Scenarios of large-scale Swedish transition from milk consumption to plant-based milk alternatives

Impact on the environment, food waste and nutrition

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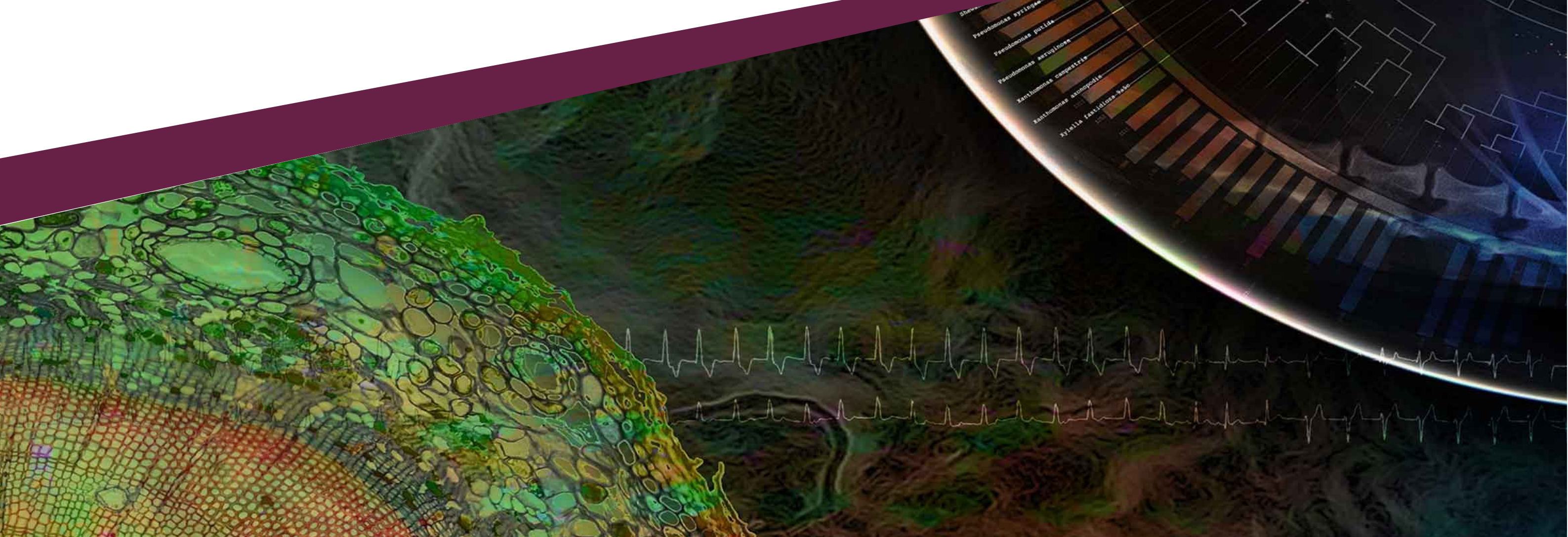

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Abstract

This master's thesis examined whether replacing cow's milk with fortified oat and pea drinks in the Swedish adult diet could make Sweden's food system be in accordance with the planetary boundaries defined in the EAT-Lancet Commission Framework. It also evaluated the nutritional consequences of this dietary substitution. Using life cycle assessment and material flow analysis, three scenarios for transitions with different combinations of oat and pea drinks were modeled and compared to a 2023 business-as-usual scenario for the Swedish adult population. Scenarios were assessed across the six EAT-Lancet Earth system processes (climate change, land-system change, nitrogen cycling, phosphorus cycling, freshwater use, and biodiversity loss), food waste across the supply chain and contributions to nutrient intake.

To support household food waste estimations, a small-scale sensory test was conducted to challenge the maximum drinkability window of the drinks. Household losses were then estimated based on the share of consumers relying on best-before dates (32 %), sensory information such as taste, smell, and appearance (26 %), and handling errors (42 %). These proportions were combined with data on surplus volumes around the best-before date and the outcomes of the sensory test. Oat and pea drinks lasted 20 and 24 days, respectively, after opening, compared to 10 days for fresh milk after opening. Since plant-based milk alternatives are UHT-treated when unopened, they remain stable until opening, while milk is affected by its fresh-product packaging. An analysis of drink losses in the entire systems showed that households were the main contributors to waste, and that total drink losses decreased by 25–30 % when replacing milk with plant-based milk alternatives.

The results showed that all plant-based test-cases had lower impacts on Earth system processes than the dairy-dominated base-case. Annual greenhouse gas emissions decreased from 1.0 to 0.5 Mt CO_2e, land-system change from 150 to 72, 81, and 63 ha, nitrogen application from 35 to 12, 11, and 13 t, phosphorus application from 1.1 to 0.4 kg, freshwater use from 4.1 to 3.3, 2.9, and 3.6 m^3, biodiversity loss from $4.5 \cdot 10^{-7}$ in the base-case to $2.2 \cdot 10^{-7}$ and $2.4 \cdot 10^{-7}$ E/MSY (extinctions per million species-years), in test-cases 1-3, respectively.

When the whole diet was assessed on a per-capita basis and compared to the 2023 global targets, all Earth system processes exceeded the safe limits except for freshwater use. Climate impact reached 2.2 tons of CO_2e per capita, well above the global 0.6 tons of CO_2e target, indicating major overshoot. Land-system change was 0.24 m^2 per capita, exceeding the global 0.16 m^2 target with moderate overshoot. Nitrogen application ranged from 49–52 kg N, far above the global 11 kg N target, and phosphorus application was 4.6 kg P, exceeding the global 1.0 kg P target – both with major overshoot. Freshwater use remained within the safe space at 49 m^3 per capita, below the global 309 m^3 target. Biodiversity loss reached $7.8 \cdot 10^{-9}$ E/MSY, surpassing the global $1.2 \cdot 10^{-9}$ E/MSY target, with major overshoot. As milk alone accounts for a relatively small portion of total dietary emissions, addressing only milk is insufficient; other components of the diet must also reduce their unsustainable resource use.

Substituting milk with oat and pea drinks can be nutritionally viable on a population-level. Oat and pea drinks provided most of the micronutrients typically supplied by milk, in similar amounts, including calcium, vitamin D, vitamin B2, and vitamin B12**.** However, they contained only about half the protein and lacked certain essential amino acids.

Replacing milk with fortified oat and pea drinks improves sustainability and lowers food waste but is not enough to align with planetary boundaries. Achieving this goal will also require broader dietary shifts, technological innovation, and systemic reductions in waste.

Keywords: planetary boundaries, EAT-Lancet Commission framework, milk substitution, milk waste, milk loss, large-scale food transition, plant-based drink alternatives, sustainable diets

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Abbreviations

AGE	Advanced glycation end product
AI	Adequate intake
AR	Average requirement
CO_2	Carbon dioxide
CVD	Cardiovascular disease
E %	Energy percentage
EU	European Union
FAO	Food and Agriculture Organization
FU	Functional unit
GHG	Greenhouse gas
ILCD	International Reference Life Cycle Data
ISO	International Organization for Standardization
IW	In-store waste
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LDL	Low-density lipoprotein
MRP	Maillard reaction product
MFA	Material flow analysis
NNR	The Nordic Nutrition Recommendations
PAR	Provisional average requirement
PW	Pre-store waste
RI	Recommended intake
SBA	Swedish Board of Agriculture
SCB	Statistics Sweden
SFA	Swedish Food Agency
SDG	Sustainable Development Goal
UHT	Ultra-high temperature
WRAP	Waste and Resources Action Programme

1. Introduction

The large scale of unsustainable agricultural production, driven by high demand for resource-intensive foods, such as cow's milk, plays a critical role in the global environmental degradation for the planetary boundaries that the planet must remain within to ensure a stable and resilient planet (Moberg *et al*., 2020; Rockström *et al*., 2009; Richardson *et al*., 2023).

Milk holds cultural importance in Sweden (Martiin, 2024) and has long been promoted as essential for health (Jönsson, 2019). However, the average Swedish diet exceeds safe per capita thresholds by 200 % to 600 % for greenhouse gas (GHG) emissions, cropland use, nutrient application, and biodiversity loss, largely due to animal-based foods like red meat and milk (Moberg *et al*., 2020, p. 1). Milk production also raises ethical concerns related to animal welfare, especially the separation of calves from their mothers (Cook & von Keyserlingk, 2024; Flower & Weary, 2001; Ventura *et al*., 2013;). Moreover, questions are also raised regarding the resilience of dairy systems in food preparedness scenarios (Hedman, 2024).

In response to these concerns, fortified plant-based milk alternatives, such as oat and pea drinks, have gained attention as alternatives to milk. However, substituting milk with plant-based milk alternatives introduces new considerations, such as the presence of anti-nutritional factors (Chalupa-Krebzdak *et al*., 2018; Reyes-Jurado *et al*., 2023; Wu *et al*., 2023; Yu *et al*., 2023) as well as the formation of heat-induced compounds (Pucci *et al*., 2024). They also differ in environmental impact, nutritional profiles, and shelf-life and storage requirements, all of which must be evaluated to understand their overall sustainability.

Alongside the high emissions from milk, dairy systems can support soil carbon sequestration and pasture biodiversity through grazing (Karlsson, 2022), and provide beef as a by-product, giving dairy-based beef systems lower environmental impact compared to beef-only systems (Mazzetto *et al*., 2020; Hietala *et al*., 2021). These are factors that currently influence resource efficiency but may change if milk production declines.

This study investigates the substitution of pasturized, fresh milk with fortified, ultra-high temperature (UHT)-treated plant-based milk alternatives, while considering how they affect environmental impacts, food waste generation and contributions to nutritional intakes at the population level. The plant-based milk alternatives chosen in this study were oat and pea drinks. Oat drinks are well-studied in sustainability research (e.g., te Pas & Westbroek, 2022; Khanpit *et al*., 2024; Kovanen *et al*., 2024; Reyes-Jurado *et al*., 2023). Pea drinks are newer to the Swedish market (Sproud, 2023) but hold particular promise due to planned large-scale domestic production by Lantmännen (2024). Peas as a crop also offer agronomic benefits such as nitrogen fixation, supporting crop rotations and soil health (Buchan *et al*., 2022).

1.1 Aim and research questions

This study investigated whether replacing pasturized, fresh milk with fortified, UHT-treated oat and pea drinks can support a transition toward staying within planetary boundaries at the per capita level, without negatively affecting the possibilities to meet the nutritional recommendations by NNR, using life cycle assessment (LCA) and material flow analysis (MFA). As mentioned, the plant-based milk alternatives chosen in this study were oat and pea drinks.

This aim was achieved by answering the following four research questions:

i. By modeling different scenarios (base-case versus test-cases), which test-case is most in accordance with the EAT-Lancet global environmental targets by Willet *et al*. (2019)?

ii. By modeling different scenarios (base-case versus test-cases), which test-case is most in accordance with the food waste targets in Springmann *et al*. (2018)?

iii. How do differences in sensory shelf-life days between milk, oat drink, and pea drink in the household influence drink loss generation?

iv. What are the potential nutritional implications for the average Swedish adult of transitioning from milk to oat drink and pea drink?

These research questions address the recommendations in a Food Waste Policy Brief published by the Swedish University of Agricultural Sciences to reduce environmental impacts, which emphasize the need to minimize losses from animal-based foods as well as challenge the current fresh-produce norm (Strid, 2019).

1.2 Background

To contextualize the environmental and nutritional considerations and food waste aspects of each drink, the following sections outlines the planetary boundaries and EAT-Lancet recommendations (1.2.1), nutrition (1.2.2), dietary recommendations for milk (1.2.3) and plant-based milk alternatives (1.2.4), the link between food waste, shelf-life and turnover (1.2.5), definitions of food loss and waste (1.2.6), and an overview of the supply chains for each drink, including loss points (1.2.7).

1.2.1 The planetary boundaries and the EAT-Lancet Commission framework

Several studies emphasize that agriculture is an essential driver of multiple planetary boundary transgressions (Moberg *et al*., 2020; Richardson *et al*., 2023; Rockström *et al*., 2009; Springmann *et al*., 2018; Willett *et al*., 2019). The planetary boundaries framework provides a scientific basis for understanding the limits within which humanity can act safely without causing irreversible environmental change. Rockström *et al*. (2009) introduced this concept with the aim of preventing large-scale disruptions to Earth's systems, in which nine planetary boundaries were identified, including climate change, ocean acidification, stratospheric ozone depletion, biogeochemical flows of nitrogen and phosphorus, global freshwater use, land system change, and biodiversity loss. In 2009, Rockström *et al.* (2009) identified three boundaries as transgressed; climate change, biosphere integrity, and biogeochemical flows of nitrogen and phosphorus. By 2023, Richardson *et al.* (2023) updated the framework, finding that six of the nine boundaries had been transgressed due to human activity, with novel entities, land system change, and freshwater use now exceeding safe limits.

Current trends in food consumption and production are expected to further exceed these planetary boundaries considerably (Springmann *et al.*, 2018). Therefore, Springmann *et al.* (2018, Figure 3, p. 552) emphasizes that the food system can only remain within planetary boundaries under the most ambitious scenario; that is, a flexitarian or plant-based diet, the highest level of technological improvements ("Tech+") and a 75 % reduction in food waste ("waste/4").

The EAT-Lancet framework study by Willett *et al.* (2019) is another important piece of research in relation to planetary boundaries and diets. It is among the first attempts to quantify a universal reference diet for nutrition and ecological thresholds in food production. The aim of this framework was to define scientific targets for healthy diets and sustainable food systems that could feed a projected population of 10 billion people by 2050 within planetary boundaries.

Building on the work of Willett *et al.* (2019), Moberg (2022) described the six Earth system processes within the EAT-Lancet Commission framework and the control variables that reflect the environmental pressures from agriculture and food production: GHG emissions (CO_2e) from food production, land use (m^2) of area for crops, nitrogen cycling (kg N) from biological fixation by plants and new reactive nitrogen from the use of mineral fertilizer, phosphorus cycling (kg P) from mineral fertilizer application, freshwater use (m^3) from crop irrigation and animal husbandry, and biodiversity loss (extinctions per million species-years (E/MSY)) from cropland and pasture occupation leading to loss of potential native species of five taxa (plants, amphibians, reptiles, birds, and mammals) (Table A1).

1.2.2 Nutrition

Essential nutrients must be obtained through the diet because the body is either unable to produce them or cannot do so in adequate amounts. Water, vitamins, minerals, proteins, lipids, and carbohydrates are the six main categories of nutrients (Morris & Mohiuddin, 2023). Of the total twenty amino acids, the building blocks of protein, nine must be obtained through the diet since the human body is unable to synthesize them (Lopez & Mohiuddin, 2024). Histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine are among the essential amino acids (Morris & Mohiuddin, 2023; Lopez & Mohiuddin, 2024).

The Nordic Nutrition Recommendations (NNR) serve as the scientific foundation for national dietary guidelines in the Nordic and Baltic countries and includes nutrient recommendations and health and environmental sustainability considerations of foods (Blomhoff *et al*., 2023). Table 1 show the daily dietary requirements for men and women in the Nordics and Baltic countries, their dietary sources, main functions and potential groups at increased risk for deficiencies.

Table 1. Daily dietary requirements according to the guidelines and recommendations proposed by the NNR, with examples of food sources, and potential health risks associated with inadequate intake

Nutrient	Daily requirement	Examples of dietary sources	Main functions	Inadequate intake risk groups
Fat	25–40 E %	Oils, nuts, seeds, dairy, meat	Energy, vitamin absorption	Rare*; Linked to GI
Saturated	< 10 E %	Butter, spreads, tropical oils		
Dietary fiber	≤ 3 g/MJ (RI)	Whole grain, fruits, berries, vegetables, nuts, seeds, pulses, β-glucans	Gut health, satiety, blood sugar/cholesterol	Low-carb diets
Protein	0.66 g/kg (AR)	Meat, fish, milk, eggs, cereals, legumes, nuts, seeds, mycoprotein	Growth, tissue repair, energy	Rare*
Vitamin D	7.5 µg (AR)	Fatty fish, egg yolk, fortified dairy, butter, margarine	Bones, calcium balance, immunity	Low sun exposure; vegans
Vitamin B2	1.3 mg (AR)	Dairy, meat, legumes, almonds, greens, mushrooms, fortified grains	Energy metabolism, cell function	Vegans, elderly
Vitamin B5	4 mg (PAR)	Organ meats, eggs, seafood, cheese, mushrooms, legumes, whole grains, vegetables, nuts	Fat and energy metabolism	Rare*
Vitamin B12	3.2 µg (PAR)	Meat, liver, dairy, fish, shellfish	Nerves, blood cells	Vegans, elderly
Calcium	750 mg (AR)	Milk, dairy, kale, broccoli, calcium-fortified foods	Bones, nerve function	Vegans, women, youth
Phosphorus	420 mg (PAR)	Meat, fish, eggs, dairy, legumes, whole-grain cereals, nuts, seeds	Bones, metabolism, cell structure	Rare*
Potassium	2 800 mg (PAR)	Potatoes, fruits, vegetables, cereals, milk, dairy, meat	Fluid balance, nerve/muscle function	Rare*
Iodine	120 µg (PAR)	Lean fish, dairy (excluding cheese), saltwater fish, eggs, iodized salt, bread	Thyroid hormones	Low intakes of fish and milk
Molybdenum	52 mg (PAR)	Cereals, vegetables, dairy	Enzyme cofactor	Rare*

AR = average requirement, E % = energy percentage, GI = glycemic index, PAR = provisional average requirement, Rare* = rare deficiency in well-balanced diets, RI = recommended intake

It must be noted that NNR use different reference values when they refer to recommendations of intake levels, based on the availability of scientific evidence to establish a precise intake, as well as the required amounts for healthy individuals (Blomhoff *et al*., 2023). Specifically, adequate intake (AI) is intakes based on observed intakes of healthy populations, in which there is not enough scientific evidence to establish a precise recommended intake (RI). RI is the daily intake level considered sufficient to meet the nutrient needs of nearly all (97-98 %) healthy individuals in a population. Average requirement (AR) is the daily intake level estimated to meet the needs of 50 % of a specific population group, used to determine the RI. Provisional average requirement (PAR) is a temporary AR set when data are insufficient for a full AR but with guidance based on available evidence. Lastly, energy percentage (E %) is the proportion of total daily energy intake that comes from a specific macronutrient (for example, fat, carbohydrates, and/or protein) expressed as a percentage of total energy intake (*ibid*.).

1.2.3 Recommendations for milk

The NNR (Blomhoff *et al*., 2023) identifies milk and dairy products as important sources of high-quality protein, calcium, iodine, and vitamins such as B2, B12, and D (when fortified). The recommendation on intake of milk and dairy products across the Nordic and Baltic countries reads: "*… intake of between 350 ml to 500 ml milk and dairy product per day is sufficient to meet dietary requirements of calcium, iodine and vitamin B12 if combined with adequate intake of legumes, dark green vegetables and fish…*" (Blomhoff *et al*., 2023, p. 231). It is also emphasized that small amounts of cheese can replace milk, in which approximately 10–20 grams of cheese can provide a similar calcium content as 100 grams of milk.

The basis for these recommendations from NNR is formulated by Bjørklund Holven and Sonestedt (2023) in a scoping review, in which they support moderate consumption of dairy products, with an emphasis on low-fat and fermented options. Although dairy products account for about half of the saturated fat intake, there is currently insufficient evidence to establish a consistent link between dairy consumption and an increased risk of cardiovascular disease (CVD). Regardless, it is recommended by Bjørklund Holven and Sonestedt (2023) and NNR (Blomhoff *et al*., 2023) as well as in global systematic reviews (Jakobsen *et al*., 2021) that dairy intake should be in low-fat forms in part to limit saturated fat intake to below 10 % of total energy, as advised due to its association with CVD risk.

Low-fat and fermented dairy products (for example, yogurt and cheese) may have favorable effects on cardiometabolic health, including modest reductions in low-density lipoprotein (LDL) cholesterol, blood pressure, and type 2 diabetes risk, and a reduced risk of colorectal cancer (Jakobsen *et al*., 2021). Low-fat dairy products also still provide high-quality protein, calcium, and essential vitamins such as B2, B12, and D. However, evidence linking dairy to increased prostate cancer risk remains limited and uncertain (*ibid*.). It is, however, mentioned in NNR that there is still scientific uncertainty about whether the protective effect of dairy against colorectal cancer stems from the dairy itself or primarily from the ability of calcium to bind bile acids (Blomhoff *et al*., 2023).

1.2.4 Recommendations for plant-based milk alternatives

In the context of transitioning from milk towards plant-based milk alternatives, NNR advises that "…if consumption of milk and dairy is lower than 350 gram/day, products may be replaced with fortified plant-based milk alternatives or other foods…" (Blomhoff et al., 2023, p. 230). However, no specific guideline is provided for individual plant-based milk alternatives, such as oat or pea drinks. Nevertheless, fortification and supplementation are emphasized as critical for individuals adopting plant-based diets, especially regarding calcium, vitamin D, and vitamin B12 (*ibid*.).

In the scoping review by Bjørklund Holven and Sonestedt (2023), it is stated that, compared to milk, plant-based milk alternatives such as those made from soy, oat, almond, rice, and pea typically contain lower levels of several micronutrients and protein. Therefore, in their conclusion, Bjørklund Holven and Sonestedt (2023) urge for a comparison of the health outcomes of plant-based milk alternatives and milk.

Beyond the NNR recommendations, oat drinks are often highlighted in nutritional research for their β-glucan content, a soluble fiber known to support gut health, enhance digestion, and reduce LDL cholesterol levels (Moshtaghian *et al*., 2024; Reyes-Jurado *et al*., 2023). β-glucans have also been associated with a reduced risk of CVD and type 2 diabetes (Paul *et al*., 2020).

1.2.5 The relationship between shelf-life, turnover and food waste

In retail, food waste is often linked to systematic risk factors such as short shelf-life, low turnover, and large minimum order sizes (Eriksson, 2015). Turnover have the largest impact on food waste levels, followed by shelf-life and wholesale pack size (Eriksson *et al*., 2014). Products with low sales volumes are more likely to go unsold, resulting in increased food waste levels. Specifically, the shelf-life of a product refers to the time from production to expiration, while turnover reflects the rate at which a product is sold and replaced (Eriksson, 2015). Consequently, when comparing milk with oat and pea drinks, it is important to acknowledge that milk has a shorter shelf-life but benefits from a high turnover in stores. Therefore, even though oat and pea drinks have a longer shelf-life and this may mitigate food waste at the retail level, the effectiveness to mitigating food waste depends on turnover (Eriksson *et al*., 2014).

1.2.6 Definitions of food waste and loss

Food waste is an urgent key issue within the 17 Sustainable Development Goals (SDGs), specifically under Target 12.3 (UN, 2021). Target 12.3 sets the objective of halving per capita global food waste at the retail and consumer levels by 2030, while also reducing food losses across production and food supply chains, including post-harvest losses. Further, household food waste is a central concern within SDG Target 12.3 and the EU Circular Economy policies (Cicatiello & Giordiano, 2018).

With food waste as an emerging issue, it is estimated by Parfitt *et al*. (WWF-UK, 2021, p. 6) that 40 % or approximately 2.5 billion tons of food are wasted across the global food supply chain. This number challenges the extensively cited 2011 measure of the Food and Agriculture Organization (FAO) of the United Nations, who estimated that one third of food is wasted.

This difference can be explained by the fact that FAO (2019), as well as the European Union (EU, 2008/98) does not consider feed, live animals, or plants still in the field, as food. Furthermore, FAO's Food Waste Index (2019) excludes harvest losses. Parfitt *et al*. (WWF-UK, 2021), on the other hand, includes both harvest and post-harvest losses, and therefore captures a broader range of losses.

Other organizations have developed frameworks for measuring food waste, such as UNEP (2021) and FUSIONS (2014). UNEP (2021) limits its definition to food waste to waste occurring in the final stages of the supply chain (retail, food service and households). This makes them potentially overlooking losses earlier in the supply chain. Consequently, due to varying methodologies across organizations, a common critique of studies estimating food waste is the lack of standardization in food waste frameworks (Hermanussen & Loy, 2024; Gjerris & Gaiani, 2013). When estimating and calculating food waste, it is, therefore, important to note that different studies and organizations use different scopes and definitions.

1.2.7 Milk-, oat-, and pea drink supply chain and losses

This section introduces the supply chains for milk, oat drinks, and pea drinks. Since the feed stage for milk as well as raw oats and peas does not generate any drink losses, these are not examined.

Figure 1 and Table 2 outlines each stage of the milk supply chain, from feed production and on-farm milking to transport, processing, retail, and household storage. Table 2 describes key activities such as automatic milking, pasteurization, and cold-chain distribution, as well as typical loss sources at each stage. Losses stem from factors such as cow health problems, road accidents, and processing-, retail-, and household waste. At retail, the first in-first out principle is applied to guarantee that milk with the shortest shelf-life is sold first (Swedish Food Retailers Federation, 2024).

It is important to acknowledge that a cold chain is essential throughout the milk supply chain to ensure quality and prevent spoilage. On the farm, milk is typically chilled to around 4 °C immediately after milking and stored in refrigerated bulk tanks (Bylund, 2003). During transport, milk is collected in insulated, temperature-controlled tankers and tested for contaminants upon arrival at the processing facility (Bylund, 2003; Henriksson, 2014), with regulations requiring that it be delivered below +10 °C (LRF, 2025). At the processing plant, milk is further cooled to +6 °C and stored prior to pasteurization (Bylund, 2003). At retail, milk is stored in glass-door or open-front refrigerators set at a maximum of +8 °C (Swedish Food Retailers Federation, 2024).

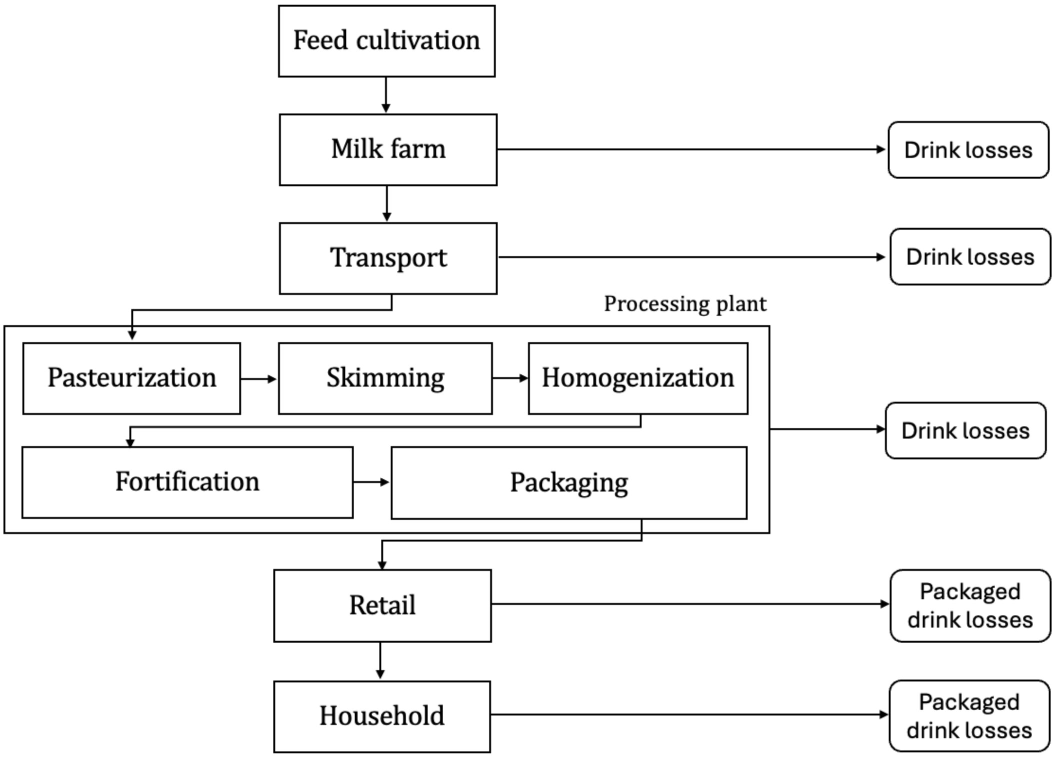

Figure 1. Simplified overview of the milk supply chain and its losses.

Table 2. Overview of the milk supply chain stages, key activities, and common losses

Supply chain stage	Activities	Reason(s) for drink loss
Feed cultivation	Crop production of grains, silage, and supplements (Henriksson, 2014)	–
Milk farm	Automatic milking of Swedish dairy breeds 2–3 times daily (Bylund, 2003; Henriksson, 2014)	Mastitis, lameness, uterine infections treated with antibiotic (Guzman-Luna *et al*., 2022; March *et al*., 2019; Franke *et al*., 2013; SBA, 2022) Equipment failures and washing losses (March *et al*., 2019)
Transport	Temperature-controlled tankers and tested upon arrival for contaminants (Bylund, 2003; Henriksson, 2014)	Road accidents (Sveriges Radio, 2024; Aftonbladet, 2024; Landsbygdensfolk, 2024)
Processing plant	Pasteurization (72 °C for 15–20 seconds, HTST) (Bylund, 2003) Skimming, homogenization, standardization, packaging (Arla, n.d.; Henriksson, 2014)	Skimming, equipment cleaning, fat-content switching, and overproduction or packaging errors (Fisher & Whittaker, 2018)
Retail	Stored in glass-door or open-front refrigerators (Swedish Food Retailers Federation, 2024)	Rejection by retailers (PW) and spoilage on shelves (IW) (Eriksson, 2015)
Household	Transported home without refrigeration Stored in household refrigerators	Expired best-before dates, sensory reasons, package size, difficulty emptying (Williams *et al*., 2020)

Figure 2 and Table 3 outlines the oat drink supply chain from Swedish oat cultivation, to the processing plant, and lastly, to household. After oat harvest, milling is required to remove the husks that are about one third of the mass (Spat Ruviaro *et al*., 2023). Losses during plant processing are assumed to be minimal and mainly related to cleaning and minor ingredient waste (based on assumptions of Oatly, 2023). The reasons for losses at retail and household are assumed to be the same as for milk, except that oat drinks, as well as pea drinks, can be stored at room temperature and kept unrefrigerated until opened, after which refrigeration is required (Dahllöv & Gustafsson, 2008). This is because UHT-treated oat and pea drink, pathogenic microorganisms and spoiling agents are eliminated by this thermal process, allowing the packaged drink to be shelf-stable for more than ten months at room temperature (*ibid*.).

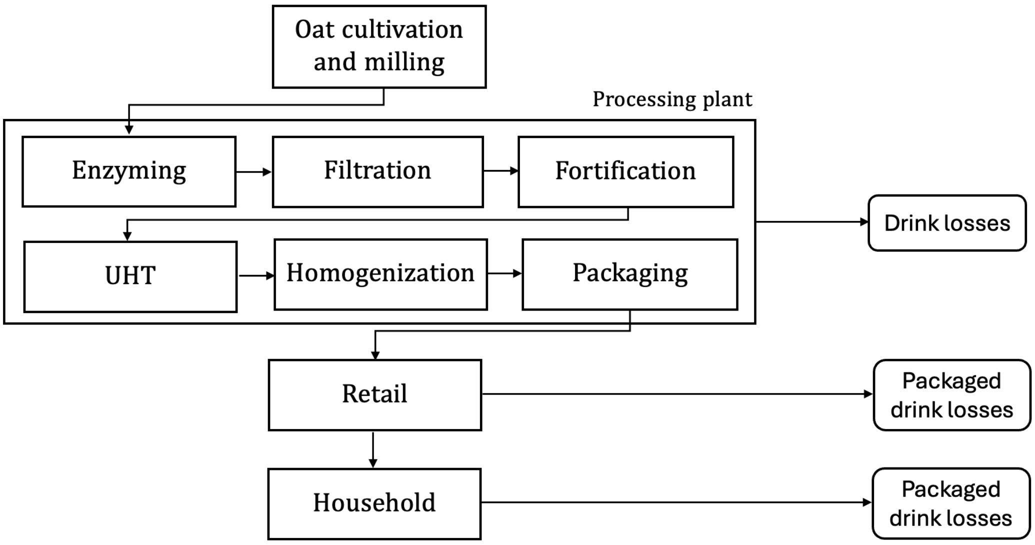

Figure 2. Simplified overview of the oat drink supply chain and its losses

Table 3. Overview of oat drink supply chain stages, key activities, and common losses

Supply chain stage	Activities	Reason(s) for drink loss
Cultivation and milling	Oat cultivation in Sweden Milling – cleaning, dehusking, and heating the oats (Oatly 2023; te Pas & Westbroek, 2022)	–
Processing plant	Mixing oats with water and grinding into slurry Enzyme treatment to convert starches into sugars Filtration to remove insoluble fibers (Dahllöv & Gustafsson, 2008; Oatly, n.d.; te Pas & Westbroek, 2022) Fortification (for example, calcium) (Oatly, n.d.; te Pas & Westbroek, 2022) UHT-treatment for long shelf-life (Dahllöv & Gustafsson, 2008) Homogenization for consistency (Oatly, n.d.)	Minor losses from cleaning and ingredients
Retail	Stored at room temperature (Dahllöv & Gustafsson, 2008)	See milk
Household	Stored at room temperature before opening and requires refrigeration after opening (Dahllöv & Gustafsson, 2008)	See milk

Figure 3 and Table 4 summarizes the pea drink supply chain. In contrast to oat drinks with oats grown in Sweden, oat drinks begins with yellow peas grown in France, and then processed into protein isolate and shipped to Sweden. At the processing plant, the powder is rehydrated and blended with other dry ingredients for fortification. The hydrated drink is then sterilized, UHT-treated, homogenized, and packaged. According to Robertsson (personal communication, 2025), the only waste generated at Sproud's facility consists of residual pea protein that settles at the bottom of the equipment. Since no fiber is filtered out, unlike in oat drink production, processing losses are assumed to be lower. Pea drink storage are assumed to follow the same conditions as oat drink at retail and in household, including room temperature storage until opening, followed by refrigeration.

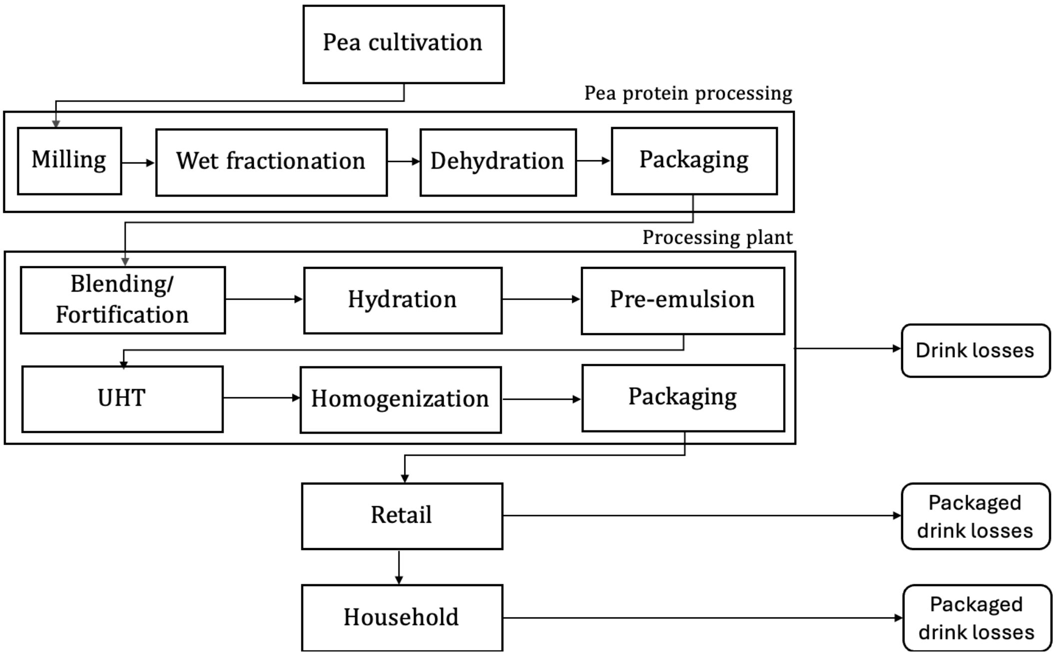

Figure 3. Simplified overview of the pea drink supply chain and its losses

Table 4. Overview of pea drink supply chain stages, key activities, and common losses

Supply chain stage	Activities	Reason(s) for drink loss
Cultivation	Yellow pea cultivation in France (Sproud, 2023)	–
Protein production	Dehulling, splitting, milling into flour Separation of the protein with wet fractionation, spray-drying for dehydration, sieving into a fine powder (Karve, 2018; Lefranc-Millot *et al*., 2018) Transport of the pea protein to Sweden (Sproud, 2023)	–
Processing plant	Blending and weighing of dry ingredients (pea protein, oil, calcium, etc.) Hydration in warm water (around 50 °C) (Roquette, 2022; Khanpit *et al*., 2024)., emulsification, sterilization (around 142 °C), homogenization (Roquette, 2022)	Residual pea protein settling at the bottom of the equipment (Robertsson, personal communication, 2025)
Retail	See oat drink	See milk
Household	See oat drink	See milk

2. Method and material

This study combined two methodological components. First, a sensory study evaluating household shelf-life (Section 2.1), which examined consumer waste patterns of milk, oat drink, and pea drink. Second, a scenario study evaluated the environmental performance and losses of drinks using life cycle assessment (LCA) and material flow analysis (MFA) (Section 2.2).

The following four scenarios were analyzed:

i. Base-case (94 % milk, 6 % oat drink, 0.1 % pea drink) (business-as-usual)
ii. Test-case 1 (35 % oat drink, 35 % pea drink, 30 % milk)
iii. Test-case 2 (70 % oat drink, 30 % milk)
iv. Test-case 3 (70 % pea drink, 30 % milk)

2.1 Sensory study to evaluate household shelf-life

To assess the sensory shelf-life of different drinks, a sensory study was conducted building on Fritz's (2022) study at the SFA. Table 5 compares the methods used in the SFA study and the present sensory study.

Table 5. Sensory criteria and methodology for the sensory study

Category	Swedish Food Agency study	Sensory study
Temperature	+4 °C and +8 °C	+8 °C
Product opening	On best-before date	On best-before date
Test environment	Sensory lab (ISO 8589)	Home refrigerator
Test panel	Trained sensory panel (in terms of sensitivity and vocabulary)	The author of this study
Method	Triangle test (ISO 4120:2021, statistical)	Tasting of daily 50 ml sample
Focus	Detect taste difference from fresh sample	Assess spoilage (sourness, odor, curdling, mold)
Scoring scale	Correct identifications in triangle test ($p < 0.05$ = significant)	Yes/no scale
Sensory critera	Taste, consistency, odor, visual (under red light to mask color)	Taste (sour), odor (sour), consistency (curdled), mold, color
Equipment	Odorless cups with lids, coded samples, red lighting, +22 °C	Regular cups, no blinding
Evaluation methodology	20 minutes at room temperature before testing	Directly from refrigerator

Key differences between the SFA study and the present sensory study include that only one type of drink packaging was tested in this sensory study, and the testing was conducted solely by the author. In the SFA study, noticeable taste changes in milk were observed after 3 days at 8 °C and after 14 days at 4 °C. In contrast, no taste changes were detected in the oat drink at either temperature in this sensory study; however, the experiment by SFA was terminated once the milk had spoiled. Therefore, this sensory study aimed to estimate the sensory shelf-life of oat and pea drinks for Swedish consumers who rely on their senses rather than expiration dates. The sensory study was conducted at a refrigerator temperature of 8 °C and included several drinks: milk with ≤ 0.5 to > 3.0 % fat content, and UHT-treated oat and pea drink with 3.0 % and 2.7 % fat, respectively (Figure 4). These specific fat percentages for oat and pea drinks were selected since they represent the most typical commercially available options in Swedish retails.

Figure 4. The drinks evaluated in the sensory study. From the left: 0.5 % milk, 1.5 % milk, 3.0 % milk, 2.7 % pea drink, and 3.0 % oat drink

To estimate the household waste rate for oat and pea drinks, incoming flow losses at the household level were first calculated from the total 38 200 tons of dairy waste reported by Åkerblom *et al*. (2021, p. 16). These losses were divided across specific dairy categories using proportional data from Torode *et al*. (2023, Table 27, p. 62), relative to the overall Swedish milk system. To apply this rate to oat and pea drinks, the losses were further divided into drink waste behaviors outlined in a study by Williams *et al*. (2020, Table 2, p. 5).

Consequently, to estimate the waste rates based on the shelf-life days for oat oat and pea drinks, a regression analysis was applied following the same principles as the milk model developed by Quested (2013). Using the percentages in Table 14 from Quested (2013, p. 26), the waste reductions could be estimated. For data points beyond day 13, where no waste rates were available, an exponential decay equation was used in Excel to predict the remaining drink loss percentages.

2.2 Scenario study to evaluate environmental performance

This study included a life cycle assessment (LCA)-perspective with a material flow analysis (MFA)-perspective to compare environmental impacts and food waste and loss patterns for milk, oat drink, and pea drink. The LCA evaluated environmental impact across three large-scale transition scenarios (test-cases 1–3) compared to a base-case, while the MFA identified physical flows of where losses occur throughout the supply chains of the three drinks. The analysis focused on the general adult population in Sweden, excluding children. The modeling was done in Microsoft Excel using both primary and secondary data, including sources such as Statistics Sweden (SCB), the Swedish Board of Agriculture (SBA), scientific literature, and databases including Ecoinvent version 3.9.11 (Wernet *et al*., 2016).

LCA is widely used to examine food waste and loss by calculating and assessing the environmental impacts associated with a product or service throughout its entire life cycle (for example, Corrado *et al*., 2017; Kim *et al*., 2020; Mayanti, 2024). The LCA framework consists of four main phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation, as originally established by the International Organization for Standardization (ISO 14040:2006; ISO 14044:2006).

The methodology of LCA has been further elaborated by the European Commission (2010) in a comprehensive ILCD Handbook. Specifically, an LCA begins by defining its system boundaries, such as a cradle-to-grave scope (European Commission, 2010). The next phase, LCI, involves collecting data on emissions and resource use from sources like Ecoinvent, SimaPro, or scientific literature. In the LCIA phase, these data are categorized into environmental impacts, in which normalization and weighting are optional to support interpretation. Interpretation is a continuous process throughout all phases to ensure well-supported conclusions. Normalization involves comparing results to reference values (*ibid.*), such as the planetary boundaries, which is the case of this study.

MFA is a well-known tool in industrial ecology for decision-making processes (Brunner & Rechberger, 2016). As well as LCA, MFA is commonly used to examine food waste and loss by mapping the flow of materials through production and food waste streams (for example, Amicarelli *et al*., 2021; Strid *et al*., 2025), analyzing food waste relative to the inputs and outputs of the system. Flowcharts are commonly used to visualize these flows to provide a clear overview of material inputs, transformations, and outputs across the system (Brunner & Rechberger, 2016). In this study, material flows were visualized using SankeyMATIC (n.d.), a web-based tool developed to generate Sankey diagrams.

2.2.1 Data sources for the Earth system processes

For milk, environmental impact data for all Earth system processes was obtained from Moberg *et al*. (2020). For oat drink, environmental impact data was gathered from impacts per liter at consumer-stage from te Pas and Westbroek (2022), except for biodiversity loss. Biodiversity loss was estimated based on Moberg *et al*. (2020) by scaling the known E/MSY value for milk ($6.4 \cdot 10^{-13}$ E/MSY/kg) according to relative land use, where proportional biodiversity damage was assumed.

As no LCA data currently exist for Swedish pea drinks, their environmental impacts beyond the transport stage were assumed as the same to those of oat drinks as calculated by te Pas and Westbroek (2022) beyond transport from Vic, France to Malmö, Sweden. Emissions specific to pea protein and transportation were modeled using Ecoinvent 3.9.11 datasets.

The full set of data sources for each drink is presented in Table 6. For milk, Moberg et al. (2020) report a freshwater consumption of 0.006 m^3, while te Pas and Westbroek (2022) estimate the total water use at 0.010 m^3, meaning that freshwater accounts for about 60 % of the total. Since te Pas and Westbroek (2022) report a total water use of 0.006 m^3 for oat drink, applying the same ratio would suggest a freshwater consumption of roughly 0.003 m^3. However, this estimate is uncertain and may not accurately reflect actual cultivation and processing conditions.

Table 6. Environmental impact data and sources per kilogram of milk, oat drink and pea drink

	Environmental impact data per kilogram of drink	Source
Milk	Climate change: 1.37 kg CO_2e Cropland use: 2.13 m^2 Nitrogen application: 0.05 kg N Phosphorus application: 0.002 kg P Consumptive freshwater use: 0.006 m^3 Biodiversity loss: $6.4 \cdot 10^{-13}$ E/MSY	Moberg *et al*. (2020)
Oat drink	Climate change: 0.45 kg CO_2e Land use: 0.7 m^2a crop eq. Nitrogen application: 0.7 kg N-eq. (marine eutrophication) Phosphorus application: 0.0006 kg P-eq. (freshwater eutrophication) Consumptive freshwater use: 0.003 m^3	te Pas and Westbroek (2022, p. 84)
Pea drink	Pea protein: Ecoinvent 3.9.11 dataset "Protein pea {FR}| protein pea production | Cut-off, U" (Nemecek, n.d.) Transport France to Malmö: Ecoinvent 3.9.11 "market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 {Europe (RER)}| Cut-off, U" (Valsasina, n.d.)	te Pas and Westbroek (2022); Ecoinvent version 3.9.11

2.2.2 Data sources and assumptions for drink quantity

To estimate milk volumes and losses across its supply chain, data from SCB (n.d.) was used, which reports annual statistics on milk from Sweden delivered to processing plants with an average fat content of 4.26 % and protein content of 3.53 %. In contrast to milk, SCB (n.d.) does not provide any statistical data for oat or pea drink. Obtaining data on oat and pea drink production in Sweden is, therefore, more challenging. Consequently, several assumptions had to be made.

To estimate the amount of oat drink quantity in Sweden, Oatly's 2023 annual report was used. Of the 506 000 tons of oats produced globally, Sweden accounted for around 6 % of Oatly's total revenue (Oatly, 2023). Based on a market share of 45–46 % in Sweden (Affärsvärlden, 2024) and that drinks represent 89 % of turnover, Sweden's total oat drink production was estimated. Oat drinks make up about two-thirds of the Swedish plant-based milk alternative market (Rundgren, 2020).

The number received using Oatly estimations, this aligned with Axfoundation's (n.d.) estimate based on oat okara generation – about two deciliter of oat okara per liter of oat drink, totaling approximately 25 000 tons of oat okara annually.

To estimate the amount of pea drink quantiy in Sweden, data on the volume of pea drink sold in Sweden was obtained via personal communication with the co-founder of Sproud (Robertsson, personal communication, 2025). It was also estimated by Robertsson (personal communication, 2025) that Sproud holds approximately 5 % of the plant-based milk alternative market. In terms of processing, it was stated that no waste occurs. However, this study assumes a small processing loss, slightly below the liquid waste for oat drink production.

In addition, since Sproud (2023) and Roquette (n.d.) both refer to a patented pea protein process, it is assumed in this study that Sproud uses Roquette's NUTRALYS® pea protein isolate.

Regarding turnover rate in the test-cases, it was assumed that oat and pea drink have the same turnover in retail as milk and, therefore, increased pre-store and in-store waste from the base-case. The turnover for milk will unaffected in the test-cases as children will continue to drink milk.

It should be noted that the test cases show the contribution of 150 ml of drinks, which is lower than the recommended amount of milk or dairy per day but reflects the statistics and assumptions described above.

2.2.3 Drink loss accounting

To avoid any confusion, the loss of liquid from its respective supply chain will be refered to as 'drink losses'. For milk, this means that the feed production losses are not accounted for. Similarly, for plant-based milk alternatives, losses during harvest, transport, sorting, and storage of raw oats or peas, as well as pea protein production for pea drink, are excluded. The transport stage for oat and pea drinks is excluded and assumed to fall under pre-store waste (PW), as these drinks do not generate transport-related waste comparable to that of milk. This is consistent with Table 3, 4, and 5 in Section 1.2.7 that exclusively refer to the liquid drink losses, excluding non-liquid wastes. Further, these tables form the basis of the calculation of drink losses.

It should, however, be clarified that emission values used to assess planetary boundary transgressions cover the entire supply chain, whereas the drink losses figures only represent the liquid forms.

2.2.4 Volume-based replacement for nutritional comparison

In the modeled scenarios, milk was replaced by an equivalent volume of oat and pea drinks to allow for a consistent comparison of nutritional intake. To estimate and compare the daily intake of essential nutrients from these drinks against the recommended intake levels of milk established by the NNR (Blomhoff *et al*., 2023), several simplifying assumptions were made. Firstly, it was assumed that the national production volumes reported by SCB reflect consumption levels. Secondly, the study assumed an even distribution of intake across the adult population, meaning that all adults were considered to consume the same volume of milk and plant-based milk alternatives daily. In 2023, Sweden's total population was 10 551 707, of which 2 072 332 were under 18 years old (SCB, n.d.).

2.2.5 Methodology for the planetary boundaries

To contextualize for the GHG emissions from the Swedish diet, this study compared national per capita dietary emissions to global per capita targets aligned with the planetary boundaries for the Earth system processes, based on Moberg *et al*. (2020). Moberg *et al*. (2020) reported a per capita annual limit of 0.67 tons of CO_2e for 2015, assuming a global population of 7.3 billion people. For comparison, the Swedish dietary carbon footprint was obtained from SCB data, similar to the methodology by Moberg *et al*. (2020). In this study, the year 2023 was chosen because it was the most recent year for which SCB provided statistics on different food categories. Consequently, the value for GHG emissions from the Swedish diet was recalculated based on 2023 data. Similarly, the per capita annual limit for 2023 was calculated by adjusting the population growth based on a global population of 8.1 billion.

2.2.6 Exclusion of children from the analysis

Since plant-based milk alternatives may not cover the nutritional needs of young children, as easily as milk, children (age 1–17) were excluded from the analysis of this study. Instead, the study focused on the environmental and waste-related aspects of milk, oat and pea drink for the general adult population. To model milk consumption among children, Swedish demographic statistics and dietary survey data were used. Population data from SCB (n.d.) provided the total number of children by age and gender. The estimates of daily milk intake were derived from dietary surveys conducted by SFA: Riksmaten Small Children 2021–24 (Moraeus *et al*., 2024) for children aged 1.5 and 4, and Riksmaten Adolescents (Moraeus *et al*., 2018) for children aged 11, 14, and 17. Milk intake for the intervening ages was calculated using linear interpolation in Excel.

2.2.7 Functional unit

In this study, the functional unit (FU) was defined as the total annual volume of drinks consumed in Sweden (milk, oat and pea drink), corresponding to 700 thousand tons of drinks. This approach ensured that scenarios were comparable, even though the aim was not to evaluate a single product but to assess the overall environmental impact of different consumption systems at both population and individual levels.

The results were presented in two ways: (1) as population-based emissions to capture the overall environmental impact at the national level, and (2) as per capita per year to allow for comparisons with planetary boundaries and capita-level targets, such as those defined by the EAT-Lancet Commission.

3. Results

This chapter presents the findings of the study, with the following structure: Section 3.1 presents the results for the sensory study, which form the basis for estimating household drink losses in the three transition scenarios. Section 3.2 details the environmental impacts of each scenario, including normalization against the EAT-Lancet Commission framework. Section 3.3 illustrates the total volume of drinks and drink losses across the supply chain stages.

3.1 Sensory study

In the sensory study, changes in taste, smell, and appearance were observed by the author to perform a sensory evaluation. The daily analysis of the drinks required paying close attention to small changes in flavor and texture, especially in the oat and pea drinks, in which spoiling indicators were less noticeable than in milk.

Table 7 summarizes the shelf-life characteristics of milk, oat drink, and pea drink. Before opening, the best-before date was 9 days for milk (Arla, n.d.) compared to 365 days for oat and pea drinks, respectively (Oatly, n.d.; Sproud, n.d.). After opening, milk was recommended for 4–5 days (Arla, n.d.), oat drink for 5 days (Oatly, n.d.), and pea drink for 7 days (Sproud, n.d.). The sensory evaluation indicated that milk could be consumed for 10 days, while oat and pea drinks lasted 20 and 24 days, respectively, based on spoilage indicators such as sour taste, odor, and/or visual changes.

Table 7. Shelf-life days and household waste rate for each product

	Best-before date		Sensory information		Household waste rate
	Shelf-life days before opening	Shelf-life days after opening	Sensory shelf-life days	Spoilage indicator	
Milk	9	4–5	10	Sour taste	3.6 %
Oat drink	365	5	20	Slight sour taste, odor change	2.4 %
Pea drink	365	7	24	Slight sour taste, visual change	2.3 %
Discarding behavior*		32 % of consumers	26 % of consumers		

Discarding behavior* = consumer drink waste behavior data from Williams *et al.* (2020)

Using the methodology described in Section 2.1 to estimate the incoming flow losses at the household, it resulted in a 3.6 % waste rate. The main reasons for discarding milk were expired best-before dates (32 % of consumers), sensory changes (26 %), and "other" factors, including packaging size, difficulty emptying, leftovers, or children refusing to finish (42 %) (Williams *et al*., 2020). When applying these waste behaviors to oat and pea drinks, and accounting for their longer best-before and sensory shelf-lives, it resulted in lower household waste rates than for milk. Specifically, extending the best-before date by one day and sensory shelf-life by 10 days gave oat drink a waste rate of 2.4 %, while extending the best-before date by two days and sensory shelf-life by 14 days gave pea drink a waste rate of 2.3 % (Table 7).

3.2 Environmental impacts of shifting from a dairy-based to a plant-based Swedish milk consumption

This section presents the modeled outcomes of a large-scale transition from milk to oat and/or pea drinks. Table 8 shows the environmental impacts of drink consumption and associated waste across the supply chains for milk, oat drink, and pea drink in each scenario, evaluated against the planetary boundaries defined in the EAT-Lancet Commission framework: climate change, land-system change, nitrogen and phosphorus cycling, freshwater use, and biodiversity loss (Willett *et al*., 2019).

Table 8. Environmental impacts of the total Swedish drink consumption and associated drink losses in each scenario, compared with the planetary boundaries from the EAT-Lancet Commission framework

Earth system process	Climate change	Land-system change	N cycling	P cycling	Freshwater use	Biodiversity loss
Unit	Mt CO_2e	ha	t N	kg P	km^3	E/MSY
Base-case	1.0	150	35	1.1	4.1	$4.5 \cdot 10^{-7}$
Test-case 1	0.5	72	12	0.4	3.3	$2.2 \cdot 10^{-7}$
Test-case 2	0.5	81	11	0.4	2.9	$2.4 \cdot 10^{-7}$
Test-case 3	0.5	63	13	0.4	3.6	$2.4 \cdot 10^{-7}$

When total emissions from drink consumption and waste are assessed for the Swedish adult population, results from test-cases 1–3 show that all Earth system processes were reduced by approximately half compared to the base-case (Table 8). For climate change, measured in megatons of CO_2-equivalents, emissions decreased from 1.0 Mt CO_2e in the base-case to 0.5 Mt CO_2e in each of the test-cases. Land-system change was reduced from 150 ha in the base-case to 72, 81, and 63 ha in test-cases 1, 2, and 3, respectively. Nitrogen application was reduced from 35 tons of nitrogen in the base-case to 12, 11, and 13 tons in test-cases 1, 2, and 3. Similarly, phosphorus application declined from 1.1 kg of phosphorus in the base-case to 0.4 kg in all test-cases. Freshwater use decreased from 4.1 km^3 in the base case to 3.3, 2.9, and 3.6 km^3 in test cases 1, 2, and 3, respectively. Biodiversity loss, expressed as extinctions per million species-years (E/MSY), fell from $4.5 \cdot 10^{-}$

[7] E/MSY in the base-case to $2.2 \cdot 10^{-7}$ E/MSY in test-case 1, and $2.4 \cdot 10^{-7}$ E/MSY in test-cases 2 and 3.

3.3 Implications of the Swedish milk shift for the environmental impact of the total Swedish diet

When the environmental impacts of drink consumption were integrated to the entire Swedish diet and global per capita targets from the EAT-Lancet Commission framework (see Appendix, Table A2), the relative effect of replacing milk with plant-based milk alternatives is small (Table 9). Table 9 presents the environmental impacts of the average Swedish diet in each scenario, benchmarked against the per capita planetary boundaries defined in the EAT-Lancet Commission framework, expressed per capita and per year for the six Earth system processes.

Table 9. Environmental impacts of the average Swedish diet in each scenario, compared to the planetary boundaries in per capita and year defined in the EAT-Lancet Commission framework

Earth system process	Climate change	Land-system change	N cycling	P cycling	Freshwater use	Biodiversity loss
Unit (capita/year)	t CO_2e	m^2	kg N	kg P	m^3	E/MSY
Global target 2023	0.6	0.16	11	1.0	309	$1.2 \cdot 10^{-9}$
Base-case	2.2	0.24	52	4.6	49	$7.8 \cdot 10^{-9}$
% of global target	360 (333–383)	149 (129–177)	464 (321–642)	462 (231–616)	16 (10–40)	634 (6 339–79)
Test-case 1	2.2	0.24	49	4.6	49	$7.8 \cdot 10^{-9}$
% of global target	353 (327–376)	149 (129–177)	445 (308–616)	462 (231–616)	16 (10–40)	634 (6 339–79)
Test-case 2	2.2	0.24	49	4.6	49	$7.8 \cdot 10^{-9}$
% of global target	353 (327–376)	149 (129–177)	444 (307–615)	462 (231–616)	16 (10–40)	634 (6 339–79)
Test-case 3	2.2	0.24	49	4.6	49	$7.8 \cdot 10^{-9}$
% of global target	353 (327–376)	149 (129–177)	445 (307–615)	462 (231–616)	16 (10–40)	634 (6 339–79)

Green: ≤ 100 % of target (within safe space). Orange: 100–200 % (moderate overshoot). Red: > 200 % (major overshoot). Range of uncertainty for the boundaries is given in parentheses, and is based on the range described in Table A1.

Climate change impact, measured in tons of CO_2-equivalents per capita and year, exceeded the global target (0.6 tons of CO_2e per capita and year for 2023) in all scenarios with major overshoot. The base-case was 2.2 tons of CO_2e per capita, corresponding to approximately 360 % (range: 333–383 %) of the global target, while the test-cases also was 2.2 tons of CO_2e per capita, corresponding to approximately 353 % of the global target (range: 327–376 %).

Land-system change remained constant at 0.24 ha per capita and year in the base-case and all test-cases, corresponding to 149 % of the global target of 0.16 ha. This represents a moderate overshoot of the planetary boundary.

Nitrogen cycling showed a decrease from 52 kg of nitrogen per capita and year in the base-case to 49 kg in all test-cases. Despite this reduction, all values remained well above the global target of 11 kg, corresponding to 444–445 % of the boundary and indicating a major overshoot.

Phosphorus cycling was consistent across all scenarios at 4.6 kg of phosphorus per capita and year. This value equates to 462 % of the global target of 1.0 kg, indicating a major overshoot of the safe operating space.

Freshwater use was unchanged in all scenarios, with a value of 49 m^3 per capita and year. This corresponds to 16 % of the global target of 309 m^3, remaining well within the planetary boundary.

Biodiversity loss showed a consistent extinction rate $7.8 \cdot 10^{-9}$ E/MSY, corresponding to 634 % (range: 79–6 339 %) of the global target of $1.2 \cdot 10^{-9}$ E/MSY, considerably overshooting the planetary boundary in all scenarios.

3.4 Large-scale transition scenarios and drink losses

Figure 5 illustrates the base-case supply chains for each drink based on Table A3 in the Appendix, in which milk started at 694 kt and ended with 655 kt consumed, with 34 kt of drink losses. Oat and pea drinks began at 41 kt and ended with 40 kt consumed, with 1 kt wasted. In Figure 5, transport and pre-store waste for milk are excluded, as well as processing and retail losses for oat and pea drinks, due to negligible volumes.

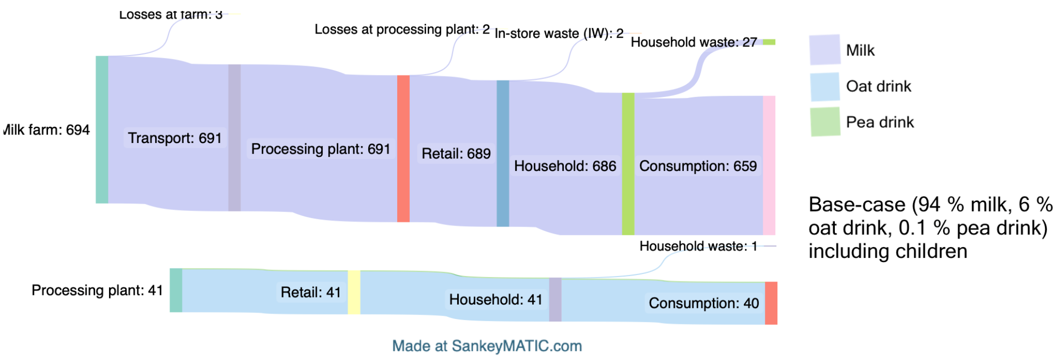

Figure 5. Drink quantity and associated losses in the base-case, presented in kilotons (kt). Top: Milk; Bottom: Oat and pea drink

In the test-cases, the equivalent consumption volume of milk, oat, and pea drinks resulted in a total consumption of 480 kt of drinks for adults. As children were excluded from the analysis based on nutritional considerations and methodology outlined in Section 2.2.6, Swedish children aged 1–17 were estimated to consume approximately 206 kt of milk annually (see Appendix, Table A4). Figure 6 illustrates the large-scale transitions (test-cases 1–3), in which test-case 2 showed the highest volume of losses. In contrast, test-case 3 had the lowest volume of losses. It should be noted that, due to negligible volumes, pre-store waste in all cases, processing losses in test-case 3, as well as losses at transport in the milk supply chain in the test-cases 1–3 for children, were excluded in Figure 6.

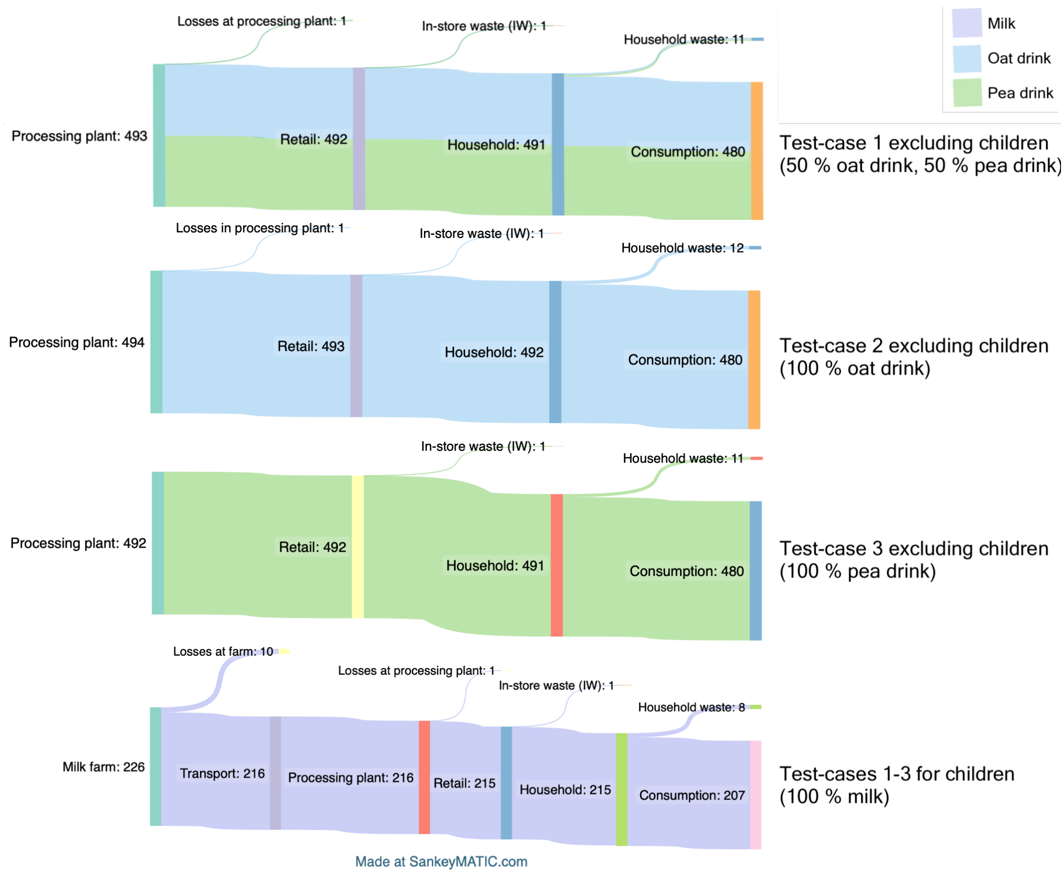

Figure 6. Drink quantity and losses in the test-cases, presented in kilotons (kt). Top: Test-case 1 (50 % oat drink, 50 % pea drink); Upper middle: Test-case 2 (100 % oat drink); Lower middle: Test-case 3 (100 % pea drink); Bottom: Test-cases 1–3 for children (100 % milk)

Table 10 summarizes the total drink losses in the supply chains for each test-case, compared to the base-case. Test-case 3 resulted in the lowest total drink losses at 24 kt per year, showing the greatest reduction at approximately 29 % relative to the base-case. Test-case 1 showed a similar reduction, with total drink losses of 25 kt (-27 %), while test-case 2 had slightly higher drink losses at 26 kt (-24 %).

Table 10. Total drink losses for the scenarios in kilotons (kt), as well as the change of total drink losses from the base-case to the test-cases in percentage (%)

Case	Base-case	Test-case 1	Test-case 2	Test-case 3
Total drink losses (kt/year)	34	25	26	24
Change from base-case	–	-27 %	-24 %	-29 %

3.5 Nutritional profile across the scenarios

Assuming a total adult consumption of 480 kt of drinks, this corresponds to an average daily intake of approximately 150 ml per person. To assess the scenarios, in which adults consume a combination of oat and pea drinks in test-case 1, oat drink in test-case 2, and pea drink in test-case 3, Table 11 compares how well 150 ml of each drink meets the NNR guidelines for nutrient intake, relative to milk in the base-case. The estimated daily contribution of each scenario to energy percentage (E %), average requirement (AR), provisional average requirement (PAR), or recommended intake (RI) is also presented in Table 11. The grey columns indicate the percentage of each nutritional requirement met.

Table 11. Estimated daily nutrient intake for the adult populations from the scenarios

150 ml of drink	Milk – base-case		Oat/pea drink – test-case 1		Oat drink – test-case 2		Pea drink – test-case 3	
Macronutrients								
Protein (g) E %	5	7 %	2	5 %	2	2 %	3	4 %
Fat (g) E %	2	3 %	4	8 %	5	5 %	4	5 %
Carbohydrates (g) E %	7	2 %	7	3 %	11	3 %	3	1 %
Fiber (g) RI	–	–	0.6	2 %	1	4 %	0.1	0.1 %
Micronutrients								
Calcium (mg) AR	186	25 %	180	25 %	180	24 %	180	24 %
Vitamin D (µg) AR	2	20 %	2	22 %	2	22 %	2	22 %
Vitamin B2 (µg) AR	0.2	17 %	0.3	25 %	0.3	24 %	0.3	24 %
Vitamin B12 (µg) AR	0.6	19 %	0.5	15 %	0.4	11 %	0.6	18 %
Vitamin B5 (mg) PAR	0.8	19 %	–	–	–	–	–	–
Phosphorus (mg) PAR	209	40 %	–	–	–	–	–	–
Potassium (mg) PAR	240	9 %	–	–	–	–	–	–
Iodine (µg) PAR	18	15 %	17	14 %	34	28 %	–	–
Molybdenum (µg) PAR	6	11 %	–	–	–	–	–	–

In 150 ml of drink, milk had the highest protein content (5 g, 7 E%), followed by pea drink (3 g, 4 E%). Oat drink had the highest fat (5 g, 5 E%), carbohydrate content (11 g, 3 E%) and dietary fiber (1 g, 4 % of RI).

All drinks contributed with similar amounts of calcium (180–186 mg), covering approximately 24–25 % of the AR. Vitamin D content was equal across all drinks (2 µg), meeting 20–22 % of the AR. Vitamin B2 contributions were were higher in the test-cases (0.3 mg, 24–25 %) compared to milk (0.2 mg, 17 %). Milk and pea drink both provided 0.6 µg of vitamin B12 (18–19 %), while oat drinks contributed less (0.4–0.5 µg, 11–15 %). Iodine content was found in milk (18 µg, 15 %) and in oat drinks (17–34 µg, 14–28 %). Milk was the only drink that supplied vitamin B5 (0.8 mg, 19 %), phosphorus (209 mg, 40 %), potassium (240 mg, 9 %), and molybdenum (6 µg, 11 %).

4. Discussion

This chapter discusses the results presented in Section 3, with the following structure: Section 4.2 discuss how the test-cases affect Sweden's alignment with planetary boundaries. Section 4.3 discuss the nutritional role of milk as well as oat and pea drink in Sweden and its public health implications. Section 4.4 addresses the implications for national food preparedness, and Section 4.5 outlines the limitations of the study.

4.1 Implications for the planetary boundaries

All test-cases resulted in notable reductions in environmental impacts compared to the base-case, particularly in relation to climate change, land use, nutrient pollution, and biodiversity loss (Table 9). Among the scenarios modeled, test-case 3 with pea drink was characterized with the lowest land-use and phosphorus cycling, lowest drink losses and a nutritional profile closest to milk. Therefore, test-case 3 was the most aligned with the EAT-Lancet global environmental targets. In general, all plant-based test-cases performed better than the dairy-based base-case in terms of environmental impacts related to planetary boundaries. However, the test-cases did not substantially reduce the total per capita emissions from food consumption in Sweden in absolute terms and the consumption remained far from meeting global environmental targets. This indicates that limiting milk consumption alone is not enough to align Swedish diets with global standards or that this dietary adjustment is too small to make an impact. This is, however, expected from Figure 4 in Moberg *et al.* (2020), since milk constitutes a relatively small share of total dietary climate impact.

Interestingly, the fact that overshoot for every Earth system process continued at similar levels in all test-cases as in the base-case, even after milk consumption was replaced, underscores a point highlighted by this research: achieving the planetary boundaries described by Springmann *et al.* (2018) requires more than simply replacing milk with plant-based milk alternatives. A full transition toward a flexitarian diet, combined with reduced food waste and improved technologies, is necessary. This study addressed two of these levers (dietary change and food waste reduction) and focused solely on liquid milk.

An important concept to consider is that this study assumes an equal per capita distribution of environmental space. However, this approach may overlook equity and historical responsibility. Lucas *et al.* (2020) argue that allocating emissions equally may be unfair, as it does not account for the greater contributions of high-income countries to environmental degradation. Allocation principles based on historical responsibility and ability to pay would assign considerably smaller environmental spaces to high-income countries (*ibid.*), such as Sweden. Hickel (2020) similarly argues that that equal per capita allocations ignore differences in financial and technological capacity to mitigate environmental degradation, as well as past emissions. Low-income countries, having contributed least to climate change and often facing greater vulnerabilities, would receive a larger share under more equitable frameworks (*ibid*.).

Therefore, under equity-based principles, such as ability to pay or historical responsibility, Sweden would receive a much smaller environmental space. As a result, the overshoot observed in this study would likely be even larger, and the transition scenarios less environmentally sufficient than they appear under equal per capita assumptions.

4.2 Implications for the generated drink losses

In terms of drink losses, test-case 3 with pea drinks achieved a 30 % reduction in total drink losses compared to the base-case (Table 10), but it remained below the 75 % food waste reduction target proposed by Springmann *et al*. (2018). Furthermore, the environmental overshoot that still exists, especially with regard to climate change, nutrient cycling, and biodiversity loss, emphasizes the importance of additional approaches in addition to changes in diets, reduced food waste and advancements in technology (*ibid*.).

When observing the quantity of drink and associated losses in Figure 5 and 6, it is evident that households are the biggest contributors to drink losses. As outlined, Williams *et al*. (2020) found that expired best-before dates is the strongest reason for milk waste. This pattern is consistently observed across several studies (for example, Dey *et al*., 2024; Quested, 2013; Kandemir *et al*., 2022). However, although consumer confusion around date labelling is well documented, producers may be unwilling to revise label formats or address this issue structurally, since reducing food waste could lower product turnover and negatively impact shareholder’s financial interests (Roe *et al*., 2020).

The WRAP Milk Model further emphasizes that short shelf-life, irregular consumption, and over-purchasing, particularly in single-person households, are the substantial drivers of milk waste (Quested, 2013). Similar studies show that poor packaging design can increase drink losses due to difficulty of emptying the package (Nilsson *et al*., 2024), oversized packaging (Williams *et al*., 2020), encouraging over-purchasing and spoilage, as well as fragile packaging, increasing damage-related losses (Hemachandra *et al*., 2024).

Therefore, to increase shelf-life days, packaging innovations have been highlighted as important strategies to mitigate these drink losses (Hemachandra *et al*., 2024; Nilsson *et al*., 2024; Uhlig *et al*., 2025; Williams *et al*., 2020), as well as UHT treated drinks instead of pasteurized and fresh drinks (Nicosia *et al*., 2022; Hemachandra *et al*., 2024). Challenging the ‘fresh food norm’ (Strid, 2019), which refers to the preference for fresh products despite their shorter shelf-life, is central to these efforts. Ambient and frozen products could help households reduce waste and contribute to meeting the food waste reduction targets proposed by Springmann *et al*. (2018). This study did not address the substantial animal losses that occur on dairy farms, where 18 % of annual beef production from female dairy breeds is lost (Strid *et al*., 2023), but this would naturally be in favor of plant-based milk alternatives, since such losses would be completely avoided.

4.3 Implications for health and nutrition

Section 4.3.1 discusses the potential population-level nutritional implications of replacing milk with fortified oat and pea drinks, focusing on the affected nutrients and the role of fortification in ensuring a sufficient intake. Section 4.3.2 discusses the potential formation of heat-induced compounds during UHT processing, and their implications for both nutrient quality and health.

4.3.1 Affected nutrients

Based on the results of this study, the potential population-level nutritional implications of transitioning from milk to oat and pea drink are generally neutral. Fortified plant-based milk alternatives, such as oat and pea drinks, provide essential micronutrients like calcium, vitamin D, vitamin B2, and vitamin B12 that are otherwise supplied by milk. Although these plant-based milk alternatives have lower protein content than milk, overall protein requirements can still be met through a varied diet as can needs of micronutrients less abundant in plant-based milk alternatives.

Fortified oat and pea drinks in the test-cases 1–3 offered several micronutrients in comparable amounts to the NNR guidelines of milk intake (Table 11). For example, calcium and vitamin D levels were similar across all drinks, and oat and pea drinks even slightly exceeded milk in terms of vitamin B2 content. Vitamin B12 content was slightly lower in oat and pea drink. Iodine was present in both milk and oat drinks, but absent in pea drink. In terms of protein, pea drink was most comparable to milk. However, its amino acid composition differs; peas are rich in lysine but low in methionine and cysteine (Bonke *et al*. 2020; Vogelsang-O'Dwyer *et al*., 2021), while oats are low in lysine (Bonke *et al*. 2020). Regarding the other macronutrients, it is worth mentioning that the micronutrient content is identical regardless of fat percentage across milk, oat drink, and pea drink. For example, both 1.5 % and 3.0 % fat drinks contain the same amounts of added vitamins and minerals.

As outlined in the milk guidelines of the NNR (Blomhoff *et al*., 2023), milk is primarily emphasized for its contributions of calcium, iodine, vitamin B12, and high-quality protein. In contrast, the micronutrients absent in oat and pea drinks, (namely, vitamin B5, phosphorus, potassium, and molybdenum) are not mentioned as contributions from milk in the NNR guidelines. Based on the results presented in Table 11 of this study, it can therefore be argued that the main limitation of oat drink in being nutritionally comparable to milk, according to the NNR, lies in its lower protein quality. Similarly, for pea drink, the nutritional comparability is limited by both its lower protein quality and the absence of iodine.

However, to compensate for nutrients no longer supplied by dairy, other food sources, both plant- and animal-based, can be included in the diet, as indicated by Table 1 (Section 1.2.2). For instance, vitamin B5 can be obtained from eggs, seafood, mushrooms, legumes, whole grains, vegetables, and nuts (Blomhoff *et al*., 2023). In terms of the lower protein content in oat and pea drinks compared to milk, general protein requirements can be met through a varied diet that includes meat, fish, eggs, cereals, legumes, nuts, seeds, and mycoprotein (*ibid*.).

Nonetheless, the results of this study suggest that the modeled test-cases could promote proper nutrition for the general adult population, as recommended by NNR (Blomhoff *et al*., 2023). This is further supported by findings from Kovanen *et al*. (2025), who emphasize that fortification improves the nutritional value of plant-based milk alternatives and makes them more comparable to milk in terms of essential nutrients.

It is important to note that the NNR (Blomhoff *et al*., 2023) consider deficiencies of these discussed micronutrients to be rare in the general Swedish population. It is also not optimal to rely on one food product to fulfil the nutrient requirements but to eat a varied diet (Blomhoff *et al*., 2023; Kristersson *et al*., 2017).

In terms of bioavailability of nutrients, both oat and pea drinks are documented to have low bioavailability of nutrients as they contain anti-nutritional compounds such as oxalates, phytic acid, saponins, tannins, cyanogenic glucosides, lectins, and trypsin inhibitors that can hinder protein digestion, reduce mineral absorption and impair gut health (Chalupa-Krebzdak *et al*., 2018; Reyes-Jurado *et al*., 2023; Wu *et al*., 2023; Yu *et al*., 2023). In addition, a study performed on rats found that plant-based milk alternatives can negatively influence satiety and nutrient absorption compared to milk (Wang *et al*., 2022).

However, a number of food processing methods, including fermentation, fortification, and enzymatic treatment, can mitigate the effects of heat-induced compounds and anti-nutrients. Fermentation can reduce phytic acid content, improving mineral bioavailability, while fortification with calcium and other minerals can compensate for potential nutrient losses (Moshtaghian *et al*., 2024).

4.3.2 Heat-induced compounds in UHT-treated plant-based drinks

In contrast to claims of positive health impact from nutrient content, concerns have been raised regarding certain heat-induced compounds in UHT-treated plant-based milk alternatives. A study by Pucci *et al*. (2024) found that UHT oat drinks contained higher levels of α-dicarbonyl compounds compared to UHT-treated milk. These compounds contribute to the formation of advanced glycation end-products (AGEs) and Maillard reaction products (MRPs), including acrylamide, a potentially carcinogenic substance. However, it is important to acknowledge that the results presented by Pucci *et al*. (2024) for all drinks are primarily expressed per gram of protein. This functional unit has the potential to exaggerate the given concentration, especially for low-protein drinks, such as oat drinks. Therefore, even though the consumer consuming oat drink is receiving less total MRP per serving, the same amount of MRPs per 100 ml will appear higher per gram of protein. As an example, LAL (lysinoalanine) in UHT milk was approximately 700 µg, while oat drink contained a range of 210–1 100 µg of LAL.

Pucci *et al*. (2024) also reported that oat drinks with 1.8 %, 1.9 %, and 3.5 % fat contained 0.64, 29.3, and 10.8 µg of acrylamide per 100 ml, respectively. This can be translated to 64, 29, and 10 µg per kilogram, respectively. However, even though oat drinks contain acrylamide, it is important to contextualize these levels. Commonly consumed foods such as French fries (ready to eat), crispbread (soft bread), breakfast cereals and instant coffee contains 500, 50–100, 300–350 and 850 µg acrylamide per kilogram, respectively (Kristersson *et al*., 2017). Therefore, acrylamide concentrations in oat drinks remain far below the levels found in these commonly consumed foods. Maintaining a varied diet is, therefore, important to minimize the intake of potentially harmful substances from any single food item (Kristersson *et al*., 2017). Nonetheless, it is important to further investigate these compounds as new plant-based milk alternatives are developed or if manufacturing processes change.

4.4 Implications for food preparedness

Recent crises, such as the Covid-19 pandemic, geopolitical conflicts such as Russia's invasion of Ukraine, and the escalating effects of climate change contributes to the challenges of sustainable food systems (Lennartsson *et al*., 2024; Swedish Food Federation, 2025). In Sweden, these disruptions have increased the debates about food preparedness in future food supply chains.

As part of Sweden's total defense strategy, the SFA (2021) was tasked by the Swedish government in 2020 to investigate which diet that would meet the nutritional requirements in an increased state of preparedness (The Swedish Civil Contingencies Agency, 2021). The SFA (2021) emphasized that food waste is unavoidable during crises due to electricity outages, transport issues, and the perishability of certain foods. Consequently, they recommended prioritizing long shelf-life staples such as grains, legumes, and preserved goods, while maintaining limited access to fortified dairy and meat products to avoid nutrient deficiencies (SFA, 2021).

However, the complex logistical network of the milk sector is especially fragile (PA Consulting, 2024). Both PA Consulting (2024) and Hedman (2024) stress that milk production depends on an integrated system of diesel, electricity, cold chains, and milk collection every one to two days, making it highly sensitive to disruption.

An interesting observation from the study by Hedman (2024) was that "*...milk is poorly suited for war…*", since during the outbreak of war in Ukraine, dairies were among the first parts of the food system to shut down (p. 31). In contrast, some Swedish farmers considered transitioning towards beef production to be more resilient in crisis situations, as it is less reliant on continuous transport and energy inputs (*ibid*.).

This suggest that the milk system is more vulnerable in crisis scenarios compared to plant-based milk alternatives and underscore the relevance of including plant-based milk alternatives in future food preparedness planning. Facilities for processing peas into protein have not existed previously in Sweden, but such infrastructure is currently under development. Lantmännen is investing in a new protein processing plant to support sustainable Swedish food production (Lantmännen, 2024). The choice of oats and peas in this study was partly based on their potential for Swedish production. Consuming plant-based foods directly, rather than using crops such as legumes for animal feed, is also more resource-efficient (Mottet *et al*., 2017) and can help ensure food sufficiency in times of crisis.

Moreover, shelf-stable plant-based milk alternatives such as oat and pea may offer logistical advantages, such as reduced reliance on cold chains and daily transport. This aligns with the recommendation to shift from fresh to storable products in order to reduce food waste, as emphasized in the Policy Brief by Strid (2019).

4.5 Implications for allocation for milk and meat in life cycle assessment

Integrating beef and milk in LCA is crucial to accurately capture environmental trade-offs and avoid misleading conclusions, especially when considering shifts in consumer demand, such as moving toward plant-based milk alternatives, which could unintentionally increase emissions related to beef if not taken into account. Mazzetto *et al*. (2020) performed an attributional LCA for beef-only systems and dairy-based beef systems. In their study, it was found that beef-only systems generally have higher environmental impact than dairy-based beef systems, primarily because suckler cows used in beef-only systems rear calves without co-producing milk, leading to higher emissions solely allocated to meat. In contrast, dairy-based systems share emissions between milk and meat and receive "credits" from beef output (p. 4). They also highlight that European beef, which is more reliant on dairy systems, generally is more climate-efficient than Latin American beef, which depends heavily on suckler herds (Mazzetto *et al*., 2020). In a Finnish context, Hietala *et al*. (2021) similarly found that dairy-based beef systems had lower environmental impact than beef-only systems.

However, Porto Costa *et al*. (2023) highlights the limitations of attributional LCA in capturing the full environmental consequences of changes within food systems, particularly when comparing beef-only systems to dairy-based beef systems. Porto Costa *et al*. (2023), therefore, highlight consequential LCA as the better LCA methodology in capturing cause-effect relationships and system-changes, such as how higher milk yields would require fewer dairy cows. Specifically, higher milk yields could reduce the number of dairy cows, and thus reduce beef co-production, and, therefore, lead to greater reliance on high-emission beef-only systems. Therefore, improvements in dairy efficiency might be partly offset by increased emissions from beef-only farms (*ibid*.). This means that attributional LCA can underestimate the true environmental impacts because it allocates emissions instead of modeling these system-changes.

4.6 Study limitations

This section outlines the main study limitations of the study. Section 4.6.1 addresses the potential bias on personal sensory judgments without a standardized test panel. Section 4.6.2 highlights data gaps, including the absence of specific LCAs, production data, and trade statistics for the studied drinks. Section 4.6.3 addresses the assumptions made about national consumption patterns and per-capita intake. Section 4.6.4 emphasizes the variability and constraints of the data sources used to estimate consumption and household food waste. Finally, Section 4.6.5 discusses the exclusion of upstream losses, such as harvest losses, which may lead to underestimation of total food waste associated with drink production.

4.6.1 Sensory study limitations

A major limitation of the sensory study lies in the absence of an objective test panel. The evaluation of spoilage was based solely on personal sensory judgments (taste, smell, and appearance) rather than a standardized or blinded sensory protocol involving multiple assessors, as done in Fritz (2022). This introduces the possibility of subjective bias. Given the context of the thesis, in which plant-based milk alternatives are examined for possible nutritional and environmental benefits, the results could have been impacted by unintentional preferences or expectations. Due to the absence of validation, generalizing the results is limited. However, for the purpose of indicating values to calculate losses in this thesis, this limited sensory study provided a better estimate than no data at all.

In future research, using an standardized sensory panel would improve the reliability and scientific accuracy of similar case studies, enabling more accurate household waste data for consumers relying on sensory information.

4.6.2 Lack of data

The lack of a LCA for pea drinks made and marketed in Sweden is a major research limitation. Unlike oat drinks, for which several Swedish-specific LCAs exist (for example, Dahllöv & Gustafsson, 2008; te Pas & Westbroek, 2022), no such LCA currently exists for Swedish pea drink production. As a result, this study relied on the results for oat drinks by te Pas and Westbroek (2022) beyond transport from France, while emissions specific to pea protein and transportation were modeled using Ecoinvent 3.9.11 datasets, as outlined in Section 2.2.6. Consequently, the data of oat drinks by te Pas and Westbroek (2022) may not be representative for pea drinks, as they differ in ingredient characteristics, energy inputs, and processing techniques at the processing plant. Due to these variations, the environmental effects of pea drinks may be misrepresented.

Another example of lack of data relates to the national data of milk production. The national data of milk production lack foreign trade data (SCB, n.d.). Consequently, foreign trade data cannot currently be used to determine actual consumption levels. In this study, imported and exported milk volumes were not estimated. This decision was made primarily to maintain clarity and feasibility within the study's scope of a Swedish setting. Estimating trade volumes would have introduced additional assumptions and uncertainties.

An additional data limitation lies in the absence of public national data on oat drink production volumes, in which the scenarios for oat drink were built on assumptions derived from financial reports by the Oatly (2023). However, Robertsson (personal communication, 2025) at Sproud estimated that Sproud holds approximately 5 % of the plant-based milk alternative market, as outlined in Section 2.2. In this study, Sproud's market share was estimated to 1.5 %, which, despite the uncertainty, falls within a reasonable range and supports the general validity of the study's assumptions.

4.6.3 Uncertainty in assumptions

Another important limitation of this study lies in the assumptions made when modeling nutrient intake from milk and oat and pea drinks. Specifically, it was assumed that national production volumes of milk (as reported by SCB), oat drink, and pea drink reflect actual consumption patterns in the Swedish adult population. This study assumes that all adults consume 150 ml of drink per day, distributed according to the market shares in each scenario (that is, 94 % milk, 6% oat drink, and 0.1 % pea drink in the base-case). In reality, intake varies widely between individuals and groups as consumption is influenced by habits, preferences, availability, and cultural factors (Fernqvist *et al*., 2024). Moreover, people do not drink the same volume every day, nor do they follow fixed proportions. This study also does not consider individual differences in nutrient absorption, which can vary both between people and over time (Morand *et al*. 2020). Nonetheless, this simplification made it easier to compare the nutritional value of each drink in a clear and consistent way for the general Swedish adult population. It helps show how nutrition might change in different replacement scenarios, but the results should be seen as rough estimates and not as exact predictions.

4.6.4 Uncertainty in data

An important limitation of this report is its reliance on specific data sources for estimating drink consumption and related losses, as shown in Table A2 in the Appendix. This is particularly critical for the incoming flow losses for the household stage, which represents the largest contributor to overall drink losses. In this study, household milk waste was estimated using a study by Åkerblom *et al.* (2021). Their study aimed to quantify food waste disposed of via household drains over the course of one year in Sweden. Data were collected through a paper-based survey involving 583 households, who self-reported the amount of edible and drinkable items poured down the drain during a four-day period (*ibid.*). However, as household food waste behavior may vary depending on season and consumer behavior (Aitken *et al.*, 2024), a four-day measurement may not fully reflect this behavior long-term. Moreover, self-reporting introduces several challenges, including the risk of self-selection bias, underreporting or underestimation of waste, and the possibility that the diary keepers are unaware of waste generated by other household members (Amicarelli & Bux, 2021; Gray, 2009).

In addition to these methodological limitations, the uncertainty surrounding household food waste is further emphasized by the wide variation in estimates from other studies, which report household milk losses ranging from 3.3 % to 20 % of retail-purchased milk (Williams *et al.*, 2020; Quested, 2013; Kandemir *et al.*, 2022; Guzmán-Luna *et al.*, 2022; Stankiewicz *et al.*, 2019). Using higher estimates from these studies would have led to assumptions of greater milk waste and larger environmental impacts.

Despite these limitations, the study by Åkerblom *et al.* (2021) was selected due to its Swedish context and its standing as one of the most comprehensive and widely recognized assessments of household food waste in Sweden. Despite the inherent limitations, the estimate may be considered reasonable since the household milk waste rate applied in this report, 3.6 %, is within the range established by the larger literature.

4.6.5 Scope of drink losses

As outlined in Section 2.2.3, non-drink losses, such as harvest losses were excluded. This scope may underestimate the total food waste associated with drink production. As mentioned in Section 1.2.6, Parfitt *et al.* (WWF-UK, 2021) highlights that post-harvest losses can represent a substantial share of total food system inefficiencies. Nevertheless, including these losses was methodologically challenging and ultimately not feasible within the scope of this study.

In general, harvest losses are more difficult to monitor consistently due to variability in data quality and reporting practices, compared to other stages in the food supply chain (WWF-UK, 2021). Harvest losses are also rarely linked directly to the volume of final processed drink. Due to these limitations, the considered drink losses in this study aligns more with the narrower definitions of food waste used by FAO (2019), the EU (2008), UNEP (2021), and FUSIONS (2014), which also exclude pre-harvest and early-stage losses. Nonetheless, future studies could benefit from expanded system boundaries that also capture upstream losses to provide a more comprehensive picture of the environmental footprint of drink production, following the approach of Parfitt *et al*. (WWF-UK, 2021).

5. Conclusions

Among the modeled scenarios, test-case 3 with pea drink aligned most closely with the EAT-Lancet global environmental targets by Willett *et al*. (2019). However, in all scenarios, several planetary boundaries remained exceeded, which demonstrates that replacing milk with plant-based milk alternatives alone is insufficient to bring Sweden within safe environmental limits.

When comparing scenarios to the food waste reduction targets in Springmann *et al*. (2018), test-case 3 again performed best, as pea drink had the longest post-opening sensory shelf-life of 24 days, reducing its probability of being discarded for sensory reasons compared to both oat drink and milk.

A transition of consumption milk with fortified plant-based milk alternatives represents a meaningful step toward improved sustainability and reduced food waste, but it cannot, on its own, achieve alignment with planetary boundaries. Achieving alignment with planetary boundaries will require a combination of strategies, including broader dietary shifts, improved technologies, and major reductions in food waste across the food system.

Differences in sensory shelf-life strongly influenced drink losses at the household level. Milk and oat drink showed shorter sensory shelf-lives, resulting in higher probabilities of discard once opened. In contrast, pea drink's longer sensory shelf-life reduced its expected household losses, making it the most favorable option from a food waste perspective.

Transitioning from milk to oat and pea drinks would lead to lower intakes of protein and some vitamins and minerals (notably vitamin B5, phosphorus, potassium, iodine, and molybdenum). However, these deficits are unlikely to pose a major risk for the general population, as they can be compensated through other dietary sources.

Although six planetary boundaries have already been transgressed, this study shows that there is still room for action through meaningful changes in how food is produced, consumed, and managed.

Future research should build on the findings of this study by conducting broader assessments that encompass a full transition away from the entire dairy system, including cheese, butter, cream, and milk powder, as well as the animal based food system more broadly. Such studies are essential to evaluate whether plant-based dietary patterns can remain within planetary boundaries while also meeting nutritional requirements.

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Populärvetenskaplig sammanfattning

Denna masteruppsats undersökte om Sverige kan minska sina utsläpp av växthusgaser, markanvändning, kväve- och fosforutlakning, vattenanvändning, biodiversitetsförluster samt sitt matsvinn genom att ersätta komjölk med havre- och ärtdryck för den vuxna befolkningen, och samtidigt upprätthålla en likvärdig näringsprofil som mjölk erbjuder. Studien jämförde därför miljöpåverkan och dryckessvinn från odling till konsumtion i hushållet i tre olika scenarier med olika sammansättningar av havre- och ärtdryck med ett basscenario från 2023 där mjölk dominerar.

För att uppskatta hushållens dryckessvinn bland konsumenter som inte strikt följer bäst före-datum utan i stället förlitar sig på sina sinnen, genomfördes en fallstudie. I denna fallstudie bedömdes hållbarheten hos öppnade förpackningar av mjölk, havre- och ärtdryck baserat på smak, doft och utseende. Fallstudiens resultat visade att havredryck kunde konsumeras i upp till 20 dagar, ärtdryck i 24 dagar, medan mjölk endast höll i 10 dagar.

Resultatet för dryckessvinn genom hela livsmedelskedjan för respektive dryck visade att scenariot med 100 % ärtdryck genererade det lägsta svinnet – cirka 30 % mindre än i basscenariot – vilket innebar att det också krävde minst primärproduktion.

Vad gäller miljöpåverkan visade resultaten att växtdrycker generellt minskade mjölkens påverkan med ungefär hälften i samtliga miljökategorier, förutom vattenanvändning. När dessa förbättringar ställdes i relation till miljöpåverkan från hela det svenska livsmedelssystemet var dock förändringen obetydlig. Detta visar att enbart minskad mjölkkonsumtion sannolikt inte är tillräcklig för att Sverige ska kunna hålla sig inom de planetära gränserna, eller att en förändring av denna storlek är för liten för att ge en mätbar effekt.

Ur ett näringsperspektiv visade studien att berikade växtdrycker kan vara ett likvärdigt alternativ till mjölk, eftersom växtdrycker tillför flera livsviktiga näringsämnen, såsom kalcium, vitamin D, vitamin B2 och vitamin B12. Samtidigt krävs en varierad kost för att säkerställa näringsbalans.

En slutsats av studien är att även om en övergång till växtbaserade drycker och minskat dryckessvinn kan bidra till att minska miljöpåverkan, är det inte tillräckligt för att ensamt åstadkomma en hållbar livsmedelskonsumtion inom planetens gränser. För att uppnå detta krävs flera åtgärder; framför allt teknologiska förbättringar och bredare kostförändringar mot ett mer växtbaserat innehåll.

Framtida forskning bör undersöka en större omställning, och inte bara av mjölk utan även av andra mejeriprodukter som ost, smör och grädde, och i förlängningen hela livsmedelssystemet, för att se om växtbaserade kostmönster både kan vara hållbara och näringsmässigt fullvärdiga.

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Appendix 1

Table A1 shows the six Earth system processes within the EAT-Lancet Commission framework and the control variables that reflect the environmental pressures from agriculture and food production, adapted from Moberg (2022). The ranges in the parentheses represent the uncertainty intervals for each boundary.

Table A12. The global planetary boundaries for the Earth system processes, adapted from Moberg (2022, p. 36), based on the EAT-Lancet Commission framework (Willett et al., 2019)

Earth system process	Control variable	Global boundary	Uncertainty range	Explanation of indicator
Climate change	GHG emissions	5.0 Gt CO_2e/ year	4.7–5.4 Gt CO_2e/year	GHG emissions from food production
Land use	Area of land used for crops	13 million km^2/year	11–15 million km^2/year	Use of crops for animal feed and plant-based products
N cycling	N application	90 Tg N/ year	65–130 Tg N/year	N from biological fixation by plants and new reactive N from the use of mineral fertilizer
P cycling	P application	8 Tg P/ year	6–16 Tg P/ year	P from mineral fertilizer application
Freshwater use	Volume of water consumed	2 500 km^3/year.	1 000–4 000 km^3/year	Decreased streams due to surface and groundwater utilized for crop irrigation and animal husbandry
Biodiversity loss	Rate of species extinctions	10 E/MSY	1–80 E/MSY/ year	Cropland/pasture occupation leading to loss of potential native species of five taxa (plants, amphibians, reptiles, birds, mammals)

Appendix 2

Table A2 present the global per capita planetary boundary targets for 2015 (obtained from Moberg *et al*., 2020) and 2023. The boundary for climate change has decreased slightly due to global population growth, from 0.67 tons of CO_2e per capita in 2015 (based on a population of 7.3 billion people) to 0.62 tons of CO_2e per capita in 2023 (based on a population of 8.1 billion people).

Table 13. Environmental impacts of the average Swedish diet, benchmarked against per capita boundaries for the control variables given in the EAT-Lancet Commission framework, presented in per capita and year

Earth system process	Target 2015	Sweden 2015	% of target (2015)	Target 2023	Sweden 2023	% of target (2023)
Climate change	0.67 t CO_2e	2.2 t CO_2e	327 (303–348)	0.62 t CO_2e	2.2 t CO_2e	360 (334–383)
Land-system change	0.2 m^2	0.3 m^2	188 (163–223)	0.16 ha	0.24 ha	149 (129–177)
N application	0.012 kg N	57 kg N	467 (323–646)	0.011 kg N	52 kg N	464 (321–642)
P application	0.001 kg P	5.0 kg P	455 (227–607)	0.001 kg P	4.6 kg P	462 (231–616)
Freshwater use	336 m^3	55 m^3	16 (10–40)	309 m^3	49 m^3	16 (10–40)
Biodiversity loss	$1.3 \cdot 10^{-9}$ E/MSY	$8.3 \cdot 10^{-9}$ E/MSY	600 (75–6 000)	$1.0 \cdot 10^{-9}$ E/MSY	$7.9 \cdot 10^{-9}$ E/MSY	634 (80–6 339)

Green: ≤ 100 % of target (within safe space). Orange: 100–200 % (moderate overshoot). Red: > 200 % (major overshoot). Range of uncertainty for the boundaries is given in parentheses

Appendix 3

Table A3 outlines the incoming flow losses of drink losses in the supply chain for milk, oat drink, and pea drink.

Table 14. Incoming flow losses at each step of the supply chain for milk and oat and pea drinks

	Incoming flow losses (%)	Source
Milk		
Milk farm	0.406	According to SBA (2022, p. 30), 0.4 % of losses on-farm is due to antibiotics. Washing losses is included (0.06 %), excluded by SBA (2021)
Transport	0.006	Estimation from Swedish articles (Sveriges Radio, 2024; Aftonbladet, 2024; Landsbygdensfolk, 2024)
Processing plant	0.25	Fisher and Whittaker (2018, p. 25) estimated that 0.2 % of drink loss is due to skimming, while equipment washing, line changeovers, product rejections are not quantified, but stated them to be small
Retail	PW: 0.002; IW: 0.2	Eriksson (2015, Table AII.2, p. 86).
Household	3.6	The total 38 200 t of dairy waste reported by Åkerblom *et al*. (2021, p. 16) was redistributed across specific dairy categories using proportional data derived from Torode *et al*. (2023, Table 27, p. 62)
Oat drink		
Processing plant	0.4	Estimations from Oatly (2023; 2024)
Retail	PW: 0.019; IW: 0.255	Eriksson (2015, Table AII.2, p. 86).
Household	2.4	Sensory study
Pea drink		
Processing plant	0.2	Estimations from Sproud (Robertsson, personal communication, 2025)
Retail	PW: 0.019; IW: 0.255	Eriksson (2015, Table AII.2, p. 86).
Household	2.3	Sensory study

Appendix 4

Table A4 presents milk consumption by Swedish children by age and gender, along with population numbers and total annual consumption.

Table 15. Number of boys and girls, their daily and annual per capita milk intake, and total annual milk consumption, presented in megatons (Mt) by gender group

Age	Persons (n)	ml/person/day	L/person/year	Mt/year
Boys				
1	54 656	102	37	2
2	59 590	137	50	3
3	59 738	209	76	5
4	60 841	280	102	6
5	61 868	291	106	7
6	62 147	303	111	7
7	64 316	314	115	7
8	63 867	326	119	8
9	64 411	337	123	8
10	64 107	349	127	8
11	64 510	360	13	8
12	64 086	387	141	9
13	66 753	413	151	10
14	65 019	440	161	10
15	64 719	403	147	10
16	63 863	367	134	9
17	63 509	330	120	8
Girls				
1	49 529	102	37	2
2	51 734	137	50	3
3	56 987	209	76	4
4	56 325	280	102	6
5	57 292	277	101	6
6	58 427	274	100	6
7	58 765	271	99	6
8	60 842	269	98	6
9	59 634	266	97	6
10	64 201	263	96	6
11	60 425	260	95	6
12	61 237	247	90	5
13	60 809	230	85	5
14	63 107	220	80	5
15	61 503	180	71	4
16	60 996	160	61	4
17	60 280	140	51	3
Total				207

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