact categories: acidification, deforestation, eutrophication, global warming potential (GWP), soil quality, non-renewable energy use, water scarcity, and particulate matter.

Finally, we use the aforementioned data to apply the method of nutritional life cycle assessment (n-LCA), which measures environmental impacts against nutrient-based functional units to calculate nutritionally-invested impacts (FAO 2021). Thus, we evaluate environmental impacts on a volume (200 ml serving size) and nutritional basis (FSI20) basis.

2 Methods

2.1 Developing the Food Substitute Index 20 (FSI20) metric

Nutritional contents were measured for 25 drinks found in Swiss supermarkets. We examined nutrient data for cow milk (n=2), almond (n=4), soy (n=7), oat (n=4), cashew (n=2), rice (n=5), and spelt (n=1) drink. A previous study measured protein, essential amino acids, phosphorus, magnesium, potassium, calcium, chloride, manganese, iron, copper, zinc, selenium, iodine, carbohydrates, vitamin C, biotin, niacin, pantothenic acid, vitamin B1, vitamin B2, vitamin B6, vitamin B12, folate, vitamin A, vitamin E, vitamin D, vitamin K1, vitamin K2, fiber, calories, and fatty acids including saturated fat (SFA), trans saturated fat (TFA), monounsaturated (MUFA), polyunsaturated (PUFA), and omega-3 (n-3) and omega-6 (n-6) contents (Walther et al. 2022).

As mentioned, we developed a novel nutrient index following the recommendations from the 'points of differentiation' framework (Green et al. 2023). This framework is inclusive of ten major points to consider when using and developing indices; Table 1 in Appendix A details each 'point' and our choice for it. For our proposed FSI20 nutrient metric (Eqn. 1), we include two types of nutrients: those for which nutrient deficiencies exist and those for which the base product (i.e., cow's milk) exceeds an adequacy ratio threshold of 20%; we include this threshold to avoid introducing new micronutrient deficiencies into the diet with the adoption of substitute products. A detailed description of this index is provided in Appendix A. Deficiencies were gathered from a previous study on omnivore, vegetarian, and vegan diets in Switzerland (Schüpbach et al. 2017). Further explanations of these weighting factors as well as the rationale for focusing on omnivore diets in this paper are provided in Appendix A. Fatty acids, protein quality, and disqualifying nutrients are assessed separately. Disqualifying nutrients are those whose consumption we should moderate to protect health (e.g., sodium, added sugar, certain fats).

$$FSI20 = \sum \left(\frac{\text{nutrient } i / \text{food } j, b}{RDA \text{ or } AI_i} \right) \times \left(\frac{1}{1 - \frac{\text{deficiency } i, d}{100}} \right) + \sum \left(\frac{\text{nutrient } i / \text{food } b}{RDA \text{ or } AI_i} \text{ if } a_{i,b} \geq 20\% \right); \text{Eqn 1}$$

i=nutrient, *j*= substitute food (e.g., PBD), *d*=nutrient deficiency in population and dietary pattern of interest, *b*= base food (e.g., cow's milk), *a_{i,b}*= adequacy ratio for nutrient *i* in base product.

2.2 Environmental assessment

A myriad of value chains exist for a single product (e.g., almond drink), complicating definitive analyses. Our paper focuses on the more common value chains based on literature, patents, and expert consultations in the food processing industry. Moreover, we focus on value chains for which we have data. Overall, data for many PBD is limited because processing data is often proprietary, even in published studies. Relatedly, few robust LCA studies on PBD have been conducted. For this study, PBD data came from literature and LCA databases (i.e., ecoinvent, Agri-footprint, and World Food LCA Database), or were calculated in absence of at-scale production data.

Our FU was 200ml and we used the Swiss Agricultural Life Cycle Assessment (SALCA) method for our impact assessment (Douziech et al. 2024). Our system boundaries are illustrated in Figure 1; we include the most relevant supply chain activities; namely, farm activities, pre-processing, and processing. Our system boundaries exclude packaging, retail, consumer, and end-of-life stages. Based on the literature, packaging can have variable impacts depending on how it is modeled (SIK 2013; te Pas and Westbroek 2022). For our study, packaging is relatively less important because the packaging is similar for all

products. Retail impacts are mostly relevant for pasteurized milk that requires refrigeration, which is not the case for our UHT drinks. Lastly, end-of-life was excluded because our products have similar shelf lives.

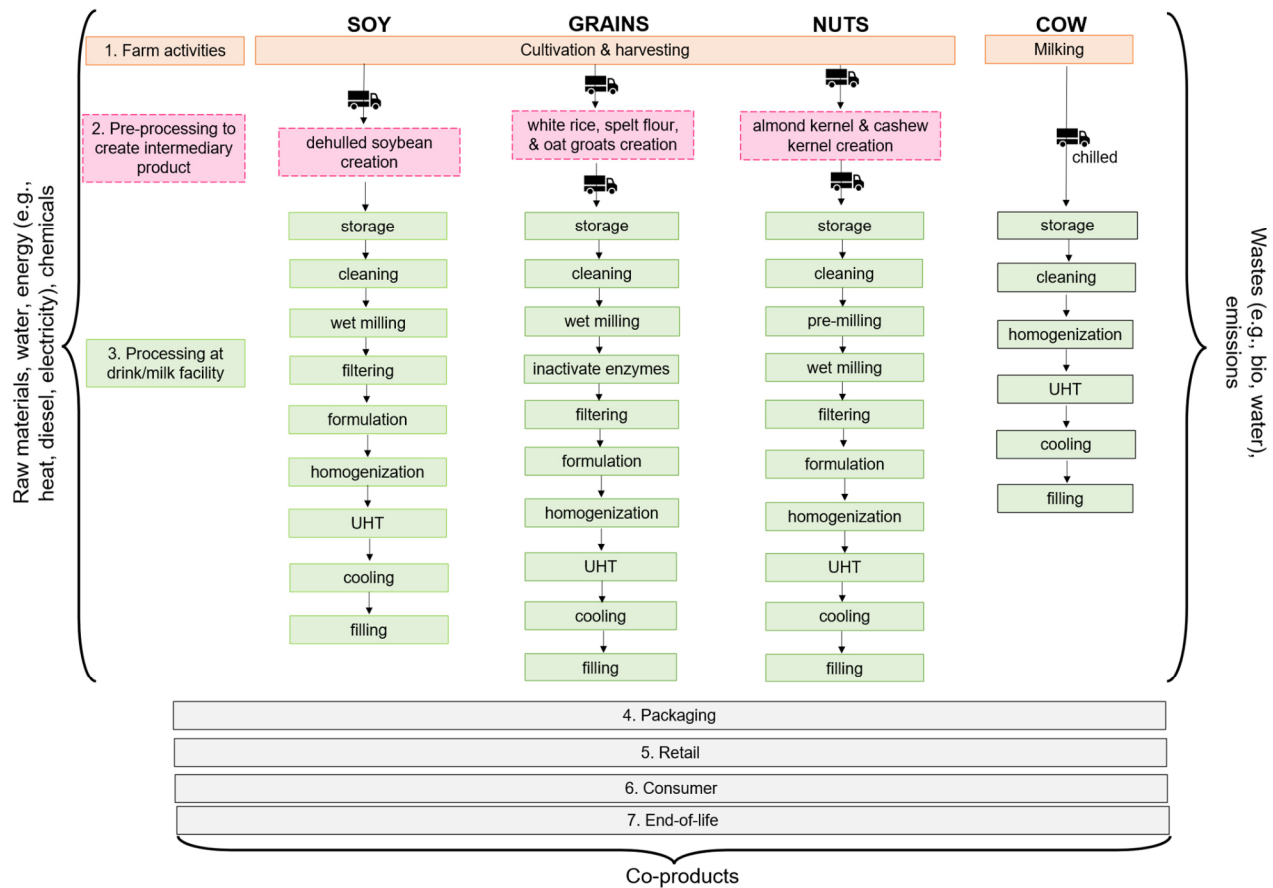


Figure 1: System boundaries of modelled value chains. The dashed lines denote the included processes. Repetitive activities, such as cooling and cleaning in place, are only represented once in the figure for the sake of clarity.

We differentiate between pre-processing and processing steps to ease explanations regarding the data and interpretation of results. Pre-processing involves all steps needed to transform the harvested plant material into the intermediate product that will be used for drink processing (e.g., dehulled soybean, spelt flour, oat groats). Pre-processing examples include drying, grinding, and steaming. These steps are often differentiated across various PBD, while the remaining processing steps are fairly similar across the drinks (Aydar et al. 2020; Mäkinen et al. 2016); examples of these steps include filtering, mixing, or UHT processing. A detailed description of the processing data is presented in Appendix B.

The country of origin for the farm stage of the base plant material (i.e., almond— Spain, Italy; cashew— Vietnam; soy — France, Italy; oat— Germany, Italy; rice— Italy; spelt— Switzerland; cow— Switzerland) was given by product information. Secondary data was used to determine the most common region for production within these countries (Appendix B Table S2). We use country-specific inventories for all base products, excluding almond, for which there was no European inventory; accordingly, we used the global average as a proxy and adapted relevant flows (i.e., electricity and water) to the requisite countries. While losses are almost never reported in PBD LCA studies, for all drinks, a loss ratio of 1.03 was assumed for the base scenario (with a minimum ratio of 1— i.e., no loss and maximum of 1.05) (te Pas and Westbroek 2022; Tóth et al. 2021). For allocation, we used economic allocation percentages from the literature or LCA databases. For the cultivation stage and pre-processing, we used economic allocation values for coproducts as given in the databases, with the exception of cashew cultivation for which we used the

allocation percentages from a previous study (Brito de Figueirêdo et al., 2016). Lastly for soy drink processing, which produces okara, we use allocation percentages from a previous study (Herrmann et al., 2024).

We conducted a Monte Carlo uncertainty analysis for GWP. We calculated base, minimum, and maximum values for energy inputs and raw materials. The variations in raw material inputs were attributed to the possible range of additives, base raw material, and co-products; these ranges can vary due to factors such as differences in flour extraction rates or the percentage of hulls by weight. For pre-processing energy, the differences were based on equipment specifications or variations in literature values. For processing energy, differences in energy inputs were calculated based on variations in the percentage of raw materials used. For a more detailed explanation, refer to Appendix B.

Transport of the raw materials was calculated from average ship or truck distances, using EcoTransit (EcoTransIT 2021). Most raw materials in Europe are transported via road (Eurostat 2022) and the same is true for Vietnam (Rementsov et al. 2020). All stages for the cow's milk were assumed to take place in Switzerland. Currently, over a third (38%) of PBD are produced in Switzerland, based on a market analysis conducted of current drinks sold, and the rest is assumed to be produced in the center of Europe (Mehner et al. 2024). Energy mixes and water flows were adapted to account for the proportion of production in Switzerland versus Europe. Transport values were calculated for the base plant materials; for other materials (e.g., sugar), the market activity was used to account for transport. Table S2 in Appendix B lists the specific region (i.e., the most common region of production for a specific crop based on the literature) in each country that we used to calculate transport distances. We included additives and fortification when data or proxy data was available. Certain data for fortification was unavailable; however, it is expected that such exclusions should have a minimal impact on results (SIK 2013).

3 Results

3.1 Nutrient profiles

Figure 2 shows the nutrient profiling system scores for each drink category; overall, cow's milk and soy drink show the most promise. The figure further illustrates that nutrient density scores within one drink category can vary substantially between products (e.g., soy and almond drink); this is partly due to the different levels of fortification. Across the drink types, four nutrients were commonly fortified: Ca and vitamins D, B2, and B12. PBD are often fortified to be competitive with the higher nutrient contents naturally found in animal milk. Table S3 in Appendix C reports fortified nutrients for each drink. In Figure 2, the minimum values of certain drinks (i.e., almond, soy, and cashew) represent unfortified versions. Of the unfortified drinks, cow's milk scores highest, followed by soy, almond, and cashew. However, when compared to cow's milk, these PBD are nutritionally poor in their natural state. Out of all drinks, including those fortified, the FSI20 nutrient density scores are highest for cow's milk; however, depending on the product selected and the level of fortification in soy drink, soy can have slightly higher nutrient density scores. Almond is the next nutrient dense drink, on average, while oat drink is comparable in certain cases. Rice drink has similar median levels to almond but overall has lower nutrient density scores. Spelt and

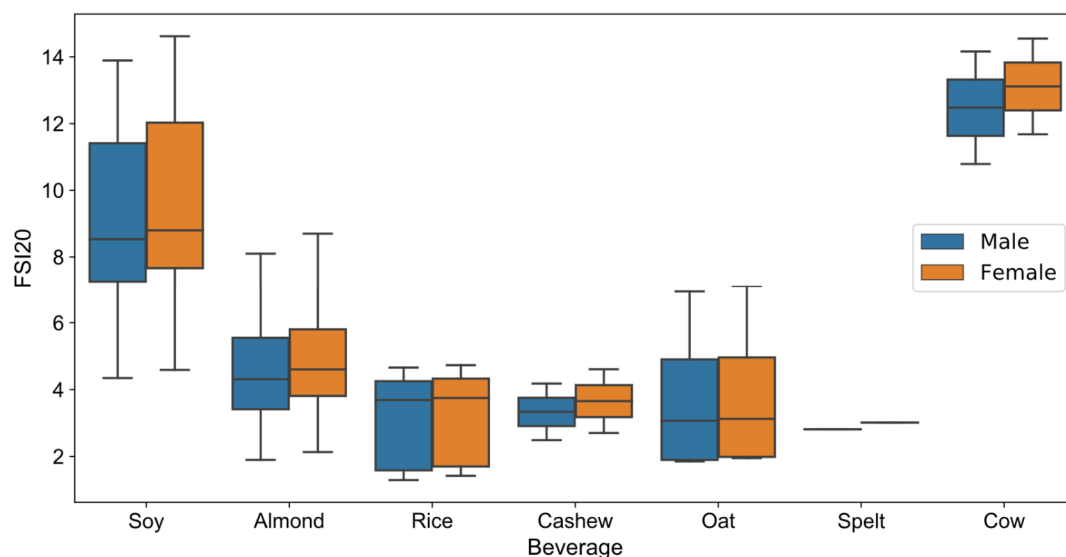


Figure 2: FSI20 scores for plant-based drinks and cow's milk. The graphs show the nutrient index scores of each drink for males and females. Cow (n=2), almond (n=4), soy (n=7), oat (n=4), cashew (n=2), rice (n=5), and spelt (n=1).

cashew have comparable median levels to oat drink.

Protein quantity and quality are key topics of discussion when substituting plant-based products for those of animal origin because, often, plant-based foods are poorer sources of amino acids, which are the building blocks of protein quality. As shown in Figure 3, for the reference pattern corresponding to infants aged six months to children aged three years, cow's milk is the only drink that meets the eAA requirements in all categories, meaning it as a complete protein with a Digestible Indispensable Amino Acid Score (DIAAS) of over 100%. Soy drink follows closely, fulfilling the requirements for all but one eAA. Cashew and oat drinks provide moderate amounts of eAA, while spelt, rice, and almond drinks are comparatively poorer sources.

For the reference pattern applicable to older children, adolescents, and adults, both cow's milk and soy drink contain sufficient amounts of all eAAs. Many of the remaining drinks have a moderate AA profile, meeting the requirements for five to six eAA, with the exception of almond drink, which is, relatively, an

inadequate source. Furthermore, in terms of overall protein content, soy drink has the highest protein concentration (37.8 g/kg), followed by cow's milk (32.6 g/kg). Nevertheless, amino acid requirements can

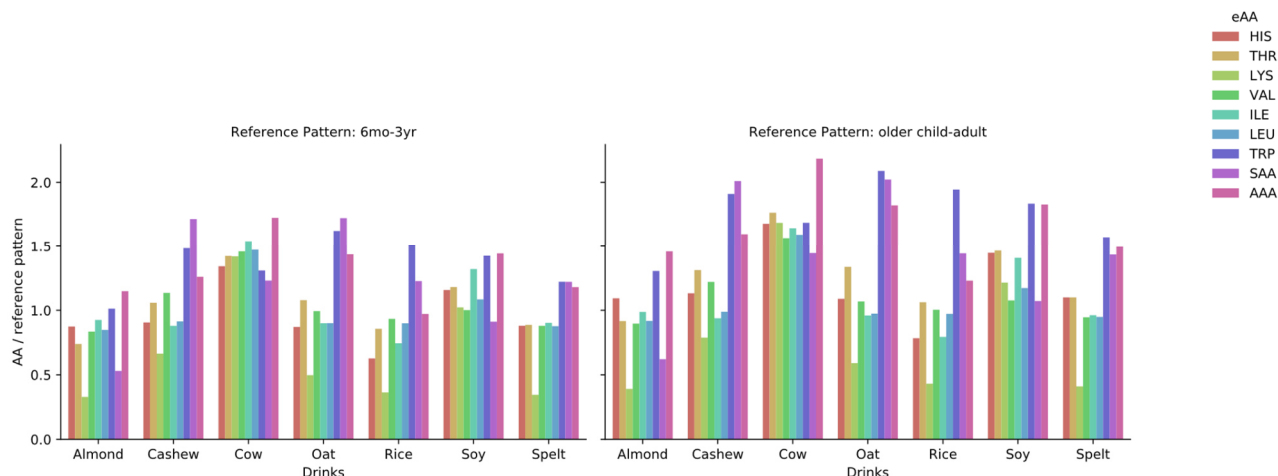


Figure 3: Essential amino acid ratios for two reference patterns: (i) infants aged 6 months to children aged 3 years and (ii) older children, adolescents, and adults. Calculated based on data from Walther et al. (2022).

be met by combining different plant-based foods within a diet, meaning that Figure 3 only provides a limited snapshot.

Results for fatty acids, which are important for physiological functions such as brain function, inflammation, and energy, are shown in Table 1. Omega 6 (n-6) and Omega 3 (n-3), which are essential fatty acids, are often reported in ratio form since they strongly affect one another by competing for the same enzymes for conversion into further forms. For the n-6:n-3 ratio, lower values are generally desirable (Benbrook et al. 2018). Cow's milk has the best profile followed by soy drink, since they are both higher in n-3. Almond drink is characterized by the worst ratio. For cow's milk, the type of production system (e.g., herbage proportions in feed) can affect these values and such possibilities are discussed in the sensitivity analysis. For unsaturated fats, the nuts are highest in MUFAs. For PUFAs, soy has the highest amount on average, but rice can also contain larger amounts; nevertheless, for most drinks, the amounts are fairly small compared to what is needed in a 2000 kcal diet.

Table 1: Nutrient ratios, fatty acid contents, and disqualifying nutrients for plant-based drinks and cow's milk (min, max). Values are calculated based on data from a previous study (Walther et al. 2022).

	Nutrient or nutrient ratio	Almond	Cashew	Oat	Rice	Soy	Spelt	Cow
Fatty acids	n-6/n-3	(126.8,234.8)	(77.7,77.8)	(83.6,105.4)	(91.6,175.1)	(6.7,7.9)	112.1	(2.2,2.7)
	Monounsaturated (g/200 ml)	(1.3,6.4)	(2.9,3.6)	(0.85,0.96)	(0.56,1.3)	(0.63,1.4)	0.6	(1.8,1.9)
	Polyunsaturated (g/200 ml)	(0.47,1.6)	(0.83,1.0)	(1.2,1.4)	(1.0,1.1)	(1.8,2.9)	1.2	(0.29,0.32)
Disqualifying nutrients	Unsaturated / SFA	(9.2,10.5)	(4.3,4.3)	(5.7,6.4)	(6.6,7.7)	(4.7,5.3)	6.9	(0.50,0.52)
	Sodium/ Potassium	(0.96,11.19)	(2.12,3.29)	(1.74,3.29)	(0,7.29)	(0.17,0.74)	3.18	(0.59,0.61)
	Trans fat (g/200 ml)	(0,0.0.01)	(0.01,0.01)	(0.01,0.01)	(0,0.01)	(0.01,0.01)	0.01	(0.27,0.31)
	Calories (kcal /kg)	(129,616)	(323,646)	(168,441)	(224,396)	(328,462)	297	(644,654)

Disqualifying nutrients in this discussion include TFA, sodium, SFA, and calories. While some drinks have added sugar, it is difficult to estimate the natural sugars present in the drinks (FAO 2021). The use of nutrient ratios as opposed to single nutrients to better reflect the food matrix have been proposed in more recent nutrient indices (Mozaffarian et al., 2021) and we incorporate those ratios here. For example, while sodium is harmful above recommended values, its effects can be mitigated by potassium (Kogure et al. 2021) and mitigation arguments have been made for using the ratio of unsaturated to saturated fatty acids as well.

When considering the moderating impacts of potassium, cow's milk and soy drink have the best profiles. Notably, almond and rice have a large range depending on the individual product. TFA are uncommon in nutrient metrics; however, they potentially present health concerns and are thus included. Of the drinks, cow's milk is much higher than PBD in TFA; nevertheless, the amount of TFA is still small when considering upper limits for a 2000 kcal diet. When examining the moderating effect of unsaturated fat on saturated fat, almond has the most favorable ratio as it is high in beneficial fatty acids, followed by spelt and rice. In some indices, energy is included as a disqualifying parameter due to concerns of obesity (Drewnowski, Amanquah, and Gavin-Smith 2021). Obesity rates in Switzerland are increasing; thus, we include it here as well. Cow's milk has the highest calorie content, though some almond drinks can also be high in calories depending on the variety. Of the PBD, oat and certain almond options have lower calorie contents.

3.1.1 Nutrient variability

The choice of production system not only affects environmental scores but also nutrient contents. The herbage proportion in cow feed across different production systems can alter n-3 and SFA contents of milk. However, based on the feed composition for dairy cows in Switzerland, the differences between farms are small (Table S4 in Appendix C). In general, cow's milk from arable land-based systems has lower beneficial n-3 contents and higher SFA contents; this is because of the higher percentage of concentrates in the feed and lower amounts of herbage. For fresh herbage percentages, there is a slightly bigger difference in nutrient contents than with total herbage. Lastly, in Table S5, we see that the level of zinc is low for beverages; consequently, the influence of a high versus low phytate diet is limited. However, for males, cow's milk, cashew, and soy drink move from somewhat adequate sources of zinc to inadequate sources of zinc under higher phytate diets.

3.2 Environmental impacts

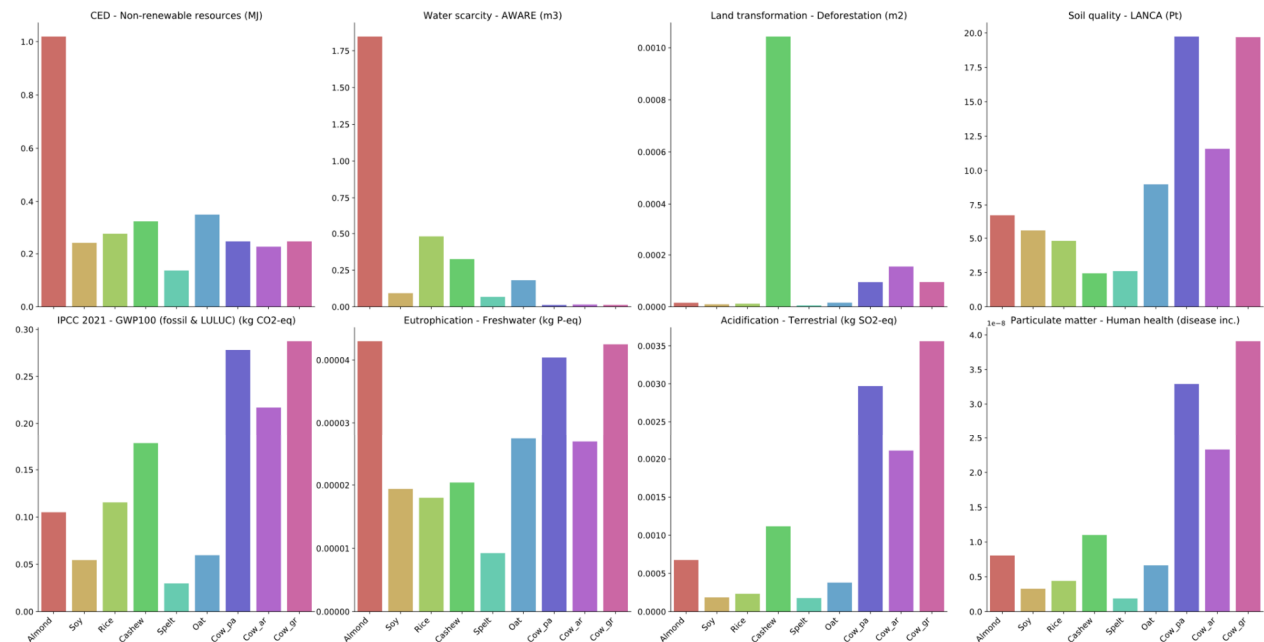


Figure 4: Environmental impacts with a functional unit of 200 ml for plant-based and cow's milk. Cow's milk comes from three systems i.e., pasture-raised (Cow_pa), grass-fed (Cow_gr), and arable-land based (Cow_ar).

Figure 4 provides environmental impacts on a volume basis. For climate impacts, cow's milk induces much higher burdens compared to PBD. The nut drinks have moderate GWP impacts, and this is partly due to the processing needed but also the lower percentage of the intermediate product (i.e., kernel) compared to the rest of the plant. Rice also has moderate impacts, due to the methane emissions caused by the anaerobic conditions resultant from flooding. Finally, soy, oat, and spelt have the lowest impacts. A similar story of cow's milk having much higher impacts than PBD is seen for acidification and particulate matter (PM). Cow's milk also has higher soil quality impacts than PBD meaning it is more disruptive to the system, although oat has similar impacts to cow's milk from arable land. For other impact categories (i.e., water scarcity, non-renewable energy, deforestation) some PBD have substantially higher impacts than cow's milk. For water use, almond has the highest impacts by far. This is due to its large water consumption and reliance on irrigation in water scarce regions (Vanham et al. 2020). Cashew has moderate impacts because while it also requires considerable amounts of water, large parts of its cultivation cycle are rainfed (Brito de Figueirêdo et al. 2016; FAO 1998). Rice also has moderate impacts due to its higher water demand. Cow's milk has the lowest water footprint, likely due to the low water stress of Switzerland (Ritchie and Roser 2024) and the specific, optimized cow production models used for our data source. Contrastingly, the base material for PBD came from more water stressed regions. This is relevant since the majority of water impacts happen during the farm stage (Carvalho et al. 2022; te Pas and Westbroek 2022). In the literature, many studies attribute higher water impacts to cow's milk; accordingly, these site-specific results may not be reflective of other contexts.

Almond drink also has the highest impacts for non-renewable energy which are largely attributed to the farm stage and pre-processing, while cow's milk and other PBD have similar energy usage values. Cashew has a very high deforestation footprint, as also indicated in other studies because they are grown in monocultures under full sun (Powell et al. 2023), meaning significant land clearing is required, while cow's milk has moderate impacts. For eutrophication, the picture is more nuanced. Drinks from almond, grass-fed, and pasture-raised cows have the highest impacts while spelt has the lowest. Unlike the other cow's milk, milk from arable-land based cows has moderate impacts along with oat, soy, cashew, and rice. Lastly, when examining the three types of cow's milk, it is evident that there can be variable impacts depending

on the production system. For most impacts, with the exception of deforestation, cow's milk from arable land has lower impacts than milk from cows that were pasture-raised or grass fed, largely due to the higher milk yield per cow (Bystricky et al. 2014). For deforestation, the difference, while small, is due to the higher amount of concentrates in the feed for cow's milk from arable land based systems.

Comparing study results to the literature is difficult due to the differences in processing stages (e.g., UHT vs. pasteurization), energy mix, system boundaries, formulation including the amount of raw base material, allocation, functional unit, and country of origin. Such conclusions have been confirmed in other studies (Carlsson Kanyama et al. 2021; Ferdouse et al. 2024). For many drinks, impacts are aligned with the literature, at least for GWP. As mentioned, discrepancies occur due to differences in value chain modeling, and the literature is not robust enough for a full benchmark while accounting for such variations. For instance, Bussa et al. (2020) reported that environmental LCA results were more favorable for PBD with a lower percentage of base material; however, such information on base material percentages is often missing from studies. Outside of GWP, data for other environmental categories are scarce, when comparing criteria of similar system boundaries, similar impact assessment methods, and comparable functional unit. Moreover, for other categories such as water use, limited studies are available for impacts that are scarcity weighted (Ramsing et al. 2023).

3.2.1 Uncertainty analysis impacts for GWP

For GWP, we conducted an uncertainty analysis based on the input ranges previously described (Appendix B). We emphasize climate-related impacts due to their significant importance and because we want to compare our findings to established data, and the majority of existing literature measures GWP. Figure 5 illustrates that the drinks with the highest potential variation in GWP is soy and oat while rice and almond have moderate ranges compared to the rest of the drinks. The variation in soy drink is likely due to the differences in steam use as well as the difference in soy sourced from Italy versus France. For oat this is due to the differences in impacts across different countries as well as variability in hull weight. For almond drink, the variation is likely due to the differences in the amount of nut material in the drink and the associated energy needed in cultivation and pre-processing. There is a 250% difference between the minimum and maximum amounts of almond content in the drinks, while the next highest difference is for rice at 65%. As almond drink has higher GWP impacts, it follows that its GWP may vary a lot depending on formulation. Spelt, cow, and cashew have the least amount of variability. For cashew drink, this is because the amount of raw material is relatively consistent (it has an 8% base material variation) and cultivation makes up the dominant impacts for this drink because the farm-level impacts for cashew nut are very high.

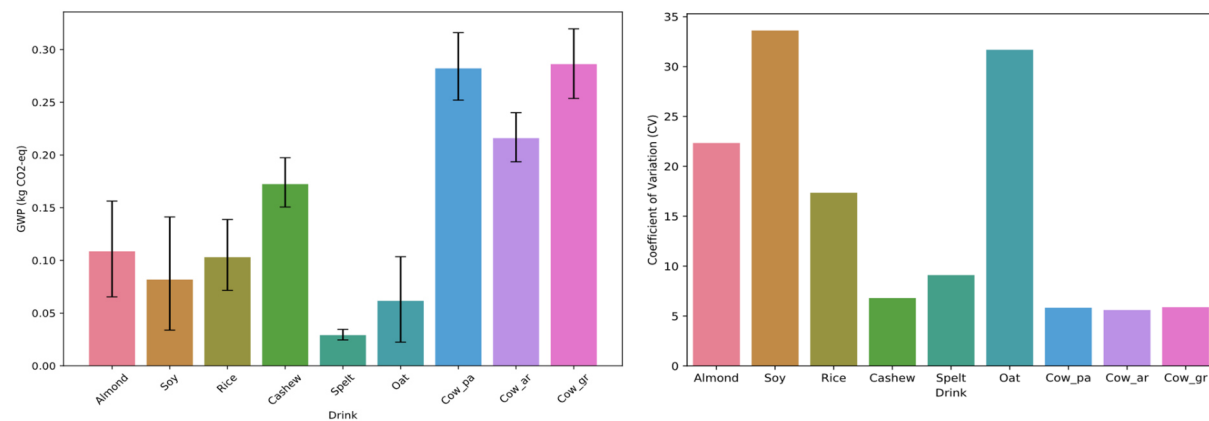


Figure 5: Panel A) Uncertainty analysis for GWP impacts of plant-based drink and cow's milk per 200 ml. The columns show the mean value and the lines represent the 2.5 and 97.5 percentile results from the uncertainty analysis. Panel B) Coefficients of variation (CV) from the uncertainty analysis.

3.2.2 Nutritionally-invested environmental impacts compared to impacts on a volumetric basis

Figure 6 illustrates how results change with the FSI20 n-FU; at times, higher nutrient densities can lead to relatively lower nutritionally-invested impacts. Such a result is commonly seen for cow's milk and soy drink. In other instances, environmental impacts are sufficiently high such that their nutrient density does not result in more favorable nutritionally-invested environmental impacts (e.g., almonds and water, cashew and deforestation). Overall, soy and spelt score the best, while cashew scores poorly. Compared to the volume-based FU, soy and almond are relatively unaffected by the use of an n-FU; this is likely because soy already has lower environmental impacts and is highly nutrient dense, while almond has higher impacts and is only of moderate nutrient density. The environmental impacts most affected by the use of the n-FU are GWP, eutrophication, soil quality, and non-renewable energy use. For water scarcity and deforestation, the FU has limited influence on results because the difference in extremes across drinks on a volume basis is already quite large.

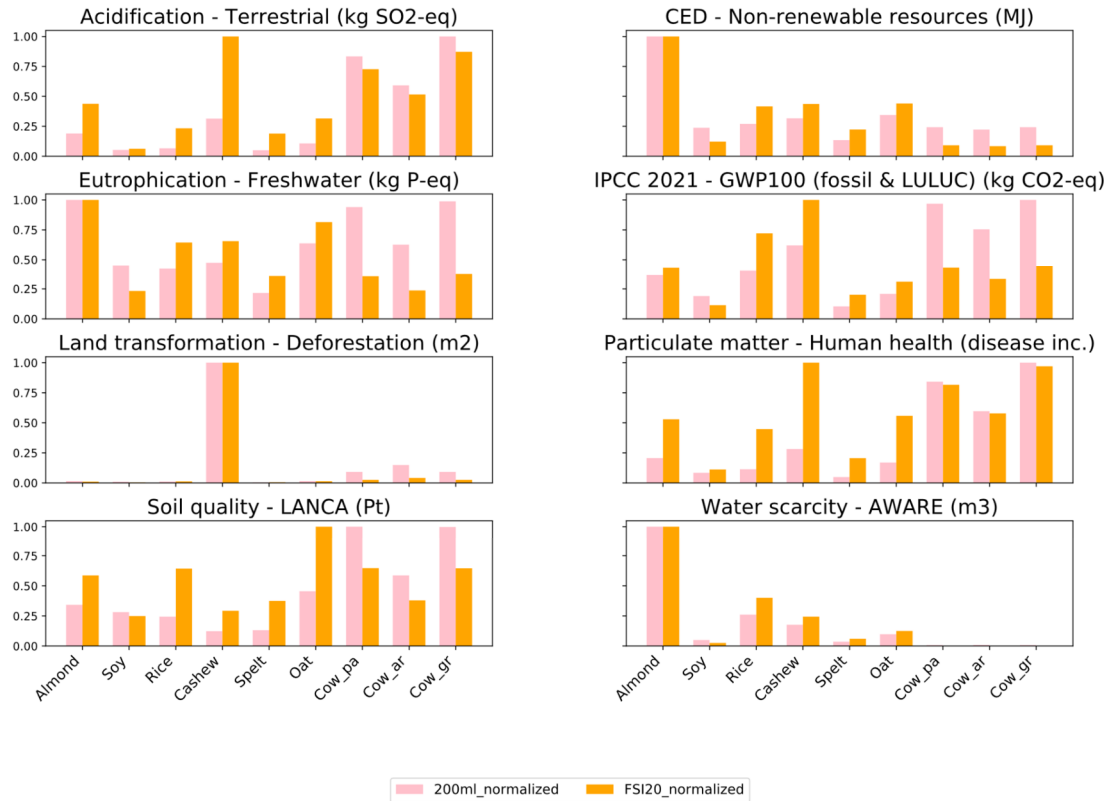


Figure 6: Impacts of drinks on a volumetric (FUS=200ml) vs. nutritional basis (FU= FSI20 nutrient profiling algorithm). Impacts for each category are relative to the maximum value for that impact group, which is scaled to 1.

4 Discussion

4.1 Evaluating environmental and nutritional tradeoffs and synergies

Holistically evaluating the nutritional and environmental dimensions of foods requires assessing tradeoffs and synergies; as no single metric can realistically capture all facets of these areas. Over all of the PBD, soy is the best alternative to cow's milk. For soy drink, environmental impacts are favorable across all categories apart from water scarcity for which it has moderate impacts. Soy drink could be optimized by reducing steam use and or switching to renewable energy sources. Even when considering unfortified amounts, soy still ranks the best out of the PBD. When considering fatty acids and disqualifying nutrients, soy, for most categories, has favorable scores when compared to the other drinks. Furthermore, lysine, an AA of concern because it is predominately found in animals, is only found in adequate amounts in soy drink and cow's milk. One topical issue is the deforestation driven by Brazilian soy production. However, currently, most Brazilian soy is used as animal feed. Despite this, impacts could change drastically if growing demand necessitates soy from Brazil. On an environmental basis, spelt is as strong as soy. Contrastingly, on a nutritional basis, it scores quite poor for most categories when compared directly against cow's milk and would need to be fortified.

The other grain-based drinks, rice and oat, have moderate environmental impacts, on average. Rice has moderate to low nutritional profile scores while oat has moderate environmental scores on average. Rice is characterized by higher water scarcity and GWP impacts, but alternative farming systems could help mitigate this. For instance, alternate wetting and drying can reduce water use when compared to traditional management strategies and result in lower GHG emissions without significantly compromising yields (Leon et al. 2021). Oat drink can reduce impacts via alternative sourcing; for instance, oats produced in Italy

have higher impacts than oats produced in Germany. More insights into the farm level in conjunction with comparative studies across countries could allow for lower impacts in the future, provided the company producing the oat drink has knowledge of its suppliers.

Of the PBD, nuts, on average, have higher environmental impacts and moderate nutrient densities. However, as shown with the uncertainty results for GWP, the impacts of almond can be much lower depending on the modelled value chain. Nuts also have a very high water use; however, a recent study showed that water use can be greatly variable within the nut food group; for example, almond has a much higher water use than other nuts such as chestnuts or walnuts (Vanham et al. 2020; Poore and Nemecek 2018). Since nuts are moderately nutrient dense, efforts could be directed at alternative nut-based PBD with smaller water requirements. This is particularly important, because, at the global scale, 1 in 4 children will live in an area of extreme water stress by 2040 (UNICEF 2020). Relatedly, almond yields can vary quite a lot from country to country (Ritchie et al. 2022) meaning that impacts will likely vary depending on where the almond is sourced from. Overall, cashew has high impacts at the farm level; however, if cashews were grown in low-input systems, as suggested in a previous study (Brito de Figueirêdo et al. 2016), these results could change. This indicates there is justification for companies to incentivize farmers to optimize their cashew farming systems. With respect to nutrition, for many categories of fatty acids or disqualifying nutrients, almond drink scores on the extreme end (either doing much better or worse than other drinks); this greatly increases the difficulty for consumers when assessing tradeoffs across products.

For most environmental impact categories, cow's milk has the highest impacts; on the other hand, it is the most nutrient dense of the investigated beverages. Accordingly, when assessing nutritionally-invested environmental impacts, cow's milk has relatively better profiles. As mentioned, cow's milk from arable land, for many categories, has lower environmental impacts compared to the other cow's milk that is pasture-raised and grass-fed. This leads to tradeoffs for consumers because grass-fed milk is often the more nutritious option (Heins 2021; Nogoy et al. 2022). We also saw a similar outcome for fatty acid profiles, which change depending on the type of feed. As mentioned, higher herbage proportions found in grass-fed and pasture-raised systems led to higher n-3 concentrations and lower SFA concentrations (Table S4). While the differences between our cow production systems were not very high; one study noted that even small differences can be relevant depending on the overall diet of the population (Benbrook et al. 2018). They noted that the small changes in fatty acids were significant because milk is the predominant source of these fatty acids in certain diets, such as in the US, in which fish does not constitute significant enough portions to meet n-3 requirements (Benbrook et al. 2018).

4.2 Future areas of work

There are three areas future work should target to more deeply understand the potential of PBD from an environmental perspective: processing vs. farm impacts, valorization of side streams, and tradeoffs across value chains. First, for many foods, the processing stage for agricultural commodities is either loosely considered or excluded because the impacts are assumed to be low compared to the primary production phase. While many PBD studies find that the farm stage is key differentiator in environmental impacts, the percentage of raw material used in the drink is small and this makes the processing impacts relatively more important for particular impact categories. For instance, in this study, for soy, the combined processing flows for certain impact categories outweighed impacts at the farm level. Other studies have found similar results (Beckerman et al. 2019; Bussa et al. 2020; Winans et al. 2020). Overall, the value chain modelled can greatly affect the relative importance of processing to farm level impacts. Second, the manner in which PBD side streams are utilized and allocated also influences the environmental impact results. This is an open area of research as the PBD market grows. The side streams of most raw material produced for PBD are used for animal feed and sometimes energy; however, there are other options being explored including valorizing their functional nutrient properties. Future work should examine how different valorization options impact results.

Third, the choice of value chain is critical for PBD. For example, while our drinks are all UHT processed, many drinks are still pasteurized. In these cases, the processing impacts are lower while the retail stage

contributes to a much greater extent. Grant and Hicks (2018) found that the largest impact group for most environmental categories was the retail stage because of the electricity needed for refrigeration. Transport assumptions (e.g., air vs freight transport), country of origin, and the influence of switching to renewable energy during PBD processing can also greatly influence results. Formulation is also important; higher base material amounts will lead to higher impacts, but also a higher nutrient density, and the choice of additives and fortification can, albeit to a smaller extent, affect results. For the latter, most studies either estimate or ignore this aspect. In this study, we used estimations based on proxy values of additives and fortifiers in LCA databases, as previously done in other studies (SIK 2013). Alternatively, a report calculated the environmental impacts of fortification based on average impacts from the chemical sector (Bussa et al. 2020). Finally, to more comprehensively assess tradeoffs across alternative value chains, it would be useful to have more company proprietary data. Currently, most input data used in the literature is based on soy, almond, and oat, and this data is often used as a proxy without any changes for other drinks like rice. In this report we calculated specific input data for the other PBD; nevertheless, additional company data could be beneficial, particularly, since processing parameters can vary by factory. As mentioned, we modelled a common value chain for each drink and their associated uncertainty values. However, myriad other value chains are possible. Accordingly, when such data is available a more intensive uncertainty analysis that utilizes software that can account for more flexibility in distribution ranges, should be conducted.

From a nutritional perspective, we considered bioavailability to the extent possible; however, there are still gaps such as interaction factors and the actual effect of fortified foods. Antinutrients such as oxalates or phytate, which can be present in plant-based foods, will decrease the bioavailability of certain nutrients such as calcium, zinc, and iron. Accordingly, vegetarians and vegans may be at a higher risk of this due to the larger proportion of plants in their diets (Schüpbach et al. 2017). On the other hand, with respect to iron, cow's milk has been shown to decrease iron absorption, particularly in children (Ziegler 2011). While we quantified the effect of dietary phytate on zinc; future work should examine the role of other antinutrients. Currently, industry actors are exploring novel PBD processing techniques to remove these antinutrients (Yang et al. 2012). For fortification, certain studies have shown that increases in fortification amounts do not always correlate to the amount in serum levels (Talsma et al. 2016). Lastly, more data is needed to understand interaction effects between individual foods and overall dietary components.

While not quantified in this study, there are two key domains to also consider; namely, antibiotic use and animal welfare. Future studies can quantify the global benefit that PBD adoption would have in these spaces because animal farming is linked to global concerns of antibiotic resistance and zoonotic diseases (Green et al. 2022). Moreover, while health is an important dimension and interlinked with nutrition, its quantification is out of scope for this paper. However, these considerations could lead to different tradeoffs for certain populations (e.g., consumption of certain drinks and increased cancer or cardiovascular risks). Finally, this study predominately focused on adults, however, children have more stringent nutritional requirements. Consequently, cow's milk may be a more ideal option for these populations (Walther et al. 2022).

5 Conclusion

We assessed the environmental and nutritional dimensions of PBD and cow's milk produced in different production systems. Overall, on an environmental basis, PBD show promise to be a more sustainable alternative to cow's milk; in particular, soy and spelt, followed by oat and rice, do well against cow's milk in most environmental categories. This picture is complicated when the nutritional dimension is introduced because cow's milk, overall, scores much better on this basis; however, this is partially diminished by cow's milk higher disqualifying nutrient scores when compared to PBD. Of the PBD, soy has a superior nutritional profile while almond and oat can have moderate nutrient profile scores. Going forward, there are options for industry to improve the environmental profile of PBD by including alternative sourcing from different countries or suppliers, vertically integrating companies to pressure raw material suppliers to pursue more

sustainable farming practices, adopting more sustainable value chains at the processing stage, transitioning to renewable energy, and sourcing raw material within a certain food group that has lower impacts (e.g., replacing almond drink with other nuts that have a lower water footprint).

It is important to remember that replacing cow's milk on a larger scale requires an understanding of group-specific substitution potentials because we want to introduce new, sustainable food products without causing micronutrient deficiencies. Short of doing diet optimizations, which are time consuming, we can use metrics such as the presented FSI20 metric. With regards to the nutritional profiles of the drinks, there are tradeoffs across micronutrients, fatty acids, and disqualifying nutrients. As personalized nutrition becomes more popular, consumers can decide which products suit them best. On the production side, industry can target fortification at products with lower environmental impacts. Going forward, implementing a balanced approach that is mindful of both the nutritional and environmental dimensions can support an optimized integration of PBD in the dairy market.

Acknowledgements

The authors would like to thank Dr. Joseph Dumpler for his support and discussions on cow's milk and plant-based drink processing.

References

- Aydar E.F., Tutuncu S., & Ozcelik B. (2020). Plant-Based Milk Substitutes: Bioactive Compounds, Conventional and Novel Processes, Bioavailability Studies, and Health Effects. *Journal of Functional Foods* 70: 103975. <https://doi.org/10.1016/j.jff.2020.103975>.
- Bär C., Sutter M., Kopp C., Neuhaus P., Portmann R., Egger L., Reidy B., & Bisig W. (2020). Impact of Herbage Proportion, Animal Breed, Lactation Stage and Season on the Fatty Acid and Protein Composition of Milk. *International Dairy Journal* 109: 104785. <https://doi.org/10.1016/j.idairyj.2020.104785>.
- BCG (2023). Taking Alternative Proteins Mainstream. BCG Global. 2023. <https://www.bcg.com/publications/2023/taking-alternative-protein-trends-mainstream>.
- Beckerman, J.P., Blondin S.A., Richardson S.A., & Rimm E.B. (2019). Environmental and Economic Effects of Changing to Shelf-Stable Dairy or Soy Milk for the Breakfast in the Classroom Program. *American Journal of Public Health* 109: 736–38. <https://doi.org/10.2105/AJPH.2019.304956>.
- Benbrook, C.M., D.R. Davis, B.J. Heins, M.A. Latif, C. Leifert, L. Peterman, G. Butler, O. Faergeman, S. Abel-Caines, & Marcin Baranski. (2018). Enhancing the Fatty Acid Profile of Milk through Forage-Based Rations, with Nutrition Modeling of Diet Outcomes. *Food Science & Nutrition* 6: 681–700. <https://doi.org/10.1002/fsn3.610>.
- Brito de Figueirêdo, M. C., Potting, J., Lopes Serrano, L. A., Bezerra, M. A., da Silva Barros, V., Gondim, R. S., & Nemecek, T. (2016). Environmental assessment of tropical perennial crops: the case of the Brazilian cashew. *Journal of Cleaner Production*, 112, 131–140. <https://doi.org/10.1016/j.jclepro.2015.05.134>
- Bussa, M., Eberhart, M., Jungbluth, N., & Meili, C. (2020). Ökobilanz von Kuhmilch und pflanzlichen Drinks. *World Wildlife Fund*, 42. https://www.wwf.ch/sites/default/files/doc-2025-04/2024_LCA_Milch-Drinks_%C3%96kobilanz_Update.pdf
- Bystricky, M., Alig Ceesay M., Nemecek T., & Gaillard G. (2014). Ökobilanz Ausgewählter Schweizer Landwirtschaftsprodukte Im Vergleich Zum Import. *Agroscope Science*. www.agroscope.ch/science

- Carlsson Kanyama, A., Hedin, B., & Katzeff, C. (2021). Differences in Environmental Impact between Plant-Based Alternatives to Dairy and Dairy Products: A Systematic Literature Review. *Sustainability*, 13, 12599. <https://doi.org/10.3390/su132212599>
- Carvalho, L. S., Willers, C. D., Soares, B. B., Nogueira, A. R., de Almeida Neto, J. A., & Rodrigues, L. B. (2021). Environmental life cycle assessment of cow milk in a conventional semi-intensive Brazilian production system. *Environmental Science and Pollution Research*, 29, 21259–21274. <https://doi.org/10.1007/s11356-021-17317-5>
- Douziech, M., Bystricky, M., Furrer, C., Gaillard, G., Lansche, J., Roesch, A., & Nemecek, T. (2024). Recommended impact assessment method within Swiss Agricultural Life Cycle Assessment (SALCA). In *Agroscope Science* 183. Agroscope. <https://doi.org/10.34776/AS183E>.
- Drewnowski, A., Amanquah, D., & Gavin-Smith, B. (2021). Perspective: How to Develop Nutrient Profiling Models Intended for Global Use: A Manual. *Advances in Nutrition*, 12, 609–620. <https://doi.org/10.1093/advances/nmab018>
- EcoTransIT. 2021. EcoTransIT World. EcoTransIT World | (blog). January 19, 2021. <https://www.ecotransit.org/en/>.
- Eurostat. 2022. Road Freight Transport by Type of Goods (2022). https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Road_freight_transport_by_type_of_goods.
- FAO (1998). Integrated production practices of cashew in India - E.V.V. Bhaskara Rao. 1998. <https://www.fao.org/4/ac451e/ac451e04.htm#fn4>.
- FAO (2021). Integration of Environment and Nutrition in Life Cycle Assessment of Food Items: Opportunities and Challenges. FAO. <https://doi.org/10.4060/cb8054en>.
- Ferdouse, J., Silva, B. Q., Baune, M.-C., Terjung, N., & Smetana, S. (2024). Life cycle assessment of hemp-based milk alternative production in Lower Saxony, Germany, based on a material flow analysis of a pilot scale. *The International Journal of Life Cycle Assessment*, 29, 652–668. <https://doi.org/10.1007/s11367-023-02264-9>
- Green, A., Blattmann, C., Chen, C., & Mathys, A. (2022). The role of alternative proteins and future foods in sustainable and contextually-adapted flexitarian diets. *Trends in Food Science & Technology*, 124, 250–258. <https://doi.org/10.1016/j.tifs.2022.03.026>
- Green, A., Nemecek, T., & Mathys, A. (2023). A proposed framework to develop nutrient profiling algorithms for assessments of sustainable food: the metrics and their assumptions matter. *The International Journal of Life Cycle Assessment*, 28, 1326–1347. <https://doi.org/10.1007/s11367-023-02210-9>
- Green, A., Nemecek, T., Smetana, S., & Mathys, A. (2021). Reconciling regionally-explicit nutritional needs with environmental protection by means of nutritional life cycle assessment. *Journal of Cleaner Production*, 312, 127696. <https://doi.org/10.1016/j.jclepro.2021.127696>
- Heins, B. (2021). Grass-Fed Cows Produce Healthier Milk. University of Minnesota Extension. 2021. <https://extension.umn.edu/pasture-based-dairy/grass-fed-cows-produce-healthier-milk>.
- Kogure, M., Nakaya, N., Hirata, T., Tsuchiya, N., Nakamura, T., Narita, A., Suto, Y., Honma, Y., Sasaki, H., Miyagawa, K., Ushida, Y., Ueda, H., & Hozawa, A. (2020). Sodium/potassium ratio change was associated with blood pressure change: possibility of population approach for sodium/potassium ratio reduction in health checkup. *Hypertension Research*, 44, 225–231. <https://doi.org/10.1038/s41440-020-00536-7>
- Kyttä, V., Kårlund, A., Pellinen, T., Pietiläinen, O., Tuomisto, H. L., Kolehmainen, M., Pajari, A.-M., & Saarinen, M. (2023). Product-group-specific nutrient index as a nutritional functional unit for the Life Cycle Assessment of protein-rich foods. *The International Journal of Life Cycle Assessment*, 28, 1672–1688. <https://doi.org/10.1007/s11367-023-02217-2>

- Leon, A., Minamikawa, K., Izumi, T., & Chiem, N. H. (2021). Estimating impacts of alternate wetting and drying on greenhouse gas emissions from early wet rice production in a full-dike system in An Giang Province, Vietnam, through life cycle assessment. *Journal of Cleaner Production*, 285, 125309. <https://doi.org/10.1016/j.jclepro.2020.125309>
- Mäkinen, O. E., Wanhalinna, V., Zannini, E., & Arendt, E. K. (2015). Foods for Special Dietary Needs: Non-dairy Plant-based Milk Substitutes and Fermented Dairy-type Products. *Critical Reviews in Food Science and Nutrition*, 56, 339–349. <https://doi.org/10.1080/10408398.2012.761950>
- Mehner, E., Ehlers, M.-H., Herrmann, M., Höchli, B., Holenweger, G., Mann, S., Messner, C., Nemecek, T., Reguant Closa, A., Schäfer, O., Stämpfli, A., Walther, B., & Douziech, M. (2024). Fleisch- und Milchersatzprodukte – besser für Gesundheit und Umwelt? vdf Hochschulverlag AG. <https://doi.org/10.3218/4194-1>
- Mozaffarian, D., El-Abbadi, N. H., O’Hearn, M., Erndt-Marino, J., Masters, W. A., Jacques, P., Shi, P., Blumberg, J. B., & Micha, R. (2021). Food Compass is a nutrient profiling system using expanded characteristics for assessing healthfulness of foods. *Nature Food*, 2, 809–818. <https://doi.org/10.1038/s43016-021-00381-y>
- Nogoy, K. M. C., Sun, B., Shin, S., Lee, Y., Zi Li, X., Choi, S. H., & Park, S. (2022). Fatty acid composition of grain- and grass-fed beef and their nutritional value and health implication. *Food Science of Animal Resources*, 42, 18–33. <https://doi.org/10.5851/kosfa.2021.e73>
- Pedolin, D., Six, J., & Nemecek, T. (2021). Assessing between and within Product Group Variance of Environmental Efficiency of Swiss Agriculture Using Life Cycle Assessment and Data Envelopment Analysis. *Agronomy*, 11, 1862. <https://doi.org/10.3390/agronomy11091862>
- Poore, J., & Nemecek, T. (2018). Full Excel Model: Life-Cycle Environmental Impacts of Food & Drink Products. <https://ora.ox.ac.uk/objects/uuid:a63fb28c-98f8-4313-add6-e9eca99320a5>.
- Powell, L. L., Capela, J., Guedes, P., & Beja, P. (2023). EU deforestation law overlooks emerging crops. *Science*, 379(6630), 340–341. <https://doi.org/10.1126/science.adf9994>
- Ramsing, R., Santo, R., Kim, B. F., Altema-Johnson, D., Wooden, A., Chang, K. B., Semba, R. D., & Love, D. C. (2023). Dairy and Plant-Based Milks: Implications for Nutrition and Planetary Health. *Current Environmental Health Reports*, 10, 291–302. <https://doi.org/10.1007/s40572-023-00400-z>
- Rementsov, A. N., Egorov, V. A., Vu, F. A., & Antonov, D. V. (2020). Formation of fuel consumption norms for cargo transportation in Vietnam. *IOP Conference Series: Materials Science and Engineering*, 832, 012067. <https://doi.org/10.1088/1757-899x/832/1/012067>
- Ritchie, Hannah, & Max Roser. (2024). Water Use and Stress. *Our World in Data*, February. <https://ourworldindata.org/water-use-stress>.
- Ritchie, Hannah, Pablo Rosado, & Max Roser. (2022). Crop Yields. *Our World in Data*. <https://ourworldindata.org/crop-yields>.
- Romeiko, X. X., Lee, E. K., Sorunmu, Y., & Zhang, X. (2020). Spatially and Temporally Explicit Life Cycle Environmental Impacts of Soybean Production in the U.S. Midwest. *Environmental Science & Technology*, 54, 4758–4768. <https://doi.org/10.1021/acs.est.9b06874>
- Scholz-Ahrens, K. E., Ahrens, F., & Barth, C. A. (2019). Nutritional and health attributes of milk and milk imitations. *European Journal of Nutrition*, 59, 19–34. <https://doi.org/10.1007/s00394-019-01936-3>
- Schüpbach, R., Wegmüller, R., Berguerand, C., Bui, M., & Herter-Aeberli, I. (2015). Micronutrient status and intake in omnivores, vegetarians and vegans in Switzerland. *European Journal of Nutrition*, 56, 283–293. <https://doi.org/10.1007/s00394-015-1079-7>
- SIK (2013). Internal Report for Oatly AB. <https://www.zaailingen.com/wp-content/bestanden/oatly.pdf>.

- Silva, B. Q., & Smetana, S. (2022). Review on milk substitutes from an environmental and nutritional point of view. *Applied Food Research*, 2, 100105. <https://doi.org/10.1016/j.afres.2022.100105>
- Talsma, E. F., Brouwer, I. D., Verhoef, H., Mbera, G. N., Mwangi, A. M., Demir, A. Y., Maziya-Dixon, B., Boy, E., Zimmermann, M. B., & Melse-Boonstra, A. (2016). Biofortified yellow cassava and vitamin A status of Kenyan children: a randomized controlled trial. *The American Journal of Clinical Nutrition*, 103, 258–267. <https://doi.org/10.3945/ajcn.114.100164>
- te Pas, C. & Westbroek C. 2022. LCA of Oatly Barista and comparison with cow's milk. Blonk Consultants. [Link](#).
- Tóth, K., Borbély, C., Nagy, B., Szabó-Szentgróti, G., & Szabó-Szentgróti, E. (2021). Measurement of Food Losses in a Hungarian Dairy Processing Plant. *Foods*, 10, 229. <https://doi.org/10.3390/foods10020229>
- UNICEF. (2020). Water Scarcity. 2020. <https://www.unicef.org/wash/water-scarcity>.
- Vanham, D., Mekonnen, M. M., & Hoekstra, A. Y. (2020). Treenuts and groundnuts in the EAT-Lancet reference diet: Concerns regarding sustainable water use. *Global Food Security*, 24, 100357. <https://doi.org/10.1016/j.gfs.2020.100357>
- Walther, B., Guggisberg, D., Badertscher, R., Egger, L., Portmann, R., Dubois, S., Haldimann, M., Kopf-Bolanz, K., Rhy, P., Zoller, O., Veraguth, R., & Rezzi, S. (2022). Comparison of nutritional composition between plant-based drinks and cow's milk. *Frontiers in Nutrition*, 9. <https://doi.org/10.3389/fnut.2022.988707>
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., ... Murray, C. J. L. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393(10170), 447–492. [https://doi.org/10.1016/s0140-6736\(18\)31788-4](https://doi.org/10.1016/s0140-6736(18)31788-4)
- Winans, K. S., Macadam-Somer, I., Kendall, A., Geyer, R., & Marvinney, E. (2019). Life cycle assessment of California unsweetened almond milk. *The International Journal of Life Cycle Assessment*, 25, 577–587. <https://doi.org/10.1007/s11367-019-01716-5>
- Yang, J., Punshon, T., Guerinot, M. L., & Hirschi, K. D. (2012). Plant Calcium Content: Ready to Remodel. *Nutrients*, 4, 1120–1136. <https://doi.org/10.3390/nu4081120>
- Ziegler, E. E. (2011). Consumption of cow's milk as a cause of iron deficiency in infants and toddlers. *Nutrition Reviews*, 69, S37–S42. <https://doi.org/10.1111/j.1753-4887.2011.00431.x>

6 Supplementary material

6.1 Appendix A: Developing the FSI20 metric

To develop the FSI20 metric, we followed the 'points of differentiation' framework (Green et al., 2023) for nutrient adequacy metrics. This framework includes ten 'points' to incorporate when developing a new profiling system for nutrient adequacy, nutrient quality, and nutrient diversity metrics. A key aim of this framework is to make metrics more comparable and transparent. In Table S1 we explain our rationale for each 'point' in the framework regarding inclusion.

Table S1: Points of Differentiation Framework for the FSI20

No.	Point	Choice	Rationale
1	Weighting	Included	Weighting is based on nutrient deficiencies for an omnivore diet in the Swiss population.
2	Energy standardization	Excluded	Metrics were not energy-standardized to prioritize the identification of micronutrient deficiencies. While standardization facilitates broad comparisons, it can artificially alter nutrient concentrations and reduce the utility of FSI20 metrics for assessing deficiency alleviation.
3	Capping	N/A	No nutrients exceeded 100% of requirements; accordingly, capping was not relevant for this metric.
4	Across-the-board vs. Group-specific	Group-specific	Analysis is constrained to the milk food group.
5	Context- and/or dietary-specific	Both included	Utilization of locally-relevant metrics provides a more accurate reflection of regional conditions and supports the development of concrete, actionable recommendations.
6	Validation	Excluded	Validating novel nutrient metrics for fortified foods needs further research (Green et al., 2023; Mozaffarian et al., 2021) and is thus excluded.
7	Disqualifying nutrients	Excluded	Disqualifying nutrients are assessed via nutrient ratios (e.g., sodium/potassium) rather than as isolated metrics (e.g., sodium) within the functional unit.
8	Reference amount	Serving size	A 200ml serving size is chosen to ensure consistency with the functional unit of the environmental LCA.
9	Selection of nutrients/ingredients	Select nutrients	Included nutrients comprise those associated with known deficiencies and those where the base product (i.e., cow's milk) exceeds a 20% adequacy ratio threshold.
10	Processing quality	Excluded	Omitted due to insufficient data.

For the weighting 'point', we gathered deficiencies for different dietary patterns in Switzerland from a previous study that measured micronutrient statuses with blood and urine samples for participants abiding by omnivore, vegetarian, and vegan diets, with the exception of calcium that was determined via intake data (Schüpbach et al., 2017). We assume these values to be representative for the Swiss population. In this study, we focus on an omnivore diet, because it is the most common dietary pattern and because deficiencies (e.g., vitamin B12, Fe, vitamin B2) that are of concern for plant-based drinks (PBD) were similar across dietary patterns due to supplementation. We use the specified weighting factors for nutrients [i.e., $1/(1 - \text{deficiency})$] instead of directly weighting by the deficiency (i.e., 0.2 for a 20% nutrient deficiency). Such a direct weighting approach will decrease the nutrient amounts and make the metric less comparable to others. We then multiply by our weighting factor; lower values of nutritional deficiencies receive weightings close to 1, meaning the food item does not receive a boost in rankings for this nutrient. Alternatively, nutrients of a high deficiency receive higher weightings.

As mentioned, we want to avoid introducing new deficiencies with the adoption of substitute products (e.g., PBD). Accordingly, we also include nutrients if they have a 20% or higher adequacy ratio in the base product (e.g., cow's milk). For example, cow's milk has an adequacy ratio of over 20% for phosphorus,

calcium, and vitamin B2. Calcium and vitamin B2 are already included in the metrics because these nutrients have associated micronutrient deficiencies, whereas phosphorus does not. Accordingly, we also include phosphorus in the metric, but we do not assign a weighting factor to it. The 20% threshold, which classifies a food as being high in a particular nutrient, was determined based on a USA Food and Drug Administration report (FDA, 2021). This threshold can be updated based on newer scientific evidence.

DRI values are from Switzerland or the DACH region (Germany, Austria, Switzerland) (SSN, 2021a, 2021b) when available; missing values are supplemented from the Institute of Medicine (Institute of Medicine, 2019). Men and women can have different DRI values, thus we calculate these groups separately. For zinc we assume a medium phytate diet. However, in the sensitivity analysis, we show how zinc adequacy values vary depending on the level of phytate in the diet.

In our study, to convert from grams to ml, densities of the raw material were used to calculate a weighted density of the milk product. Densities from the raw plant material were collected from the following literature sources: almond (Aydin, 2003); soybean (Tavakoli et al., 2009); cashew (Nath & Chauhan, 2021); spelt (Krystyna et al., 2018); rice (Bhattacharya, 2013); oat (Shah et al., 2016).

6.2 Appendix B: Processing & uncertainty analysis methodology

Processing inputs were adapted from SIK (2013). For certain steps (e.g., wet milling, UHT, filtering, mixing), the impacts can vary based on the time needed for processing and the weight of the raw material in the product. Data on processing durations are proprietary; accordingly, we adjusted the SIK 2013 values based on the raw material weights in the various milks. Other processing steps (e.g., storage, cooling, filling) were used as is. For cow's milk we considered indirect UHT. Energy use for homogenization was calculated based on Eqn 1. We assumed the drinks were homogenized at scale, and, accordingly, we used the specified parameters for such a setup, as given in a previous study (Bylund 2015). In the absence of specific homogenization data for PBD, we used cow's milk as a proxy. In reality, most PBD may have a lower capacity than cow's milk because the latter likely has more optimized processing lines as it is an older technology. Nevertheless, such an assumption is not expected to strongly influence results.

$$E = \frac{Q_{in} \times (P_1 - P_{in})}{36,000 \times \eta_{pump} \times \eta_{elec.motor}}; Eqn 1$$

E = Electrical effect, kW; Q_{in} = Feed capacity, l/h; P_1 = Homogenization pressure; P_{in} = Pressure to the pump;
 η_{pump} = Efficiency coefficient of the pump; $\eta_{elec.motor}$ = Efficiency coefficient of the electrical motor

For formulation, we estimated added sugar and added salt by subtracting the lowest sugar and salt concentrations per drink in each beverage category from the rest of the drinks in that category. Environmental impacts of sugar and salt generally constitute a minimal proportion of impacts; thus, these estimations were satisfactory for our purposes.

The inventory for spelt cultivation was taken from the SALCA database; pre-processing impacts (e.g., drying and transport) used values for wheat as a proxy. Here, 1 kg of spelt produces 0.75kg of spelt flour and for the uncertainty analysis this value varies based on differences in values to reflect the differences in extraction rates (Heshe et al., 2015). This intermediary product is then transported to the final factory for processing into spelt milk. The inventory for rice cultivation and drying stems from Agri-footprint; transport distances between the farm and first factory are assumed to be the same as for spelt. The electricity needed to mill 1 kg of rice into 0.7 kg of white rice was taken from a previous study (Brodt et al., 2014). This white rice is then transported to the rice milk factory for latter processing. The oat farm and drying inputs are from the Agri-footprint inventory; transport between the farm and the pre-processing factory is assumed to be the same as for spelt.

Inputs needed to create 700 g of oat groats from 1kg of oats were taken from a previous study (SIK 2013); these values then vary based on the hull weight (Girardet & Webster, 2011). The groats are then transported to the final factory and processed into oat milk.

Almonds in this study are cultivated in Italy and Spain but as mentioned, there is no inventory for these countries, so we used the WFLDB global average as a proxy. Next, for pre-processing, inputs needed for hulling and shelling were taken from the WFLDB and the appropriate flows were adapted to the requisite Spanish and Italian contexts. For transport from the preprocessing facility to the almond milk facility, we used distances from Italy and Spain. Cashew impacts, also based on the cashew inventory in WFLDB, were calculated in a similar manner to almond except the coproducts in the cultivation stage were changed to those for cashew; it was assumed that the nut was separated from the rest of the fruit manually in Vietnam. The cashew nut was then shipped via sea to Europe for hulling and shelling. Energy and transport (outside of the transport calculated for shipping and trucking the cashew from Vietnam to Europe) were assumed to be the same as for almond and only the coproduct weights were adjusted. For missing pre-processing data, we calculated the energy needed based on equipment specifications assuming an 80% efficiency, and, in the absence of factory data, that no energy is reused. Lastly, we use the soy inventory for cultivation and drying from Agri-footprint. After harvesting, soy is dried then transported to the soymilk facilities. During pre-processing, steam is used for dehulling. The baseline (Grant and Hicks 2018) and maximum (Development Commission of SMEs, 2003) values were collected from the literature and the minimum was calculated from Grant and Hicks (2018) assuming a lower loss rate. These dehulled soybeans are then processed into soy milk. Data for the cow production systems at the farm and for processing come from previous studies (Bystricky et al., 2014; Chandarana et al., 1984; Keller et al., 2016).

For the uncertainty analysis, additional assumptions were applied to raw material sourcing and transport. In instances where base materials were sourced from two countries, the base scenario assumed a 50% contribution from each. The uncertainty analysis inversely shifted these percentages for Country A and B, ranging from 0% to 100%. Moreover, transport values vary by weight which changes depending on the scenario. Lastly, water use varies depending on the changes in the raw material inputs. When the additive amounts were not specified on the label, as was the case for all ingredients except red algae, we used a baseline value of 0.1%. For the minimum and maximum, we assumed 0.05% and 0.5%, respectively. Finally, to determine nutritionally-invested environmental impacts, we used the FSI20 metric as the functional unit.

Table S2: Production regions for base material

Base Material	Country	Specific Region	Source
Almond	Italy	Gangi, Sicilia	I.Stat, 2024
Almond	Spain	Cordoba, Andalusia	Statista, 2020
Cashew	Vietnam	Binh Phuoc	VEIGO, 2021
Rice	Italy	Vercelli, Piedmont	I.Stat, 2024
Oat	Germany	Ulm & Bremerhaven	USDA, 2022
Oat	Italy	Puglia	I.Stat, 2024
Soy	France	Toulouse	Pitchers et al., 2023
Soy	Italy	Roncajette, Veneto	I.Stat, 2024
Spelt	Switzerland	Plains region	SALCA, 2024
Cow	Switzerland	Variable	SALCA, 2024

6.3 Appendix C: Nutrient variability

Table S3: Fortification of animal and plant milks. [Number] is a count of the sample size.

Beverages	Nutrients fortified
Soy	[1] none [2] vitamin B2, vitamin B12, vitamin D, Ca [3] Ca (red algae) [4] vitamin B2, vitamin B12, vitamin D, Ca [5] none [6] none [7] vitamin D, Ca
Almond	[1] none [2] vitamin B2, vitamin B12, vitamin E, vitamin D, Ca [3] none [4] vitamin B12, vitamin D, Ca
Rice	[1] vitamin E (sunflower oil) [2] vitamin E (sunflower oil), Ca (red algae) [3] vitamin E (sunflower oil), Ca (red algae) [4] vitamin E (sunflower oil), Ca (red algae) [5] vitamin E (sunflower oil)
Cashew	[1] none [2] none
Oat	[1] Ca (red algae) [2] vitamin E (sunflower oil) [3] vitamin E (sunflower oil) [4] vitamin B2, vitamin B12, vitamin D, vitamin E (sunflower oil), Ca
Spelt	[1] vitamin E (sunflower oil)
Cow	[1] none [2] none

Table S4: Influence of herbage proportions (Bystricky et al., 2014) on n-3 and saturated fat contents in cow's milk. Calculated based on fat content of milks in this study. Formulas were derived from data in a previous study (Bär et al., 2020).

Herbage proportion	Nutrient type	Nutrient content (g / 100 g fat)	Herbage type	Production system	g nutrient / 200 ml
5%	n-3	0.69	fresh herbage	arable	0.05
30%	n-3	1.01	fresh herbage	grass	0.07
52%	n-3	1.30	fresh herbage	pasture	0.09
53%	n-3	0.84	total herbage	arable	0.06
90%	n-3	1.30	total herbage	grass	0.09
92%	n-3	1.33	total herbage	pasture	0.10
5%	SFA	61.68	fresh herbage	arable	4.50
30%	SFA	60.59	fresh herbage	grass	4.42
52%	SFA	59.61	fresh herbage	pasture	4.34
53%	SFA	61.20	total herbage	arable	4.46
90%	SFA	59.56	total herbage	grass	4.34
92%	SFA	59.45	total herbage	pasture	4.33

Table S5: Zinc bioavailability in beverages across different diets of variable phytate intake.

Beverage	Males			Females		
	Low phytate diet	Medium phytate diet	High phytate diet	Low phytate diet	Medium phytate diet	High phytate diet
Soy	6.2%	4.9%	4.3%	9.8%	8.6%	6.9%
Almond	2.4%	1.9%	1.7%	3.8%	3.3%	2.7%
Rice	1.0%	0.8%	0.7%	1.6%	1.4%	1.1%
Cashew	5.6%	4.4%	3.8%	8.7%	7.6%	6.1%
Oat	0.5%	0.4%	0.4%	0.8%	0.7%	0.6%
Spelt	1.4%	1.1%	1.0%	2.2%	1.9%	1.6%
Cow	6.4%	5.0%	4.4%	10.1%	8.8%	7.1%

Supplementary references

- Brito de Figueirêdo, M. C., Potting, J., Lopes Serrano, L. A., Bezerra, M. A., da Silva Barros, V., Gondim, R. S., & Nemecek, T. (2016). Environmental assessment of tropical perennial crops: The case of the Brazilian cashew. *J Cleaner Prod*, 112, 131–140. <https://doi.org/10.1016/j.jclepro.2015.05.134>
- Brodth, S., Kendall, A., Mohammadi, Y., Arslan, A., Yuan, J., Lee, I.-S., & Linquist, B. (2014). Life cycle greenhouse gas emissions in California rice production. *Field Crops Research*, 169, 89–98. <https://doi.org/10.1016/j.fcr.2014.09.007>
- Bylund, G. (2015). *Tetra Pak Dairy Processing Handbook*. <https://www.tetrapak.com/insights/handbooks/tetra-pak-dairy-processing-handbook>
- Bystricky, M., Alig Ceesay, M., Nemecek, T., & Gérard, G. (2014). Ökobilanz ausgewählter Schweizer Landwirtschaftsprodukte im Vergleich zum Import. *Agroscope Science*, 2. www.agroscope.admin.ch/science
- Chandarana, D. I., Frey, B. C., Stewart, L. E., & Mattick, J. F. (1984). UHT Milk Processing—Effect on Process Energy Requirements. *Journal of Food Science*, 49(3), 977–978. <https://doi.org/10.1111/j.1365-2621.1984.tb13262.x>
- Development Commission of SMEs. (2003). Soya based food products. <https://www.dcmsme.gov.in/old/publications/pmryprof/food/ch22.pdf>
- FDA. (2021). CFR - Code of Federal Regulations Title 21. <https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/cfrsearch.cfm>
- Girardet, N., & Webster, F. H. (2011). CHAPTER 14 - Oat Milling: Specifications, Storage, and Processing. In F.H. Webster & P. J. Wood (Eds.), *Oats* (Second Edition) (pp. 301–319). AACCI International Press. <https://doi.org/10.1016/B978-1-891127-64-9.50019-1>
- Grant, C. A., & Hicks, A. L. (2018). Comparative life cycle assessment of milk and plant-based alternatives. *Environmental Engineering Science*, 35(11), 1235-1247. <https://doi.org/10.1089/ees.2018.0233>
- Green, A., Nemecek, T., & Mathys, A. (2023). A proposed framework to develop nutrient profiling algorithms for assessments of sustainable food: The metrics and their assumptions matter. *The International Journal of Life Cycle Assessment*, 28(10), 1326–1347. <https://doi.org/10.1007/s11367-023-02210-9>
- Green, A., Nemecek, T., Smetana, S., & Mathys, A. (2021). Reconciling regionally-explicit nutritional needs with environmental protection by means of nutritional life cycle assessment. *Journal of Cleaner Production*, 312, 127696. <https://doi.org/10.1016/j.jclepro.2021.127696>
- Herrmann, M., Mehner, E., Egger, L., Portmann, R., Hammer, L., & Nemecek, T. (2024). A comparative nutritional life cycle assessment of processed and unprocessed soy-based meat and milk alternatives including protein quality adjustment. *Frontiers in Sustainable Food Systems*, 8. <https://doi.org/10.3389/fsufs.2024.1413802>
- Heshe, G. G., Haki, G. D., Woldegiorgis, A. Z., & Gemede, H. F. (2015). Effect of conventional milling on the nutritional value and antioxidant capacity of wheat types common in Ethiopia and a recovery attempt with bran supplementation in bread. *Food Science & Nutrition*, 4, 534–543. <https://doi.org/10.1002/fsn3.315>
- Heuze, V., Thiollet, H., Tran, G., Lessire, M., & Lebas, F. (2017). Soybean hulls. *Feedpedia*. Institute of Medicine. (2019). *Nutrient Recommendations: Dietary Reference Intakes (DRI)*. https://ods.od.nih.gov/HealthInformation/Dietary_Reference_Intakes.aspx
- I.Stat. (2024). Crops: Areas and production—Overall data—Provinces. Crops- Areas and Production. <http://dati.istat.it/Index.aspx?QueryId=37850&lang=en>

- Keller, R., Jungbluth, N., & Eggenberger, S. (2016). Milk processing–life cycle assessment of a detailed dairy model and recommendations for the allocation to single products. ESU Services, Zurich.
- Mozaffarian, D., El-Abbadi, N. H., O’Hearn, M., Erndt-Marino, J., Masters, W. A., Jacques, P., Shi, P., Blumberg, J. B., & Micha, R. (2021). Food Compass is a nutrient profiling system using expanded characteristics for assessing healthfulness of foods. *Nature Food*, 2(10), 809–818. <https://doi.org/10.1038/s43016-021-00381-y>
- Pitchers, J., Ferrand, N., Pull, M., Minette, S., Abella, M., & Debaeke, P. (2023). Opportunities and risks of double cropping in southwestern France with a focus on soybean and sunflower crops. *OCL*, 30, 16. <https://doi.org/10.1051/ocl/2023016>
- Schüpbach, R., Wegmüller, R., Berguerand, C., Bui, M., & Herter-Aeberli, I. (2017). Micronutrient status and intake in omnivores, vegetarians and vegans in Switzerland. *European Journal of Nutrition*, 56, 283– 293. <https://doi.org/10.1007/s00394-015-1079-7>
- SSN (2021a). DACH-Referenzwerte. Société Suisse de Nutrition SSN. <https://www.sge-ssn.ch/grundlagen/lebensmittel-und-naehrstoffe/naehrstoffempfehlungen/dachreferenzwerte/>
- SSN (2021b). Schweizer Referenzwerte. Société Suisse de Nutrition SSN. <https://www.sge-ssn.ch/grundlagen/lebensmittel-und-naehrstoffe/naehrstoffempfehlungen/empfehlungen-blv/>
- Statista (2020). Spain: Almond production per region 2020. Statista. <https://www.statista.com/statistics/765119/production-from-almonds-in-spain-by-community-autonomous/>
- USDA (2022). Crop Production Maps. <https://ipad.fas.usda.gov/ogamaps/cropproductionmaps.aspx>
- VIEGO (2021, August 8). Vietnam Cashew Nuts: A complete guide to cashew market in Vietnam. VIEGO GLOBAL. <https://vieloglobal.com/a-complete-guide-to-cashew-market-in-vietnam/>