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Life Cycle Assessment of Novel Bread Containing Upcycled Apple Pomace

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Abstract

This study evaluates the life cycle environmental impacts of producing rye bread containing upcycled apple pomace (AP) and compares the results with those of conventional rye bread. A comparative, attributional life cycle assessment (LCA) was conducted using six ReCiPe 2016 midpoint indicators and a cradle-to-bakery-gate system boundary. Two functional units were applied: 1 kilogram of bread and 100 grams of dietary fiber.

For the 1-kg functional unit, two allocation approaches for AP were modeled: zero-burden and mass-based allocation. For the dietary-fiber functional unit, the two allocation approaches were combined with upper and lower estimates of AP fiber content from the literature, resulting in four scenarios. Across all 1-kilogram scenarios, the AP bread showed lower environmental impacts than the reference rye bread. The largest reductions occurred under the zero-burden scenario. For the dietary-fiber functional unit, all scenarios also resulted in environmental reductions except one: the combination of low fiber content and mass-based allocation for AP production, in which freshwater eutrophication and water consumption increased slightly.

A national-scale estimate suggests that valorizing the approximately 9.1 tonnes of AP generated annually in Sweden could replace ingredients in roughly 114,000 loaves of bread and prevent 15.5 tonnes of ingredient use, leading to notable reductions in global warming potential, land use, and water consumption. The study's results indicate that incorporating upcycled AP into bread production offers meaningful environmental benefits and supports broader goals related to circular food systems, food loss and waste reduction, and Swedish food security.

Keywords

life cycle assessment, novel food, waste valorization, upcycling, apple pomace, EPD environmental product declaration, PCR product category rules, SimaPro, circular economy, IVL Swedish Environmental Research Institute.

Sammanfattning

Denna studie utvärderar miljöpåverkan från produktion av rågbröd som innehåller återbrukade äppelpressrester (AP) genom en livscykelanalys och jämför resultaten med konventionellt rågbröd. En jämförande, attributionell livscykelanalys genomfördes med sex midpoint-indikatorer enligt ReCiPe 2016 och med systemgränsen vagga till bagerigrinden.

Två funktionella enheter tillämpades: 1 kilogram bröd och 100 gram kostfiber. För den funktionella enheten 1 kilogram bröd modellerades två allokeringmetoder för AP: nollfördelning av miljöpåverkan och massbaserad allokering. För den funktionella enheten kostfiber kombinerades dessa två allokeringmetoder med övre och nedre uppskattningar av fiberinnehållet i AP baserat på litteratur, vilket resulterade i fyra scenarier. För samtliga scenarier med den funktionella enheten 1 kilogram uppvisade brödet med AP lägre miljöpåverkan än referensbrödet. De största minskningarna observerades i scenariot med nollfördelning av miljöpåverkan. För den funktionella enheten kostfiber resulterade samtliga scenarier i minskad miljöpåverkan, med ett undantag: kombinationen av lågt fiberinnehåll och massbaserad allokering för AP-produktionen, där sötvatteneutrofiering och vattenförbrukning ökade något.

Av de cirka 9,1 ton AP som årligen genereras i Sverige skulle valoriseringen komma att kunna ersätta ingredienser i omkring 114 000 brödlimpor och minska användningen av ingredienser med cirka 15,5 ton. Detta skulle leda till betydande minskningar av klimatpåverkan, markanvändning och vattenförbrukning. Resultaten indikerar att användning av återbrukade äppelpressrester i brödproduktion ger väsentliga miljöfördelar och bidrar till cirkulära livsmedelssystem, minskat matsvinn och stärkt svensk livsmedelsförsörjning.

Nyckelord

livscykelanalys, innovativa livsmedel, avfallsvalorisering, upcycling, äppelpressrester, miljövarudeklaration, produktkategoriregler, SimaPro, cirkulär ekonomi, IVL Svenska Miljöinstitutet

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I would like to express my sincere appreciation to my life partner Simon Söderholm, friends, and family for their unwavering support throughout my entire education. I look forward to all that awaits us as we step into the next chapter together.

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Ivana Šarić Söderholm

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List of Abbreviations

AP	Apple pomace
APB	AP bread
EPD	Environmental Product Declaration
FAO	Food and Agriculture Organization of the United Nations
FLW	Food losses and food waste
GHG	Greenhouse gases
GWP	Global warming potential
HF	Higher fiber content
IPCC	Intergovernmental Panel on Climate Change
IVL	Swedish Environmental Research Institute
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LW	Lower fiber content
MA	Mass-based allocation up until the apple pomace collection stage
RB	Rye bread
SDG	Sustainable Development Goal
UN	United Nations
ZB	Zero burden until the apple pomace collection stage

1

Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), the world's leading research body for assessing climate change causes and consequences, climate change impacts are currently straining global food security and agricultural stability (IPCC, 2023). The climate and the food system are mutual influential systems; rising temperatures, increasing climate extremes, and altered hydrological patterns degrade ecosystems and their food-providing services (ibid), while the growing food production and its associated transport and market activities, including food losses and waste (FLW), account for 34% of greenhouse gas (GHG) emissions (Crippa et al., 2021). The food system's impact on the climate and environment extends far beyond its own degradation. It is the largest single driver of biodiversity loss, responsible for around 80% of global biodiversity decline, and consumes up to 70% of the world's freshwater resources (UN Food Systems Coordination Hub, 2023). Agriculture alone occupies 44% of Earth's habitable land (OWID, 2024) and drives roughly 75% of global deforestation (OWID, 2021).

Approximately one-third of all food produced globally is wasted or lost each year (FAO, 2019), accounting for approximately 8-10% anthropogenic GHG emissions (IPCC, 2019). The associated environmental impacts not only include the waste destination but also the embedded impacts in the previous life cycle stages, such as in the cultivation and production stages (FAO, 2019). In Sweden alone, FLW amounted to 1.3 million tonnes in 2023 (Livsmedelsverket, 2024). This indicates that a substantial portion of the food sector's already significant environmental impact is avoidable, but also that reducing this waste represents a highly effective strategy for

mitigating climate change (IPCC, 2019). In response, the valorization of food industry by-products through innovative approaches, such as upcycling, has gained increasing attention (Aschemann-Witzel et al., 2023). Food upcycling is closely aligned with circular economy principles, involving redirecting edible by-products, that would otherwise be wasted, back into human consumption. Moreover, it aligns with the UN Sustainable Development Goals (SDG) 12.3 to halve FLW across the supply chain by 2030, and SDG 12.5 for a substantial portion to be reduced via prevention, reuse and recycling (UN, n.d). Furthermore, upcycling foods is consistent with Sweden’s national food strategy that aims to increase food availability through FLW reduction (Livsmedelsverket et al., 2018).

One promising example of a food by-product with high potential for valorization is AP generated from apple juice production (Gómez & Martinez, 2018). AP has traditionally been considered waste and is largely used as animal feed in Sweden. However, it contains important nutritional properties, including high concentrations of dietary fiber and antioxidants, suggesting that it could be better utilized for human consumption instead. Furthermore, integrating AP into commonly consumed products could represent a meaningful step toward decreasing environmental impacts through sustainable ingredient use, decreasing reliance on primary agricultural inputs, as well as reducing FLW. Currently, in the project “Blood & Turnip” they are partaking in, the Swedish Environmental Research Institute (IVL) is exploring Swedish industrial food side streams with untapped potential in upcycling these into products for human consumption. One novel product they are looking to develop is rye bread containing AP residue. To evaluate the environmental sustainability of the AP bread, a comparative (LCA) will be performed against a benchmark rye bread with a similar ingredient profile, to assess the environmental benefits of substituting conventional ingredients.

1.1 Aim and Objective

This thesis explores the potential of upcycling AP residue to reduce environmental impacts in food production, using its incorporation into bread as a case study. Specifically, it investigates the environmental trade-offs associated with replacing traditional bread ingredients with AP, assessing the balance between decreased agricultural impacts and potentially increased impacts from processing AP from waste into a viable ingredient.

IVL has an interest in aligning the LCA as closely as possible with Environmental Product Declaration (EPD) requirements. Accordingly, the EPD rules have influenced the methodological approach, although only to the degree that they align with the core purpose of this study. The results of this work may later serve as a basis for developing a complete EPD for the product.

To fulfill the aim and objective, the following research question will be answered in the thesis:

R1: What are the life cycle environmental impacts of producing industry-scale rye bread containing upcycled AP?

R2: Using a generic rye bread recipe as a representative example, how do the novel bread's environmental impacts compare to those of conventional bread types?

2

Background

This chapter establishes the conceptual and theoretical framework for the study. Food loss and waste are discussed since apple press residues currently constitute a waste stream, and to contextualize the global and Swedish food waste problem. As terminology for food waste varies across the literature and stages of the supply chain, the concepts and definitions applied in this report are clarified. The concept of food upcycling is then introduced as a potential solution to food waste. Data on Swedish apple press residues are reviewed to quantify flows and assess their nutritional composition, emphasizing their potential as food ingredients and determining fiber content for subsequent use in the LCA. An accessible overview of the LCA methodology is provided, followed by a review of previous LCA studies on bread and baked goods, including those incorporating upcycled side streams.

2.1 Food Loss and Waste

There is no consensus in the literature on how FLW, food loss (FL) and food waste (FW) should be defined due to its complexity (FAO, 2019). Some parameters include whether inedible food should be included, if food diverted to alternative uses such as animal feed constitutes loss or waste, and which parts of the value chain are being referred to. The present study adopts the FAO's (2019) definitions of FLW, FW, and FL:

1. FLW encompasses all food initially intended for human consumption but lost across the entire supply chain;
2. FW is limited to losses occurring at the retail, food service, and consumer levels;
3. FL loss refers to losses occurring upstream in the production and post-harvest stages.

Furthermore, all three concepts consider food to be lost or wasted as soon as it is diverted from human consumption. In this report, food loss (FL) is the focal point seeing that the targeted AP is a bi-product currently treated as waste during the processing stage of apple beverage production.

A knowledge gap remains regarding where and why food is lost or wasted globally, as well as the magnitude of these losses (ibid). As mentioned previously, a rough approximation suggests that of all food produced annually, the global FLW amounts to around one-third and FL approximately 14%. In Sweden, the distribution between FL and FW is 30% and 70%, respectively (Naturvårdsverket, 2024). With Sweden's 2023 FLW totaling 1.3 million tonnes, this means roughly 400,000 tonnes are lost early in the agricultural steps each year. Food lost in the beginning stages of the supply chain carry embedded valuable inputs such as land, water, fertilizers and energy (UFA, 2020). Repurposing these FLs would spare those inputs from being lost.

2.2 Food Upcycling

According to the Upcycled Food Association (ibid), a food product can be considered upcycled if it

1. contains ingredients that would otherwise have gone to waste;
2. is intended for human consumption;
3. gains added value either through improved resource efficiency and reduced emissions compared to the waste management method it replaces, or functionally, by enhancing the nutritional quality of the food product it becomes part of.

Unlike recycling, upcycling does not involve downcycling or a loss of value (Aschemann-Witzel et al., 2023). Instead, upcycled food creates a cradle-to-cradle metabolism where food retains its status as fit for human consumption. This is illustrated in the food waste hierarchy in Figure 1, which ranks waste management strategies by priority (Moshtaghian et al., 2021). Food upcycling is preferred over animal feed, composting, incineration, and disposal. Furthermore, redistribution and prevention are considered to be prioritized above upcycling, since the latter involves additional processing, which consumes energy and entails associated environmental impacts.

Sustainability assessments indicate that, when these upcycled ingredients replace conventional ones, they can help to reduce the demand for additional agricultural inputs and lower environmental pressures associated with primary production, although the extent of this benefit depends on the specific product and processing pathway (Thorsen et al, 2024).

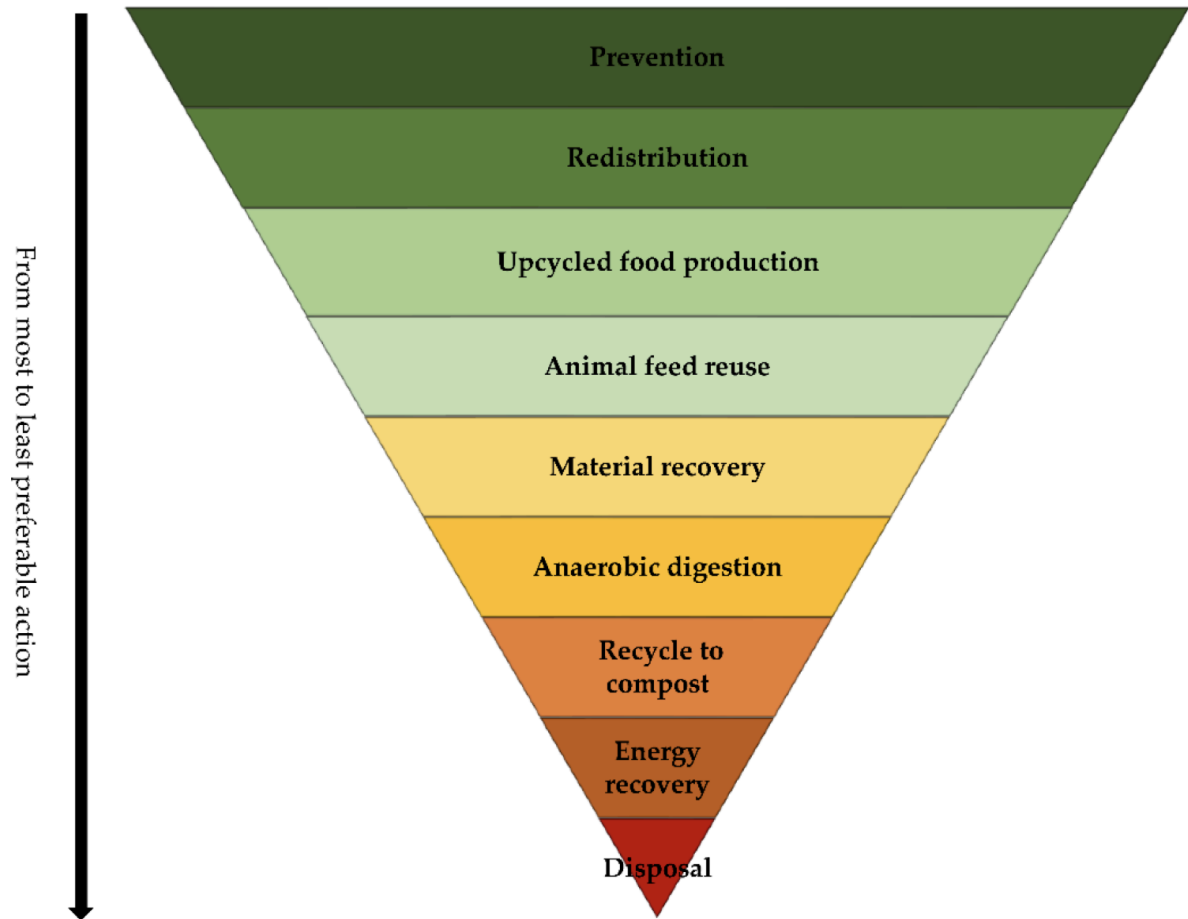


Figure 1. Food waste management hierarchy illustrates the preferred order of how to handle FLW (Moshtaghian et al., 2021).

However, upcycling food products is inherently dynamic, with ingredients considered "upcycled" only as long as the side streams are still underutilized or considered innovative. For example, whey protein was once qualified as an ingredient in upcycled food products due to their origin as a side-stream (UFA, 2020). Seeing that it is an established ingredient today, it no longer contributes to food waste reduction and is therefore not considered upcycled anymore.

2.3 Apple Pomace

2.3.1 National Apple Pomace Figures

Global apple production reaches around 86 million tonnes annually, and a substantial share is processed into beverages such as juice and cider (Gómez & Martínez, 2018; Sánchez et al., 2021). Apple processing generates pomace, a fibrous by-product consisting of peels, pulp and cores, which comprises approximately 25-30% of the processed apple mass (Floberg Karlsson & Viitala, 2019).

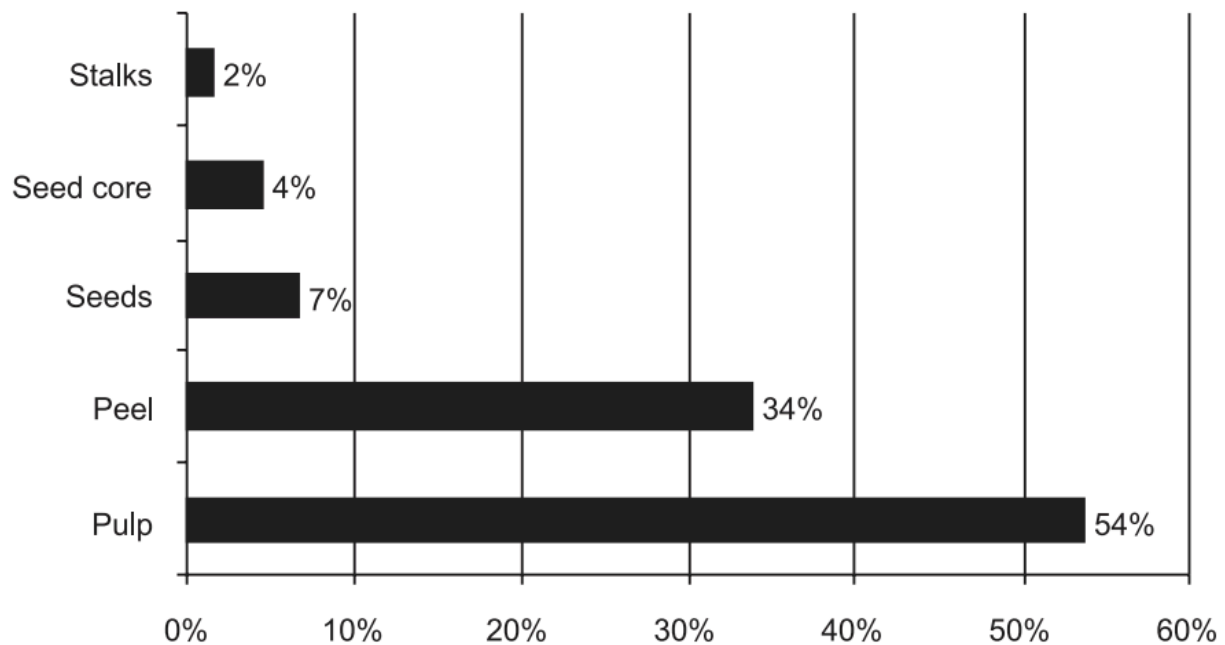


Figure 2. Solid residue shares from apple juice production (Kołodziejczyk et al., 2007).

As the most commonly grown fruit in Sweden, apples could help in supporting national food self-sufficiency (SLU, 2024). The annual domestic apple consumption ranges between 36,000-37,000 tonnes (SLU, 2021), with a production value of ~349 million SEK recorded in 2023 (Jordbruksverkets statistikdatabas, n.d.). Apple cultivation is highly concentrated in the

region of Skåne, where half of Sweden's commercial apple producers operate, while accounting for ~90% of the national yield and ~84% of the total orchard area.

Although precise data on AP production in Sweden is unavailable, estimates can be derived from apple beverage yields. Approximately 22% of Sweden's total apple yield is categorized as industrial fruit, which is used in the production of must, cider, juice, applesauce as well as other smaller-scale processed products such as purées, jams, and concentrates (SLU, 2023). Due to the lack of detailed data on the end use distribution of industrial apples, this study adopts a simplified assumption - that the pomace derived from the 22% of apples allocated to industrial processing corresponds to the share typically generated during beverage manufacturing, previously reported as 25%. Based on this assumption and an annual apple harvest of 36,500 tonnes, it is estimated that approximately 9,125 tonnes of AP are produced each year in Sweden through beverage production.

Limited data exist concerning current AP management in Sweden. A survey by Jönsson (2010) of six juice producers in Skåne and Gotland documented a total annual AP production of about 500 tonnes, with 75% allocated as cattle feed and 25% as wild animal feed (Jönsson, 2010). Agriportance (n.d.) supports its use as an alternative forage due to its nutritional fiber content. However, the product's high moisture content poses storage challenges, in turn making it susceptible to microbial spoilage which sometimes results in disposal by landfilling (Floberg Karlsson & Viitala, 2019). The acidic nature of AP can hinder seed growth processes, and its fermentation in ruminant digestive systems has been associated with toxic effects. Other reports suggest that alternative uses include composting, biogas generation, mushroom production, and application as a soil enrichment (Eldrimner, 2023). The variation in reported uses across different years suggests a potential shift in management strategies over time, however, it may also reflect inconsistencies in the literature, highlighting the uncertainty surrounding current practices.

2.3.1 Nutritional Composition of Apple Pomace

Upcycling AP into a food-grade ingredient has nutritional benefits in that it is particularly high in dietary fiber, with total fiber content ranging from 45% to 51% of its dry weight, including both soluble and insoluble fractions (Zaky et al., 2024). Fresh AP typically contains 70-85% moisture

(15-30% dry matter), so this corresponds to a fiber content on a wet weight basis of approximately 6.8-15.3%. In addition, AP retains 90-95% of the fruits original polyphenols after juicing, of which the compounds are known for their antioxidant, anti-inflammatory, and potentially anti-diabetic effects. AP also provides small amounts of essential vitamins and minerals, such as vitamins A and C, potassium, and calcium. As a source of dietary fiber and bioactive compounds, AP's nutritional profile offers functional advantages when incorporated into food products, and is a suitable candidate for nutritionally enriching baked goods (Sudha, 2011).

Regarding safety, there is some concern about the cyanide content in apple seeds, which is released when the seeds are crushed (Eldrimmer, 2023). Cyanide is a substance that can impair the body's ability to transport oxygen and may cause serious health effects if consumed in large amounts. However, IVL conducted a laboratory analysis and found that the levels in apple press residue are sufficiently low to not be classified as a health risk (IVL, 2025). According to (Eldrimner, 2023), the Swedish National Food Agency has also stated that no public health warnings are necessary for apple seeds. Additionally, hydrogen cyanide is both soluble in water and starts to evaporate at 25°C. This means that both the pasteurisation of apple press residue and the baking of AP bread reduce cyanide levels. To experience acute effects from hydrogen cyanide, one would need to consume approximately 800 grams of raw apple press residue (ibid). In this study, however, the press residue constitutes as little as 5% of the total bread composition, making such a risk negligible.

2.4 Life Cycle Assessment

LCA is a method used to quantify the environmental impacts of a product, service or process throughout its entire life cycle, with stages including raw material extraction, manufacturing, use phase and end-of-life treatment (Baumann & Tillman, 2004). There are four phases making out LCA: goal and scope definition, inventory analysis, impact assessment and interpretation (ibid; Curran, 2017; ISO, 2006b; ISO 14040, 2006c).

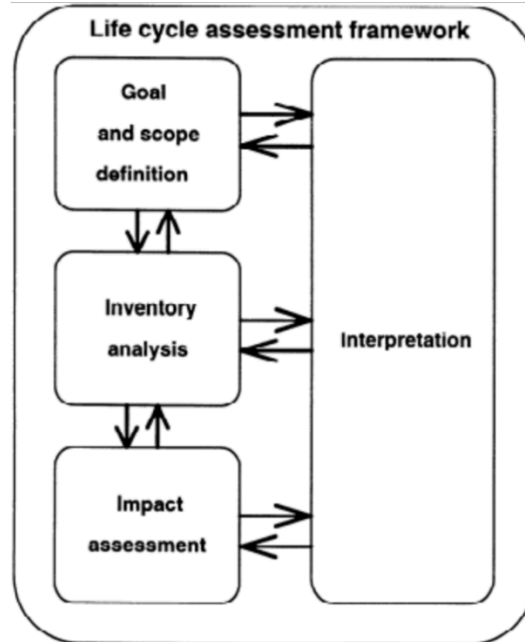


Figure 3. The LCA framework (Curran, 2017), illustrating the four main phases and their iterative relationships.

In the first phase, the functional unit, system boundaries and impact categories are defined. The functional unit is the reference point to which the magnitude of all inputs and outputs is related (Baumann & Tillman, 2004). The system boundaries can be temporal, geographical, and they define which LCA stages are considered as well as how flows, such as by-products or multiple outputs, are allocated. Impact categories, such as climate change, eutrophication and acidification, are also selected in the first phase and can be chosen based on relevance or adherence to standards.

In the second phase, the inventory analysis, all inputs and outputs within the system boundaries are identified and quantified (ibid). These are then converted into environmental loads and assigned across a set of impact categories in the impact assessment phase, and subsequently characterized so that each impact category is quantified in a single unit. One example is climate change, which includes GHG emissions such as carbon dioxide, methane and nitrous oxide etc, which are converted into carbon dioxide equivalents and thus characterized as global warming potential (GWP).

Finally, in the interpretation phase, the impacts across all categories are evaluated, and hot spots can be identified, indicating where to concentrate mitigation efforts (ibid).

2.5 Environmental Product Declaration

An EPD is a third-party verified document that presents comparable information about the environmental impacts associated with a product or service throughout its life cycle (EPD International, 2024c). It is a Type III environmental declaration developed in accordance with ISO 14025, which defines the criterias and procedures for creating standardized environmental information (ISO, 2006a). The foundation of an EPD is an LCA carried out according to ISO 14040 and ISO 14044, where the former outlines the general framework for conducting LCAs and the latter specifies methodological requirements and guidance for each phase (ISO, 2006b; ISO, 2006c). The assessment covers a cradle-grave system boundary, which includes all life cycle stages from raw material extraction to end-of-life management (EPD International, 2024c). EPDs are prepared in accordance with PCRs, which provide detailed methodological rules for specific product categories to ensure that results are consistent and comparable among similar products (EPD International, 2024d).

Because these rules are extensive and often specific, section 3.2.6 *Alignment with the Bakery Products PCR* details a comparison between the methodological approach used in this thesis and the requirements set out in the Bakery Products PCR.

2.6 Previous Studies

Existing AP research focuses on nutritional aspects, and several LCAs have examined bread and bakery products, but none have quantified the environmental implications of substituting conventional bread ingredients with AP, or the balance between prevented and added burdens in such systems.

The most relevant study for comparison is the Swedish LCA by Hildersten et al. (2025), as it evaluates a rye bread similar to the reference product used in the present study. Whole-grain rye bread was assessed using cradle-to-retail system boundaries and a functional unit of 1 kg of

bread. The authors report a climate impact of 0.81 kg CO₂-eq per kilogram of bread, which aligns with earlier Scandinavian values of 0.73-0.79 kg CO₂-eq/kg. Their results show that ingredient production and agricultural cultivation dominate climate impacts, contributing 41% and 33% respectively, whereas baking contributes negligibly because the bakery uses renewable electricity.

Another study, although reflecting German conditions, is the LCA by Braschkat et al. (2003), which assessed eight bread-production scenarios using a functional unit of 1 kg and cradle-to-consumer system boundaries. One of the scenarios includes industrial factory production, which offers a point of comparison with large-scale bakery systems. Similar to Hildersten et al. (2025), the authors identify agricultural cultivation as the main contributor to greenhouse gas emissions. In addition, the study finds that cultivation is also the dominant source of eutrophication, acidification, and ozone-depleting emissions. The authors also report that baking constitutes the main hotspot for energy use, particularly in smaller-scale or domestic production systems.

Extending the comparison further, Notarnicola et al. (2017) conducted a cradle-to-gate LCA of 21 national breads using a functional unit of 1 kg, assessing the GWP. Reported climate impacts range from 0.5 to 6.6 kg CO₂-eq/kg. As in the previous studies, agriculture is consistently identified as the dominant hotspot across all breads. Baking is the second major hotspot, since oven heating requires substantial energy input. Factors such as dough size, shape and moisture content affect the energy use. The overall climate impact is also affected by country-specific parameters such as the electricity mix, the distance over which cereals are transported, and variations in the efficiency of producing key ingredients. Together, these factors explain the considerable variation in emissions observed across European breads.

Taken together, these studies show that agricultural cultivation and ingredient production are the primary drivers of environmental impacts in bread systems, while baking contributes more modestly depending on the system context. These patterns are relevant for the present thesis because incorporating AP affects the ingredient composition of bread and may influence impacts at these upstream stages.

3

Methodology

In the present chapter, the goal and scope, functional unit, system boundaries, modelling scenarios and assumptions are defined. Subsequently, the study's extent of alignment with the EPD standard is detailed, and the LCA software and data collection process are also described to ensure methodological transparency and reproducibility. Thereafter, the ingredient profiles of the breads are examined, as their composition directly influences the LCA results. Lastly, LCI is presented to specify the sources of all data used in the study.

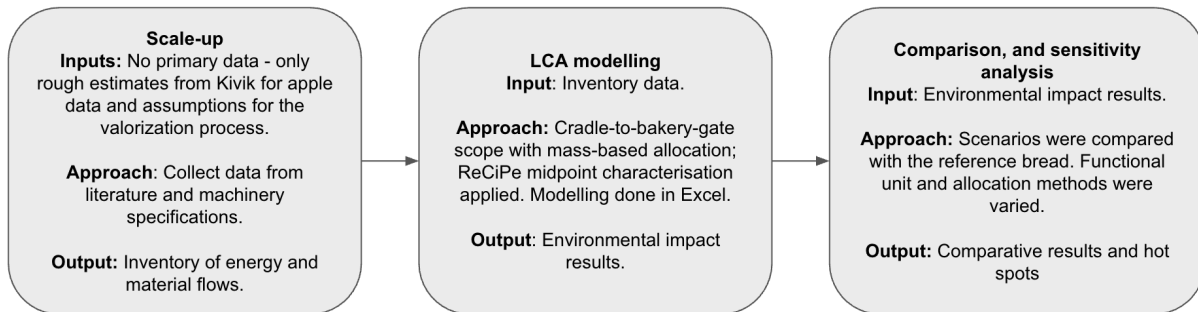


Figure 4. Overview of the research design, summarizing the main stages of scale-up, LCA modelling, and comparison of scenarios.

In the figure above, an overview of the research design is provided, and the following subchapters describe each stage in greater detail.

3.1 Goal and Scope

The goal of the LCA was to quantify and compare the environmental impacts of a novel rye bread product incorporating upcycled AP to a conventional rye bread alternative, in order to evaluate its potential to reduce the environmental footprint of bread production.

The intended application of this work was to inform decision-making in areas such as public sector food procurement, circular food innovation, and strategies for food waste upcycling. Furthermore, it aimed to contribute to the environmental assessment efforts within IVL's Blood & Turnip project, specifically relating to food valorization.

The intended audience included multiple stakeholders, including Axfoundation, which developed the original AP bread recipe and sought insights into its environmental performance; bread producers, who could use the findings to explore initiatives for reducing the environmental impact of their products; apple producers, who might consider opportunities for upcycling apple processing by-products; public sector meal planners and policymakers, with a focus on adopting circular food principles; and academics and industry professionals engaged in research and development within the field of sustainable food systems.

3.1.1 Functional Unit

The primary functional unit applied in this comparative attributional LCA is 1 kg of ready-to-eat bread produced on an industrial scale. No temporal parameter was considered, as bread is a consumable product.

3.1.2 System Boundaries

This study adopted a cradle-to-ingredient-gate system boundary, covering all inputs and outputs from raw material extraction through agricultural production and ingredient processing, up to the point where the ingredients were ready for use in bread production. The actual bread production process, including baking, as well as subsequent life cycle stages such as packaging, distribution, retail, consumer use, and disposal, were excluded from the analysis. These stages were assumed to be equivalent across both bread types and, as such, their environmental impacts were expected to cancel each other out. Although baking lies outside the system boundary, the functional unit reflects the weight of the bread after baking, since moisture loss during baking alters the final mass. Using the post-baking weight ensures consistency with how bread is usually reported.

As part of the Blood & Turnip project, this study focused on Sweden, aiming to reflect Swedish conditions for agricultural activities, ingredient processing, and transportation. Sweden-specific

data were, however, available only for the electricity supply, while all other processes were modelled using global or European datasets due to limited access to primary or Sweden-representative data. This modelling approach introduces some uncertainty into the assessment. Swedish-specific information was used for key parameters such as national AP production volumes, the scale and seasonality of large-scale apple juice processing, and production peak periods.

In an interview conducted with representatives from Kiviks Musteri AB in April 2025, only annual processing volumes, waste destinations for AP, and a general outline of valorization process steps were provided. No detailed process values or specific data were available. This direct input from Kiviks Musteri AB strengthened the study's Swedish focus but also required the use of secondary data sources and generic machine specifications for life cycle modeling. The relevant equipment was selected based on the calculated AP flows deduced from the information provided by Kiviks Musteri AB.

3.1.3 Impact Categories and Assessment Method

The environmental impact categories used in this study are GWP, land use, water consumption, terrestrial acidification, freshwater eutrophication and marine eutrophication. These categories reflected the main environmental pressures highlighted by Poore and Nemecek (2018) and presented in Our World in Data (2022), which identified climate impacts, land occupation, water use, and nutrient-related emissions as key indicators for assessing food systems. The selection also aligned with the impact indicators used in the EPD International system (2024a) for agri-food products, while remaining consistent with the scope of this thesis. Although GHG emissions are often the primary focus in LCAs, both sources highlighted that land occupation, water use, acidification, and nutrient pollution were equally critical. Food production is a major driver of global land-use change, freshwater withdrawals, and aquatic pollution, making it essential to consider these impacts alongside climate-related outcomes. Furthermore, including these categories reduced the risk of burden shifting.

3.1.4 Sensitivity Analysis and Allocation Methods

In the base scenario for the AP bread, allocation of environmental impacts for AP was based on the polluter pays principle (PPP) and a cut-off approach, as required by the PCR for bakery products (EPD International, 2024b). AP was treated as a waste by-product of juice production, meaning that all upstream impacts were attributed to the intended products, and AP was only assigned impacts from the point of collection and onward processing.

However, if AP were to become an established ingredient, the zero-burden approach would no longer have been appropriate. To capture this possibility, a sensitivity analysis was performed using mass-based allocation for upstream processes shared with apple beverage production. Economic allocation would have been preferable if a market price existed for AP, but in its absence, mass allocation was used as a proxy. Under this scenario, the environmental burden attributed to AP was expected to fall between zero and the mass-based allocation value, providing insight into potential changes if AP were commercialized.

In addition to the primary functional unit of 1 kg bread, an alternative functional unit of 100 g dietary fiber was included as part of the sensitivity analysis. This approach was chosen to reflect the nutritional function of the breads, since both AP bread and conventional rye bread provided similar dietary fiber content per serving, thereby fulfilling the intended functional property of rye bread. However, the fiber content in AP bread could vary compared to rye bread due to the range of fiber values for raw AP reported in the literature. By expressing results per 100 g fiber and including scenarios for both lower limits (LF) and upper limits (HF) of fiber content in AP bread, the analysis enabled an exploration of how sensitive the results were to these variations. While the total fiber content in AP bread fell within a similar range to that of rye bread, it was still valuable to examine how even small differences in fiber content could influence the environmental impacts of AP bread compared to conventional rye bread.

Sensitivity Analysis (Fiber)

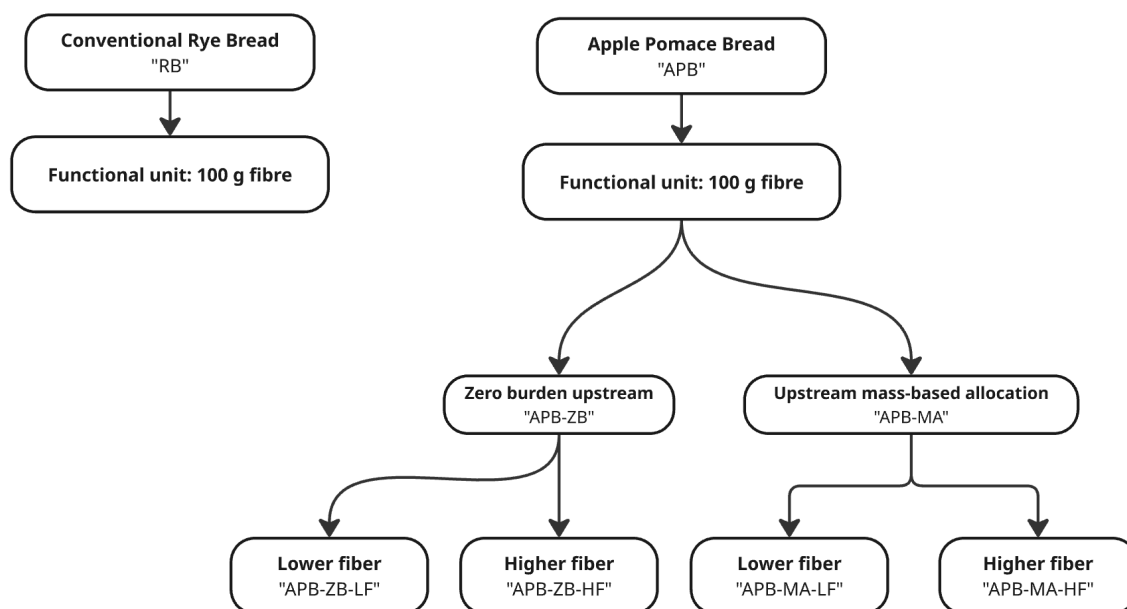


Figure 5. Overview of the scenarios used for the 100 g fiber functional unit. The diagram shows one RB and four AP bread scenarios, which vary according to the allocation approach applied to the AP ingredient (zero-burden or mass-based) and the assumed fiber content of AP bread (lower- or higher-fiber).

In total, four scenarios are defined for the AP bread under the 100 g fiber functional unit, reflecting the two allocation approaches (zero-burden and mass-based) and the lower-fiber (LF) and higher-fiber (HF) content ranges reported for the AP ingredient. These four AP bread scenarios are compared against the 100 g fiber reference rye bread (RB). The structure of these scenarios is illustrated in Figure 5.

3.1.5 Assumptions

Several assumptions were required due to data limitations. Some bread ingredients did not have exact SimaPro database matches: bread syrup was modelled as beet molasses; both coarse and hydrothermally treated rye flour were modelled as rye flour; rye sourdough was represented as a mixture of tap water and rye flour; and fresh baking yeast was modelled as fodder yeast. The rye flour ecoinvent dataset was created by substituting wheat grain for rye grain in the wheat flour dataset. More customized datasets were not possible within the project's scope and timeframe,

and no primary data were available. In accordance with Axfoundation's confidentiality requirements, only a simplified recipe with grouped ingredients was presented.

Bread recipes were standardized as much as possible. For AP bread, post-baking moisture loss was provided by Axfoundation. For rye bread, no such data were available; therefore, the same relative moisture loss was assumed. Both breads had similar ingredient water content, with AP bread containing 37.9% water, and the reference bread 36.6%. This may have led to minor uncertainties in the results due to potentially additional moisture in AP bread from AP and syrup.

3.2 Alignment with the Bakery Products PCR

This study drew methodological guidance from the PCR for Bakery Products within the EPD International (EPD International, 2024b). The aim of this thesis was not to produce an EPD but to compare the environmental impacts of conventional bread with bread containing upcycled AP. Since IVL expressed interest in aligning the assessment with EPD principles, the LCA was designed to follow the PCR framework to the extent that it fits the study's purpose and data availability. The Bakery Products PCR defines requirements regarding system boundaries, data quality, allocation, and reporting. In this study, some of these requirements were followed while others were intentionally simplified or excluded.

The functional unit followed the structure specified in the PCR, using one kilogram of bread as the reference unit. Mass-based allocation was applied in line with the PCR's co-product allocation rule on PPP, where only the environmental burdens from the AP collection and valorization are assigned to the pomace (*ibid*). The system boundary differs from the cradle-to-grave scope required by the PCR, as it covers only the upstream processes up to the ingredient-gate. The core and downstream stages of the bread life cycle were excluded. The reason is because these stages were considered highly uncertain, as factors such as the bread's shape and size influence baking time and electricity demand, while packaging choices would depend on the supplier rather than the product formulation itself. Similarly, the distribution, use, and end-of-life phases were not defined for the upcycled bread, which is not yet available on the market. For this reason, and because the study aimed to evaluate the environmental implications of the ingredient substitution

rather than the full production and consumption of the bread, the assessment was limited to the upstream processes up to the ingredient-gate.

According to the Bakery Products PCR, LCAs conducted for EPD purposes shall be attributional and stand-alone (ibid). Accordingly, the present assessment followed the attributional approach, meaning that it represents the environmental profiles of two product systems under consistent system boundaries without modelling market effects or system substitutions. However, this study adopted a comparative rather than stand-alone design, as a stand-alone assessment would not meet the thesis aim of evaluating the environmental effects of substituting conventional ingredients with upcycled AP. The selected impact categories, including GWP, terrestrial acidification, freshwater and marine eutrophication, land use, and water consumption, correspond broadly to several of the default PCR indicators such as climate change, acidification, and eutrophication, but do not include photochemical ozone creation, abiotic depletion, or ozone depletion. These were omitted due to time limitations in the scope of the study.

The data used in this study comprise a mix of primary, proxy, and selected generic data, as defined by the PCR (ibid). Primary data were available for the formulation of the AP bread, including the quantities of ingredients and the total weight before and after baking. For the reference bread, a generic recipe of similar composition was used to enable comparison, which means that no primary data were available for that product. All remaining flows, including those describing the generation and valorization of AP, were established through proxy data based on industrial machinery specifications and literature values. These proxy flows were modelled using background datasets from Ecoinvent 3.10, which are considered selected generic data within the EPD framework. While this approach ensures temporal consistency, since the database was last updated in March 2024 and thus meets the PCR requirement that data be no older than three years, it did not fully satisfy the representativeness criteria, as the data reflect generalized industrial conditions rather than Swedish site-specific production. Minor inputs such as cleaning agents, bakery utilities, and packaging were excluded from the inventory, which means that the 99 percent completeness criterion specified in the PCR was not fulfilled.

Overall, the study followed the methodological intent of the Bakery Products PCR, particularly regarding the functional unit definition, allocation approach, and the use of an attributional LCA

method, but diverged in scope, data specificity, and completeness. These deviations result from the exploratory and pre-commercial nature of the product. The resulting LCA cannot serve as a verified EPD but provides a transparent and PCR-inspired methodological foundation for potential future EPD development within IVL.

3.3 LCA Software and Data Collection

The LCI data were sourced from the Ecoinvent 3.10 cut-off by classification database, compiled in March 2024, and accessed through SimaPro version 9.6.0.1. Environmental impacts for all bread products and ingredients were assessed using the ReCiPe 2016 Midpoint (H) characterization method, where characterization factors were applied to convert inventory flows into impact category indicator results expressed in equivalents. The results were then exported from SimaPro and processed in Excel to produce tables and figures. The production systems for both bread types were modeled exclusively using secondary data, as no primary data were available. Market datasets for all ingredients were obtained from the Ecoinvent database. However, for process stages involving apple juice production and the conversion of AP into a food-grade ingredient, no complete ready-made datasets were available. These stages were instead modeled and assembled using generic datasets within the Ecoinvent database, with input amounts derived from machinery specifications and supported by values reported in scientific literature.

3.4 Ingredient Selection and Modeling

The recipe for AP bread was provided internally through the Blood & Turnip project at Axfoundation Torsåker gård, an initiative focused on developing nutritionally balanced recipes with minimized environmental footprints. The recipe incorporated coarse rye flour and hydrothermally treated cut rye, however, in this study, these two ingredients were replaced with rye flour for two main reasons. First, the original ingredients were uncommon in conventional rye bread recipes, which reduced the comparability between breads. Second, the study used only secondary data from the Ecoinvent database, which did not cover datasets for these two specific ingredients. Therefore, rye flour was chosen as the closest proxy due to its similar agricultural origin. Likewise, rye sourdough was modeled using a mixture of tap water and rye flour. These

adjustments ensured that both recipes contained ingredients that could be directly compared to one another, allowing the substitution of conventional ingredients with AP to be assessed, as illustrated in Table 1.

Table 1. Recipe for 1 kg of AP bread sourced internally from the Blood & Turnip project and 1 kg of rye bread sourced from online sources (Godare, n.d.)

Ingredient	Rye Bread (g)	AP Bread (g)	Ingredients substituted (g)
Rapeseed oil	17.3	24	-6.7
Rye flour	345.92	298	47.92
Wheat flour	484.28	424	60.28
Water	576.53	558	18.53
Salt	20.75	13.6	7.15
Fresh yeast	28.83	20	8.83
AP	-	80	-
Bread syrup	-	56	-
Total	1473.6	1473.6	136.01

The pre-baked and post-baked weights of the AP bread were explicitly stated in the source material, with a total input of ingredients amounting to 1,473.6 g and a final post-baked output of 1 kg. However, the post-baked weight of the conventional rye bread was not provided. Therefore, a similar moisture loss was assumed for the rye bread, being approximately 32%. This corresponds closely to the 30% moisture-loss assumption applied in the European bread LCA meta-study by Notarnicola et al. (2017). The factors driving moisture loss during baking are complex, including baking time, temperature, initial moisture content, size and shape of the bread, and the bread's position in the oven. Given that the baking process, which was outside the scope of this study, was similar for both bread types and that their respective water contents were comparable, this assumption was considered reasonable for the purpose of this analysis.

3.5 Life Cycle Inventory

A rough process outline and annual AP flows were provided during personal communication with Kiviks Musteri AB (2025), as well as inspired by Zdravkovic et al. (2021) study. Available literature and technical data were used to align the modeled system with this outline wherever possible. More granular details about the inventory can be found in Appendix A.

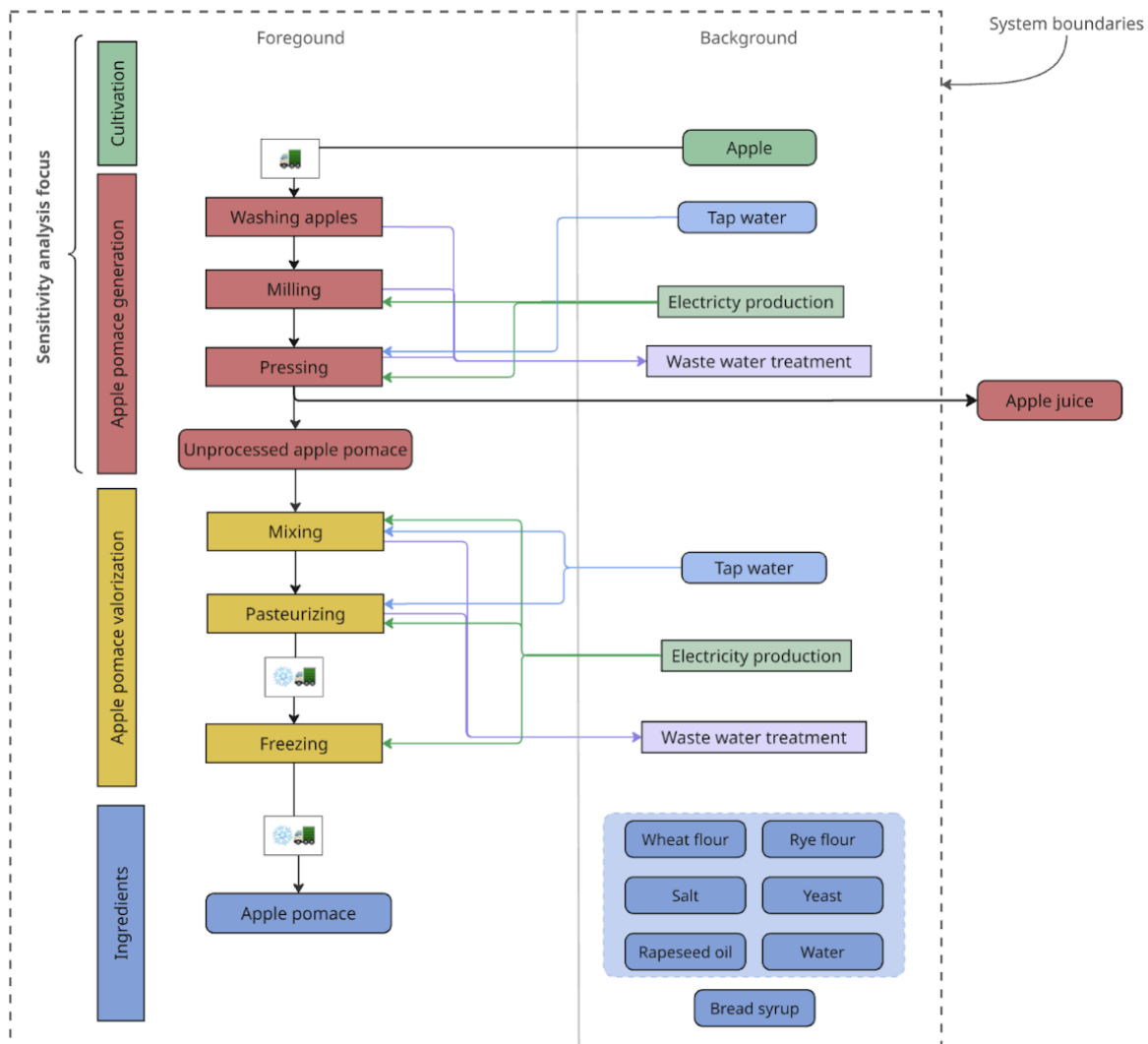


Figure 6. System flowchart for AP bread and reference bread. In the ingredients stage, the blue boxed ingredients indicate the complete system boundaries for the reference rye bread and represent the overlap in ingredients between the two bread models. Boxes with hard edges denote processes, while boxes with soft edges denote materials. Foreground processes are shown on the left side of the diagram and background processes on the right.

Foreground processes are modelled specifically for this study, which include only the AP generation and valorization processes, as can be seen in Figure 6, while background processes use secondary data. These include energy supply, water use, and wastewater treatment.

The modeled system for AP bread begins with the cultivation of apples, which are assumed to be transported to nearby juice processing facilities (Kiviks Musteri AB, 2025). In line with a previous apple processing LCA study by Coelho et al. (2022), in Sweden, a distance of 50 km was modeled for this transport, using a 16-32 metric ton EURO6 truck, reflecting typical Swedish conditions for local fruit supply. In accordance with Zdravković et al.'s LCA of apple-juice production (2021), the apple process involves washing, milling, and pressing the apples using the Voran series, as can be seen in detail in Appendix A.4.1. Specifically, the elevator SA400, centrifugal mill RM4 (Voran Maschinen GmbH, n.d), and belt press EBP1200 (Voran Maschinen GmbH, 2014) are modeled, each with a nominal throughput of 3,000 kg apples per hour according to manufacturer specifications. Considering a typical production period of September to November (Kiviks Musteri AB, 2025), about three months, rough assumptions make out that the facility operates five days per week for eleven hours per day. Under these conditions, the processing line is more than capable of handling the annual flow of 2,000 tonnes of apples within this timeframe, as it is well within the capacity limits of the selected machines. Since no case-specific measurements were available, all water consumption in the generation process is based on Zdravkovic et al. (2021) study, while all electricity use for the elevator, mill, and pressing steps is modeled using the technical specifications of the Voran series. Cleaning of machinery is assumed to use tap water, and wastewater is treated off-site.

Table 2. LCI for the production of 80 grams of AP ingredient, corresponding to the amount used in 1 kg of ready-to-eat AP bread. Values are shown for both the zero-burden and mass-based allocation scenarios, with all process steps and Simapro modules listed.

Stage	Processes and materials	Simapro module	Amount (APB-ZB)	Amount (APB-MA)	Unit
Generation of AP					
	Apples	Apple {GLO}	0	0.020	kg
	Transportation (orchard-plant)	Transport, freight, lorry 16-32 metric ton, EURO6 {RER}	0	0.0011	tonne·km
	Washing apples	Tap water {Europe without Switzerland}	0	0.0091	kg
	Milling	Electricity, medium voltage {SE}	0	0.000054	kWh
	Pressing	Electricity, medium voltage {SE}	0	0.000023	kWh
	Machine cleaning	Tap water {Europe without Switzerland}	0	0.0011	kg
	Waste water	Wastewater, average {Europe without Switzerland}	0	0.010	kg
Valorization of AP					
	Mixing	Electricity, medium voltage {SE}	0.00070	0.00070	kg
	Heat treatment	Electricity, medium voltage {SE}	0.0012	0.0012	tonne·km
	Machine cleaning	Tap water {Europe without Switzerland}	0.0028	0.0028	kg
	Transport (plant-storage)	Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing {GLO}	0.0023	0.0023	kWh
	Freezing storage	Electricity, medium voltage {SE}	0.0032	0.0032	kWh
	Transport (storage-bakery)	Lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing {GLO}	0.0058	0.0058	kg
	Waste water	Wastewater, average {Europe without Switzerland}	0.0028	0.0028	kg

The unprocessed AP is then collected for valorization in a hypothetical process model, as this practice is not currently implemented. Out of the 3,000 kg apples processed hourly, approximately 750 kg of AP is generated as a by-product. All downstream machines are selected to accommodate said flow rate or more. The AP is first mixed in industrial paddle mixers to achieve a homogeneous texture, followed by pasteurization to ensure microbial safety and prolong shelf-life. For mixing, the PerMix PAM-750 vertical paddle mixer (PerMix, n.d.) is selected for its suitability for moist, fibrous food residues like AP. The electricity used for mixing is derived from machinery specifications. After mixing, pasteurization is modeled using the TEK-2PH-J juice and fruit-purée pasteurizer as a proxy, with throughput and electricity use based on manufacturer specifications (Tekmash, n.d.). Both steps require additional water for equipment cleaning. At the end of each day, a simplified assumption is made that the AP is transported to a freezing storage. Storage and freezing are modeled based on the required inventory and energy demand, calculated from annual pomace flows in Appendix A.2.5.

Table 3. Inputs at the bakery gate for both AP bread and the reference bread.

Stage	Processes and materials	Simapro module	Amount (APB-ZB)	Amount (APB-MA)	Unit
Bakery gate					
AP	AP	Valorized AP (modelled)	80.00	-	g
Bread syrup	Bread syrup	Molasses, from sugar beet {GLO}	56.00	-	g
Fresh yeast	Fresh yeast	Fodder yeast {GLO}	20.00	28.83	g
Rapeseed oil	Rapeseed oil	Rape oil, crude {RoW}	24.00	17.30	g
Rye flour	Rye flour	Rye flour {RoW}	298.00	345.92	g
Water	Water	Tap water {Europe without Switzerland}	558.00	576.53	g
Wheat flour	Wheat flour	Wheat flour {RoW}	424.00	484.28	g
Salt	Salt	Sodium chloride, powder {GLO}	13.60	20.75	g
Total	Total		1473.60	1473.61	g

From cold storage, the frozen AP ingredient is transported by refrigerated truck to bakeries. At the bakery, the rest of the ingredients have also been purchased and transported, as can be seen in Table 3.

4

Results and Interpretations

In this chapter, contribution analyses and characterization results for the different breads are included, as well as estimated results on a Swedish nation-wide scale.

4.1 Contribution Analysis

Figures 7-9 show the relative ingredient contributions to the environmental impacts of the different bread scenarios. These include the reference bread (RB), the AP bread where upstream AP impacts are cut off before the collection stage (APB-ZB), and the AP bread where upstream AP impacts are allocated using a mass-based approach (APB-MA). Because the figures present relative contributions, they apply to both functional units used in this study: 1 kg of ready-to-eat bread and 100 g of dietary fiber. While the stacked bar charts are shown in this section, the tables with the exact numerical percentages are provided in Appendix B1.

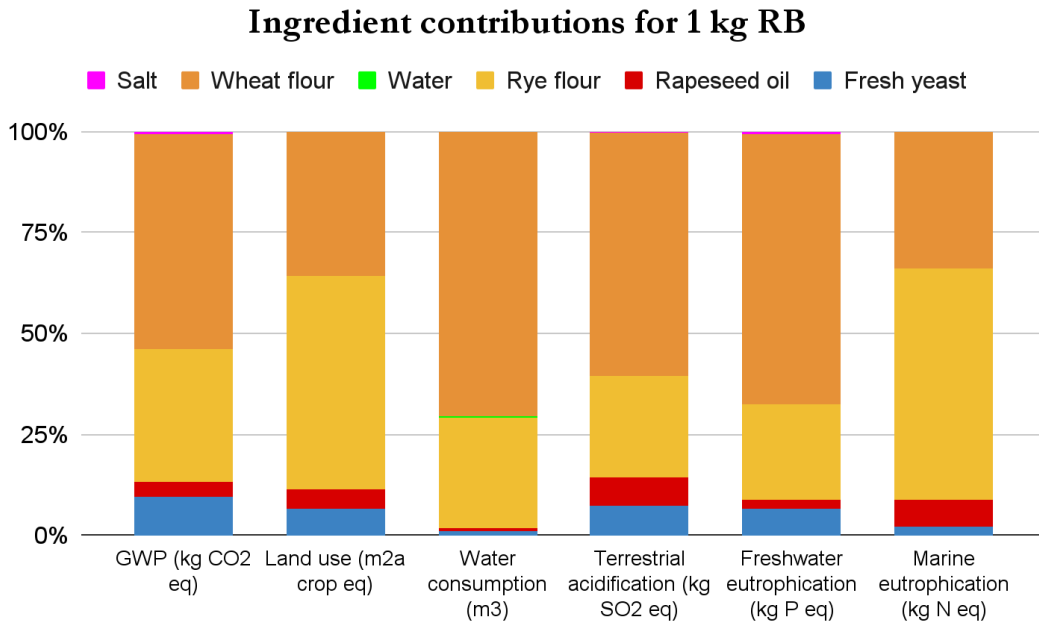


Figure 7. Characterized ingredient contributions to environmental impacts of 1 kg RB, presented across six midpoint categories.

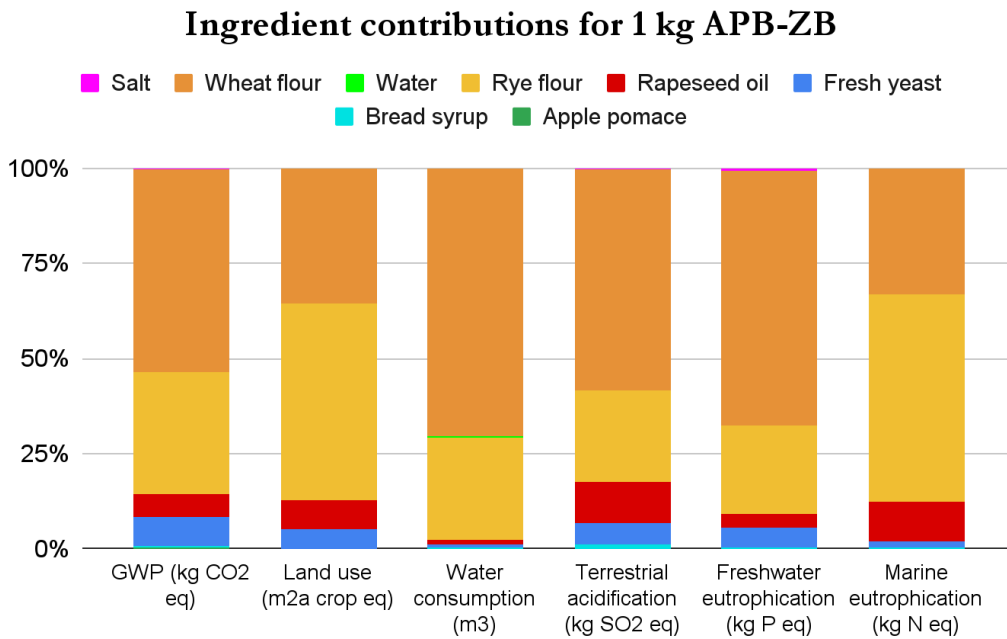


Figure 8. Characterized ingredient contributions to environmental impacts of 1 kg APB-ZB, presented across six midpoint categories.

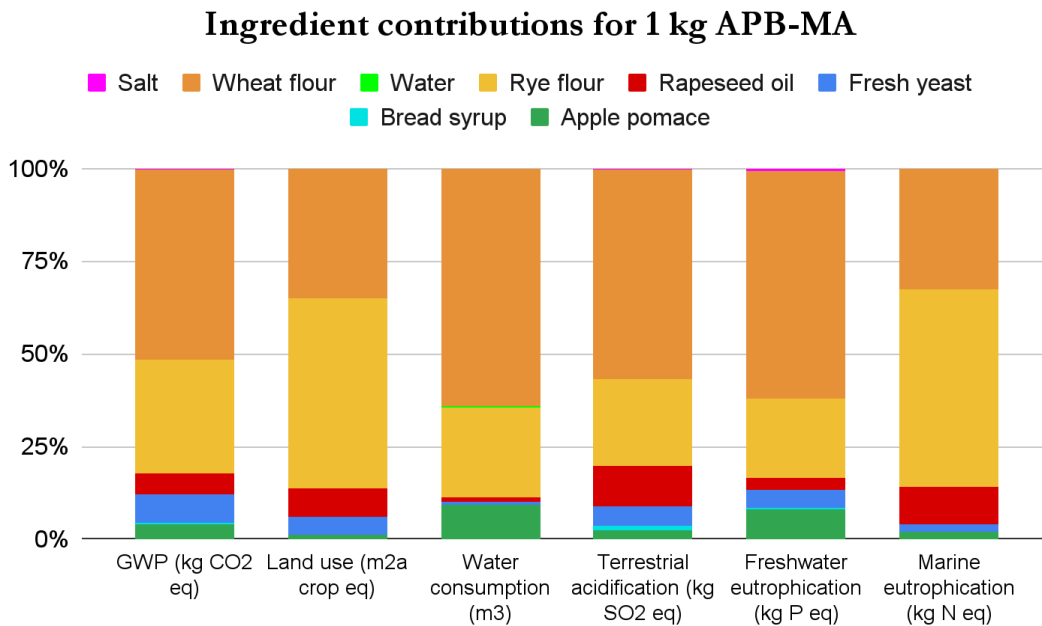


Figure 9. Characterized ingredient contributions to environmental impacts of 1 kg APB-MA, presented across six midpoint categories.

Across all scenarios, wheat flour is the primary contributor in four out of six midpoint categories: GWP, water consumption, terrestrial acidification, and freshwater eutrophication. Rye flour dominates impacts related to land use and marine eutrophication, while also representing the second-largest contributor in the remaining categories. Fresh yeast and rapeseed oil show moderate contributions, whereas salt and water contribute negligibly across all impact categories. Bread syrup impacts appear only in the APB-ZB and APB-MA formulations and are negligible, while the RB recipe does not include this ingredient in its formula.

For the AP ingredient under the zero-burden assumption, Appendix B.2 shows that transport and electricity are the dominant contributing processes. Transport drives most impacts, while electricity mainly affects water consumption. However, since the AP ingredient contributes less than 1% to all midpoint categories in the ZB bread system, these hotspots become negligible at the bread level.

In contrast, the APB-MA scenario shows more substantial contributions from the AP-MA ingredient, particularly to GWP (4.16%), water consumption (9.15%), and freshwater eutrophication (8.17%), also seen in Appendix B.2.

Table 4. Relative contribution results by step processes to different impact categories, expressed as percentages of the total impact for AP ingredient under mass-based allocation scenario.

AP-MA	Global warming	Land use	Water consumption	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication
Electricity	0.49%	0.13%	0.21%	0.30%	0.17%	0.05%
Water	0.05%	0.00%	0.31%	0.03%	0.03%	0.00%
Transport	10.10%	0.30%	0.04%	2.67%	0.96%	0.10%
Waste water treatment	0.05%	0.00%	-0.31%	0.03%	0.34%	0.50%
Apple production	89.30%	99.57%	99.75%	96.97%	98.50%	99.35%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

These increases are directly attributable to the environmental burden of apple production, which becomes the dominant contributing phase for the AP ingredient under the mass-based allocation scenario. Table 4 shows that apple production accounts for 89.30% of GWP, 99.75% of water consumption, and 98.50% of freshwater eutrophication. Although AP-MA contributes only minimally to land use, terrestrial acidification and marine eutrophication in the bread system, the small contribution it does have originates almost entirely from the apple production phase. Aside from apple production, transport is the only process that contributes meaningfully to the AP ingredient, accounting for 10.10 percent of GWP and representing the single outlier among the other processes.

4.2 Characterization Results

4.2.1 Functional Unit: 1 kg Ready-to-Eat Bread

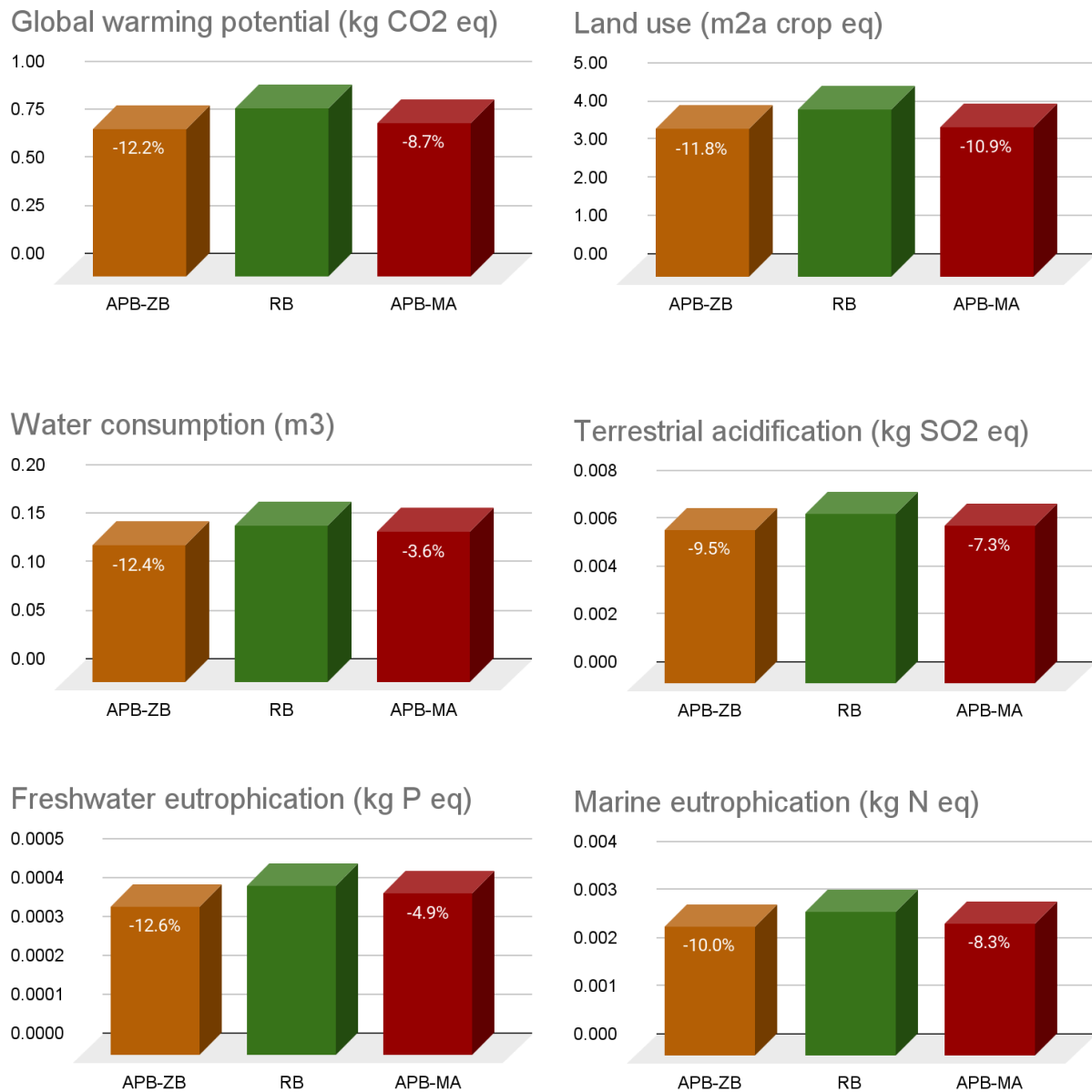


Figure 10. Environmental impacts across six midpoint categories for APB-ZB, RB and APB-MA, as well as the relative differences between the reference bread and the two AP bread scenarios.

Figure 10 shows that both AP-enriched breads perform better environmentally than the reference rye bread. The APB-ZB scenario shows the greatest overall reductions. In the APB-MA scenario,

reductions are more modest, reflecting the inclusion of burdens from apple production under mass-based allocation. Nevertheless, the APB-MA still performs better than the reference bread in all categories.

Table 5. Net changes in ingredient quantities and associated environmental impacts resulting from substituting conventional ingredients with 80 g of AP in the bread recipes. The table also shows the net impacts of the AP ingredient under both modelling approaches (ZB and MA) and the overall differences between the AP breads and the reference RB.

	Mass (g)	Mass (%)	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
Conventional ingredients								
<i>Wheat flour</i>	-60.28	-12.45%	-5.8E-02	-2.0E-01	-1.4E-02	-5.3E-04	-3.6E-05	-1.3E-04
<i>Rye flour</i>	-47.92	-13.85%	-4.0E-02	-3.2E-01	-6.1E-03	-2.5E-04	-1.4E-05	-2.4E-04
<i>Water</i>	-18.53	-3.21%	-7.5E-06	-3.0E-11	-1.9E-05	-2.0E-08	-3.8E-09	-3.7E-10
<i>Salt</i>	-7.15	-34.46%	-1.9E-03	-1.1E-04	-3.0E-05	-9.5E-06	-1.1E-06	-2.8E-07
<i>Fresh yeast</i>	-8.83	-30.63%	-2.6E-02	-8.8E-02	-5.3E-04	-1.6E-04	-8.7E-06	-2.2E-05
<i>Rapeseed oil</i>	6.7	38.73%	1.3E-02	8.2E-02	5.0E-04	2.0E-04	3.8E-06	7.7E-05
<i>Bread syrup</i>	56	100.00%	3.3E-03	3.6E-03	2.8E-04	6.3E-05	1.3E-06	7.6E-06
Total	-136.01		-1.1E-01	-5.2E-01	-2.0E-02	-6.8E-04	-5.6E-05	-3.0E-04
AP ingredient								
AP-ZB	80	100.00%	2.9E-03	1.4E-04	3.4E-05	4.0E-06	3.4E-07	8.7E-08
AP-MA	80	100.00%	3.4E-02	4.0E-02	1.4E-02	1.6E-04	3.4E-05	5.1E-05
AP breads								
APB-ZB	0	0	-1.1E-01	-5.2E-01	-2.0E-02	-6.8E-04	-5.5E-05	-3.0E-04
APB-MA	0	0	-7.7E-02	-4.8E-01	-5.8E-03	-5.2E-04	-2.2E-05	-2.5E-04

Because AP-ZB contributes negligibly to the overall impacts, as indicated by the contribution analysis, and replaces higher-impact ingredients including 47.9 g rye flour, 60.3 g wheat flour and 8.8 g yeast (Table 1), the environmental burdens of said conventional ingredients are reduced.

To further examine these trade-offs, Table 5 provides a quantified comparison of the prevented and added environmental impacts resulting from the substitution. It presents the reductions associated with the displaced conventional ingredients, the added impacts from the AP ingredient under both modelling approaches, and the resulting net changes. Both AP bread scenarios benefit from reducing primary production of conventional ingredients with relatively high environmental burdens, but APB-MA achieves smaller net savings because the added impacts from the AP-MA ingredient are driven by apple production.

4.2.2 Functional Unit: 100 g Fiber

This section presents the environmental results using 100 g of dietary fiber as the functional unit. The reference bread contains 118 g fiber per kilogram, while the AP breads were modelled using two bounds based on literature variability in AP composition.

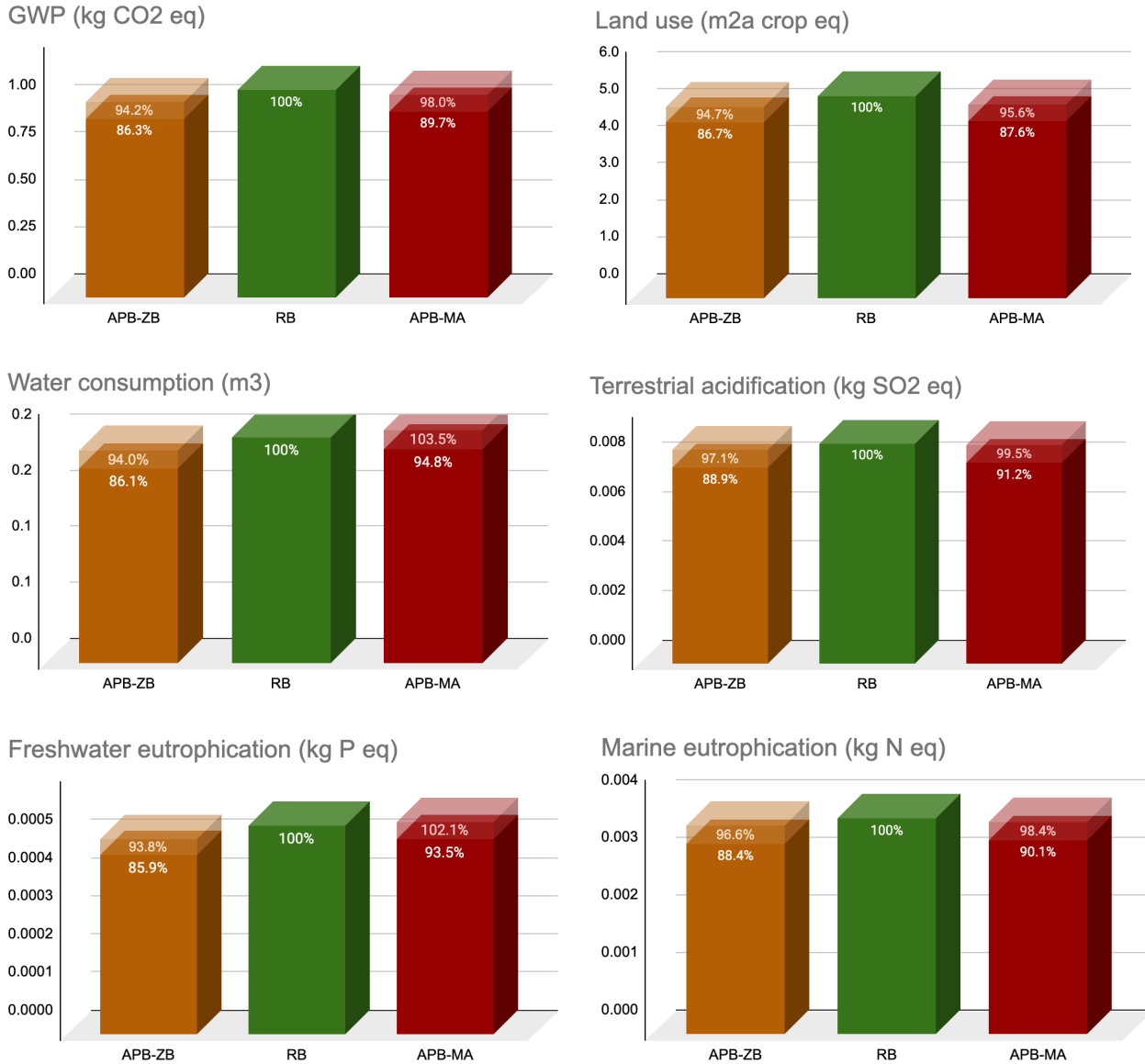


Figure 11. Characterized environmental impacts per 100 g dietary fiber across six midpoint categories for the reference RB and the four APB scenarios, reflecting both allocation methods and lower- and upper-fiber bounds.

A high-fiber (HF) variant includes 120 g fiber per kilogram of AP bread, and a low-fiber (LF) variant includes 110 g fiber per kg of AP bread. To obtain 100 g of fiber, a larger quantity of dough is required for the APB-LF than for the APB-HF. Specifically, the AP bread with lower fiber contents requires 1976 g of ingredient input, compared to 1810 g for higher-fiber AP bread and 1841 g for RB.

Figure 11 shows that the environmental impacts of the high-fiber cut-off bread (APB-ZB-HF), the high-fiber allocation bread (APB-MA-HF), and the low-fiber cut-off bread (APB-ZB-LF) are consistently lower than those of the reference bread across all impact categories. The reductions also follow the same order, with the high-fiber cut-off bread achieving the largest decreases, including at least an 11% reduction in every category. The only exceptions to this ordering are water consumption and terrestrial acidification, where the high-fiber APB-MA and the low-fiber APB-ZB show nearly identical reductions.

The low-fiber APB-MA also shows reductions in most impact categories, but these reductions are much smaller. In two categories, freshwater eutrophication (+2.1%) and water consumption (+3.5%), impacts increase relative to the reference bread. This outcome is driven by two factors. As previously mentioned, the lower fiber content requires a larger total ingredient input to supply 100 g of fiber, which leads to increased environmental burden. Additionally, under mass-based allocation, the AP ingredient carries upstream burdens from apple cultivation that contribute notably. This can be deduced based on the fact that within the allocation-based AP bread system, the AP ingredient's relative contributions are 9.15% and 8.17% to these two categories respectively (Appendix B1), of which the apple production accounts for more than 98% of the environmental impacts (Table 4).

4.2.2 Estimated National Impact of AP Valorization

One year of Swedish apple juice production generates approximately 9.1 tonnes of AP. Based on the substitution rate modelled in this study and looking at the base scenario of 1 kg of zero burden AP bread, this quantity would be sufficient to replace ingredients in roughly 114,000 loaves of bread per year.

Table 6. Estimated national-scale environmental impacts from valorizing 9.1 tonnes of AP into bread.

114062.5 loaves	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
APB-ZB	-12,547	-59.313	-2,281	-78	-6	-34

The resulting environmental impacts include decreases across all environmental impact categories, with GWP by 12,547 kilograms of CO₂ equivalent, land use by 59,313 square metres of crop-equivalent area and water consumption by 2,281 cubic meters.

Table 7. Estimated national-scale ingredient savings from valorizing 9.1 tonnes of AP into bread.

Ingredients	Wheat flour	Rye flour	Water	Salt	Fresh yeast	Rapeseed oil	Bread syrup	Total
Tonnes	-6.88	-5.47	-2.11	-0.82	-1.01	0.76	6.39	-15.51

On a national scale, this corresponds to avoided use of 6.9 tonnes of wheat flour, 5.5 tonnes of rye flour, 2.1 tonnes of water, 0.8 tonnes of salt, and 1.0 tonne of yeast, while requiring 0.76 tonnes of rapeseed oil and 6.39 tonnes of bread syrup, resulting in a net reduction of 15.5 tonnes of ingredient use overall.

5

Discussion

6.1 Environmental Performance

An important starting point for the discussion is to evaluate whether the reference model developed in this study aligns with established LCA values for rye bread found in the literature. Hildersten et al. (2025) reported a climate impact of 0.81 kg CO₂-eq per kilogram of rye bread in a Swedish context using ReCiPe midpoint indicators, which is consistent with earlier Scandinavian estimates of 0.73-0.79 kg CO₂-eq per kilogram. While they used the same impact assessment method as what was used in the present study, a cradle-to-retail system boundary was applied, whereas this study used a cradle-to-bakery-gate boundary. When Hildersten's result is adjusted to reflect a bakery-gate scope, the corresponding impact is approximately 0.60 kg CO₂-eq per kilogram. This is lower than the 0.88 kg CO₂-eq per kilogram calculated for the reference bread in the present study, and the difference can partly be explained by differences in recipe composition. Hildersten's bread contains a greater proportion of rye flour relative to wheat flour, whereas the reference bread here contains more wheat than rye, which leads to higher impacts because wheat flour is the more emission-intensive ingredient. Furthermore, Hildersten's dataset reflects Swedish production conditions, while the present model relies on a mix of global and European datasets due to limited availability of Swedish LCI data, which may also influence the results. On the other hand, the reference bread in this study falls within the broad European range of 0.5-6.6 kg CO₂-eq per kilogram of bread reported by Notarnicola et al. (2017). Considering what geographical coverage was available for the data sets, comparing the impacts to that of European breads offers a relevant benchmark.

The findings show that incorporating valorized AP in bread can reduce environmental impacts across a wide range of categories, although the magnitude of reduction depends strongly on the functional unit, as well as the allocation method and fiber content applied to the AP ingredient. Under the 1 kg functional unit, the AP breads exhibited lower environmental impacts than the reference rye bread. This holds true under both the zero-burden scenario, where AP carries no upstream impacts prior to its collection, and the mass-based allocation approach, where the AP ingredient carries with it a share of apple juice production burdens. As expected, the zero-burden scenarios resulted in the largest reductions, since the substitution of wheat flour, rye flour and yeast occurs with negligible added upstream burdens. Even under mass-based allocation, however, the 1 kg scenario still showed improvements relative to the reference bread, with the environmental impact savings from substituting conventional ingredients overpowering the added environmental burden from the AP ingredient.

With regards to the functional unit of 100 g of dietary fiber, all AP bread scenarios, except one, showed reduced impacts across every category. The only instance where impacts increased occurred in the scenario combining the lower fiber content with mass-based allocation for the AP ingredient. In this case, freshwater eutrophication and water consumption increased slightly. Two factors explain this outcome: first, the lower fiber content required a larger total ingredient mass to provide 100 g of fiber; and second, in the APB-MA system, the AP ingredient carries its largest burdens specifically in these two categories, contributing 8.17 percent to freshwater eutrophication and 9.15 percent to water consumption, with apple cultivation overwhelmingly dominating these impacts. This is consistent with the contribution analysis, which identified wheat, rye and AP-MA as major hotspot processes.

Lastly, when the results are scaled to the national level, they show that 15.5 tonnes of ingredients would be saved and their primary agricultural inputs avoided, of which 6.9 tonnes are wheat flour and 5.5 tonnes are rye flour. This, in turn, leads to reduced impacts associated with producing these ingredients, thereby lowering the strain on the food system. The environmental savings include a decrease in global warming potential by 12,547 kilograms of CO₂ equivalent, land use by 59,313 square metres of crop-equivalent area, and water consumption by 2,281 cubic metres. More effective use of by-products generated early in the supply chain through upcycling them into food-grade ingredients can support a systematic mitigation strategy against waste and enable

and encourage a more circular food system. This also aligns with Sweden's national food strategy, which aims to increase food availability through food loss and waste reduction (Livsmedelsverket et al., 2018).

6.2 Limitations and Data Uncertainty

Although this study followed several methodological requirements of the EPD system and the Bakery Products PCR, such as applying an attributional LCA, using the polluter pays principle, and implementing mass-based allocation in line with PCR guidance, it was not possible to fully comply with these frameworks. The product assessed in this thesis is not yet established on the market and has no planned industrial operations, which made it impossible to obtain process-specific information from a real supplier. The PCR states that data related to environmental aspects should be as specific and representative of the studied process as possible, but this could not be achieved here. Instead, energy use, water use, and process steps in the inventory were approximated using industrial machinery specifications and published literature on apple juice production. Because no specific data could be obtained, it was not possible to document process-level details that the PCR would normally require, such as the actual fuel type and transportation.

Because the valorization process has not yet been implemented in practice, the modeled inventory flows are hypothetical, which introduces additional uncertainty. A future production facility may use different processing steps or energy sources, which would influence the resulting impacts. Some stages were likely simplified - for example, the model assumes that AP is transported to the freezing facility at the end of each processing day. In reality, AP is highly susceptible to microbial spoilage due to its high moisture content (Floberg Karlsson and Viitala, 2019) and would likely need to be frozen immediately after processing. This would affect storage requirements and could alter the environmental profile of the AP ingredient.

Furthermore, a central limitation of this study is the reliance on non-Swedish LCI datasets. Only electricity production reflects Swedish conditions, while all other datasets are global or European. Since the goal of the study was to model bread production in a Swedish context, the absence of localized agricultural and processing data introduces uncertainty. This is especially relevant for apple cultivation, which was a notable contributor to water consumption, GWP and freshwater eutrophication under mass-based allocation. Agricultural data can vary greatly between regions

because farming practices, irrigation use and fertilizer application differ, which can in turn lead to substantially different environmental impacts (Hildersten et al., 2025). Therefore, the lack of localized datasets likely overestimates the upstream impacts of the conventional ingredients and the AP ingredient, meaning that the national estimates of decreased emissions and primary production of agricultural inputs should be interpreted with caution.

The reference rye bread formulation also introduces uncertainty. Rye breads may vary in their ingredient proportions. The chosen recipe was selected because it closely resembled the modeled AP bread. However, one of the ingredients, bread syrup, was not present in the reference recipe, although it contributed less than one percent to all impact categories. Ideally, the comparison bread would have been a fruit-containing product such as Lingongrova, which is more functionally similar to bread with upcycled AP. This option was not feasible because no datasets for lingonberries exist in ecoinvent or Agri-footprint, and using proxy berries would have introduced additional uncertainty.

Furthermore, moisture loss during baking also introduces uncertainty. Evaporation depends on bread properties such as size, shape and ingredient composition (Notarnicola et al., 2017). While weight pre- and post-baking was given for the AP bread by Axfoundation (2025), no published data exist for moisture loss or the weight post-baking in rye-wheat bread recipes. Thus, moisture loss had to be assumed. This affects the total ingredient inputs required per kilogram of final bread and therefore affects environmental impacts.

6.3 Recommendations

Future studies should build on this work by incorporating site-specific data once a supplier has a defined operational setup or once AP bread enters the market. At that stage, IVL or similar organizations could use this study as a foundation and complete the full PCR requirements by gathering primary information on AP processing, energy and water use, freezing practices, and transportation modes and distances. It will also be important to measure moisture loss during baking for the reference rye bread, since this directly affects ingredient inputs and associated impacts. Future research should also identify a more functionally comparable reference product, such as a fruit- or berry-containing bread, provided that suitable LCI datasets are available.

Finally, studies should examine alternative valorization pathways for AP and consider consequential LCA to understand system-wide effects, such as substitutions in animal feed.

6

Conclusions

The results show that, across all scenarios except one, the AP bread reduced environmental impacts in every impact category, including global warming potential, land use, water consumption, terrestrial acidification, and eutrophication. For the functional unit of 1 kilogram of bread, the size of the reductions depended mainly on how upstream burdens were assigned to AP. Under the base scenario, where AP is treated as a waste and carries no upstream impacts before its collection, the environmental benefits were the largest. This reflects the most realistic early-market situation and provides a clear incentive for companies to develop and use upcycled AP. If the product becomes established on the market, AP may no longer be classified as a waste and would instead receive upstream burdens through mass-based allocation. Even in this case, the 1 kilogram AP bread still had lower impacts across all categories compared to the reference rye bread.

For the functional unit of 100 grams of dietary fiber, four scenarios were modeled, combining two fiber contents with the two allocation methods. All four scenarios resulted in reductions, with the greatest improvements occurring in the high-fiber, zero-burden scenario. The smallest reductions occurred in the low-fiber, mass-based scenario. Only in that case did two impact categories, freshwater eutrophication and water consumption, increase slightly, while all other categories still showed decreases.

Overall, the results indicate that AP bread is environmentally preferable to traditional rye bread. The use of AP reduces the need for primary agricultural inputs and helps redirect edible side streams to human consumption rather than waste. When scaled to national AP availability, the results suggest that AP bread could meaningfully cut impacts and ingredient demand in Sweden, supporting both environmental sustainability and national food security.

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A

Appendix: Detailed Inventory

The inventory calculations in Appendix A are presented using a reference flow of 3,000 kg of apples, rather than the 80 g of AP used in the main functional unit (1 kg of bread). This larger reference flow reflects the operational scale of industrial apple-juice production and corresponds to the nominal hourly throughput of the machinery modeled (Vorán SA400, RM4, EBP1200). Using this scale ensures that water use, electricity demand, and processing efficiencies are calculated under realistic loading conditions, which would not be possible if the inventory were based directly on the small quantity of AP incorporated into one kilogram of bread.

All results derived from the 3,000 kg reference flow are subsequently allocated and scaled down to match the 80 g AP ingredient used in the functional unit.

A.1 Apple Pomace Generation

These AP generation processes build on Zdravković et al.'s LCA of apple-juice production (2021), replicating the process steps up until the AP by-product is produced, involving washing, milling and pressing. However, contrary to their study, the collection tank and pipe-screen filter (ERS25, Vorán) were neglected because they were assumed to generate negligible amounts of AP compared to the preceding steps. As previously mentioned, this study adopted their methodology for cleaning capital goods.

Table A1. Energy and water inputs for apple juice production up to pomace generation with a reference flow of 3000 kg apples, based on calculations done in 3.5.

Process Step	Mass	25% mass		Simapro module
		allocation	Units	
Apples	3000	750	kg	Apple {GLO} market for apple Cut-off, U
Transportation (orchard → facility)	165	41.25	tonne·km	Transport, freight, lorry 16-32 metric ton, EURO6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U
Washing apples	1370	342.5	kg	Tap water {Europe without Switzerland} market for tap water Cut-off, U
Milling	8.05	2.01	kWh	Electricity, medium voltage {SE} market for electricity, medium voltage Cut-off, U
Rack-and-cloth pressing	3.43	0.86	kWh	Electricity, medium voltage {SE} market for electricity, medium voltage Cut-off, U
Machine cleaning/ maintenance	159.38	39.84	kg	Tap water {Europe without Switzerland} market for tap water Cut-off, U

A.1.1 Transportation - Orchard to Juice Processing Facility

Coelho et al (2022) modeled a Swedish apple-juice production in their study and, consistent with their findings, it was assumed that processing facilities were sited close to orchards. Accordingly, a 50 km haul from orchard to processing plant by a Euro 6 truck was applied in the report. Their study used a 16-32 ton capacity vehicle, however, because SimaPro lacks truck datasets with that capacity, the next-best option was selected, being 7.5-16 ton Euro 6 truck

A.1.2 Washing and Milling - Water and Energy Use

According to Zdravković et al. (2021), a conventional apple-juice production system uses 555.7 kg of tap water per 1 217 kg of apples. For a reference flow of 3 000 kg of apples, this corresponds to approximately 1 370 kg of water.

For apple milling, the present study used the same equipment model as Zdravković et al. (2021), but upsized for higher throughput: the Voran Elevator SA400 paired with a Centrifugal Mill RM4 (n.d.). An alternative option was the SA300, but its 1 000-3 000 kg/h capacity would force the system to operate at its maximum when processing 3 000 kg, making it unsustainable. The drive motor and mill motor have rated power outputs of 0.55 kW and 7.50 kW, respectively (Voran Maschinen GmbH, n.d.). These values were assumed to remain constant for inputs ranging between 3,000 to 8,000 kilograms per hour. This resulted in 8.05 kWh to wash and mill 3000 kg of industrial apples.

A.1.3 Rack-and-Cloth Press - Energy Use

The next step was a rack-and-cloth press, which squeezes mash between cloth belts under high pressure (Zdravkovic et al., 2021). Pomace, containing pulp, seeds, stems, peel and core fragments, and juice emerged as two separate streams. The two available models (100P2 and 180P2) are too small to handle 3 000 kg/h of apples, with the larger machine having a maximum capacity of 1 200 L/h (Voran Maschinen GmbH, nd.). Assuming 1 L of juice equals 1 kg of juice and coupling it with the machine product specification's promise of 75 % juice yield (Voran, nd.), processing 3 000 kg of mash would produce 2 250 liters of juice and 750 kg pomace. Since the sizes of these machines are not dimensioned for a system processing 3 000 kg of mash, the energy consumption for a 3 000 kg input could be estimated by extrapolating from the 100P2 and 180P2 performance data. The estimated energy consumption is approximately 3.4 kWh for 2 250 kg juice and 750 kg pomace output/h.

A.1.4 Cleaning Machines - Water Use

In the Zdravković et al. (2021) study, 172.3 L of tap water was used to clean equipment after processing 1 217 kg of apples. Normalizing to 3 000 kg yields would require approximately 425 L of water. Although Zdravković et al. use smaller-scale equipment, it was assumed that the throughput is the primary driver of plant sizing, thus the cleaning-water requirement was scaled proportionally. As Zdravkovic et al. (2021) do not provide detailed data on the distribution of wash water across all equipment units, and no additional sources specifying such data could be

identified, the volume was assumed to be evenly distributed among the units, as can be seen in Table A2.

Table A2. Allocation of water usage for the processing steps in the juice production per 1000 kg apples. The chosen equipment is borrowed from Zdravkovic et al.'s (2021) LCA on juice production.

#	Equipment	Share of wash water (%)	Volume (L)	Within system boundaries (binary)
1	Elevator	12.5	53.13	1
2	Integrated mill	12.5	53.13	1
3	Rack-and-cloth press	12.5	53.13	1
4	Collection tank	12.5	53.13	0
5	Pipe-screen filter	12.5	53.13	0
6	Buffer tanks #1	12.5	53.13	0
7	Buffer tank #2	12.5	53.13	0
8	Pasteurizer/filling unit	12.5	53.13	0
	Total	100	425	

The processes included in the present study's system are #1, #2 and #3, which makes 159.38 L per 3000 kg of apples.

A.2 Apple Pomace Valorization

In this section, the reference flow is defined as 750 kg of apple pulp. As described earlier, 750 kg of AP was obtained from the pressing of 3,000 kg of industrial apples. Table 3 presents all inputs associated with the AP processing stages.

Table A3. Energy and water inputs associated with processing 750 kg of AP, including heat treatment, cleaning, cold storage, and transportation steps.

Process Step	Input		Simapro module
	amount	Unit	
Mixing	6.60	kWh	Electricity, medium voltage {SE} market for electricity, medium voltage Cut-off, U
Heat treatment	11.00	kWh	Electricity, medium voltage {SE} market for electricity, medium voltage Cut-off, U
Machine cleaning	26.56	kg	Tap water {Europe without Switzerland} market for tap water Cut-off, U
Transport (apple juice processing facility → freezing storage)	21.90	tonne·km	Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing {GLO} market for transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing Cut-off, U
Freezing storage	30.42	kWh	Electricity, medium voltage {SE} market for electricity, medium voltage Cut-off, U
Transport (freezing facility → baking facility)	53.89	tonne·km	Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing {GLO} market for transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing Cut-off, U
Waste water	26.56	kg	Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U

A.2.1 Mixing - Energy Use

The next step in the process was to mix the AP into a homogeneous texture to make it more digestible. The PerMix PAM-750 vertical paddle mixer (PerMix, n.d.) was selected as a suitable industrial machine due to its throughput capacity and it being designed to handle moist, fibrous foods such as AP. The PAM-750 offers a working capacity of 525 liters. It was assumed that each mixing cycle takes 15 minutes, which allows for 4 batches per hour:

$750 \text{ kg} \div 4 \text{ batches} = 187.5 \text{ kg per batch.}$

With a measured bulk density of 446.5 kg/m^3 (Ivashchuk et al., 2024), this mass corresponds to a volume of:

$187.5 \text{ kg} \div 446.5 \text{ kg/m}^3 \approx 0.42 \text{ m}^3 = 420 \text{ liters.}$

According to the manufacturer's specifications, the PAM-750 is equipped with an 11 kW motor (PerMix, n.d.). However, the actual energy consumption was adjusted to 60% of rated power, resulting in an estimated electricity use of 6.6 kWh per hour. This adjustment was assumed because paddle mixers are mechanically load-dependent systems: their energy draw varies with filling level, material resistance, and viscosity. In this case, the mixer was not fully loaded ($\approx 85\%$ fill), and the moist AP was relatively easy to mix, requiring less than the motor's maximum.

In contrast, the other processes in this system, such as milling, pressing and pasteurization, were assumed to use energy to generate heat or constant mechanical pressure. These processes operate with stable energy profiles based on throughput or temperature, and their energy demands are typically not sensitive to small changes in load or material texture. Therefore, they were modeled using fixed kWh values derived from manufacturer specifications or flow-based extrapolation. For the paddle mixer, however, a load-adjusted estimate better reflects real industrial performance and avoids overestimating energy use in the LCA.

A.2.2 Heat Treatment of the Pomace - Energy Use

The high sugar and fiber content of AP creates an ideal environment for bacteria, molds, and fungi unless it is properly treated (Kausar et al., 2024). According to Maurya et al. (2025), pasteurization is a type of thermal processing that ensures food safety and extends the shelf-life by deactivating microbial growth without compromising nutritional value.

No pasteurization equipment specifically designed for the treatment of AP has been identified in the Voran product series or in other publicly available online sources. Therefore, this study uses the TEK-2PH-J juice and fruit-purée pasteurizer (Tekmash, n.d.) as a proxy. According to the manufacturer, this machine is capable of processing 0.8-1.5 tonnes per hour with a motor power rating of 11-15 kW, and an average power consumption of 10-12 kWh/h (Tekmash, nd).

Assuming a fixed average power draw of 11 kW and a throughput of 750 kg per hour, the estimated energy requirement for pasteurization is $P \cdot t = 11 \text{ kW} \cdot 1 \text{ h} = 11 \text{ kWh}$.

A.2.3 Cleaning Machines - Water Use

The water consumption for cleaning the PAM-750 mixer is based on the cleaning water allocated to milling equipment in Table A2, adapted from Zdravković et al. (2021). Since mixing involves a material of similar texture and residue characteristics as milling, the same cleaning water volume is assumed and scaled linearly. From the table, 53.13 L is the water of 3 000 kg of apples. For a throughput of 750 kg of AP, the scaled cleaning water requirement becomes:

$$(53.13 \text{ L} \div 3\,000 \text{ kg}) \cdot 750 \text{ kg} = 13.28 \text{ L}$$

Thus, 32.7 liters of water per hour is assumed for cleaning the mixer.

With regards to the water volume used for cleaning the pasteurizer, the same rationale for cleaning the mixer is applied, the cleaning volume is assumed to scale directly with throughput, giving 13.27 L. Thus, cleaning of both the mixer and the pasteurizer consumes in total 26.56 litres of water.

A.2.4 Transportation From Apple Juice Processing Facility to Freezing Storage

To estimate the distance between apple pressing facilities in Skåne, which are sufficiently large to make apple press residues-to-ingredient conversion economically viable, and nearby freezer storage facilities, Kiviks Musteri and Kullabygdens Musteri were selected as examples. Norfrig freezer storage, located at Industribyn 2, 273 35 Tomelilla, is 29.7 km from Kiviks Musteri at Karakåsvägen 45, 277 35 Kivik (Google Maps, 2025c), while Frigoscandia, located at Billesholmsvägen 6, 267 40 Bjuv, is 28.6 km from Kullabygdens Musteri AB at Mjöhultsvägen 354, 263 93 Mjöhult (Google Maps, 2025d). Based on these two examples, the average transport distance is approximately 29.2 km, which in turn results in the transport work amounting to $29.2 \text{ km} \cdot 0.750 \text{ tonnes} \approx 21.9 \text{ tonne} \cdot \text{km}$.

A.2.5 Freezing Storage - Energy Use

This section estimates the freezer capacity and energy demand required to store AP between its seasonal generation and year-round withdrawal. Annual AP generation at Kivik is 750 t/yr. Since production occurs over 12 weeks, the weekly production rate is:

$$750 \text{ t} \div 12 \text{ wk} \approx 62.5 \text{ t/wk}$$

Withdrawals occur evenly throughout the year:

$$750 \text{ t} \div 52 \text{ wk} \approx 14.42 \text{ t/wk}$$

Because production is seasonal while use is continuous, inventory accumulates during the 12-week production period. The peak inventory is:

$(62.5 - 14.42) \text{ t/wk} \cdot 12 \text{ wk} = 48.08 \text{ t/wk} \cdot 12 \text{ wk} = 576.96 \text{ t}$, which determines freezer room capacity.

The average annual inventory is:

$$\frac{576.96}{2} \text{ t} = 288.48 \text{ t}, \text{ used for estimating residence time.}$$

With a bulk density of 446.5 kg/m³ (Ivashchuk et al., 2024), the volume needed to store 705 kg AP is:

$$705 \text{ kg} \div 446.5 \text{ kg/m}^3 \approx 1.58 \text{ m}^3$$

The freezer room volume required for storing the peak annual inventory is:

$$V = 576.96 \text{ t} \cdot 0.446 \text{ t/m}^3 = 257.32 \text{ m}^3$$

The average time material remains in storage is:

$$\tau = 288.48 \text{ t} \div 750 \text{ t/yr} = 0.385 \text{ yr}$$

Frozen-storage SEC is 50 kWh/m³·yr (Duiven & Binard, 2002). Thus, The storage energy for 705 kg is:

$$E = 1.58 \text{ m}^3 \cdot 50 \frac{\text{kWh}}{\text{m}^3 \cdot \text{year}} \cdot 0.385 \text{ year} \approx 30.42 \text{ kWh per 705 kg pomace}$$

A.2.6 Transportation from Freezing Storage to Bakery

Pågen and Fazer, two of the largest bakeries in Sweden (Brödinstitutet, n.d.), have been selected as candidates for incorporating upcycled AP as a bread ingredient. Pågen has two bakeries, one in

Gothenburg and one in Malmö (Pågen, nd.), and Fazer has its bakeries in Umeå, Eskilstuna and Lidköping (Fazer, nd). In this study, the bakeries closest to the cold storage facilities were chosen. Pågen at Kopparbergsgatan 19, 214 44 Malmö and Norfrig have a distance of 73.1 km (Google Maps, 2025b), and Fazer at Kartåsgatan 3A, 531 40 Lidköping is 70.6 km away from Frigoscandia (Google Maps, 2025a.). The average distance is thus $\frac{73.1+70.6}{2} = 71.85 \text{ km}$ and the transportation work to transport 0.750 metric tonnes over said distance is $71.85 \text{ km} \cdot 0.750 \text{ tonnes} \approx 53.89 \text{ tonne} \cdot \text{km}$. This is considered the most realistic scenario in terms of logistical efficiency, environmental impact, and cost-effectiveness.

A.2.7 Waste

The solid waste is assumed to be negligible. The waste water comes from the tap water used to clean the machinery.

A.3 Ingredient Dataset Modelling

Rye flour, represented by the dataset “Rye flour {RoW}| market for rye flour | Cut-off, U (tweaked inputs)”, was obtained by adapting the existing process “Wheat flour {RoW}| market for wheat flour | Cut-off, U”. Specifically, one of its inputs, “Wheat flour {RoW}| wheat grain processing, dry milling | Cut-off, U” was adjusted. Within this milling process, two technosphere inputs related to raw material supply, “Wheat grain {AU}| market group for wheat grain | Cut-off, U” and “Wheat grain {RoW}| market for wheat grain | Cut-off, U”, were replaced with “Rye grain {GLO}| market for rye grain | Cut-off, U”. The mass inputs were kept to ensure consistency in processing assumptions.

Due to limited data on the specific inputs and processing steps involved in producing hydrothermally treated cut rye, it is here assumed to consist only of its main ingredient, without accounting for additional steps like fermentation, heating, or cooling. This choice is made to maintain consistency when comparing two types of bread, one with upcycled AP and one without. Since hydrothermally treatment is not necessary in the novel bread, using standard bread ingredients makes the comparison more relevant and applicable to the general bread market. As a

result, hydrothermally treated cut rye is represented by a modified version of Rye flour {RoW}| market for rye flour | Cut-off, U (inputs tweaked).

Bread syrup was modeled using the Ecoinvent dataset for *Molasses {GLO} | market for | Cut-off, U*”, while rapeseed oil used “*Rapeseed oil, refined {RER} | market for | Cut-off, U*”. Yeast was modeled using the Ecoinvent dataset “*Fodder yeast*. Salt was modeled using *Sodium chloride {RoW} | market for | Cut-off, U*”. Water was assumed to be municipal tap water with data from “*Water, tap, at user {RER} | market for | Cut-off, U*”.

The production phase in the bakery is included in the foreground system. The facility is modeled as a large industrial bakery operating in Sweden. The main processes include ingredient mixing, kneading, dough resting and fermentation, dividing, and baking. Electricity consumption for baking is modeled using the Ecoinvent dataset for medium-voltage electricity specific to Sweden: “*Electricity, medium voltage {SE} | market for | Cut-off, U*”.

B

Appendix: Characterized Results

This appendix presents the full characterized life cycle impact results for all bread ingredients across all functional units and modelling scenarios. Results are shown for both allocation approaches (zero-burden and mass-based) and for the lower- and upper-fiber content scenarios used in the 100 g fiber functional unit. To avoid duplication, tables already presented in the Results chapter are omitted. The numerical values presented here correspond directly to the summarized results reported in Chapter 4 and provide full transparency of the impact contributions.

B.1 Relative Contribution of Ingredients for the 1 kg Bread

Functional Unit

This section presents the relative contributions of each ingredient to the environmental impacts of producing 1 kg of bread. Results are expressed as percentages of the total impact for each category

Table B1. Relative contribution results by ingredient to different impact categories, expressed as percentages of the total impact for RB.

1 kg RB	GWP	Land use	Water consumption	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication
Fresh yeast	9.71%	6.50%	1.07%	7.26%	6.47%	2.37%
Rapeseed oil	3.71%	4.83%	0.81%	7.29%	2.24%	6.61%

Rye flour	32.74%	52.90%	27.21%	25.05%	23.66%	56.98%
Water	0.03%	0.00%	0.36%	0.01%	0.03%	0.00%
Wheat flour	53.18%	35.76%	70.50%	60.01%	66.88%	34.01%
Salt	0.64%	0.01%	0.05%	0.39%	0.72%	0.03%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B2. Relative contribution results by ingredient to different impact categories, expressed as percentages of the total impact for APB-ZB.

APB-ZB	GWP	Land use	Water consumption	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication
AP-ZB	0.35%	0.00%	0.02%	0.06%	0.08%	0.00%
Bread syrup	0.43%	0.09%	0.20%	0.97%	0.33%	0.28%
Fresh yeast	7.68%	5.12%	0.85%	5.57%	5.14%	1.83%
Rapeseed oil	5.86%	7.61%	1.28%	11.18%	3.56%	10.19%
Rye flour	32.13%	51.67%	26.76%	23.85%	23.32%	54.57%
Water	0.03%	0.00%	0.40%	0.01%	0.03%	0.00%
Wheat flour	53.05%	35.50%	70.46%	58.08%	67.00%	33.11%
Salt	0.48%	0.01%	0.04%	0.28%	0.54%	0.02%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B3. Relative contribution results by ingredient to different impact categories, expressed as percentages of the total impact for APB-MA.

APB-MA	GWP	Land use	Water consumption	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication
AP-MA	4.16%	1.02%	9.15%	2.49%	8.17%	1.86%
Bread syrup	0.41%	0.09%	0.18%	0.95%	0.30%	0.27%
Fresh yeast	7.38%	5.06%	0.77%	5.43%	4.72%	1.80%

Rapeseed oil	5.64%	7.53%	1.16%	10.91%	3.27%	10.00%
Rye flour	30.90%	51.15%	24.31%	23.27%	21.43%	53.56%
Water	0.03%	0.00%	0.36%	0.01%	0.03%	0.00%
Wheat flour	51.02%	35.14%	64.02%	56.67%	61.57%	32.49%
Salt	0.46%	0.01%	0.04%	0.27%	0.50%	0.02%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

B.2 Apple Pomace Ingredient Scenarios

This section provides detailed results for the environmental performance of the AP ingredient under different modelling approaches. Characterization results are shown for both the zero-burden and mass-allocation scenarios, while process contributions are expressed only for the zero-burden scenario.

Table B4. Relative contributions of AP ingredient processing steps to each impact category, expressed as percentages of the total impact under the zero-burden scenario.

AP-ZB	Global warming	Land use	Water consumption	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication
Electricity	5.78%	37.72%	87.33%	12.62%	17.35%	28.57%
Water	0.04%	0.00%	8.88%	0.08%	0.18%	0.07%
Transport	94.14%	62.25%	12.61%	87.20%	80.10%	51.18%
Waste water treatment	0.04%	0.03%	-8.82%	0.09%	2.37%	20.19%
Apple production	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B5. Characterized results for individual ingredients in 80 g of AP-ZB.

80 g AP-ZB	Input amount	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
Electricity	5.12E-03	1.55E-04	4.90E-05	2.80E-05	4.72E-07	5.49E-08	2.33E-08
Water	2.83E-03	1.15E-06	4.57E-12	2.84E-06	3.08E-09	5.80E-10	5.69E-11
Transport	8.08E-03	2.52E-03	8.09E-05	4.04E-06	3.26E-06	2.54E-07	4.17E-08
Waste water treatment	2.83E-03	1.15E-06	3.44E-08	-2.82E-06	3.39E-09	7.50E-09	1.64E-08
Apple production	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	1.89E-02	2.68E-03	1.30E-04	3.20E-05	3.74E-06	3.17E-07	8.15E-08

Table B6. Characterized results for individual ingredients in 80 g of AP-MA.

80 g AP-MA	Input amount	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
Electricity	5.43E-03	1.64E-04	5.20E-05	2.96E-05	5.00E-07	5.82E-08	2.47E-08
Water	4.36E-02	1.77E-05	7.04E-11	4.38E-05	4.74E-08	8.94E-09	8.75E-10
Transport	1.25E-02	3.38E-03	1.19E-04	5.67E-06	4.37E-06	3.28E-07	5.34E-08
Waste water treatment	4.36E-02	1.77E-05	5.30E-07	-4.35E-05	5.22E-08	1.15E-07	2.53E-07
Apple production	8.00E-02	2.99E-02	3.98E-02	1.42E-02	1.59E-04	3.35E-05	5.07E-05
Total	1.85E-01	3.35E-02	4.00E-02	1.42E-02	1.64E-04	3.40E-05	5.10E-05

B.3 Characterized results for 1 kg Bread Functional Unit

In this section, the characterized impact results for the 1 kg bread functional unit are reported. All impact categories are presented for each ingredient, complementing the relative contributions in Section B.1 and providing the numerical basis for the results discussed in Chapter 4.

Table B7. Characterized results for individual ingredients in 1 kg of RB.

1 kg RB	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
Fresh yeast	8.55E-02	2.86E-01	1.73E-03	5.17E-04	2.83E-05	7.12E-05
Rapeseed oil	3.27E-02	2.12E-01	1.30E-03	5.19E-04	9.81E-06	1.98E-04
Rye flour	2.88E-01	2.32E+00	4.39E-02	1.78E-03	1.04E-04	1.71E-03
Water	2.34E-04	9.30E-10	5.78E-04	6.27E-07	1.18E-07	1.16E-08
Wheat flour	4.69E-01	1.57E+00	1.14E-01	4.27E-03	2.93E-04	1.02E-03
Salt	5.63E-03	3.22E-04	8.58E-05	2.75E-05	3.14E-06	8.00E-07
Total	8.81E-01	4.39E+00	1.61E-01	7.12E-03	4.38E-04	3.00E-03

Table B8. Characterized results for individual ingredients in 1 kg of APB-ZB.

APB-ZB	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
AP-ZB	2.68E-03	1.30E-04	3.20E-05	3.74E-06	3.17E-07	8.15E-08
Bread syrup	3.32E-03	3.61E-03	2.84E-04	6.27E-05	1.27E-06	7.56E-06
Fresh yeast	5.93E-02	1.98E-01	1.20E-03	3.58E-04	1.97E-05	4.94E-05
Rapeseed oil	4.53E-02	2.94E-01	1.81E-03	7.20E-04	1.36E-05	2.75E-04
Rye flour	2.48E-01	2.00E+00	3.78E-02	1.54E-03	8.92E-05	1.47E-03
Water	2.26E-04	9.01E-10	5.60E-04	6.07E-07	1.14E-07	1.12E-08

Wheat flour	4.10E-01	1.37E+00	9.96E-02	3.74E-03	2.56E-04	8.94E-04
Salt	3.69E-03	2.11E-04	5.62E-05	1.81E-05	2.06E-06	5.24E-07
Total	7.73E-01	3.87E+00	1.41E-01	6.44E-03	3.83E-04	2.70E-03

Table B9. Characterized results for individual ingredients in 1 kg of APB-MA.

APB-MA	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
AP-MA	3.35E-02	4.00E-02	1.42E-02	1.64E-04	3.40E-05	5.10E-05
Bread syrup	3.32E-03	3.61E-03	2.84E-04	6.27E-05	1.27E-06	7.56E-06
Fresh yeast	5.93E-02	1.98E-01	1.20E-03	3.58E-04	1.97E-05	4.94E-05
Rapeseed oil	4.53E-02	2.94E-01	1.81E-03	7.20E-04	1.36E-05	2.75E-04
Rye flour	2.48E-01	2.00E+00	3.78E-02	1.54E-03	8.92E-05	1.47E-03
Water	2.26E-04	9.01E-10	5.60E-04	6.07E-07	1.14E-07	1.12E-08
Wheat flour	4.10E-01	1.37E+00	9.96E-02	3.74E-03	2.56E-04	8.94E-04
Salt	3.69E-03	2.11E-04	5.62E-05	1.81E-05	2.06E-06	5.24E-07
Total	8.04E-01	3.91E+00	1.56E-01	6.60E-03	4.16E-04	2.75E-03

B.4 100 g fiber Functional Unit

In this section, the characterized impact results for the 100 kg bread functional unit are reported, with four scenarios for the AP bread. All impact categories are presented for each ingredient, complementing the relative contributions in Section B.1 and providing the numerical basis for the results discussed in Chapter 4.

Table B10. Fiber per ingredient, with AP being derived from (Zaky et al., 2024) and the rest of the ingredients from the Swedish Food Agency's food database (Livsmedelsverket, 2025).

Ingredient	AP	Syrup	Rye flour	Rapeseed oil	Salt	Water	Wheat flour	Yeast
g fiber/100 g	6.8-15.3	0	18.8	0	0	0	3.1	0

Table B11. Characterized results for individual RB ingredients using the 100 g fiber functional unit

RB	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
Fresh yeast	1.07E-01	3.57E-01	2.16E-03	6.46E-04	3.54E-05	8.90E-05
Rapeseed oil	4.08E-02	2.65E-01	1.63E-03	6.48E-04	1.23E-05	2.48E-04
Rye flour	3.60E-01	2.90E+00	5.48E-02	2.23E-03	1.29E-04	2.14E-03
Water	2.92E-04	1.16E-09	7.23E-04	1.00E-06	1.48E-07	1.45E-08
Wheat flour	5.85E-01	1.96E+00	1.42E-01	5.34E-03	3.66E-04	1.28E-03
Salt	7.04E-03	4.02E-04	1.07E-04	3.40E-05	3.93E-06	9.99E-07
Total	1.10E+00	5.48E+00	2.01E-01	8.89E-03	5.47E-04	3.76E-03

Table B12. Characterized environmental impacts for individual AP bread ingredients under the 100 g fiber functional unit (zero-burden, lower-fiber scenario)

APB-ZB-LF	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
AP	3.59E-03	1.74E-04	4.29E-05	5.00E-06	4.24E-07	1.09E-07
Bread syrup	4.45E-03	4.84E-03	3.80E-04	8.40E-05	1.70E-06	1.01E-05
Fresh yeast	7.96E-02	2.66E-01	1.61E-03	4.81E-04	2.64E-05	6.63E-05
Rapeseed oil	6.08E-02	3.95E-01	2.42E-03	9.66E-04	1.82E-05	3.69E-04
Rye flour	3.33E-01	2.68E+00	5.07E-02	2.06E-03	1.20E-04	1.98E-03
Water	3.03E-04	1.21E-09	7.51E-04	1.00E-06	1.53E-07	1.50E-08
Wheat flour	5.50E-01	1.84E+00	1.34E-01	5.02E-03	3.44E-04	1.20E-03
Salt	4.95E-03	2.83E-04	7.54E-05	0.000024	2.76E-06	7.03E-07
Total	1.04E+00	5.19E+00	1.90E-01	8.64E-03	5.13E-04	3.62E-03

Table B12. Characterized environmental impacts for individual AP bread ingredients under the 100 g fiber functional unit (zero-burden, higher-fiber scenario)

APB-ZB-HF	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
AP	3.29E-03	1.60E-04	3.93E-05	5.00E-06	3.89E-07	1.00E-07
Bread syrup	4.08E-03	4.44E-03	3.48E-04	7.70E-05	1.56E-06	9.29E-06
Fresh yeast	7.29E-02	2.43E-01	1.47E-03	4.40E-04	2.41E-05	6.07E-05
Rapeseed oil	5.57E-02	3.62E-01	2.22E-03	8.84E-04	1.67E-05	3.38E-04
Rye flour	3.05E-01	2.46E+00	4.64E-02	1.89E-03	1.10E-04	1.81E-03
Water	2.78E-04	1.11E-09	6.88E-04	1.00E-06	1.40E-07	1.38E-08
Wheat flour	5.04E-01	1.69E+00	1.22E-01	4.59E-03	3.15E-04	1.10E-03
Salt	4.53E-03	2.59E-04	6.90E-05	0.000022	2.53E-06	6.44E-07
Total	9.50E-01	4.76E+00	1.74E-01	7.91E-03	4.70E-04	3.32E-03

Table B13. Characterized environmental impacts for individual AP bread ingredients under the 100 g fiber functional unit (mass-based, lower-fiber scenario)

APB-MA-LF	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
AP	4.49E-02	5.37E-02	1.91E-02	2.20E-04	4.56E-05	6.84E-05
Bread syrup	4.45E-03	4.84E-03	3.80E-04	8.41E-05	1.70E-06	1.01E-05
Fresh yeast	7.96E-02	2.66E-01	1.61E-03	4.81E-04	2.64E-05	6.63E-05
Rapeseed oil	6.08E-02	3.95E-01	2.42E-03	9.66E-04	1.82E-05	3.69E-04
Rye flour	3.33E-01	2.68E+00	5.07E-02	2.06E-03	1.20E-04	1.98E-03
Water	3.03E-04	1.21E-09	7.51E-04	8.14E-07	1.53E-07	1.50E-08
Wheat flour	5.50E-01	1.84E+00	1.34E-01	5.02E-03	3.44E-04	1.20E-03
Salt	4.95E-03	2.83E-04	7.54E-05	2.42E-05	2.76E-06	7.03E-07
Total	1.08E+00	5.24E+00	2.09E-01	8.85E-03	5.58E-04	3.69E-03

Table B14. Characterized environmental impacts for individual AP bread ingredients under the 100 g fiber functional unit (mass-based, higher-fiber scenario)

APB-MA-HF	GWP (kg CO2 eq)	Land use (m2a crop eq)	Water consumption (m3)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)
AP	4.11E-02	4.92E-02	1.75E-02	2.02E-04	4.18E-05	6.27E-05
Bread syrup	4.08E-03	4.44E-03	3.48E-04	7.70E-05	1.56E-06	9.29E-06
Fresh yeast	7.29E-02	2.43E-01	1.47E-03	4.40E-04	2.41E-05	6.07E-05
Rapeseed oil	5.57E-02	3.62E-01	2.22E-03	8.84E-04	1.67E-05	3.38E-04
Rye flour	3.05E-01	2.46E+00	4.64E-02	1.89E-03	1.10E-04	1.81E-03
Water	2.78E-04	1.11E-09	6.88E-04	7.46E-07	1.40E-07	1.38E-08
Wheat flour	5.04E-01	1.69E+00	1.22E-01	4.59E-03	3.15E-04	1.10E-03
Salt	4.53E-03	2.59E-04	6.90E-05	2.22E-05	2.53E-06	6.44E-07
Total	9.88E-01	4.80E+00	1.91E-01	8.11E-03	5.11E-04	3.38E-03

