Improving sustainability in the Dutch food processing industry

BO project Verhoging duurzaamheid voedselverwerking in de keten

PUBLIC

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Executive summary

Sustainable food processing is required for healthy and equitable food systems and a circular economy. Currently, efforts and initiatives to improve the sustainability of food processing in the agri-food chain are increasing. This report describes the results of the project 'BO project Verhoging duurzaamheid voedselverwerking in de keten'. The project started with the following research questions: which sustainability strategies are most effective, under which conditions and for which products, and which main opportunities and barriers can be leveraged and addressed to increase sustainability of food processing at a national level. Increasing the sustainability of processing within agri-food chains presents challenges due to the complexity of the food system, the diversity of products and processes, the interdependencies among chain actors, and the need for supportive conditions across market, policy and other external domains. To effectively compare the sustainability impacts of alternative food systems, it is essential to assess their cumulative effects across the entire chain. This requires the development of robust methods to evaluate which interventions contribute to measurable sustainability improvements.

Thereto, this project aimed to 1) map the food processing landscape in the Netherlands through identifying and characterising current food process chain practices, 2) identify drivers and barriers for increasing the sustainability of food process chains, 3) develop a sustainable processing assessment framework, 4) use the developed assessment framework, identify promising solutions for a systemic transition to sustainable food processing in the Netherlands, and 5) develop a roadmap for more sustainable processing.

This project compared different food processing scenarios using an environmental sustainability assessment framework for various case studies relevant to the Dutch food processing industry. The assessment framework is based on the Agro-Chain greenhouse gas Emissions (ACE) calculator which was further developed within the project to be able to calculate the environmental sustainability of the case studies. The ACE calculator assesses greenhouse gas (GHG) emissions, energy use and water use of food chains. The ACE calculator provided insight into sustainability hotspots in the chain and showed the effect of alternative food chain configurations on environmental sustainability impact. The calculator is designed for comparison studies of various configurations. Next to indicator values, insights into variability of the results and into the influence of the various inputs on the outcomes are provided. The sustainability assessment framework was applied in various relevant case studies.

To guide case study selection within the Dutch food processing sector, the relative production value, the relative export value, the number of companies per sector, and, for environmental sustainability relevancy, the primary energy use per sector, and the global warming potential (GWP) and water use data were used. The key product categories in the Dutch food processing sector include dairy products, meat and processed meat products, bakery and confectionary, processed fruits and vegetables, potato products, oils and fats, beverages, fish and seafood processing, and a large share is other foods which includes sugar, tea, coffee, convenience and ready meals and herbs and spices (FNLI, nd).

To define case study focus further, we asked: 'Which developments are affecting sustainability in the Dutch food processing industry?' Based on project team discussions, literature search, and building on our expertise and experiences with the sector, we decided to present five relevant domains in which developments are affecting the food processing industry, focusing on the perceived sustainability improvements in these domains. The five domains include protein source, circularity, packaging materials, agricultural practices, and value chain length and organisation. Other relevant topics which did not exclusively feature as a separate domain because the perceived sustainability improvements are less evident, but are interwoven with most, are viability of business cases, consumer preferences and habits, food safety, and the energy transition and electrification.

Case studies have been assessed on sustainability effects of the 'perceived sustainability improvements' using the assessment framework (see Table 1). Please note that the conclusions are case dependent and that they only cover greenhouse gas (GHG) emissions, energy use, and water use as selected sustainability indicators.

Table 1 Case studies with scenarios, domain and main results

	"Current domain scenario"	"Perceived sustainability improvement"	Domain issue	Summary of results
Apple juice	Apple juice from concentrate from Poland (in Tetrapak)	Fresh, local apple juice (in glass bottle)	Value chain length / transport, packaging materials, and organisation and circularity	The differences between the local and the long chain in terms of GHG emissions and energy consumption are not big. The use of glass is more resource-intensive than e.g. Tetrapak.
Bread: wheat bread	Centralized, industrial bread	Decentralized, local bakery, baking at home	Value chain length and organisation	Industrially produced par-baked bread that is finished baked in supermarkets induces slightly higher GHG emissions than completely industrially baked bread or than bread from a local bakery. This is due to that two baking steps, freezing and frozen storage and distribution are required for par-baked bread. Baking at home had lowest GHG emissions and energy use when using a bread baking machine.
Pulses: brown beans	Conventionally cultivated pulses in can or glass	Organically cultivated brown beans Beans in pouch or tetrapak	Agriculture, packaging materials and energy source	Conventionally cultivated pulses usually requires less land and water than organically cultivated pulses. Heat generated from grid electricity (Dutch electricity mix) does not have a lower carbon footprint than heat from natural gas. Pouch and Tetrapak induce less GHG emissions than metal cans and glass.
French fries	Frozen French fries	Chilled French fries	Value chain length and organisation	Overall, the environmental impact differences between the two chains are small. The chilled French fries perform slightly better in terms of GHG emissions and energy use. The freezing process and longer storage times of the frozen fries makes it more energy-intensive compared to chilled fries.
Protein sources	Meat patties	Plant-based meat replacers, pulse patties	Protein source/transition	The chicken burger and plant-based options are a lot more sustainable in terms of GHG emissions and water use than the beef burger, with canned beans having the lowest environmental impact. The water footprint was mainly influenced by the presence of the other ingredients as both olive oil and rice protein require a lot of water during the production phase. Highly refined ingredients are more resource intensive than less refined ingredients.

The results of the case studies are case specific and dependent on certain assumptions. An attempt was made to generalize the findings of the case studies to the meso level of food systems or domains. We showed that the choice of food packaging can have a large contribution to the environmental impact of the consumable product, but the exact materials determine the final outcome. We found that it is not a given that local food products are more environmentally sustainable than food products that have a longer food chain organisation and that waste management is important for decision-making in every value chain. We found the small difference in environmental sustainability between frozen and chilled French fries to be caused by the freezing process and longer storage times of the frozen fries (making it more energy-intensive compared to chilled fries). The slightly higher product loss at retail of the chilled fries (2% compared to 1% for frozen fries) has a negligible impact on the environmental sustainability. It was evident that plant-based meat alternatives outperform beef (and not the chicken burger) in terms of GHG emissions, but we also showed that by applying fewer refining steps for plant based burger production even more reductions in GHG emissions would be possible. We also found that organic cultivation of brown beans had a slightly higher environmental impact (in the agricultural phase) than conventional cultivation of brown beans, but this may be different per crop category and per impact category outside of the ones addressed in this study.

Results were presented and discussed in 2 webinars with several companies in the bread and bakery sector and the processed vegetables and fruits sector. Companies were very interested in the approach and results of the project. The results of the case studies were inspiring, although generalizing findings of case studies to other domains or food systems remains challenging. However, in the discussions with companies the value of the tool was evident; it showed where environmental sustainability hotspots are in the chain and in their own operations. The calculator could handle different interventions to show what improvement can be made when choosing for example another raw material, another packaging material, crops from a different origin or by changing technology. There is a need for quantitative environmental sustainability tools that can help companies in decision-making for reducing their impact and the ACE calculator can be part of the solution.

Additionally, in another activity the project aimed to provide a comprehensive overview of near-term and expected future enablers, barriers, and potential measures for enhancing sustainability within the Dutch food processing industry based on a literature review and a series of expert consultations took place in 2024. The result is a structured roadmap that identifies short-, medium-, and long-term opportunities and challenges across three stakeholder domains: industry, government, and society (Vernooij & Vollebregt, 2025 for more details). A range of measures has been identified to support sustainability in the Dutch food processing industry, many of which can be implemented in the short term. These include targeted training on circular economy principles, investments in equipment and infrastructure to improve resource efficiency, and enhanced collaboration across companies to enable circular supply chains. Developing harmonised sustainability indicators and transparent labelling, such as a European-wide food sustainability label, is essential to guide industry decisions and inform consumers. Policy measures like pilot projects, tax incentives, regulation of green claims, and removal of conflicting incentives further support this transition. Longer-term structural reforms, including true pricing and tax adjustments, are needed to embed sustainability within the industry's economic framework. Effective progress depends on coordinated stakeholder collaboration, adaptive policymaking, and ongoing monitoring.

Overview of publications resulting from this project:

- Berghout, J. A. M., & Siccama, J. W. (2024). Local or long chain foods: what is the more sustainable choice? A case study on apple juice.
- Rodriguez Illera, M., & Siccama, J. W. (2025). Uncovering the different environmental impacts of protein choices.
- Siccama, J. W., & Broeze, J. (2025). Pulses in many forms: what is the more sustainable choice? A case study on brown beans.
- Siccama, J. W., & Rodriguez Illera, M. (2025). Frozen or chilled: what is the more sustainable choice? A case study on French fries.
- Vollebregt, H. M., & Broeze, J. (2025). Data naar impact: duurzaamheid in ketens en verwerking. Voedingsindustrie, vol. 32, no1, February 2025, p48-51.
- Berghout, J. A. M., & Siccama, J. W. (2025). Centralized or decentralized: what is the more sustainable choice? A case study on bread.
- Vernooij & Vollebregt (2025) Perceived sustainability enablers, barriers and measures over time for the Dutch food processing industry: Info sheet and visualisations.

1 Introduction

Enhancing sustainability in food processing is essential for mitigating environmental impacts, such as the excessive consumption of water, energy, and raw materials, along with the generation of waste and greenhouse gas emissions. Sustainable food processing plays a pivotal role in the transition towards healthy, equitable food systems and the development of a circular economy. The sustainability of food processing must be considered throughout the entire agri-food chain, starting with the activities on the farm such as sorting, washing, and storage, and (primary) food processing at different scales and locations. Currently, efforts and initiatives are increasing to improve the sustainability of food processing in the agri-food chain. However, the question remains which strategies are most effective, under which conditions and for which products, and which main opportunities and barriers can be leveraged and addressed to increase sustainability of food processing at a national level.

Increasing the sustainability of processing within agri-food chains presents challenges due to the complexity of the food system, the diversity of products and processes, the interdependencies among chain actors, and the need for supportive conditions across market, policy and other external domains. To effectively compare the sustainability impacts of alternative food systems, it is essential to assess their cumulative effects across the entire chain. This requires the development of robust methods to evaluate which interventions contribute to measurable sustainability improvements.

This report describes the results of the project ‘BO project Verhoging duurzaamheid voedselverwerking in de keten’. The project focuses specifically on sustainable processing of agricultural materials into food, considering food chains with at least one processing step in the Netherlands. Sustainability has many aspects and in this project we focus on environmental sustainability including greenhouse gas (GHG) emissions, water and energy consumption as this is tangible and measurable in the food industry. Moreover, food processing research focuses on energy, water and electricity data that can be used in our research.

This project aims to 1) map the food processing landscape in The Netherlands through identifying and typifying current agri-food chain practices, 2) identify drivers and barriers for increasing the sustainability of agri-food chains, 3) develop a sustainable processing assessment framework, 4) identify promising solutions for a systemic transition to sustainable food processing in The Netherlands, with the use of the assessment framework, and 5) develop a roadmap for more sustainable processing.

Chapter 2 describes the approach for each of the above aims followed by the results of that approach in chapter 3. Chapter 4 contains the conclusions and recommendations of the report.

2 Materials and methods

The approach for the project comprises the following steps: 1) sketch the current situation, identify drivers and barriers, 2) find opportunities and challenges and 3) develop an assessment framework. The assessment framework is then used to compare a current scenario with alternative scenarios for 6 case studies (Figure 1).

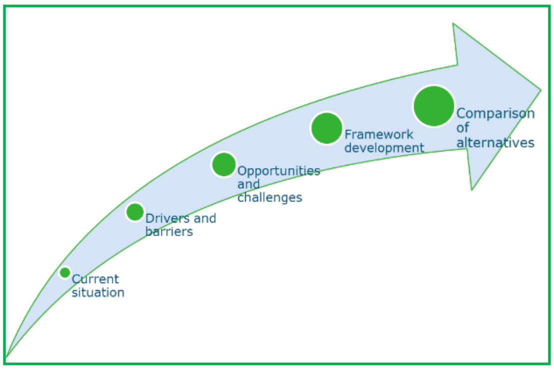


Figure 1 Project approach

To structure and detail the way of working, we are using a multi-level perspective based on the transition model of Geels (Geels, 2002; Geels & Schot, 2007) as shown in Figure 2, left. The transition model has three levels: the macro (landscape), meso (patchwork of regimes), and micro level (niches). For this project on sustainability of food processing in the Netherlands, we translated this into the landscape of sustainability in the Dutch food processing chain (macro), regimes or existing systems (meso), and niches or case studies (micro) (Figure 2, right).

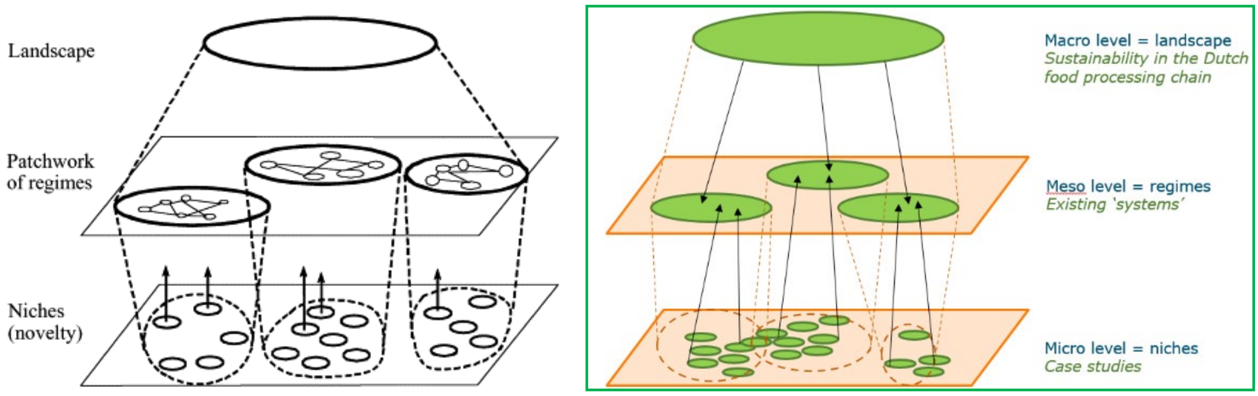


Figure 2 Left: multi-level perspective of Geels (2002), right: translated to this project

In this project, the macro level describes the landscape of sustainability in the Dutch food processing chain in the broadest sense, including national challenges such as climate change and nitrogen emissions. The meso level deals with the existing food systems in the food processing chain and new systems that can arise. Our approach is guided by exploring current persistent assumptions about improved sustainability, or 'myths', in relation to the topic of sustainable processing. The micro level is about the initiatives and innovations taking place at relatively small scale – e.g. company scale – which can potentially become part of the regime level, or are already shaping new norms in the regime level.
The reflection on various product chains (case studies) could support policy making and may lead to generalized insights into which solutions contribute most to making food processing in the chain more sustainable.

2.1 Landscape of the Dutch food processing industry

An overview of relevant sectors for the Dutch food processing industry is created using databases and literature. To guide the selection of case studies, the project conducted a preliminary assessment of sustainability hotspots – a specific stage, product, process or activity having a high negative impact on sustainability indicators - in the Dutch agri-food processing chain.

A selection of relevant sustainability indicators is made based on relevant themes in the Dutch food processing industry.

2.2 Perceived sustainability improvements

In order to help define further case study focus, we asked: 'Which developments are affecting sustainability in the Dutch food processing industry?' and 'What are the perceived sustainability improvements?' Largely based on project team discussions, literature search, and building on our expertise and experiences with the sector, we decided to present five relevant domains in which developments are affecting the food processing industry, including the perceived sustainability improvements in these domains. These are then reflected on in the case studies. The domains were updated over the course of the project, for example when related domains were merged or separated.

2.3 Development of roadmap drivers and barriers

To develop a roadmap of drivers and barriers to enhance sustainability in the Dutch food processing industry, various literature and expert consultations about sustainability enablers, barriers, and measures for the Dutch food processing industry were held. A full list of the literature references can be found in the info sheet of Vernooij & Vollebregt (2025).

2.4 Development of the assessment framework

Quantification of sustainability indicators of alternative food chain and food processing designs is required to prioritise options for improvement on sustainability. In this project we use an assessment framework based on food chain design as depicted in Figure 3. In the context of the chain of processed foods, the main elements to cover are the agricultural production at farms and the post-harvest operations and logistics, the processing in factories including waste and by-product management and combining these elements in case of multiple ingredients, and the distribution to end-users. Although not explicitly shown in Figure 3 the chain scope in this project is extended to include storage and distribution of food products as well.

The assessment tool used and further developed in this project is the Agro-Chain greenhouse gas Emission calculator (ACE calculator) developed by WFBR and extended in the underlying project (Broeze, 2019; Broeze et al., 2023). The ACE calculator uses a life cycle assessment (LCA)-based footprint methodology, estimates the impacts of a food processing chain based on several underlying data sets and case specific data and results include total and activity specific impacts. Originally the ACE calculator focusses on the estimation of greenhouse gas (GHG) emissions, expressed in CO_2-equivalents. The ACE calculator is further introduced in Section 2.4.1. In this project the ACE calculator is extended with 1) energy and water indicators, 2) a more detailed approach on food processing, 3) impacts of waste valorisation and waste management, 4) improved input and output data management, and 5) generation of automatic visualisations of the resulting output.

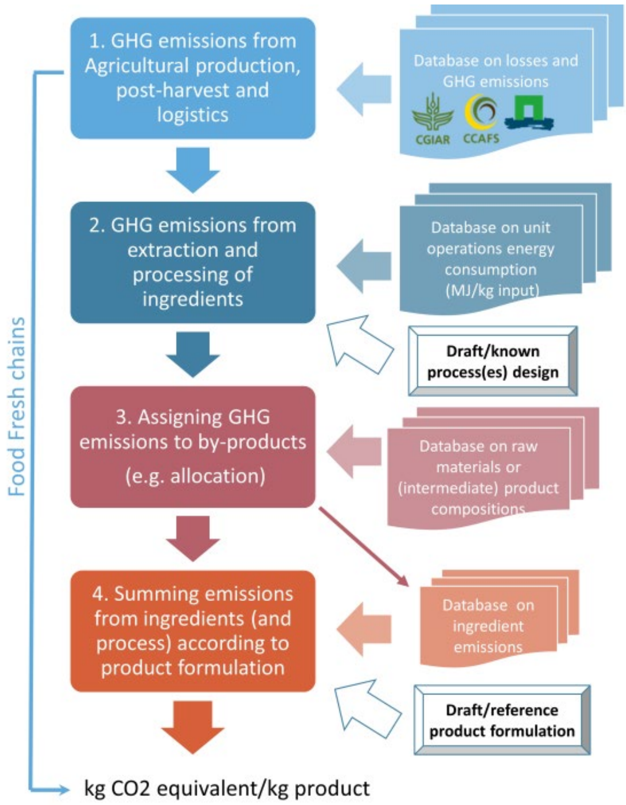


Figure 3 ***Stepwise LCA-based approach and framework used in the in the ACE calculator*** *(Rodriguez-Illera et al., 2019)****.***

Section 3.4.3 describes the differences between the ACE calculator and full life cycle analyses (LCA) on several aspects and shows that the ACE calculator could be very useful to compare different scenarios and strategies in improving sustainability in food chains.

2.4.1 Introduction to ACE calculator

The ACE calculator has been developed to estimate GHG emissions (Broeze, 2019; Broeze et al., 2023). In the underlying project the calculator is extended to include energy and water footprints as well. Next to supply chain design and operations, the calculator is capable to compare impacts of various raw materials and ingredient choices and different production and processing scenarios to support chain and process design. The ACE calculator supports scenario analyses on a wide variety of interventions that can potentially lower the impact and contribute to more sustainable food chains, as listed in Annex 1. A limited version of the tool is available in the public domain, with output limited to GHG emissions and the underlying data is not updated (Broeze, 2019).

The calculator is specifically designed to be applied on chains, and not to focus on a specific chain operation. This chain approach allows to place the impacts of the chain operations in perspective of the total impacts in the chain. It requires definition of the scope in each use case, this supports the user in considering all operations in the chain. Viewing the results from the point of view of a certain chain part then provides insights in scope 1, 2 and 3 impacts. Scope 1 impacts are the direct emissions due to the activities of the company, this includes use of resources (on site fuel use) in its factories or transport means. Scope 2 covers indirect emissions due to purchased energy for use by a company (electricity, heat or cooling). Scope 3 covers all other emissions in the value chain, both up- and downstream, that are occurring outside of the company and are not under the companies responsibility. The scopes have been formally defined for emissions, they can also be used for other aspects, such as water use.

Within the calculator different chain and processing configurations, or scenarios, can be compared on effects on the environmental sustainability indicators. The entire chain from raw materials until consumption can be considered, as well as waste or side stream management. Also parts of an agri-food chain can be analysed. The calculator supports a wide variety of interventions, such as alternative country of sourcing, transport modality, waste management and waste valorisation and packaging. From the calculations the net effects of

an intervention per unit of food can be compared. This comparison allows to assess the differences between the alternative scenarios as well as where the differences originate from. With these results, interventions can be prioritised on contribution to improved environmental sustainability. Next to that, identification of impact hotspots identifies aspects for which impact reduction is key. Furthermore, the aspects that influence the outcomes the most are identified, having accurate data on these aspects is of importance.
To estimate the impacts associated to a food product the following aspects have to be considered:

- Addressing all emissions / resource uses from agricultural production and post-harvest operations required for the food products as defined in the scoping.
- The volume of required materials must be corrected to include food loss and waste in the different chain stages.
- Allocation of the impacts to the food product of interest taking into account possible fractionation processes and possible other outputs from the underlying food chain.

The level of detail and accuracy that can be achieved depends on the available data. Data can be replaced and supplemented with case specific data, such as company data or data from literature.

2.4.1.1 Inputs, calculations and outputs

Inputs

The ACE calculator requires input data, such as specification of raw materials or ingredients, chain and processing activities, packaging materials, transport modality and distances, etc. To determine the associated impacts for the defined functional unit in the specific case study the input parameters are multiplied with the impact factors available in the ACE calculator resulting in the total impacts and the impact per activity.

The calculator includes data for different food categories and products and for supply chain operations that are linked to the choices made by the user. Examples of this data are the footprints of the primary production of certain crops given the country of origin and emissions due to various modes of transport. In Annex 1 the incorporated data is specified. All data can be replaced and supplemented with case specific data from the user. The accuracy of the calculations is improved with use of case specific data if available.

Calculations

The intended agri-food chain is modelled as a chain of unit operations, see Figure 4. This can be a linear chain but it can also have branches. For each unit operation j there are incoming mass flows m_{ij}^{in} (in kg) of material *i* that are converted by the unit operation to outgoing mass flows m_{kj}^{out} of material *k*. The conversion of materials i to k depends on the unit operation and is determined by process parameters α_{ij}^{in}. The output variables of the unit operations are the environmental sustainability indicators y_{ij}^{out}, and are calculated from the incoming flows and parameters as

$$y_{ij}^{out} = f_j(\{m_{.j}\}, \{\alpha_{.j}\})$$
$$m_{ij}^{out} = g_j(\{m_{.j}\}, \{\alpha_{.j}\})$$

with f_i and g_j functions of all incoming mass flows $\{m_{.j}\}$ and parameters $\{\alpha_{.j}\}$ associated with unit operation *j*.
Outgoing mass flows can go into another unit operation (internal flows) or are treated as a byproduct (a side stream with economic value). Similarly, ingoing mass flows can come from other unit operations or are raw materials. Raw materials include crops, ingredients as well as packaging materials. In general there is a main outgoing material flow of interest, the food product of interest manufactured in the agrifood chain.

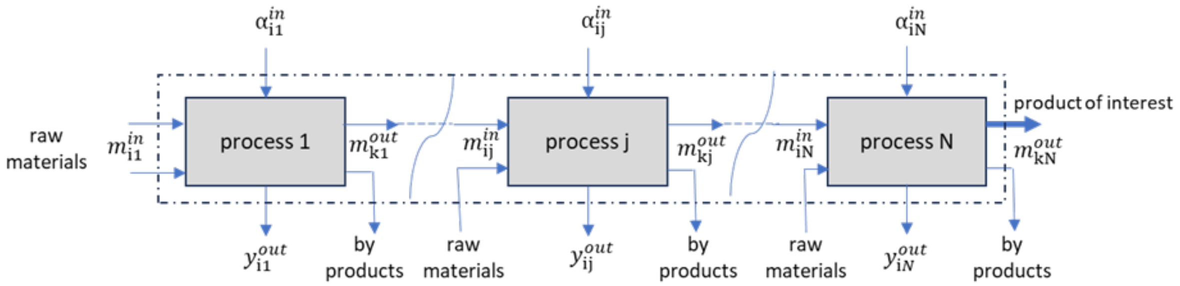


Figure 4 Chain of unit operations from raw materials to product of interest with inputs and outputs.

The goal is to estimate the value of the environmental sustainability indicator $\tilde{y}_i$ per kg of product. The total value of indicator $\tilde{y}_{i,total}$ associated with the whole agri-food chain is equal to the sum over all unit operations of the corresponding indicator values, y_{ij}^{out}, j , added to the sum of indicator values of incoming raw materials, $y_{im_jj}^{in} = m_{m_jj}\tilde{y}_{im_jj}^{in}$, giving

$$\tilde{y}_{i,total} = \sum_j y_{ij}^{out} + \sum_{m_j,j} y_{im_jj}^{in}$$

with m_j only part of the raw material flows of unit operation j and not of the internal material flows.

One could just divide $\tilde{y}_{i,total}$ by the mass of the product of interest m_{poi} to get the indicator per unit mass of product, but then one neglects that a part of the total value of the sustainability indicator should be associated with the possible byproducts of the chain. There are various methods to perform such byproduct valorisation (see Section 3.4.2.3 for what is available in the ACE calculator on this). Economic allocation is the default option in the calculator, where a price p_l [€/kg] is associated with each outgoing material. The sustainability indicator $\tilde{y}_{i,total,allocated}$ is then calculated in the case of economic byproduct validation as follows

$$\tilde{y}_{i,total,allocated} = \frac{p_{poi}}{\sum_l p_l}\frac{\tilde{y}_{i,total}}{m_{poi}}$$

where p_{poi} is the price of the product of interest.

Outputs

The outputs from the ACE calculator include:

1. *Sustainability indicator values* for given scenarios. The total impact value or footprint is given, as well as the impact per chain operation.
2. *Scenario data* The chain configuration and all input data can be stored and imported in the calculator.
3. *Uncertainty and sensitivity analyses results* To provide insight into the variability of the outcomes an uncertainty analyses is performed. To assess which inputs and model factors are sources of uncertainty and are impacting the indicator outcomes the most, sensitivity analyses are performed.

2.5 Application of assessment framework on case studies

To illustrate the value of the ACE calculator, several case studies are analysed. Case studies were selected based on relevancy for the Dutch food processing landscape, perceived sustainability improvements, existing sustainability myths, existing scientific literature on comparison of alternative scenarios and relevancy to the identified food systems in Section 3.2. Even though dairy and plant-based alternatives to e.g. milk are very relevant to the Dutch food processing sector, recent life cycle studies and a critical review paper showed the hotspots in the chains (Khanpit et al., 2024; Sandström et al., 2022) for various environmental sustainability indicators and therefore it was decided to focus on other chains first in this project.

Results were presented and discussed in 2 webinars with several companies in the bread and bakery sector and the processed vegetables and fruits sector.

3 Results

3.1 Landscape

The key product categories in the Dutch food processing sector include dairy products, meat and processed meat products, bakery and confectionary, processed fruits and vegetables, potato products, oils and fats, beverages, fish and seafood processing, and a large share is other foods which includes sugar, tea, coffee, convenience and ready meals and herbs and spices (Figure 5A (FNLI, n.d.)).

There are many ways to look at the value or relevancy of the sectors and for this project it was decided to look at the relative production value, the relative export value, the number of companies per sector, and for environmental sustainability relevancy the primary energy use per sector, and the global warming potential (GWP) and water use data.

The export value of Dutch produce (in billion euros) in 2022 per sector is displayed in Figure 5B (Jukema et al., 2022). Sectors with the largest share in export value include meat, dairy and eggs, and potatoes and vegetables. Figure 5C shows the number of companies, the number includes small and large companies. The bread and bakery sector has most companies, followed by other food companies, drinks, butcheries and meat processing and the dairy industry.

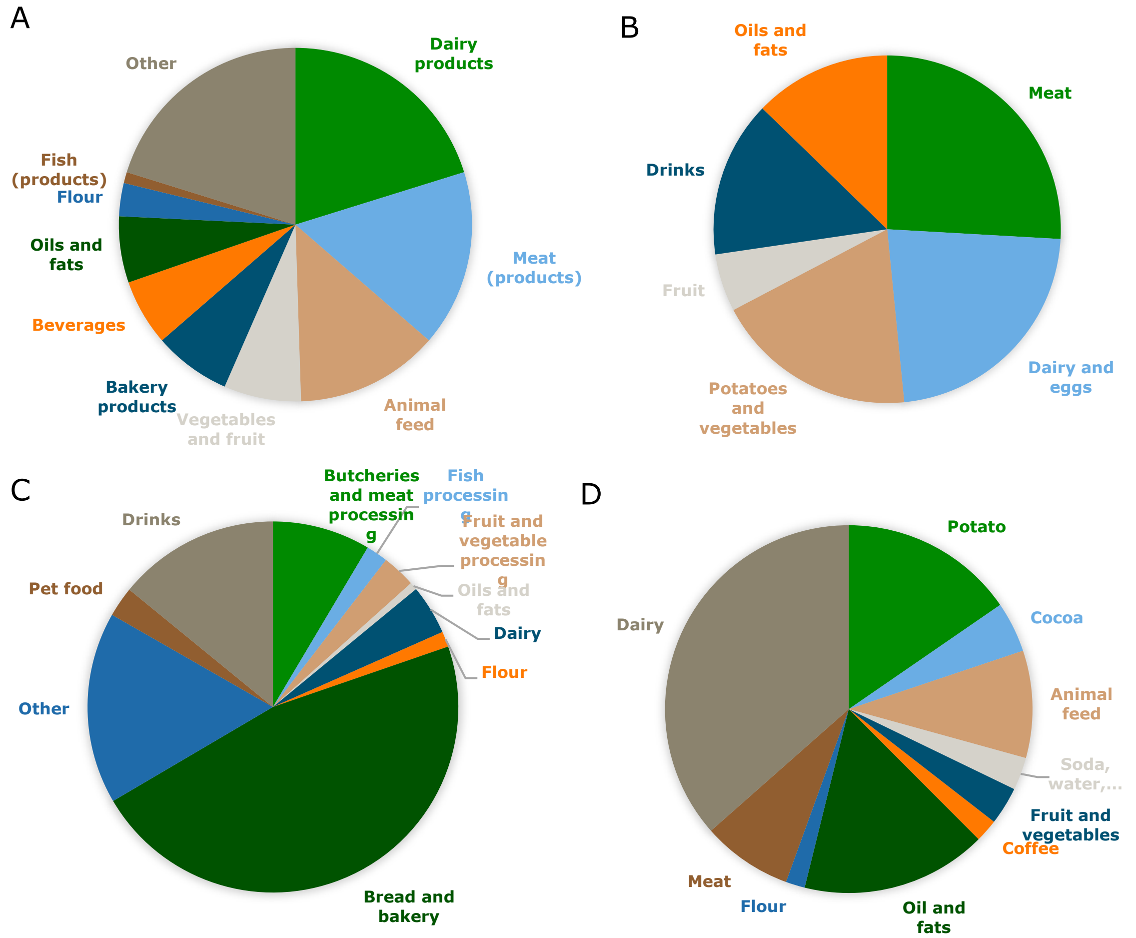


Figure 5 ***A. Production value per sector in the food processing industry (2021) (FNLI, n.d.), B. Export value of Dutch product in billion euros*** *(Jukema et al., 2022)* ***C. Size of the Dutch food industry sectors (as a percentage of the no of companies)*** *(*StatLine - Bedrijven; Bedrijfstak*, n.d.)****, D. primary energy consumption (TJ) per processing sector in 2020*** *(voor Ondernemend Nederland, n.d.)*

Figure 5D shows the primary energy consumption for the Dutch food sectors. From that graph it is evident that the dairy industry, the potato industry, oils and fats, animal feed and meat industry are large energy consumers, which is explained by the large energy use in the agricultural production phase of animals and energy intensive processing steps such as heat-requiring operations like baking, pasteurization, drying and many more (Corigliano & Algieri, 2024).

According to the FNLI Monitor Levensmiddelenindustrie (2024), the food processing industry (including the tobacco sector) accounted for 12.3% of total CO_2 emissions in the Netherlands in 2022 (FNLI, n.d.). Table 2 shows the main environmental impacts for several food products per food sector. It is a small extract of data from the RIVM database, where at least two products per food sector were included; one with the highest and one with the lowest global warming potential (GWP) value to show the range for each product category. The table shows that environmental impacts differ between food sectors and products. With colours the highest (red) and lowest (green) values are indicated for this specific set of data. Water consumption is relatively high for tea. Global warming potential (GWP) is mainly high for most of the meat and meat products, cheese, fish and oils and fats, which is no surprise as animal-based products have high GHG emissions in the primary production phase.

A logical selection for case studies would thus be on the sectors bakery and bread for the large number of companies, the meat sector (and alternatives) from the GHG emissions and export value point of view, the dairy sector and the potatoes or vegetables processing industry from an export value and energy consumption point of view.

To have insights into advantages and drawbacks of the alternatives in food processing, a proper assessment of indicators covering multiple dimensions (economic, environmental, safety, etc.) is needed. This multitude of dimensions is for example present in the Triple P approach in which sustainable development is expressed in the dimensions People, Profit, Planet with many underlying aspects specifying these three dimensions. Often, the choice of indicators originates from the desire to address a certain (sub)dimension of sustainability, or to address possible trade-offs and dilemmas between specific indicators.

In the case of the food processing industry and the focus of this project, most often the energy consumed in the process is considered a critical output parameter to look at, considering the associated costs and its environmental impact (such as of fuel consumption, and electricity generation). High energy prices and net congestion are expected to remain a relevant driver for energy use reduction and for shifting to alternative energy sources for the years to come in the Netherlands.

Next to energy, water use of food chains is an aspect that is gaining more attention as challenges and limitations are actual and expected to increase in the Dutch food system. Food processing requires water of suitable quality to be able to use water as ingredient, in processing and in cleaning.

Table 2 ***Environmental impact per kilogram product of food products – at least two products of each product group were selected. Source:*** *(*Milieubelasting van Voedingsmiddelen | RIVM, *n.d.)*. ***The colour scheme ranges from the lowest (dark green) to the highest (red) values within each impact aspect.***

Numbers up until distribution								
Name	**Product Group**	**Global Warming ($kg CO_2$ eq)**	**Terrestrial Acidification ($kg SO_2$ eq)**	**Freshwater Eutrophication (kg P eq)**	**Marine Eutrophication (kg N eq)**	**Land Use (m^2a crop eq)**	**Water Consumption (m^3)**
Pre-baked frozen fries	Potatoes and tuber crops	2,436	0,009	0,000290	0,002744	1,320	0,044
Peeled potatoes	Potatoes and tuber crops	0,339	0,003	0,000082	0,000841	0,247	0,006
Whole grain bread	Bread	0,826	0,005	0,000107	0,002036	0,804	0,014
Croissant	Bread	2,049	0,009	0,000217	0,004049	3,062	0,032
Chicken egg	Eggs	3,356	0,054	0,000379	0,004425	3,554	0,086
Strawberries	Fruit	4,522	0,005	0,000265	0,001680	0,329	0,306
Apple	Fruit	0,316	0,002	0,000048	0,000383	0,178	0,026
Breakfast cake	Pastries and cookies	1,133	0,007	0,000160	0,002294	1,449	0,027
Pound cake (butter)	Pastries and cookies	4,973	0,068	0,000353	0,009677	3,109	0,064
Wheat flour	Grains and binding agents	0,815	0,008	0,000165	0,003477	1,393	0,009
White rice	Grains and binding agents	2,301	0,017	0,000247	0,003311	1,065	0,298
Carrot	Vegetables	0,239	0,002	0,000048	0,000562	0,174	0,005
Paprika / bell pepper	Vegetables	2,359	0,001	0,000090	0,000197	0,057	0,133
Hummus (plain)	Savory sandwich spread	5,587	0,009	0,000324	0,004979	9,673	0,102
Peanut butter	Savory sandwich spread	8,014	0,010	0,000302	0,005944	6,546	0,162
Mayonaise	Savory sauces	5,065	0,028	0,000500	0,007319	7,484	0,045
Tomatosauce (glass)	Savory sauces	1,020	0,006	0,000101	0,000595	0,374	0,045
Beef croquet	Savory snacks	5,859	0,090	0,000256	0,015906	3,567	0,052
Popcorn	Savory snacks	0,809	0,006	0,000129	0,002116	1,435	0,080
Cheese Gouda, 48+	Cheese	12,534	0,180	0,000367	0,025239	5,175	0,100
Mozzarella	Cheese	8,050	0,115	0,000236	0,016198	3,322	0,065
Buttermilk	Milk and dairy products	1,304	0,018	0,000039	0,002430	0,578	0,010
Quark (full cream)	Milk and dairy products	4,252	0,055	0,000114	0,007686	1,579	0,035
Mineral water, average	Non-alcoholic beverages	0,209	0,001	0,000008	0,000001	0,005	0,004
Tea	Non-alcoholic beverages	6,194	0,141	0,002248	0,040160	18,460	3,985
Flaxseed	Nuts and seeds	1,391	0,014	0,000456	0,004882	10,380	0,113
Peanuts, unsalted	Nuts and seeds	6,777	0,007	0,000209	0,005391	5,782	0,165
Brown beans (glass)	Pulses	1,478	0,009	0,000295	0,001849	1,796	0,062
Chickpeas	Pulses	6,217	0,008	0,000464	0,005074	8,838	0,066
Chocolate (milk)	Sugar, candy, sweet spreads & sauces	5,575	0,058	0,001489	0,009876	6,590	0,051
Ice pop	Sugar, candy, sweet spreads & sauces	0,710	0,003	0,000077	0,000802	0,307	0,027
Butter, salted	Fats and oils	11,245	0,164	0,000333	0,023001	4,719	0,091
Low-fat margarine	Fats and oils	2,159	0,008	0,000193	0,003842	4,477	0,050
Mackerel fillet, smoked	Fish	1,736	0,004	0,000114	0,001107	0,013	0,013
Tilapia	Fish	18,882	0,082	0,000795	0,004767	5,647	0,084
Roast beef	Meat and poultry	27,144	0,484	0,001019	0,080362	13,891	0,217
Chicken filet	Meat and poultry	6,422	0,059	0,000569	0,005214	4,654	0,090
Soy drink, plain	Meat and dairy substitutes	0,664	0,002	0,000037	0,000196	0,339	0,010
Vegetarian schnitzel	Meat and dairy substitutes	4,357	0,042	0,000288	0,005286	2,966	0,079
Smoked beef	Processed meats	24,334	0,433	0,000907	0,071717	12,233	0,195
Liver pâté	Processed meats	4,873	0,045	0,000395	0,005524	3,390	0,051

3.2 Perceived sustainability improvements – brief introductions

This section briefly introduces five domains relevant to the Dutch food processing sector, and their perceived sustainability improvements. Perceived sustainability refers to perceptions influenced by trends, myths and dogmas as well as innovations on micro scale (Silva, 2025). An example of a sustainability myth is 'local foods are always more sustainable than foods from far' (see e.g. Majewski et al. (2020). Despite the trend of consolidation, there is an opposing trend with focus on local produce and products, local breweries and urban agriculture (Muilwijk et al. 2018). These were identified taking literature and discussions into account, and are further explored in the case studies. Table 3 presents the domains and their potential influence on sustainability in the food processing industry.

Table 3 ***Domains and the potential influence on sustainability in the food processing industry***

Domains	**Potentially impacting sustainability in the food processing industry in the following way:**
1. Value chain length and organisation	Growing demand for transparency, local sourcing, and short chains may shift processing closer to production or consumption sites and might require new logistics and IT integration (e.g. McGrath et al. (2021)

2.	Circularity, resource use efficiency	Improving resource efficiency and circularity involves redefining waste as input, valorizing side streams, redesigning processes to minimize energy/water use, and aligning with circular design principles (e.g. cradle-to-cradle) (e.g. Stillitano et al. (2021)
3.	Protein source	The shift from animal to plant-based and novel proteins (e.g., legumes, fermentation, insect, cellular) demands new processing technologies, equipment, safety protocols, and supply chains tailored to different raw material properties (e.g. Yu et al. (2023)
4.	Packaging materials	Reducing fossil-based and single-use packaging affects product shelf life, logistics, and food safety, potentially changing processing formats, co-packing practices, and plant location decisions (e.g. Ncube et al. (2020)
5.	Agriculture	Agriculture as a source of raw materials for food processing; climate change, soil degradation, and biodiversity loss might affect availability, quality, and price of those inputs (e.g. Bozzola et al. (2023)

Table 4 presents the domains, dominant situation, perceived sustainability improvements, and link with the case studies. The case studies will be further introduced in chapter 3.5.

Table 4 Overview of five domains including a brief description of the dominant situation, perceived sustainability improvements, and link with the case studies in this report.

Domains		**Dominant situation**	**Perceived sustainability improvements**	**Link with case studies**				
				Apple juice	Protein source	French fries	Bread	Pulses
1	Value chain length and organisation	Untransparent, ‘long’, central processing	Transparent, ‘short’, decentral processing	X		X	X	
2	Circularity, resource use efficiency	Low value, few closed cycles, linear resource use	High value, closed cycles, circular resource use	X				
3	Protein source/transition	Mainly animal-based	Mainly plant-based		X			
4	Packaging materials	Plastic	Biobased alternatives, glass, packaging minimisation	X				X
5	Agriculture	Conventional, intensive	Organic, regenerative, nature-based					X

Three other relevant topics which did not exclusively feature as a separate domain because the perceived sustainability improvements are less evident, but are interwoven with most, are: 1) viability of business cases, 2) consumer preferences and habits and 3) the energy transition from predominantly fossil based to renewable sources. Within the current economic system these are very relevant to consider because of their determinant effect for food processing business decisions (they have to be economically viable), and directions (consumer preferences and habits largely shape food value chains and systems). Additionally, food safety rules and regulations are also not exclusively mentioned and are considered the boundaries of the food processing system, describing the ‘rules of the game’ to engage in food processing activities.

In Annex 2, the five domains are discussed in more detail. From a food systems perspective, they serve as a means to grasp the complexities of sustainability transitions, while specifying the likely relevance for the food processing industry in the Netherlands. The descriptions are meant to serve as general introductions to the domains and are not encompassing the complexity of each domain in detail. Since we assume that the readers of this report are generally familiar with the domains, this is positioned in the Annex.

3.3 Roadmap: sustainability enablers, barriers and measures

This chapter summarises the results of various literature and expert consultations about sustainability enablers, barriers, and measures for the Dutch food processing industry, which are separately published as a brief info sheet (Vernooij & Vollebregt, 2025). Vernooij & Vollebregt (*ibid.*) present a forward-looking narrative on how sustainability may develop in the Dutch food processing industry across three future horizons: predictable (2024–2027), foreseeable (2027–2034), and probable (2034–2050). Their work identifies key enablers and barriers, focused on three actor groups – industry, consumers/society, and government – and measures for industry and policy (Table 5).

Table 5 Overview of the included elements, actors and time periods in Vernooij & Vollebregt (2025)

Enablers and barriers	**Predictable (2024-2027)**	**Foreseeable (2027-2034)**	**Probable (2034-2050)**
Food processing companies			
Consumer/Society			
Government			
Measures	**Predictable (2024-2027)**	**Foreseeable (2027-2034)**	**Probable (2034-2050)**
Food processing industry			
Policy			

This activity aimed to provide a more general inventory of sustainability barriers, enablers, and measures for the Dutch food processing industry, to complement the detailed case studies. The approach was inspired by the butterfly framework for the assessment of transitions towards a circular and climate neutral society by (Bos et al., 2022) (Figure 6) and by a roadmap document of the Fraunhofer Institute (Moller et al., 2018).

Figure 6 The butterfly framework (Bos et al., 2022).

The methods included a literature study in 2023, covering 28 relevant studies published between 2015 and 2023. Due to limited research specifically on sustainability in the Dutch food processing sector, studies were included from comparable regions and broader themes such as circular bioeconomy transitions. To contextualize and validate these findings, expert input sessions were held in 2024. Using draft visualisations (as published in Vernooij & Vollebregt, 2025), experts from the Dutch Ministry of Agriculture, Fisheries, Food Security and Nature and Wageningen Food & Biobased Research (WFBR) provided feedback, additions, and refinements. The final visualisations incorporate their input, with some adjustments for clarity.

A brief summary of perceived and expected sustainability enablers and barriers:

For *food processing companies*, regulatory compliance, sustainability-driven talent attraction, and emerging policies (e.g., Corporate Sustainability Reporting Directive CSRD) may drive sustainability progress in the short term. Yet, internal knowledge gaps, high input costs, and rigid production systems pose ongoing barriers. Over time, systemic shifts in supply chains, economic conditions, and operational models could unlock new resilience and innovation opportunities – though uncertainty due to external factors remains high.

Consumer and societal factors show a mixed picture. While awareness and Non-Governmental Organisation (NGO) advocacy are growing, affordability, entrenched habits, and social media–driven consumption continue to impede sustainable behaviour. Future scenarios point to potential tipping points in public attitudes, especially with generational shifts and better-designed food environments, but structural challenges like obesogenic settings and lack of scalable circular business models persist.

Governmental roles are shaped by both promise and fragmentation. Though constrained by competing priorities and inconsistent regulation, enablers such as EU packages, increasing geopolitical awareness, and integration with broader climate and health goals suggest avenues for more effective governance. Progress will depend on clearer long-term visions, strategic coordination, and consistent policy follow-through.

The analysis highlights a range of suggested *measures* for both policy and industry - ranging from near-term actions such as targeted training, circular supply chain initiatives, and sustainability labelling, to longer-term strategies including true pricing, simplified consumer choices, and shifts in taxation structures. These measures, drawn from literature and expert input, reflect a broader call for adaptive strategies, ongoing monitoring, and stronger collaboration between public and private stakeholders.

For full detail and all visualisations, see Vernooij & Vollebregt (2025). A part of the visualisations is included here (Figure 7).

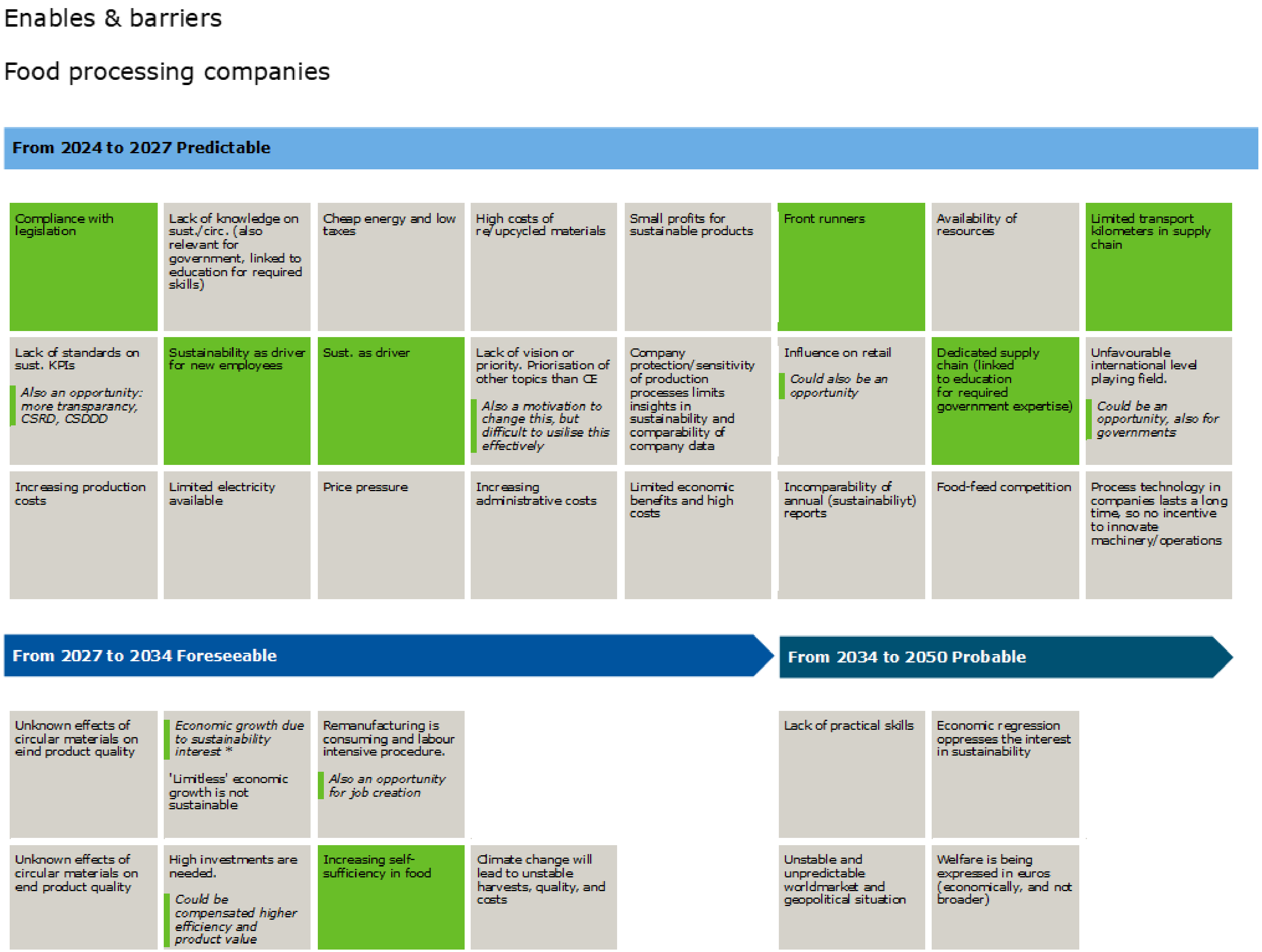


***Figure 7** Part of the visualisations presenting the enablers, barriers, and measures, for full details see Vernooij & Vollebregt (2025).*

3.4 Assessment framework

To execute the quantification as presented in the assessment approach shown in Figure 8 is proposed following the life cycle analysis methodology. In this project this methodology is worked out in detail to support scenario assessments of alternative food chains and food processing. The details of each step are described in the subsections of Section 3.4.1. The realised extensions, necessary to incorporate energy and water use as indicators and to enlarge the applicability to food processing scenarios, of the ACE calculator are presented in Section 3.4.2. A brief comparison with other sustainability assessment tools is presented in Section 3.4.3.

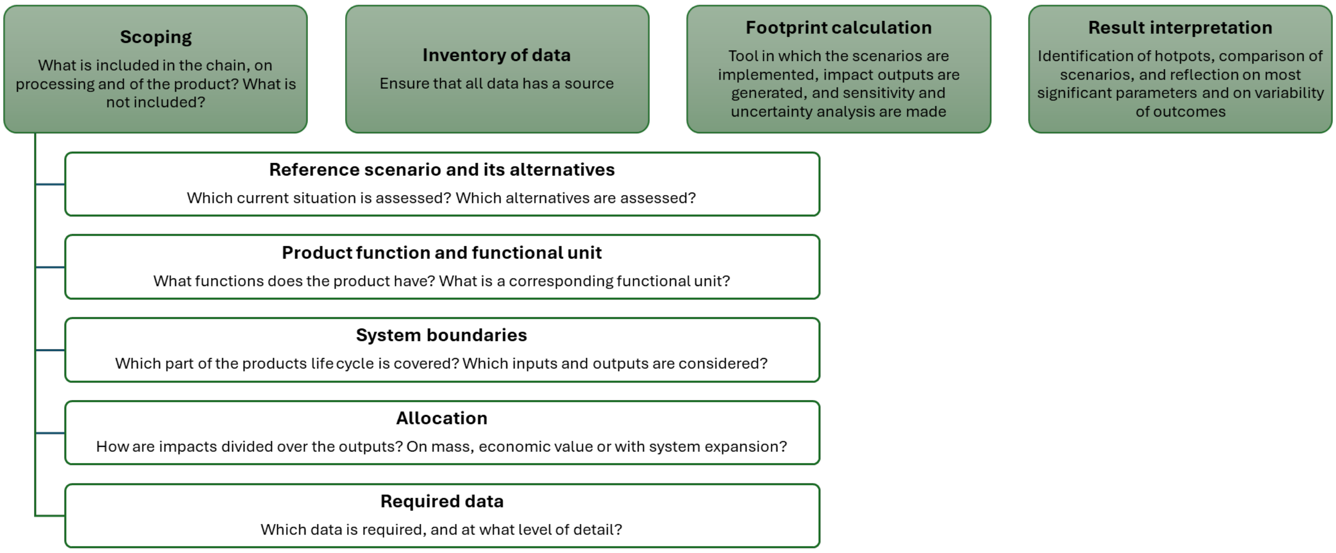


Figure 8 Assessment approach for scenario studies on sustainability indicators.

3.4.1 Case study scoping

A proper case study scoping, addressed in a systematic manner is necessary for adequate case study assessment. This is particularly important when looking at any life cycle assessments for footprint calculations since these are affected by what is in and out of scope and consequently by the assumptions that are made regarding all activities in the food chain. Adequate scoping requires that multiple aspects are thought through and that the associated choices on these aspects are made before the required data is gathered and calculations are performed, see Figure 17. The scoping topics are presented below.

In this project scoping was executed by experts of the project team and with input from WFBR experts on the chain and product of the case study. Furthermore, case study results were compared with results from other studies.

Reference scenario and it’s alternative(s)
In each case study two or more different agri-food chains are analysed and compared. In this project they represent a current configuration and perceived more sustainable alternative(s).

Functional unit
A functional unit has to be defined that describes the end product. For example, 1 kg of sellable product, or a 200 gram portion of a product, etc. The functional unit can be further specified, i.e. nutritional functionality such as protein content and protein quality (Sonesson et al., 2017).

System boundaries
A key aspect of the scoping is to define the system boundaries. Preferably, the entire chain from origin of the raw materials to end-of-life of the product is incorporated. Covering the entire chain allows for a fair comparison

of the alternatives. However, this is not always necessary if several parts of the chain, and the associated impacts of this part, are identical.

As recommended by the European Commission, all materials used in a process (including e.g. packaging materials) should be addressed, as well as co-products, by-products and waste streams of the foreground system. Impacts associated to production and end-of-life of capital goods may be omitted unless their substantial contribution can be clearly explained (EU, 2021[1]).

Allocation

The resulting impacts have to be assigned to the output material streams of the chain. The main output will be the food product under consideration as specified in the functional unit. Next to this, additional output material streams exist. The additional output materials are by-products (having an economic value) and waste streams.

In this research the following strategies to assign the impacts to the output materials different strategies are considered:

1. Mass allocation: the impacts are divided over the different output materials according to their mass.
2. Economic allocation: the impacts are divided over the different output materials according to their economic values.
3. System expansion: the impacts include avoided emissions due to the output material replacing another material that has a certain impact.

Typically, the by-products and waste streams occurring in food chains have different uses or destinations, such as a technical non-food application or use of animal feedstock as high-valued applications and (an)aerobic digestion for biogas production, incineration with energy recovery, or other low-valued uses. For high-valued applications, including use as feedstock of side streams, economic allocation is the most commonly applied allocation method (Dominguez Aldama et al., 2023). For waste management the system expansion routes allows for incorporation of aspects such as replacement of non-renewable sources by renewable sources.

Required data

The choices made for the scoping up until this point define the required data and the level of detail of the data. Required data consists of data describing the specific case, such as product mass, composition, chain configuration, logistic detail, packaging specification, processing steps, equipment and yields, and other aspects and impact data that can be used to convert all activities to impact values (e.g. GHG emissions intensities from fuels and raw materials). The level of detail should be sufficient to cover the differences between the alternatives. For instance, in case different transport modalities are investigated, the transport distance has to be included.

Inventory of data

The data inventoried should be relevant to the case and regime, considering the relevant scenarios with possible differences in supply chain design, processing, food losses and food waste, packaging and logistics.

All data should be traceable to its sources. And, ideally, standardised input files are used as input for the footprint calculation. This standardisation allows for easier repetition and updates of the calculations, and it supports the development of a case study library.

Footprint calculation method

Another key aspect is the footprint calculation method to determine the impacts of each activity in the scenario and the resulting total impact. The ACE calculator is an example of a footprint calculation method.

Apart from the calculation of the impacts based on the provided input data, there are several analyses features that strengthen tool output that are part of the assessment framework. This includes the following, which are incorporated in the ACE calculator:

[1] COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations.

- Sensitivity analysis to determine which inputs are affecting the resulting impact the most. Obtaining data of good quality for these inputs is essential to generate output data of good quality. Next to this, the processes or activities related to these inputs will represent a hotspot in impact.
- Uncertainty analysis to determine the variation in resulting outputs given a certain variation in the input data. This information can be used to decide if outputs from different scenarios lead to significantly different results.

As for the input data, ideally, standardisation of output data and files is incorporated in the calculation tool.

Results interpretation

The last step of the assessment approach is interpretation of the results. The results of the footprint calculations can be analysed on differences in total impact between scenarios and on hotspots in the sustainability indicators for each scenario. The effect of the alternative scenario can be interpreted as contributing or not to more environmentally sustainable food chains.

3.4.2 Further development of ACE calculator

The goal of the ACE calculator is to provide *insights* in the effects of *interventions* on *environmental sustainability* in the *food production and distribution chain*. Specifically the GHG emission in kg CO_2-eq/kg product, energy use in J/kg product, and green water use in liter water/kg product, and blue water use in liter water/kg product.

In this section the realised extensions are described:
- energy use and water use as environmental indicators;
- uncertainty and sensitivity analyses;
- operations in food processing.

In the project we defined various unit operations relevant for the Dutch food processing industry. This includes processes like sorting, washing, mixing, baking, drying, packaging, etc. Corresponding parameters to calculate e.g. the unit operations energy use, water use, efficiency, separation factor, etc, are estimated from literature and/or from discussion with experts. Furthermore, a graphical user interface has been realised.

3.4.2.1 Energy use

For insight into energy use both direct and indirect energy use has to be taken into account. Direct energy use refers to use of energy resources for the activities in the chain, such as fuel for transport and for heating processes in food industry. Indirect energy use, or embodied energy, refers to energy required to produce materials used in the chain, such as energy use for feed or fertilizer production as part of the footprint at farms and energy use required for production of packaging materials and processing aids as used in the food industry. The energy sources, renewable or not, are also investigated and part of the output of the calculator. Also the CO_2-equivalents calculations require information about the energy sources.

To make energy use explicit in the ACE calculator data on direct and indirect energy use is required. The following approach and data is included in the chain stages:
- Primary production: Embodied energy of the crop, for instance from data on a selection of crops from (Paris et al., 2022).
- Transport and storage: Amount of energy needed for transport and storage derived from diesel use and required electricity for cooling and refrigerated storage.
- Processing: as a consistent database on energy use for food processing is not available, this is derived from user input on energy use (fuel, steam, gas) and its sources.

Energy use is expressed in the amount of energy per functional unit.

3.4.2.2 Water use

The concept of "water footprint" (*Globalization of Water: Sharing the Planet's Freshwater Resources - Arjen Y. Hoekstra, Ashok K. Chapagain - Google Boeken*, n.d.; Hoekstra, 2003) provides a framework to analyse the link between human consumption and the appropriation of the globe's freshwater. There are two aspects of water footprints to consider: consumptive water and water required to assimilate pollution as defined by Hoekstra et al., (2003). Consumptive water is the sum of the blue and green water footprints. Blue water footprint (BWF) refers to the volume of surface and groundwater consumed (evaporated) because of the production of a good and the Green water footprint (GreenWF) refers to the rainwater consumed. The agricultural sector accounts for about 85% of global blue water consumption (Shiklomanov, 2000). Due to the emergence of drought in certain areas, the GreenWF will become more and more relevant. The water required to assimilate pollution, the grey water footprint (GreyWF), refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. This last footprint is generally not included in accounting for water consumption for food products because the waste water treatment may vary per operator and legislation according to the country and includes a certain degree of recycling depending on the operator. The grey water footprint is not included in the ACE calculator.

Figure 9 indicates at which food chain parts the various water footprints are relevant to consider, and thus which inputs and data is required. As data source for the blue and green water footprints for the production at farms the ACE calculator makes use of the data from (Mekonnen & Hoekstra, 2010, 2011a). Regarding water uses in food processing the user is required to provide inputs.

Water use is expressed in Liter of water per functional unit.

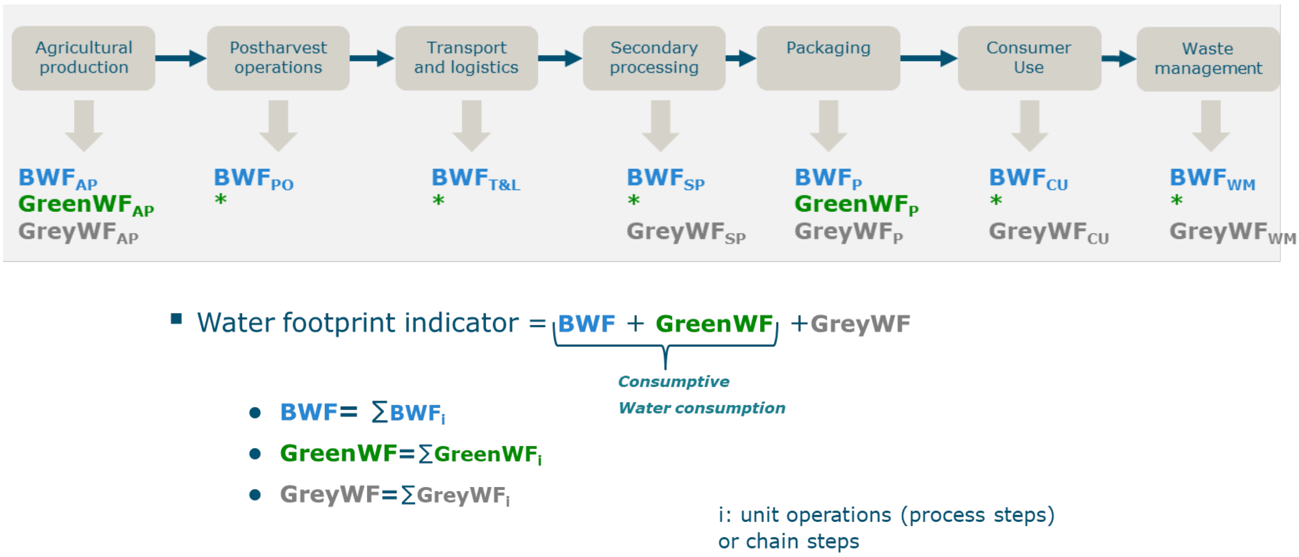


Figure 9 ***Steps and water usage types included in the calculation of the overall water footprint indicator and consumptive water footprint. Steps with an asterisk (*) are not so common but could be relevant in specific cases when rainwater is used.***

3.4.2.3 Impact allocation

The resulting footprints must be allocated to the output materials in the food chain. If output material next to the intended food product have an economic value, part of the impact must be allocated to these materials. Impact of waste management for output materials without economic values is ideally also taken into account as part of the total footprints. This is incorporated in the ACE calculator. This section provides a more detailed description on the reasoning and used methodology.

The destination of the generated waste can impact the overall sustainability of the product. The waste valorisation scenarios can be classified according to the food recovery hierarchy (Environmental Protection Agency et al., 2019), see Figure 10. The food recovery hierarchy proposes the most preferred to least preferred options for food waste management considering the most benefits for the environment, society, and the economy.

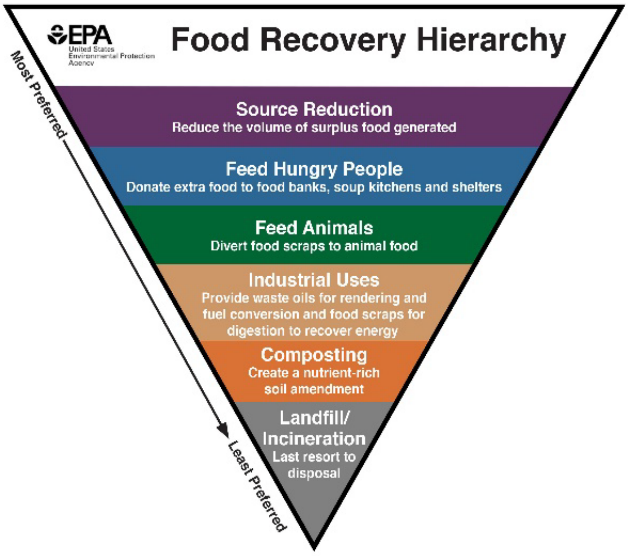


Figure 10 ***Food Recovery Hierarchy indicating the most preferred to least preferred option from top to bottom. Source: United States Environmental Protection Agency (EPA).***

In the ACE calculator accounting of impacts is available by considering the possible economic value of the materials and its valorisation or destination (position in the food valorisation hierarchy) as follows:

- (established) co-products with added value (e.g., food) and by-products that can potentially be valorised (as food, feed, etc.) will follow an **economic allocation** method distributing the overall impact of the chain among the different co-products proportionally to their value;
- for waste materials used in lower-value applications—such as anaerobic digestion, composting, incineration (with or without heat recovery), or landfill—impacts and benefits (e.g., energy recovery) are assessed using **system expansion**. This involves expanding the system boundary to account for the substitution of a hypothetical avoided product (e.g., fuel, chemical, or feedstock) and its respective impact. This substitution represents the potential replacement effect in the final application, as illustrated in Figure 11.

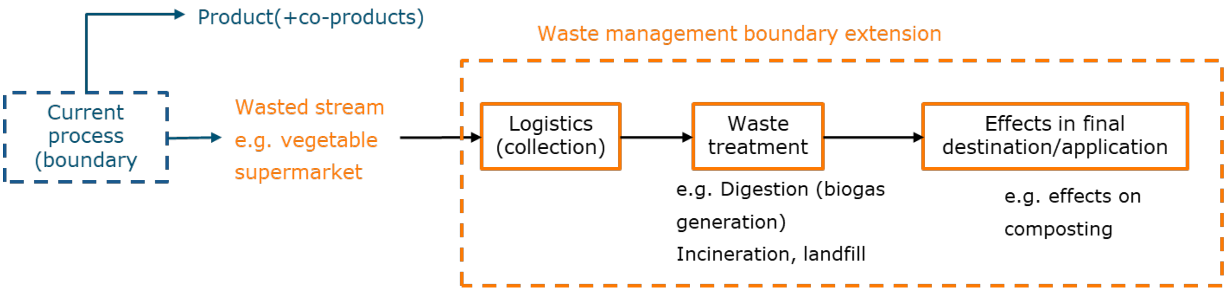


Figure 11 ***System (and boundary) expansion to deal with wasted materials.***

Table 6 provides the calculations rules, needed material information and possibly avoided products for each possible destination of side streams or wasted material and specifies the default allocation method following the colour scheme of the Food Recovery Hierarchy depicted in Figure 19. These calculations are available in supporting files to generate input values for the ACE calculator.

Table 6 Calculation rules, required information, avoided products and type of allocation used per type of side stream destination available for the ACE calculator.

Side stream destination	Calculation rules	Material information	Avoided products	Default allocation method
Food	Default economic value estimated on macronutrient composition (in €/kg macronutrient), macronutrients: protein, carbs, fat, fibres	Mass, Composition	Food	Economic allocation
Feed	Economic value is directly related with the digestible energy and digestible protein content. Needed information: • Nutrient calorific value (MJ/kg nutrient). • Digestibility (%) (per target animal) as estimated from composition. • Penalty for water content.	Mass, Composition	Feed	Economic allocation
Digestion (incl. biogas production)	Avoided emissions (kg CO_2/kg nutrient)[1] Assumed losses from biogas to electricity and heat	Mass, Composition	Gray electricity, peat	System expansion
Incineration (heat recovery)	Nutrient calorific value (MJ/kg nutrient) Avoided emissions (kg CO_2/kg nutrient)[2] Penalty for water content	Mass, Composition	Peat	System expansion
Composting	Net emissions due to handling and processing per kg of food waste	Mass		-

[1] Emissions from the fuels and materials that are replaced with the biogas produced by digestion;[2] Emissions from the fuels and materials that are replaced.

Below the assumptions for each waste valorisation route / management option are described.

1. **Food**
   The food price of the waste stream based on the macronutrient composition and the FrieslandCampina macronutrient relative price per kilogram according to their Milk price system[2]. The value of the prices is varying monthly but currently keep approximatively constant with a protein/fat/lactose price ratio of 6:4:0. In our analysis in this project we used average values observed at the end of 2022 which where protein 570 euro/kg, fat 285 euro/kg, carbohydrates/dietary fibre 57 euro/kg which gives a ratio of 6.3:3.1:0.06.
2. **Feed**
   The price of the material is based on the digestibility of the macronutrients per animal, which are calculated according to the equations listed by CVB, 2018[3]. Based on the digestibility the total feed price was calculated using the feed value prices ('Voederwaarde prijzen') as reported by Wageningen Livestock Research (Klop, 2024).
3. **Digestion to biogas**
   The waste stream is anaerobically digested into biogas. The biogas is used directly to produce electricity and heat, which is the most common application of biogas in the Netherlands. The conversion efficiency to biogas (expressed as biomethane production) is strongly dependent on the macronutrient composition of the feed. The macronutrient conversion factors were obtained from (Broeze & Garcia Chavez, 2023). The biogas is used in a co-generation plant, with around 35% of the energy from biogas is used to generate electricity and an additional 40-50% is available for heat generation(*Outlook for Biogas and Prospects for Organic Growth World Energy Outlook Special Report Biomethane*, n.d.). A consequential approach with system expansion (replacement of other source or material) for digestion to biogas is used in the assessment. The GHG emissions are determined based on the replacement of fossil fuel-based electricity and heat. The GHG emissions of grey electricity (386 kg CO_2-eq/MWh) and of peat (386.3 kg CO_2-eq/MWh) are used. Consequently, the digestion of the

[2] Guaranteed milk price - FrieslandCampina Global - FrieslandCampina
[3] https://www.cvbdiervoeding.nl/pagina/10100/kerntaken.aspx

waste streams to biogas results in a net negative contribution to the total GHG emissions of the final product.

4. **Incineration with heat recovery**
   The efficiency of incineration with heat recovery is based on the composition of the waste stream. The energy yield is calculated from the lower heating value (LHV). The energy content of the waste stream is calculated using the caloric content of the different macronutrients. A consequential approach with system expansion for incineration with heat recovery is used in the assessment. The GHG emissions are determined based on the replacement of fossil fuel-based heat. The GHG emissions of peat (386.3 kg CO_2-eq/MWh) are used. The net contribution to the total GHG emissions of the final product can be either negative or positive. This is based on the water content of the waste stream, when the water content is too high the LHV can be negative, i.e. it costs more energy to incinerate the waste stream than it will gain.
5. **Composting**
   For composting a net positive contribution, i.e. 28 g CO_2-eq/kg composted waste (Eriksson et al., 2015), to the total GHG emissions of the final product is used. Biogenic carbon is not considered. The positive contribution is based on the emissions for production of windrows, the compositing process and production of soil amendment as described in (Eriksson et al., 2015). A consequential approach for composting is used in this assessment.

3.4.2.4 Uncertainty and sensitivity analyses

Typically, environmental impact assessments have several limitations, that include

- uncertainties, expressed in error margins of input data;
- outcomes that can vary a lot depending on the assumptions;
- outcomes expressed in a specific value, that can be interpreted as an exact outcome, whereas a range of outcome values would be a better representation given the error margins in input data and the effect of assumptions.

To evaluate the uncertainty in the outcomes, to obtain insight into the sources of uncertainties and into which inputs and model factors are impacting the outcomes the most the ACE calculator features uncertainty and sensitivity analyses. The uncertainty and sensitivity analysis outcomes can be used in an iterative process to obtain outcomes with lower uncertainty by filling data gaps as much as possible. Inputs and parameters with high sensitivity should be estimated with higher precision to reduce the uncertainty in these aspects and thereby reducing the uncertainty in the outcomes.

It is noted that error margins are associated with these parameters. It was outside the scope of this project to perform a detailed study to their statistics in the Dutch food processing industry. Here we used rough estimates of standard deviations of the parameters, based on literature studies and experts opinions. This to get insight in the variation of the sustainability indicators. The latter is estimated from Monte-Carlo simulations, where a number of calculations, typically n=1000, of an indicator is performed and where for each calculation the parameter set is randomly chosen according to the statistics of each parameter. This will give n different values of the indicator from which its averaged value $\bar{\tilde{y}}_i$ and standard deviation $\Delta\bar{\tilde{y}}_i$ is calculated.

To get insights in the sensitivity of an indicator to interventions, we performed a sensitivity analysis where we calculated for each parameter β_j in the agri-food chain the relative change in indicator $\tilde{y}_i$ as a result of a relative change in the parameter,

$$S_{ij} = \frac{\delta\tilde{y}_i}{\tilde{y}_i} \bigg/ \frac{\delta\beta_j}{\beta_j}$$

where δ indicates a small change.

<u>Uncertainty analysis</u>

"An uncertainty analysis quantifies the variability of the model output caused by the incomplete knowledge or misspecification of the modeler" (Cariboni et al., 2007). This is determined by considering the uncertainty of all assumptions to calculate the uncertainty of the outcomes, expressed in the standard deviation. Within the ACE calculator this is implemented by subscribing a 10% variation with a normal distribution around the given value in all input values, performing Monte Carlo simulations with the accordingly adjusted input data and analysing the model outcomes to determine the resulting variability in the outcomes. Typically 1000 simulations are performed with the variable input values. Figure 12 shows schematically the set-up of the Monte Carlo simulations for the uncertainty analysis. If desired the variation in the input data can be adjusted to accommodate for input values with varying uncertainty.

If the uncertainty in the outcomes is too high, the user should look at the results from the sensitivity analysis and try to reduce the uncertainty of the parameters with the highest sensitivity index (see below). Figure 13 shows an example of the effect of differences in the uncertainty in input data and parameters. In case the difference between scenario outcomes is significantly different there is less need to reduce the uncertainty.

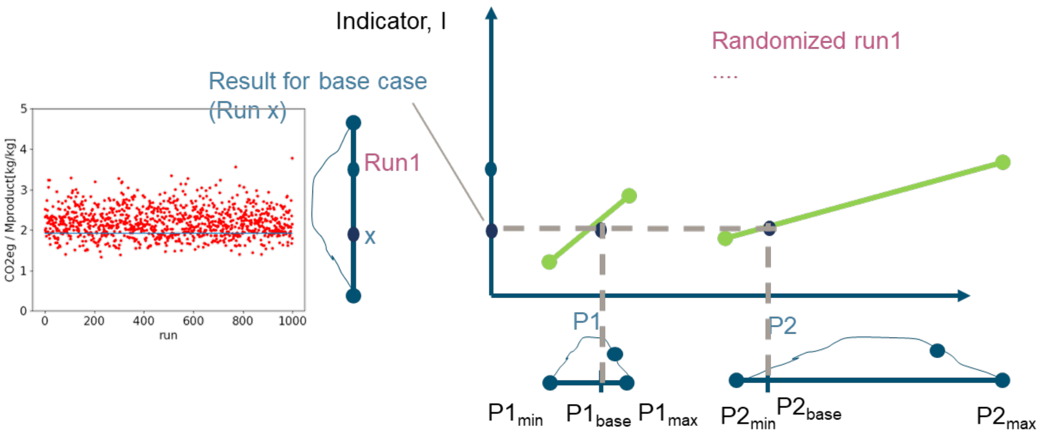


Figure 12 Scheme of the Monte Carlo simulations with certain input variations around the base case and resulting in outcome values from which variability in outcomes is determined.

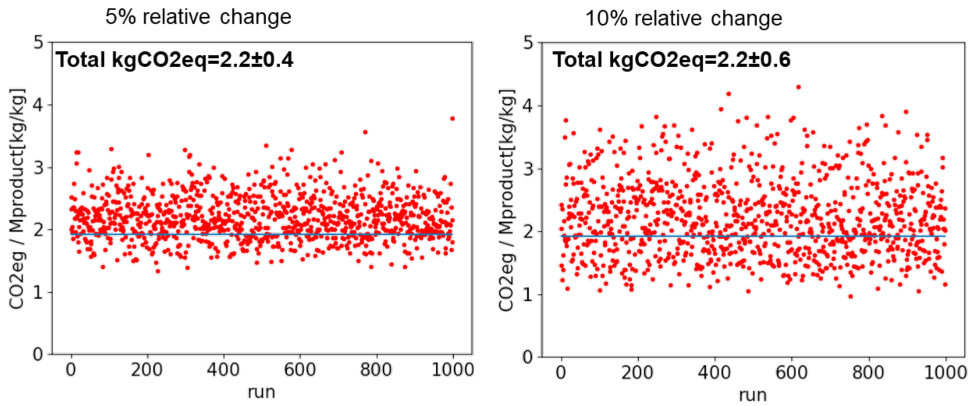


Figure 13 Example of Monte Carlo simulation outcomes with different input variability.

<u>Sensitivity analysis</u>
The sensitivity analysis shows which inputs or parameters affect the outcomes the most. In the ACE calculator the effect of the uncertainty of each input or parameter on the outputs is determined. The sensitivity is expressed in the sensitivity index, this index is defined as the ratio between the variability of the output divided by the variability of the input. The sensitivity index has a value between 0 and 1, with values closer to 0 implying that the input does not have an effect on the outcome, and values closer to 1 indicating that the input has a large effect on the outcome. The observed sensitivities should be explainable within the context of the case study.

Reducing the uncertainty of the highest ranking parameters in the sensitivity index will reduce the overall uncertainty on the outcomes. Figure 14 shows an example of ranked parameters for a certain outcome. The highlighted parameters on the y-axis have a larger impact on the outcome than the other parameters.

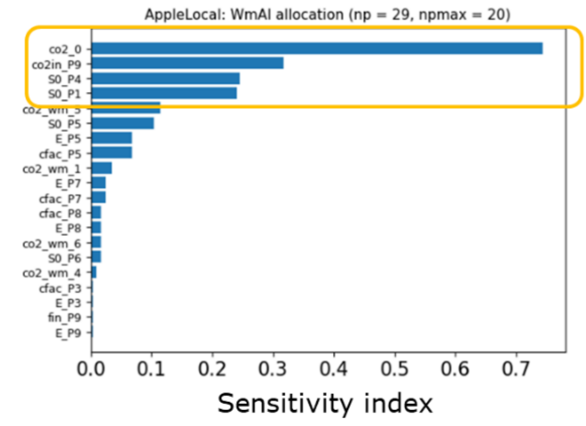


Figure 14 Example of ranked sensitivity indices.

3.4.2.5 Implementation of ACE calculator

Within the project the ACE calculator Python implementation is realised and a graphical user interface (GUI) is developed (Figure 15).

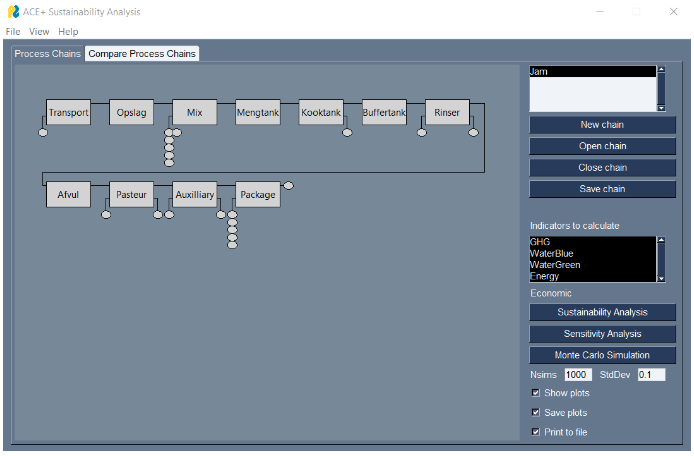


Figure 15 Snapshot of GUI ACE calculator

The realised software supports the following:

- Building a scenario by combining the building blocks of the intended chain.
- Specification and adjustment of input values and parameters of each material and building block. Data as specified in this report is available, and data values can be adjusted if required.
- The scenarios can be stored and can be imported in the tool.
- Selection of the sustainability indicators to investigate.
- Selection of the allocation methods to assign impacts to output materials and to include side stream and waste management strategies.
- Execution of the following analyses for a scenario:
  - calculation of the resulting impacts;
  - uncertainty analysis;
  - sensitivity analysis.
- Display, export and formatting of the graphs from
  - the overall results and of the results split along the chain and processes;
  - the resulting outcomes from the uncertainty analysis;
  - the resulting outcomes from the sensitivity analysis.
- Export of input data and outcomes data for a scenario.
- Comparison of scenarios on selected indicators by running the mentioned analyses on more than one scenario and generating graphs with outcomes of all scenarios.

The ACE calculator is supported with several additional calculation rules implemented in Excel, such as on the feed prices and on the waste management impacts. The resulting values from these calculations must be specified in the calculator as inputs.

In the project we defined various unit operations relevant for the Dutch food processing industry. This includes processes like sorting, washing, mixing, baking, drying, packaging, etc. Corresponding parameters to calculate e.g. the unit operations energy use, water use, efficiency, separation factor, etc, are estimated from literature and/or from discussion with experts.

3.4.3 ACE versus other tools

The incorporation, and easy addition, of data covering many food products and the capability to include multistage logistics and processing are unique features of the ACE calculator that make the calculator a valuable addition to existing tools (Broeze, et al., 2023).

The ACE calculator is intended for scenario analyses and for comparing these scenarios. The calculator is not suitable for substantiating footprint claims. In the EU environmental claims must be substantiated through formalized methodology (Ragonnaud & Ashton, n.d.).

- Product Environmental Footprint (PEF) prescribes how the environmental impact should be assessed and reported and which database should be used. This, amongst others, requires that essential data should be derived from primary data. For example: at least 80% of the calculated impact should be based on primary data (with fallback option of underpinned selection of secondary data). In general, acquiring primary data is very time consuming.
- For a few product categories more details have been set out in PEFCR's (PEF Category Rules), which amongst others prescribe which level of detail the supply chain must be analyzed, which allocation method may or should be used and which data must be obtained from primary data.

The ACE calculator addresses a small subset of the sustainability impact categories aimed at by PEF and PEFCR. Generally, ACE calculator analyses are less detailed than intended by PEF(CR). ACE calculator analyses may be made PEF or PEFCR compliant through addressing all requirements in the assessment; this will inevitably require collection of the required primary data, aligning the level of detail of the analyses with the requirements by the PEF(CR), and aligning used secondary data to the requirements by the PEF(CR). Even with these measures the ACE calculator analyses will be limited to a few impact categories, not fully addressing all categories required by PEF(CR).

To further place the ACE calculator into the landscape of environmental footprint analyses tools Table 7 summarises the differences between the ACE calculator and a full life cycle analysis (LCA).

Table 7 Differences between the ACE calculator and full life cycle analyses (LCA) on several aspects.

Topic	ACE calculator	LCA
Purpose	Rapid assessment of: - estimate of a product's impacts; - contributions of individual operations along a supply chain to the final products' impact; - net effect of an intervention.	Detailed impact analysis of product or operation.
Scope	From farm to fork (may be reduced). Limited number of impact indicators.	Defined in the study.
Practical relevancy	Obtaining quantitative insight in which operation(s) in the production and supply chain contribute most to the product's impact, and how this may be reduced. Iteratively detailing of operations is supported, so that hotspots can further analysed.	For formal reporting.
Provided (secondary) data	An (expanding) rich set of secondary data; these facilitate the analyses of complete supply chains including unknown parts of the supply chain.	Data are commonly derived from LCA database and previous LCA models.
Required resources	Inevitably the production and supply chain configuration must be specified. Depending on the required accuracy, the collection of data is most time-consuming. Since common operations are predefined, the actual modelling and analysis can be done quickly.	Mostly laborious; depends on availability of previous LCA models.

3.5 Case study results

This project focusses on post-harvest operations in chains of processed food products. Therefore, activities required for raw material or ingredient production are not made explicit in the quantifications of the different chain activities. In the results interpretation some specifics of the relevant primary production and/or processing into ingredients can be mentioned. Raw material and ingredient impact is visualized in all cases since it places the impact of the post-harvest activities in perspective.

All case studies, except that of the waste valorization of apple juice have been published in the form of factsheets (see example in Figure 16). The weblinks to the factsheets are included in each section. The following sections provide detailed descriptions of the case studies, with more background information on references and data sources, a detailed presentation of the results, as well as more explanations on parameter sensitivity and uncertainty. The presented graphs in this chapter provide the results given all specified assumptions and the associated data values. Next to this, the standard deviation around the average outcome values is given based on calculations of the scenario with 10% variation for each scenario parameter.

The case studies are listed in Table 8 linked to the sustainability domains they represent. The number in each column represents the section in which the case study and the regimes are discussed.

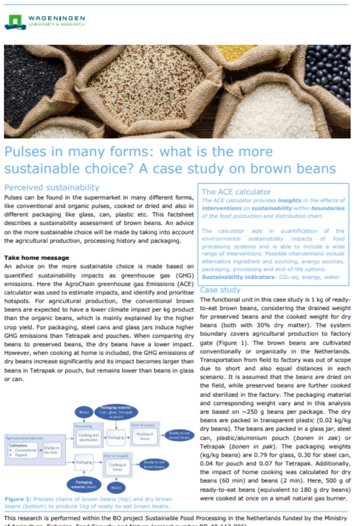


Figure 16 ***Snapshot of a case study factsheet (pulses)***

Table 8 ***Case study matrix***

Domains		Dominant situation	Perceived sustainability improvements	Case studies (section #)				
				Apple juice	Protein source	French fries	Bread	Pulses
1	Value chain length and organisation	Untransparent, 'long', central processing	Transparent, 'short', decentral processing	3.5.2		3.5.4	3.5.1	
2	Circularity, resource use efficiency	Low value, few closed cycles, linear resource use	High value, closed cycles, circular resource use	3.5.3				
3	Protein source/transition	Mainly animal-based	Mainly plant-based		3.5.5			
4	Packaging materials	Plastic	Biobased alternatives, glass, packaging minimisation	3.5.2				3.5.6
5	Agriculture	Conventional, intensive	Organic, regenerative, nature-based					3.5.6

3.5.1 A case study on bread: value chain length and organisation

In the bread case study, the domain of value chain length and organisation is studied by comparing centralized and decentralized food chains. In the *centralized bread chain*, the raw or intermediate products are processed at one central location and distributed to different locations, for instance to supermarkets. In the *decentralized bread chain*, the bread ingredients (flour) are directly shipped to local hubs, where they are processed and sold. For example, the production of bread in bakery shops or the final baking of parbaked bread in bakery sections of supermarkets. The perceived sustainability improvement is to shift from centralized to decentralized food chains – given the shorter transport distances within the decentralized chain.

The case study on bread compared four different chain scenarios, namely the *central*, *central par-bake, decentral bakery* and *decentral home*. The two central scenarios provide bread for the supermarket. In case of the scenario *central*, the bread is fully baked at an industrial bakery and transported to the retailer. Not all breads are sold at the retailer, in the central scenario 11% of bread is unsold (according to FLW brood Nederland). For the *central par-bake*, the first stage of baking is performed at the industrial bakery after which the bread is frozen. The final baking is done on-demand at the retailer. Because of the on-demand baking, the percentage of unsold bread is lower, namely 5%. The *decentral bakery* scenario describes the case of a local bakery shop that makes their own bread. The local bakery also deals with unsold bread, on average this is estimated at 7.5%. In the *decentral home* scenario, the consumer purchases the bread ingredients in the supermarket and makes the bread at home, either with an oven or with a bread baking machine. Due to the long shelf-life of the dry bread ingredients, losses at the retailer were assumed negligible. Please note that the consumer losses were considered out-of-scope for this study.

A fact sheet summarizing the bread case study is available on https://edepot.wur.nl/687844 (Berghout & Siccama, 2025).

3.5.1.1 Assumptions and data

The different steps in the process chains of the four bread scenarios are shown in Figure 17. The functional unit in this study is 1 kg of ready-to-eat bread. Each scenario uses the same recipe. The recipe consists of wheat flour (61.7%), water (36.1%), salt (0.9%), yeast (0.6%) and bread improver (0.6%) (Zisopoulos et al., 2015). The ingredients are sourced in Europe. The environmental impacts of the different ingredients are listed in Table A.1 in 0. All scenarios start with the transport of the bread ingredients from the mill/ingredient supplier to (industrial) bakery or retailer, the transport is by truck and covers 100 km in each scenario. The central scenarios require an additional 100 km for transport of the (par-baked) bread from the industrial bakery to the retailer. For the decentral home scenario, the transport step to consumer in Figure 26 is added for clarification purposes. Note that the transport from retail to consumer is excluded from the environmental impact analysis as it is assumed negligible.

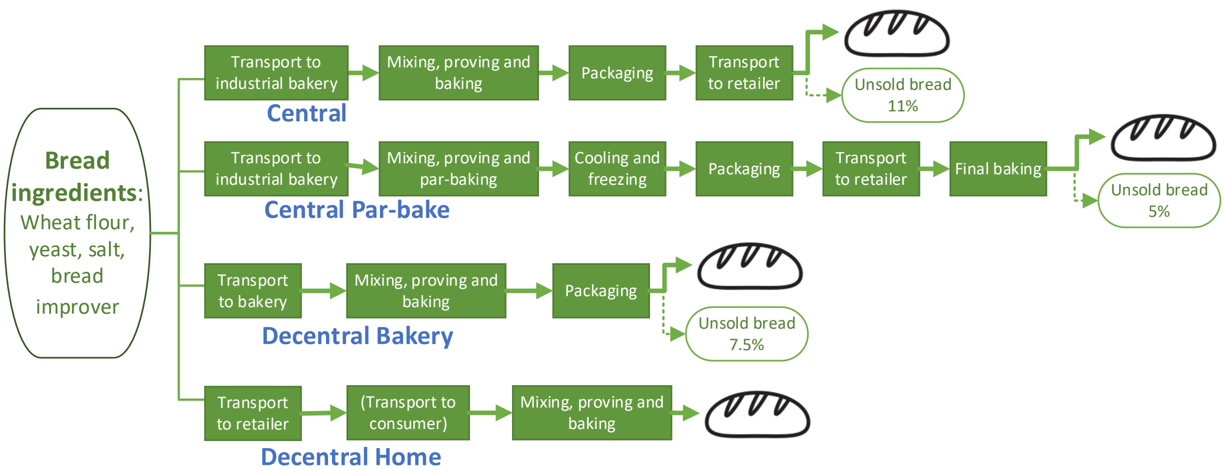


Figure 17 Different steps in the process chain of Central, Central Par-bake, Decentral Bakery and Decentral Home.

The processing varies between the different scenarios. Central and central par-bake use the same equipment but differ in baking time and cooling process. The industrial bakery bakes the *central* bread at 235°C for 35 minutes. The bread is then cooled by using fans, packed in plastic bags and transported to the retailer (Zisopoulos et al., 2015). For the *central par-baked* bread, the par-baking in the industrial bakery is done at 160°C for 30 minutes. The bread is then frozen, packed in plastic bags and transported to the retailer. At the retailer the bread is baked off at 220°C for 10 minutes (Zisopoulos et al., 2015). For the *decentral bakery* scenario, the bread is baked in a batch oven equipped with a sole made of 'stone'. The bread was baked at 230°C for 20 minutes. There is no active cooling after baking, but the bread is cooled down by itself before it is packed in plastic bags. For the *decentral home* scenario, the bread was baked either in an electrical oven or in a bread baking machine. For the electric oven the energy consumption is 1.6 kWh/loaf, for the bread baking machine the energy consumption is 0.36 kWh/loaf (Real Bread Campaign, 2024). For the comparison of the different scenarios, it was assumed that 50% of the bread for decentral home is baked in an electric oven and 50% in a bread baking machine. For more information on the process equipment read Table A.3 for the central scenario, Table A.4 for the decentral par-bake scenario, Table A.5 for the decentral bakery and Table A.6 for the decentral home in 0.

The bread was packed in plastic bags, for 1 kg of bread a plastic package of 10 g was used. All scenarios used the same package material, except for the decentral home scenario where no packaging material was used. The environmental impact of the packing material is listed in Table A.2 in 0. The packaging of the ingredients (i.e. wheat flour, yeast, salt and bread improver) is excluded from this study.

It was assumed that the unsold bread at the retailer and local bakery goes to animal feed. Also, the bread losses in the factory during processing go to animal feed. In this study economic allocation was applied, therefore the prices of consumer bread and animal feed bread are set. For the consumer bread, a price of 2.5 euro/kg bread is used (please note that whole breads usually weigh around 700-800 g – the price was adjusted accordingly). The price of consumer bread was kept the same in each scenario. For the bread repurposed to animal feed, the price was calculated based on the nutritional composition i.e. the feed value, which resulted in 25cts/kg.

3.5.1.2 Results

The GHG emissions and the energy consumption follow a similar trend which is related to the GHG emissions from natural gas and/or electricity required to provide the energy (Figure 18 and Figure 19). Ingredients and processing have the largest contributions on the GHG emissions and energy. The differences between scenarios are mainly attributed to the processing as the agricultural production is kept the same for all. In Figure A.1 and Figure A.2 in Annex 3, the contributions to GHG emissions and energy consumption of each individual process are illustrated. The central par-bake requires more processing steps than the other scenarios. The introduced freezing step (freeze_6) and the frozen storage step (store_10) consume a significant amount of energy. Central par-baking requires on average 18-34% more energy in processing than central and decentral bakeries (Figure 19).

The same recipe is used in the different bread case scenarios. However, more raw materials are needed to produce 1 kg of ready-to-bread in case the share of unsold bread is larger. The scenarios central, central par-bake, decentral bakery and decentral home have 11%, 5%, 7.5% and no unsold bread respectively. In the central scenario, the GHG emissions of ingredients are 0.47 kg CO_2/kg bread, whereas it is 0.42 kg CO_2/kg bread in the decentral home scenario. The effect on the total emissions remains, however, small (Figure 27). The central par-baked bread requires more energy due to the additional process steps (two times baking instead of one, and a freezing step). On the overall picture, this has more impact than the energy saved by having less unsold bread. Furthermore, the contribution of transport to GHG emissions and energy consumption is small (<3.5% of total). Thus, transport is not an important driver to choose for centralized or decentralized in this case study. Keep in mind that the transport distance and the variation between scenarios in this case study is small, i.e. min 100 km and max 200 km. With longer distances the transport would contribute more to the overall GHG emissions and energy consumption.

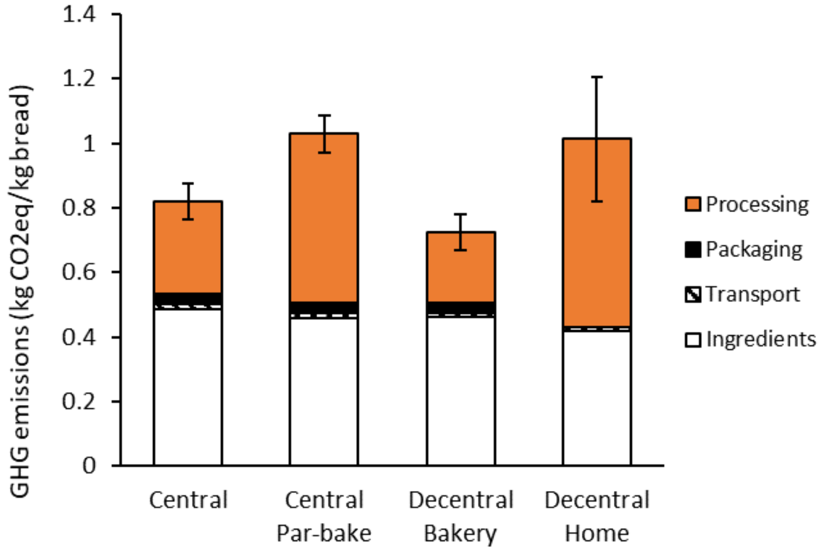


Figure 18 GHG emissions of ready-to-eat bread for different bread case scenarios.

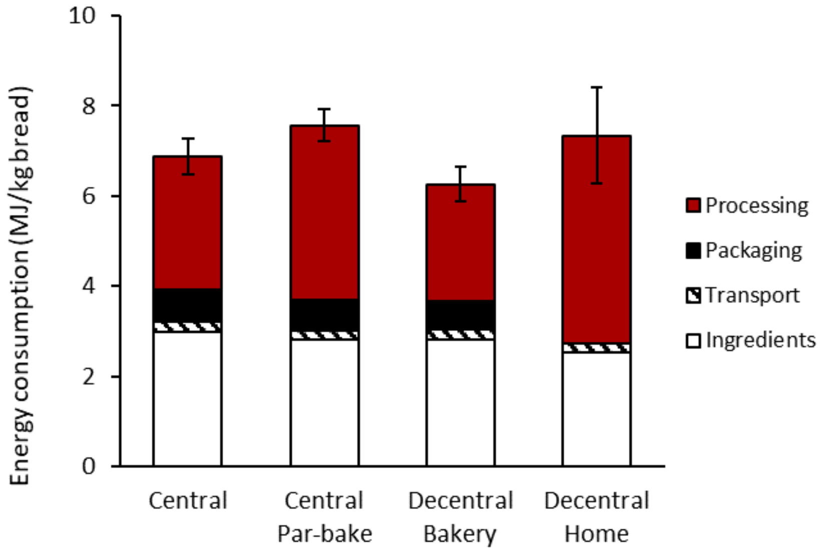


Figure 19 Energy consumption of ready-to-eat bread for different bread case scenarios.

For decentral home, it is assumed that 50% of bread is baked in an electric oven and 50% in a bread baking machine. When evaluating the energy consumption of the individual appliances (Figure 20), the difference between using an oven or bread baking machine is significant. The oven uses four times more energy than the bread baking machine needs per kg of bread. In total the energy consumption of at home oven baked bread is 2.5 times larger than of bread baked in a bread baking machine.

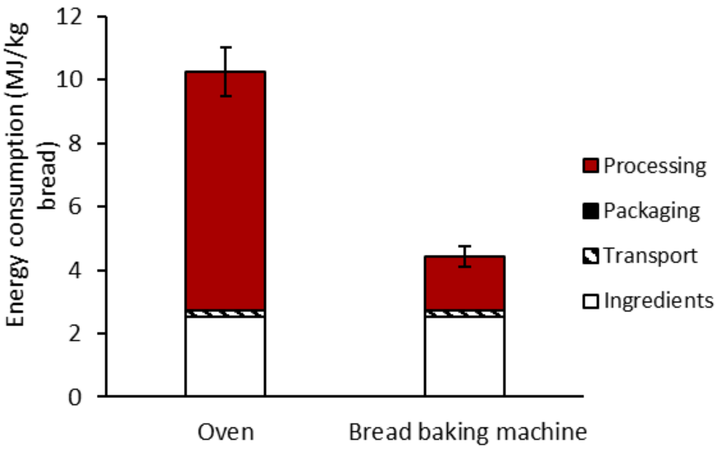


Figure 20 Energy consumption of ready-to-eat bread for different baking devices at home.

The ingredients are the main contributors to the water consumption (Figure 21). The differences observed between scenarios are related to the losses in the supply chain, namely processing losses and unsold bread. To produce the plastic, blue water (supplied potable water) is required, but no green water (rain, surface or ground water) is used (Table A.2). Cleaning of equipment is out of scope of this study; therefore, no water use is attributed to the processing.

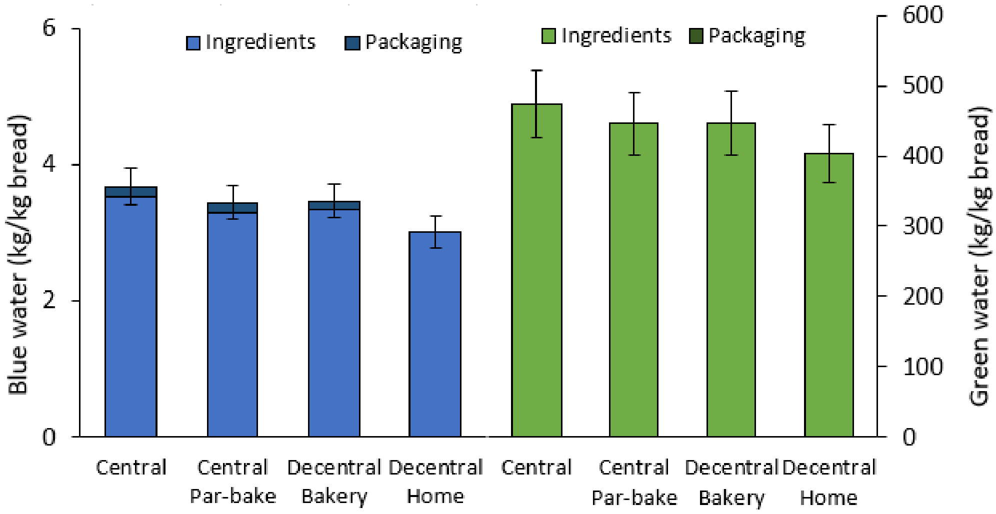


Figure 21 Blue and green water consumption for different bread case scenarios.

For every sustainability indicator (GHG emissions, energy consumption, blue water consumption and green water consumption), a sensitivity analysis was performed to determine which parameters influence the outcome the most. The results of the sensitivity analysis of the GHG emissions are shown in Figure A.3. The sensitivity analysis of the energy consumption led to the same sensitive parameters as for the GHG emissions and is therefore not reported separately. Note that for the *decentral home* scenario the sensitivity analysis was only performed on the oven scenario not on the bread baking machine. The results indicate that the wheat flour ingredient is one of the most sensitive parameters. Wheat flour is also the main ingredient in bread. The energy for baking is a more sensitive parameter in the decentral home oven scenario than in the other scenarios (central, central par-bake and decentral bakery). The high energy consumption of the oven at home makes this parameter more sensitive. Reducing the energy consumption of baking, as was also indicated with the bread baking machine scenario, reduces the overall GHG emissions significantly. The sensitive parameters can help to focus on what measures to take to improve the overall sustainability of a product. However, not all sensitive parameters can be altered. For example, the weight loss during baking (S0-Bake) is also a sensitive parameter, because water evaporation results in less product. However, this weight loss by evaporation is needed to obtain the final product, as a wet/soaking bread is undesired.

The results of the sensitivity analysis of the blue water footprint are shown in Figure A.4. The sensitivity analysis of the green water footprint indicated the same sensitive parameters as for the blue water footprint and is therefore not reported separately. Similar as in the sensitivity analysis of the GHG emissions, the wheat flour is the most sensitive parameters. Wheat flour is the main constituent of bread, hence a change in water consumption during wheat production will affect the overall water footprint of the bread. Note that the bread improver has a higher water footprint than wheat, however, since only a small quantity of improver is used in bread (0.6%) the effect on the overall water footprint will be limited.

3.5.1.3 Conclusion

The results indicate that the *central par-baked bread* was slightly less environmentally sustainable than bread from the *central* or *decentral bakery*, as the two baking steps and freezing step required in par-baking increased the energy consumption. *Decentral home baked bread* is more environmentally sustainable when baked in a bread baking machine than the three other routes or when an oven is used for home baking. It can be concluded that a decentralized food chain is not necessarily more sustainable than a centralized food chain, but that it depends on more factors such as choice of equipment, and management of unsold products.
A fact sheet summarizing the bread case study is available on https://edepot.wur.nl/654609 (Berghout & Siccama, 2024).

3.5.2 A case study on apple juice: value chain length and packaging

One of the perceived sustainability improvements in food chains is to shift from long, international food chains to local food chains within the regime 'value chain length and organisation'. Distinctions between local and long chains are not only related to transport distances, but also processing operations and packaging solutions could differ. Thereto also the regime of packaging is included in the apple juice case study. A comparison of sustainability of local and long chains should take such differences in consideration. In this case study an environmental sustainability impact comparison of apple juice produced in the Netherlands (*local chain*) versus apple juice produced from a concentrate that is transported to the Netherlands (*long chain*) is presented (Figure 22). The *local chain* for apple juice is marked by its decentralized and short structure, local sourcing of raw materials in NL, and utilization of glass as packaging material. Conversely, the *long chain* for apple juice is characterized by its centralized and lengthy structure, external sourcing of raw materials, and TetraPak® packaging.

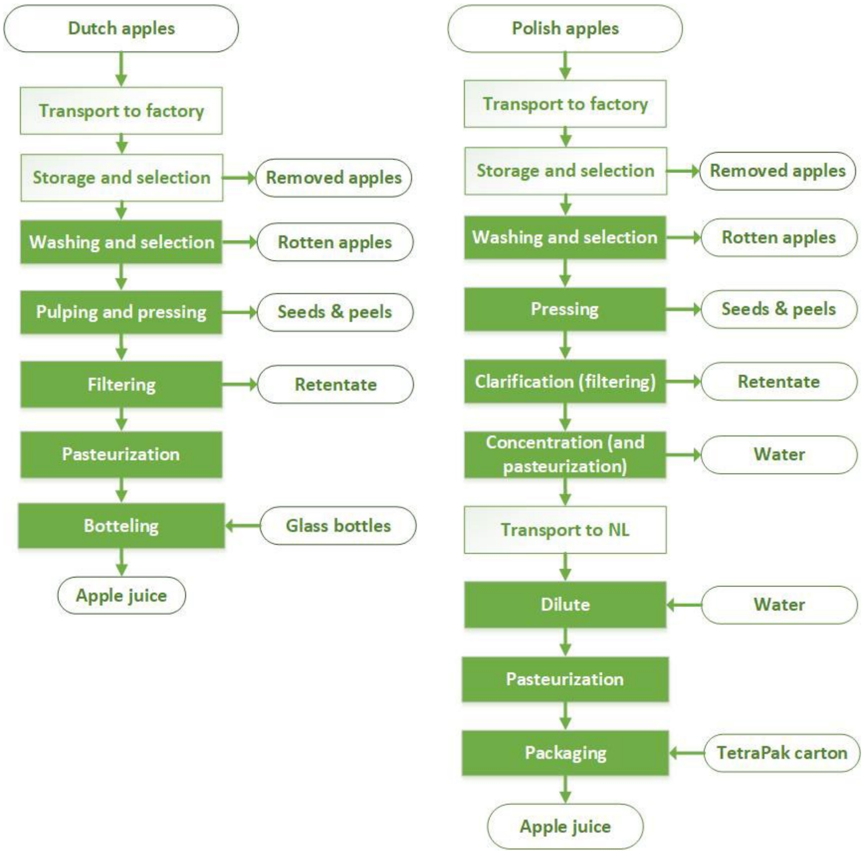


Figure 22 Local apple juice production chain (left) and long apple juice production chain (right).

3.5.2.1 Assumptions and data

The functional unit in this case study is 1 kg apple juice. This study applies a cradle-to-factory-gate boundary approach, which considers the impacts throughout the apple juice supply chain – from apple cultivation to the production and bottling of the final product. Thus, the last food mile (retail and consumer) was excluded in the scenario comparison. In both chains the transport of apples is from the orchard to the factory. In the local chain this is only 1 km as the processing happens close to the orchard. For the *local chain* the transport from orchard to factory is 100 km. Furthermore, the *long chain* also involves the transportation of apple juice concentrate from Chelm in Poland to the Netherlands, this distance is estimated at 1500 km. For the impact of primary production of the Dutch and Polish apples the GHG emissions and energy consumption of European average values are used. The blue and green water footprint of apples are reported per country (Table A.7).

For the analysis of impact associated with the apple processing into apple juice, information on processing and yields was used: from the production process of e.g. Appelsientje apple juice[4] to represent the *long chain*, and

[4] based on Keuringsdienst van Waarde episode 2012 https://www.npostart.nl/keuringsdienst-van-waarde/08-11-2012/KRO_1572893

from various Dutch companies specializing in local juice production, such as Zuver[5], Flevosap[6], and Schulp[7], for the *local chain*. Data on yields in each unit operation was obtained either directly from the companies, from published sources or derived from mass balances. For the local chain, data was found on the overall mass balance, whereas for the long chain, mass balances were performed using the water/dry matter data for different streams in addition to the total mass balance. The composition of Appelsientje Goudappeltje served as the benchmark for the final product in the *long chain*. The specific energy used (in MJ/kg input or per kg of water removed) was gathered from literature or calculated, and the energy source was assumed to be grey electricity from the grid, except for the concentration step in the *long chain* which uses steam from natural gas. The energy consumption and yield of each unit operation are reported in Annex 3 in Table A.9 (local chain) and Table A.10 (*long chain*). After processing, the juice is filled into bottles/packages. The *local* juice is put in glass bottles, whereas *long chain* juice is packed in a TetraPak carton. The environmental impact of the packaging materials is listed in Table A.8. The generated side streams (except water) go to animal feed in both chains.

3.5.2.2 Results

The *local chain* has on average a slightly higher environmental impact in terms of GHG emissions, energy consumption and blue water use than the *long chain* (Figure 23). The green water use, on the other hand, is larger in the *long chain*. The larger GHG emissions and energy consumption in the *local chain* are mainly caused by the packaging material used (Figure 24). In the *local chain*, the apple juice is packed in recyclable glass bottles. This packaging material is associated with a high energy demand in the production process due to melting at high temperatures. The high energy demand results in more GHG emissions, hence the high GHG emissions associated with the packaging material. When selecting deposit glass instead of recycled glass both the GHG emissions and energy consumption will be lower. The washing process is much more energy-efficient compared to glass recycling. Alternatively, using TetraPak instead of recycled glass would make the *local chain* also more sustainable. When choosing the deposit glass, the *local chain* is on average slightly more sustainable than the *long chain* (Figure 24). This is because the *long chain* has higher energy consumption in processing and in transport compared to the *local chain*. The processing in the *long chain* is more intensive which resulted in a higher energy consumption. Specifically, the evaporation step to produce the concentrate is energy intensive (Figure A.6). The transport indeed contributed to the GHG emissions and energy consumption of the *long chain*, as the concentrated juice needs to be transported by truck from Poland to the Netherlands. For the *local chain*, transport is negligible for the GHG emissions and energy consumption given the short distance. For the water footprints, the agricultural production of the apples is the main contributor and is not the same for local and long chain (Figure 25). The *local chain* uses Dutch apples and the *long chain* Polish apples. In the Netherlands the apple orchards are partly irrigated (blue water), whereas the orchards in Poland almost fully rely on rainwater (green water) (Table A.7).

[5] https://www.zuverfruitsappen.nl/ons-verhaal
[6] https://flevosap.nl/veelgestelde-vragen?id=3957#vraag-3957
[7] https://schulp.nl/over-schulp/hoe-maken-wij-sap/

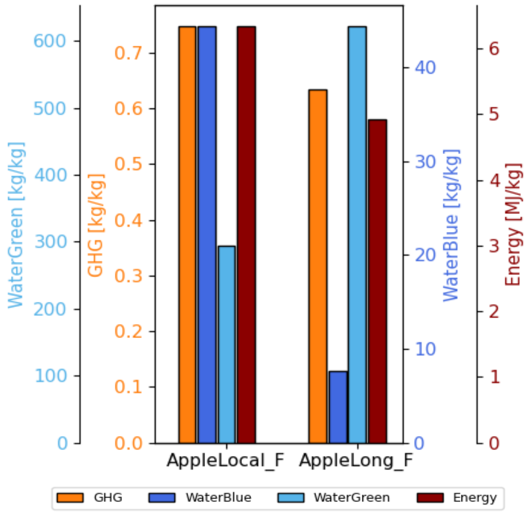


Figure 23 GHG emissions, water, and energy consumption for the local and long chain apple juice production scenarios.

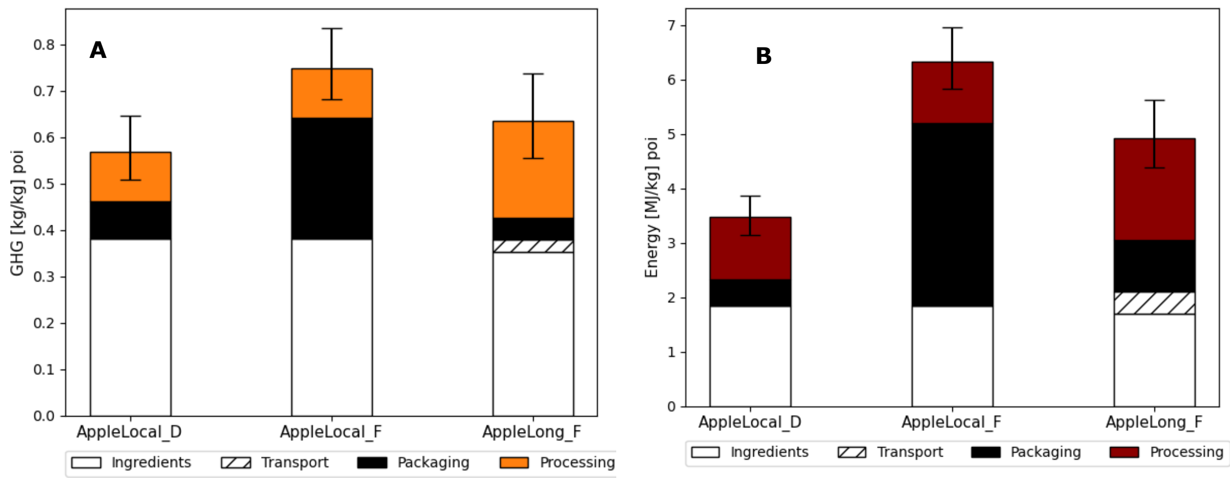


Figure 24 GHG emissions (A) and energy consumption (B) of the local and long chains. AppleLocalD presents the scenario in which deposit glass bottles are used instead of single-use recyclable glass bottles to reduce the environmental impact.

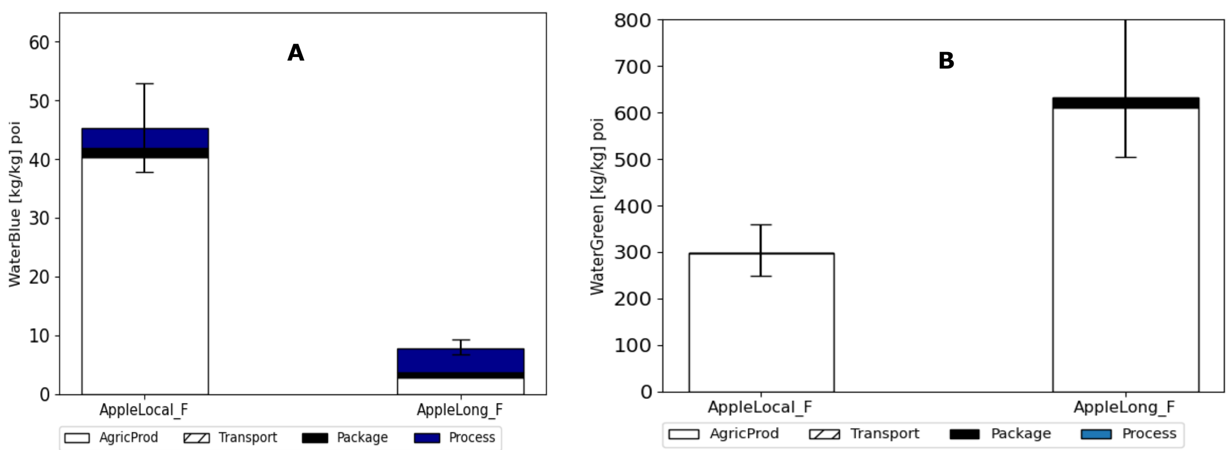


Figure 25 Blue water consumption (A) and green water consumption (B) of the local and long chains.

The sensitivity analysis indicated that the yields in process steps are the main sensitive parameters for GHG emissions and energy consumption (Figure A.7). For the *long chain*, the concentration and dilutions steps are the most sensitive parameters for the GHG emissions and energy consumption. In practice you could concentrate less or more. Concentrating more will cost more energy (as more water needs to be evaporated) but will make the transport more efficient. The dilution factor needs to be the same as the concentration factor, as the final apple juice needs to have the same composition as before concentration. Energy and GHG emissions could be reduced by changing transportation means and by optimizing the concentration and dilution processes further. In the *local chain*, the removal of the rotten apples during selection is the most sensitive parameter for the GHG emissions and energy consumption together with the energy consumption of the production of glass. GHG emissions could be lowered by optimising the selection and pressing process of apples to reduce losses and thus increase the juice yield.

The sensitivity analysis of the water footprints indicates that the removal of rotten apples after washing is the most sensitive parameter in both local and long chain (Figure A.8). Losses in the supply chain require more input material, in this case more apples, and as the apples are associated with a large water consumption during cultivation the losses are sensitive parameters affecting the outcomes most strongly.

3.5.2.3 Conclusion

The differences between the local and the long chain in terms of GHG emissions and energy consumption are not big. For the local chain with deposit glass, the GHG emissions are about 15% lower and energy consumption about 30% lower on average than for the long chain. Whereas for the local chain with single use glass bottles the GHG emissions are about 15% higher than for the long chain and for energy consumption it is 25% higher. For water, blue and green water footprint differences can be observed, mainly caused by the agricultural production. The apple orchards in the Netherlands use more blue water for irrigation compared to Poland for the water supply, whereas in Poland the orchards can almost fully rely on rainwater (green water).

Regarding the GHG emissions and energy consumption, some postharvest improvement opportunities that could be made based on the identified hotspots are:

- The selected packaging material has a large impact on the GHG emissions and energy demand. Selecting a package based on its footprint can reduce the overall environmental impact significantly.
- For the *local chain*, GHG emissions could be lowered by optimising the selection and pressing process of apples to reduce losses and thus increase the juice yield.
- For the *long chain*, energy and GHG emissions could be reduced by changing transportation means and by optimizing the concentration and dilution processes further.
- All side streams go to animal feed in both chains. However, valorising side streams to food (e.g. apple sauce) could improve overall sustainability.

3.5.3 A case study on apple juice: circularity or resource use efficiency

The apple juice chain is also used for the assessment of the different waste valorisation scenarios within the circularity or resource use efficiency regime. The waste valorisation scenarios are discussed in Section 3.2.2. This is the same processing chain as described in Section 3.5.2 Local vs *long chain*: apple juice. To assess the impact of different valorisation routes the effect on the GHG emissions (kg CO_2-eq/kg) is evaluated. The impact on the energy consumption and water use was not included.

3.5.3.1 Assumptions and data

The assumptions related to the processing of the local and the long apple juice chain can be found in Section 3.5.2. In the apple juice chains, waste is generated during several stages in the chain. In this study we focus on the discarded material occurring during processing. For the *local chain*, in four processing steps waste is generated, namely selection after apple storage, removal of rotten apples after washing, press cake (apple pomace) and the residues after filtration (retentate). For the *long chain*, in five processing steps waste is generated: after apple storage, removal of rotten apples after washing, press cake (apple pomace), the residues after centrifugation and the residues after clarification/filtration (retentate). In the *long chain* also, water is removed in the concentration step, but this is not considered as discarded material as this is pure water.

For all waste streams we used the composition of apple pomace, as about 65% of the generated waste is apple pomace. The other 35% consists of removed apples and filter residue. The average composition of apple pomace is: 25% w/w solids, protein 20 g/kg dry matter (DS), fat 20 g/kg DS, carbohydrates 600 g/kg DS and dietary fibre 150 g/kg DS.

To assess the impacts of the possible destinations of the waste streams, as assumed to have the composition of apple pomace, the calculation rules as specified in Section 3.4.2.3 are applied.

3.5.3.2 Results

The local and the long apple juice chain differ in overall process yield (Figure 26), although not significant. The *local chain* has a lower average yield, which indicates that more waste is generated. The bigger the waste stream, the more important the decision on waste valorisation route will be. The yield is not affected by the waste valorisation route itself but is solely based on the process losses generated in each chain.

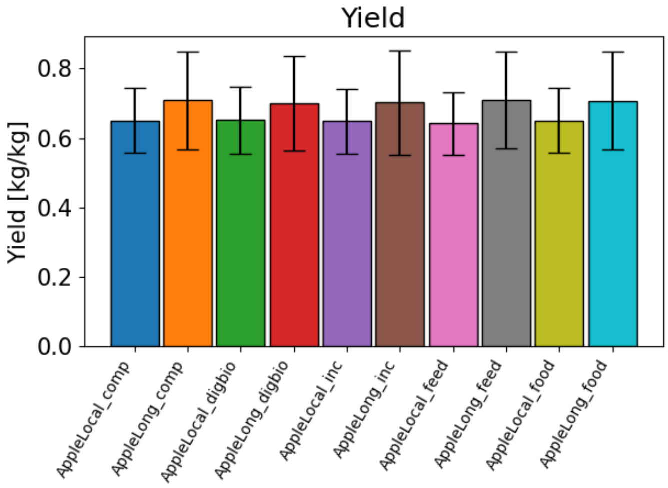


Figure 26 ***The process yields of apple juice in the local chain and long chain. Abbreviations: 'comp' is composting, 'digbio' is digestion to biogas for electricity and heat recovery, 'inc' is incineration with heat recovery.***

Figure 27 indicates that the selected waste valorisation strategy has an impact on the GHG emissions of the apple juice. However, in the *long chain* the waste valorisation strategies are not significantly different from each other based on the overlapping error bars. Furthermore, the *long chain* has lower GHG emissions than the *local chain* when the same waste valorisation scenario is selected for each valorisation route. This is a direct consequence of the lower yield of apple juice in the *local chain*.

The selected waste valorisation impacts all four categories: ingredients, processing, transport and packaging. By performing waste valorisation, the total GHG emissions are divided between the main product (apple juice) and the waste streams. In case of economic allocation (food and feed), this means that if a waste stream is worth more in one scenario than the other, more GHG emissions will be allocated to the waste stream, hence the GHG emissions of the apple juice will go down. For the scenarios with system expansion (digestion to biogas and incineration with heat recovery) the 'saved' GHG emissions are divided over the four categories based on the existing amounts.

The waste valorisation with digestion to biogas leads to the lowest average emissions for both the local and the long chain. This indicates that the most preferred options in the food recovery hierarchy, food and feed, (Figure 10) do not lead necessarily to a more sustainable scenario in terms of GHG emissions. The impact of waste valorisation on the GHG emissions depends on the composition of the waste stream and on the prices of the product of interest (both for application of the waste material as feedstock or in food, and of the apple juice). The generated waste streams during apple juice production are high in water content (75% water). This means that the food and feed price of these streams are relatively low. Furthermore, incineration with heat recovery is not as interesting as the large quantities of water reduce the nett gained energy. In this case, there is still a positive nett energy gain for incineration of apple pomace but a feedstock with higher dry matter content is more beneficial for heat recovery.

Furthermore, in Table 6 it is indicated that feed and food use economic allocation, whereas digestion to biogas and incineration with heat recovery use system expansion as allocation method. Selecting system expansion for the feed and food, may change the overall picture. In case system expansion is used for feed and food knowledge of competing feed and food that you want to replace by using apple pomace is required.

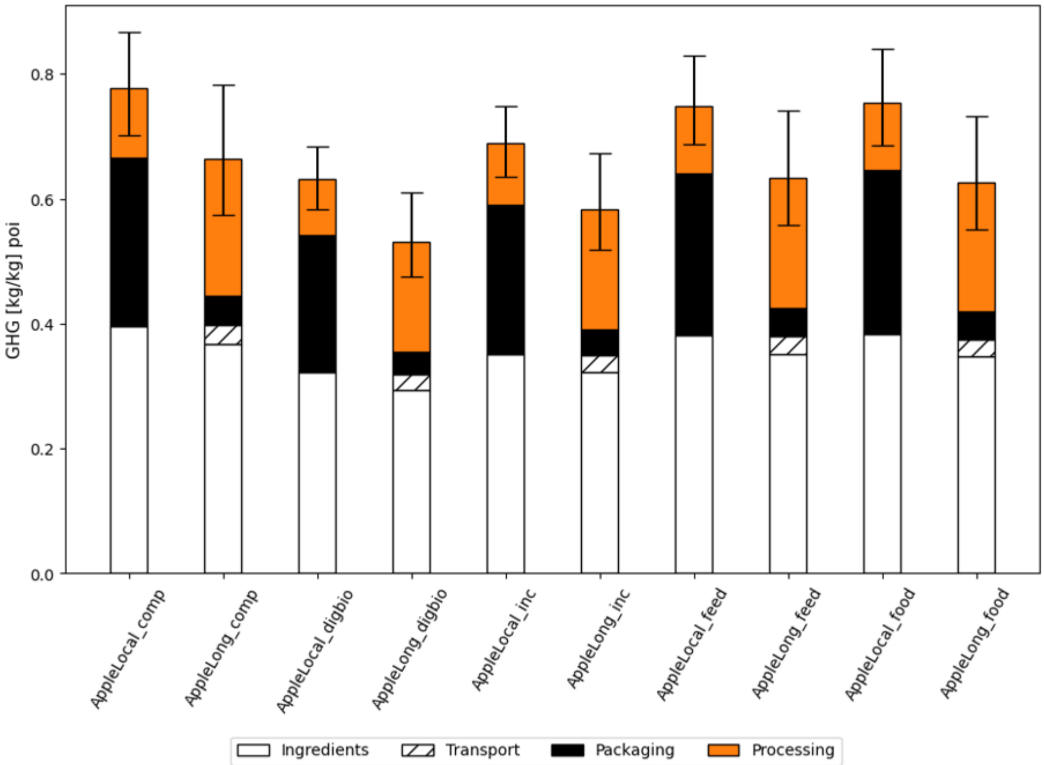


Figure 27 **Comparison of GHG emissions results per kg of apple juice for the long and local chain with different waste valorisation routes. Abbreviations: 'comp' is composting, 'digbio' is digestion to biogas for electricity and heat recovery, 'inc' is incineration with heat recovery.**

Waste is generated at different locations in the processing chain of both local and long chain apple juice. The hotspots for waste valorisation are the processing steps where most waste is generated. Figure A.9 and Figure A.10 illustrates the GHG emissions along the chain for the *local chain* and *long chain*, respectively. In both figures, the digestion to biogas is selected waste valorisation route. Valorisation to biogas will reduce the overall GHG emissions of the product. This effect is the most noticeable for both local and long chain in the pressing step, where the apple pomace (press cake) is valorised, indicating that pressing is a hotspot for waste valorisation. Other hotspots for waste valorisation in both chains are selection after apple storage (i.e. removal of rotten apples) and the residues after filtration (retentate). In addition, the removal of rotten apples after washing is considered a hotspot in the *long chain*.

3.5.3.3 Conclusion

The comparison of GHG emissions indicates that for both chains, the digestion to biogas slightly outperforms the other waste valorisation strategies to reduce the GHG emissions of the apple juice. As the waste stream is suitable for digestion and its high water content makes other valorisation options less interesting. In terms of waste generated in the process, the pressing step is the hotspot for waste valorisation in both the local and the long apple juice chain. Both chains indicate that the differences between waste valorisation strategies are not significant though. The results of this case study indicate that the most preferred options in the food hierarchy do not lead necessarily to a more sustainable scenario in terms of GHG emissions. The best waste valorisation strategy depends on the composition of the waste stream and the price of the product of interest. Therefore, the selection of the best waste valorisation option is case specific and should be evaluated for each case separately. Nevertheless, food loss and waste prevention and reduction is the preferred strategy for sustainable food processing chains.

3.5.4 A case study on French fries: value chain organisation

Many products can be found in different forms at the retailer, for example as a frozen product or refrigerated product. These forms require a different organisation of the value chain. Frozen and refrigerated products differ in shelf-life, storage conditions and to some extent also in processing history. In this case study an environmental sustainability impact comparison of frozen and chilled French fries is made. The system boundary includes agricultural production, processing, distribution and retail. The first part of the chain (agricultural production, pre-processing and par-frying) is the same for both products (Figure 28), but the chains differ from each other in post-processing as the frozen fries are cooled down to freezing temperature, whereas the chilled fries are cooled down to refrigerated temperature. The consequent storage and transport are also adapted to these temperatures. Furthermore, the storage durations at the factory (post-processing) and at the retailer are shorter for the chilled fries due to their shorter shelf life. The shorter shelf life also results in more unsold fries at the retailer, which is 2% for the chilled fries compared to 1% for the frozen fries.

A factsheet summarizing the French fries case is available here: https://edepot.wur.nl/690140 (Siccama and Illera, 2025).

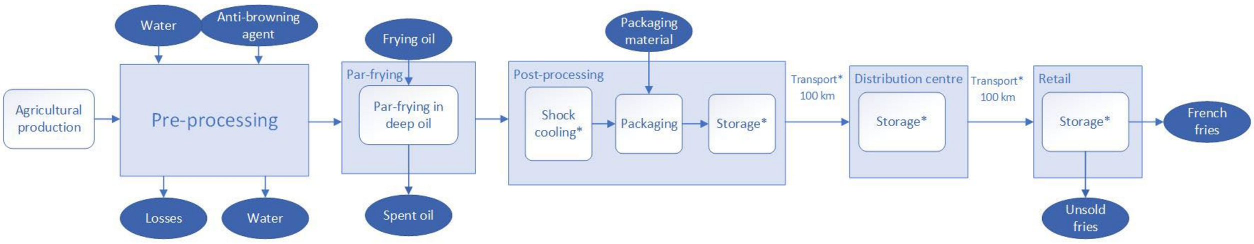


***Figure 28** The process to produce and distribute 1 kg of French fries. * Frozen fries are shock cooled in freezer, and stored and transported frozen, while chilled fries undergo these steps at refrigerated temperatures.*

3.5.4.1 Assumptions and data

The functional unit is 1 kilogram of French fries. An attributional approach is used with economic allocation. The price of 1 kg French fries was set at €1.70 for both frozen and chilled fries. The French fries are made of potatoes that are cultivated in the Netherlands. The environmental impacts of the potatoes and other ingredients are listed in Table A.11 in 0. The transportation from field to factory is not included in the case study, as this is assumed to be equal in both scenarios. Also, the storage of potatoes before processing is neglected. The processing starts with the pre-processing. During the pre-processing (Figure 29), the potatoes are peeled, washed and sorted, followed by cutting. The rejects from sorting and cutting and the potato peels go to animal feed, for a price of €0.03 per kg – based on the composition. After blanching, the potato strips are dipped in sodium acid pyrophosphate (SAPP), which is used to prevent chemical browning of the French fries. The strips are dried with hot air before going to the par-fryer. For par-frying, rapeseed oil is used. For every kg of potato input, 0.05 kg rapeseed oil is needed. The rapeseed oil is obtained from rapeseed cultivated in Denmark and Germany. Pre-processing, par-frying and post-processing all take place in the same factory. Processing requires both natural gas (for heat) and grey electricity. The energy consumption and water use of each process step is reported in Table A.12 and Table A.13 in 0. During the post-processing, the frozen French fries are cooled down to -18ºC, whereas the chilled fries are cooled down close to 0ºC but do not freeze. After cooling, both the frozen and chilled fries are packed in plastic packaging and put in a cardboard box (secondary packaging). Before shipment to the retailer the fries are stored at a storage facility at the factory. In the case of the frozen fries, it is assumed that they are stored for on average 150 days frozen (J. Evans & Brown, 2012). The chilled fries are stored for 1.5 days at the factory before shipment to retail. The French fries are transported over 100 km from factory to retailer by truck. In the case of the frozen fries, the transport is in a frozen truck. The chilled fries are transported in a refrigerated truck. The retail distribution centre is not included. The frozen fries are on average 4 days at the retailer before being sold, for the chilled fries this is 1.5 days. It was assumed that the unsold fries (2% for chilled fries and 1% for frozen fries) go to animal feed. The price is based on the composition. For the frozen fries "Albert Heijn Krokante friet" (Table A.14 in 0) is used as reference, the feed price based on composition is €0.154/kg. For the chilled fries "Albert Heijn Verse friet" (Table A.14 in 0) is used as reference, the corresponding feed price is €0.172/kg. The price of the chilled fries is a bit higher, because of the higher fat content. Please note that similar products may have a different composition.

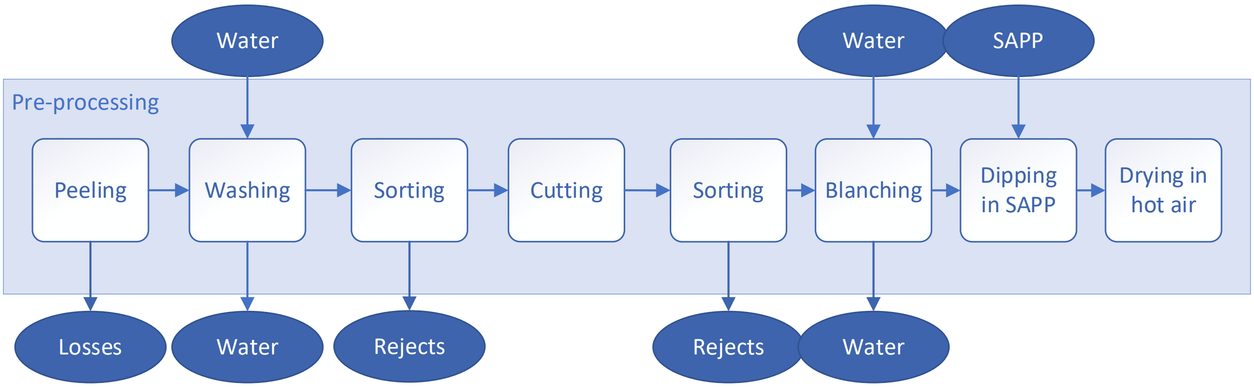


Figure 29 Pre-processing in French fries production. Pre-processing is the same for the frozen and the chilled fries.

3.5.4.2 Results

The resulting environmental impact in GHG emissions in kg CO_2-equivalents per kg product, blue water (e.g. ground water), green water (e.g. rainwater) and energy consumption are displayed in Figure 30. The frozen fries have a higher impact in terms of GHG emissions (15% more) and energy use (11% more). This can be explained by the freezing of the frozen fries, which uses twice the energy of the chilling. Additionally, frozen fries use longer storage times at both the factory and retail with freezers demanding more energy than refrigerators. The blue and green water use of the chilled fries is slightly higher, although negligible on the overall water footprint. This minor difference is due to higher losses at the supermarket (2 compared to 1%), requiring slightly more raw materials to produce 1 kg of chilled fries.

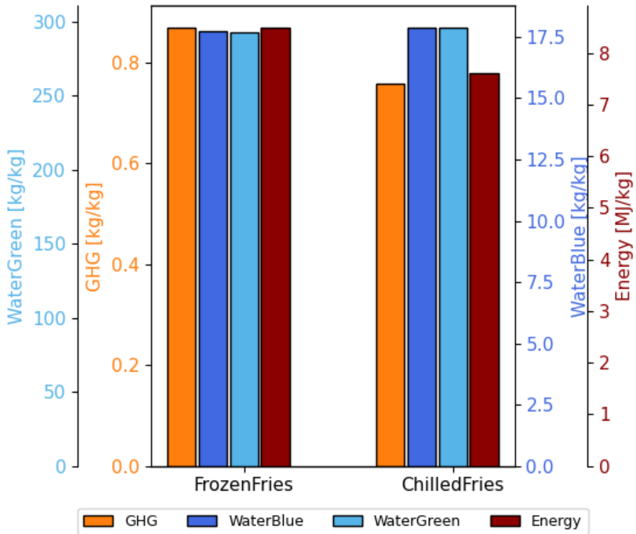


Figure 30 GHG emissions, water, and energy consumption for the frozen and chilled French fries.

Figure 31 and Figure 32 break down the GHG emissions and energy consumption per chain stage, highlighting the hotspots of each chain. The GHG emissions and energy consumption follow similar trends and ingredients and processing are the most important contributors. The impact of ingredients is similar for both chains, as they make use of the same raw materials. The processing is responsible for the differences observed between frozen and chilled fries, given the higher energy consumption for the frozen fries processing and storage. The contribution of packaging is relatively small. The impact of transport is bigger than of the packaging. The impact differences of frozen transport versus chilled transport appears negligible.

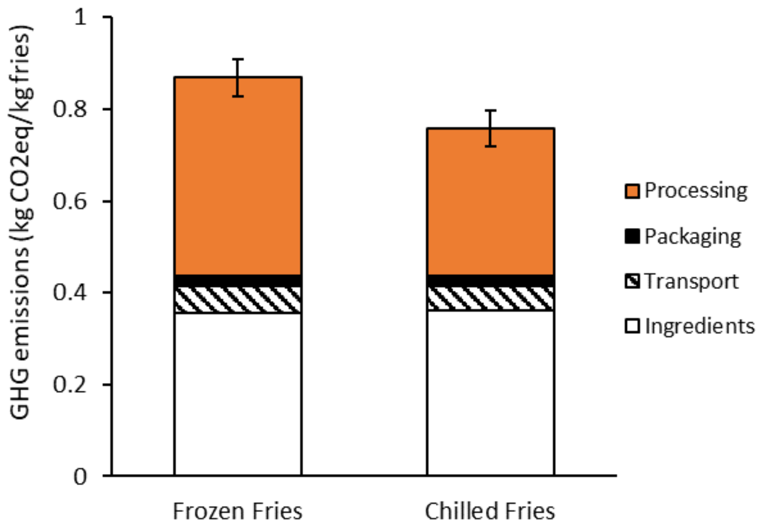


Figure 31 GHG emissions of frozen and chilled French fries.

Figure 32 Energy consumption of frozen and chilled French fries.

Figure 33 zooms in on the contribution of the different processing and storage steps to the energy consumption. The *fries pre-processing* include the steps that are identical for both frozen and chilled fries, i.e. peeling until drying in hot air (Figure 38). Furthermore, the *par-frying* step is also identical in both chains, the par-frying has the largest contribution to the energy consumption of processing. The par-frying requires both natural gas and electricity and is energy intensive because the oil is heated to 180°C (Walker et al., 2018) also the water evaporation during par-frying demands a lot of energy as the potato loses 24% of its mass via water evaporation (Somsen, Capelle and Tramper, 2004). The freezing process, storage at the factory, and storage at the retailer significantly contribute to the higher energy consumption of frozen fries. The freezing of the frozen fries requires about twice the energy of chilling. Although, the energy consumption of the storage units at the factory is low compared to the retail because of the highly efficient freezers and refrigerators. The long storage time (150 days) of the frozen fries results in a noticeable impact of the energy consumption. The storage at the distribution centre is negligible for both chains, due to the same efficient freezers and refrigerators and short storage times. The retail freezers and refrigerators are less efficient. This is partly because they are opened frequently by the consumers. Also, the quantity of product is smaller in these units thus they are more sensitive to temperature fluctuations as there is less of a buffering effect when opening the door of the freezers and refrigerators.

Annex 3 provides the individual contribution of the ingredients and all process steps to the GHG emissions (Figure A. 11) and energy consumption (Figure A. 12) for frozen fries and chilled fries. The frying is the most intensive processing step both in terms of GHG emissions and energy consumption. In terms of the primary production (ingredients/packaging), the fries and the oil have the largest contributions.

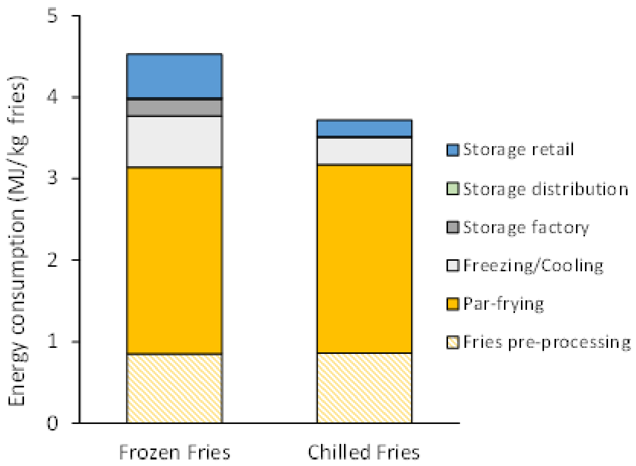


Figure 33 Contribution of different processing steps to energy consumption.

3.5.4.3 Conclusion

The chilled French fries perform slightly better in terms of GHG emissions and energy use. The freezing process and longer storage times of the frozen fries make it more energy-intensive compared to chilled fries. The slightly higher product loss at retail of the chilled fries (2% compared to 1% for frozen fries) has a negligible impact on the environmental sustainability.

Overall, the environmental impact differences between the two chains are small. However, the following aspects can be highlighted:

- Despite the much longer storage time of the frozen fries at the factory, the energy consumption remains relatively low because the freezers used for longer storage are very energy efficient.
- Retail freezers are much less efficient, with energy demand about 10 times higher than at the factory. Optimizing freezing at retail, including reducing storage time, would help lower energy use and environmental impact.
- The differences of impact of food waste at retail are relatively small. Although out-of-scope for this case study, losses at the consumer could be larger for chilled fries due to the limited shelf-life compared to frozen fries. Setting the boundary until the consumer may change the overall picture in terms of sustainability.

3.5.5 A case study on protein sources: protein source/transition

Protein can be obtained from a wide range of foods, broadly categorized into animal-based and plant-based sources. While traditional animal-derived proteins such as from meat, eggs, and dairy have long been dietary staples, there is growing interest in plant-based alternatives like legumes, nuts, seeds, and soy, as well as emerging sources such as insect protein and lab-grown meat. The consumption of meat is associated with a high environmental impact. Therefore, eating (more) plant-based is often recommended. There are many meat alternatives available on the market, with different ingredients. In this case study an environmental sustainability impact comparison of meat burgers, plant-based burgers and canned beans is made. Meat burgers included in this study are made from beef or chicken. The plant-based burgers in this study vary in the protein-source used in the recipe, namely pea protein isolate or pea protein concentrate. By making these comparisons not only will the difference between meat and plant-based be evaluated, but also within these product categories different products are evaluated on their environmental impact. The process flows of the five different products in scope are shown in Figure 34.

A factsheet summarizing the case study on protein sources is available here: https://edepot.wur.nl/690141 (Illera & Siccama, 2025).

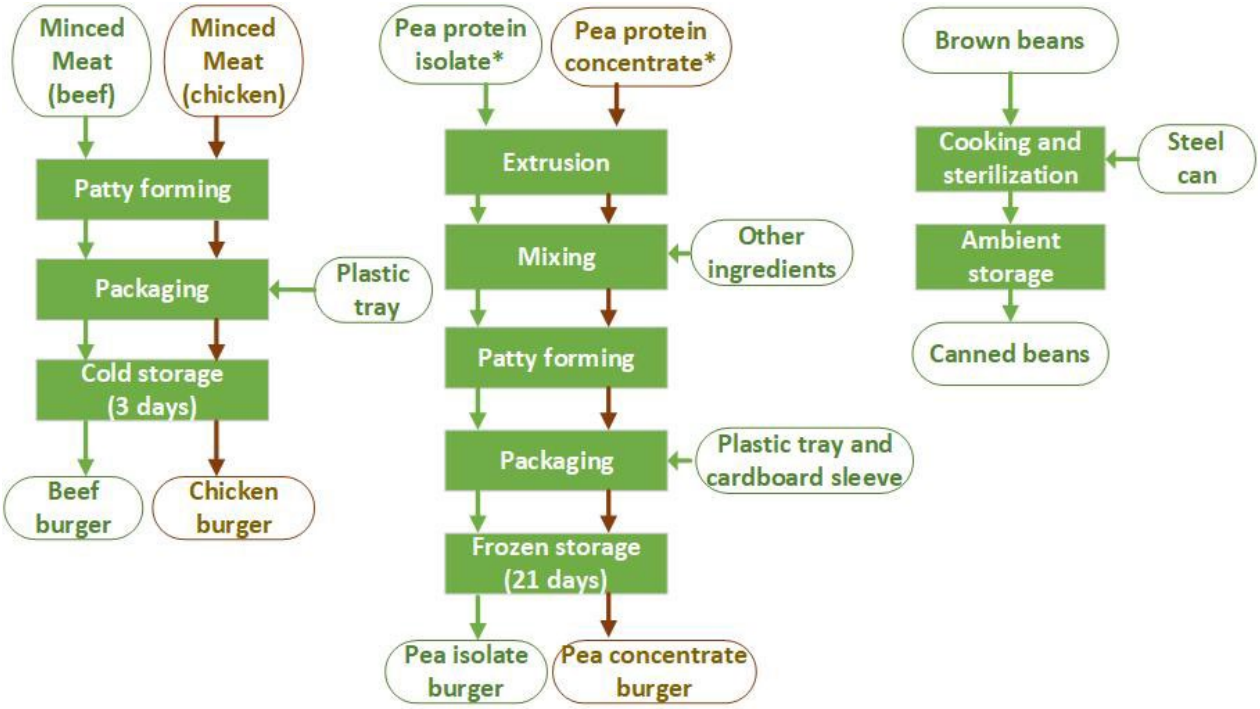


Figure 34 ***Simplified steps to produce 1 kilogram of meat, plant-based burgers or canned beans. *The primary production, post-harvest activities and preprocessing (fractionation) are considered in the impacts of the ingredients.***

3.5.5.1 Assumptions and data

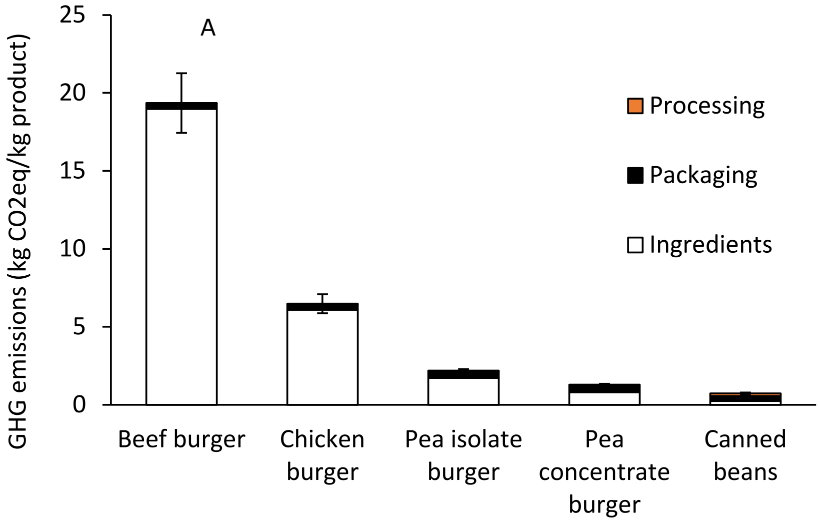
The functional unit in this study is 1 kg of burger or 1 kg of canned beans. The boundary of the system is from agricultural production to factory gate. Distribution and retail are considered out-of-scope in this case study. The meat burgers are made with minced beef or chicken meat. The beef comes from Dutch cows and the chicken comes from Denmark. For simplification no other ingredients were considered in the meat burgers. Two plant-based burgers are assessed; a burger made with pea protein isolate and one made of pea protein concentrate. Next to the protein-source, also other ingredients are added that provide taste and texture. The formulations are based on commercial burgers. The pea protein isolate burger is based on the Beyond Meat burger. The pea concentrate burger is based on the Heura vegan burger. The Beyond Meat burger and the Heura burger list their ingredients, but do not provide the exact quantities of each ingredient, only the exact amount of pea protein isolate and pea protein concentrate is reported, respectively. The quantities of the remaining ingredients were estimated based on the nutritional composition and order on the label (as they are ordered in terms of quantity). The recipes used for the calculations can be found in Table A.15 (Beyond Meat Burger) and Table A.16 (Heura burger). The peas used for the protein concentrate and protein isolate are grown in Western Europe (Netherlands, France and UK). For the manufacturing of pea protein concentrate and pea protein isolate, a fractionation is performed of the pea into a protein-rich fraction (concentrate or isolate) and a starch-rich fraction. The energy used in this fractionation process and corresponding GHG emissions are attributed to the ingredients and are not part of the burger making. The canned beans in this study are brown beans grown in the Netherlands. The environmental impact indicators of the ingredients used in meat and plant-based burgers and of the brown beans can be found in Table A.17.

To make a burger from the pea protein concentrate or isolate, the protein ingredients first need to be extruded before they are mixed with the other ingredients of the burger. For extrusion, there are two options; high moisture and low moisture extrusion, also referred to as high moisture extrudates (HME) and low moisture texturized vegetable proteins (TVP) (Saerens et al., 2021). We assumed low moisture extrusion was used for both pea protein burgers. For low moisture extrusion, around 0.25 kg water is added for every 1 kg of protein ingredient. The energy consumption of this extrusion process is about 0.26 kWh/kg (Saerens et al., 2021). The product loss in the extrusion process is estimated at 5% (Heller & Keoleian, 2018). Except for the extrusion step, the other processing steps are the same for all burgers. First, all ingredients are mixed, next the mixture is shaped into patties, followed by packaging. The plant-based burgers are frozen, whereas the meat burgers are refrigerated. There are no other product losses assumed in the production process. The packaging of all burgers consists of a plastic tray, and a plastic foil to cover the tray. For the plant-based burgers, there is also a paperboard sleeve around the tray that contains the product information. The plant-based burgers are frozen and stored for 21 days in the freezer at the factory before distribution. The meat burgers are chilled after packaging and stored for 3 days on average at the factory before distribution. For the canned beans, the raw brown beans have been pre-cooked followed by heating in the steel can for preservation purposes. The canned beans are stored at ambient temperature for 21 days before leaving the factory. It is assumed that the storage at ambient temperature does not consume energy. The energy consumption of the different processing steps of the meat burgers, plant-based burgers and canned beans can be found in Table A.*18*.

3.5.5.2 Results

Figure 35A shows that the GHG emissions impact of the beef burger is about 3 times larger than the chicken burger, and 9 and 15 times larger than the pea protein isolate and pea protein concentrate burgers. The GHG emissions of the canned beans are almost 2 times lower than of the pea concentrate burger. Ingredients have the largest GHG emissions contribution to the burgers (Figure 35A). For the canned beans, packaging and ingredients have the largest contributions (0.31 and 0.25 kg CO_2-eq/kg product). The contribution of processing of the burgers is relatively small as mixing and patty forming is not energy intensive and the storage times are short. The extrusion process of the pea proteins is energy demanding, but only 16% of the final pea isolate burger consists of extruded pea isolate (Table A.15) and for the pea concentrate burger this is 24.5% pea concentrate (Table A.16), which reduces the impact on total basis.

It could be argued that expressing the GHG emissions per kg protein would be better in this context as protein is the key component in the product as this case study focuses on 'protein sources'. Therefore, also a comparison was made based on the GHG emissions expressed per kg of protein (Figure 35B). The resulting impacts as presented in Figure 44A were divided by the protein content in the burgers and canned beans to obtain the GHG emissions per kg protein. The beef burger contains 20% protein, the chicken burger 17% protein, the pea isolate burger 16% protein, the pea concentrate burger 19% protein and the canned brown beans 6% protein. When the GHG emissions are expressed per kg protein, the trend of the GHG emissions of the plant-based burger and canned beans changes, as the pea concentrate burger now has the lowest emissions. This is because the protein content of brown beans is much lower than the protein concentrate burger. Furthermore, the canned beans and the protein isolate burger now have similar GHG emissions, also because of the higher protein content of the pea isolate burger. The relative GHG emissions of the beef burger became smaller compared to the other products, given its high protein content. Nevertheless, the impact is still higher than of the other studied products.



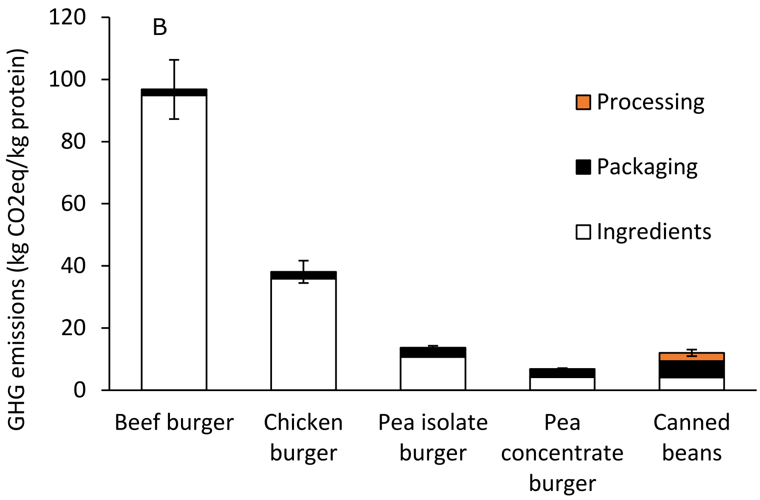


Figure 35 ***GHG emissions of the different burgers and the canned beans. (A) GHG emissions expressed per kg of product. (B) GHG emissions expressed per kg of protein.***

Furthermore, the plant-based protein sources were analysed in more detail. It was found that the degree of refining of plant-based protein sources matters (Figure 36). The pea protein isolate (most refined option) has highest protein purity: 82% protein, and highest GHG emissions. Pea protein concentrate with 54% protein has a much lower impact, while the brown beans with only 6% protein have the lowest impact. More refining means more energy which is directly reflected in the processing emissions. The peas used in the pea concentrate and isolate travel similar distances from field to factory. However, note that more raw material is needed to produce more refined ingredients, therefore both the ingredients and transport associated GHG emissions are larger for the protein isolate compared to the concentrate. Please remember that the plant-based burgers consist of more ingredients than the pea protein isolate/concentrate, thus the protein source only makes up a part of the ingredient GHG emissions illustrated in Figure 44.

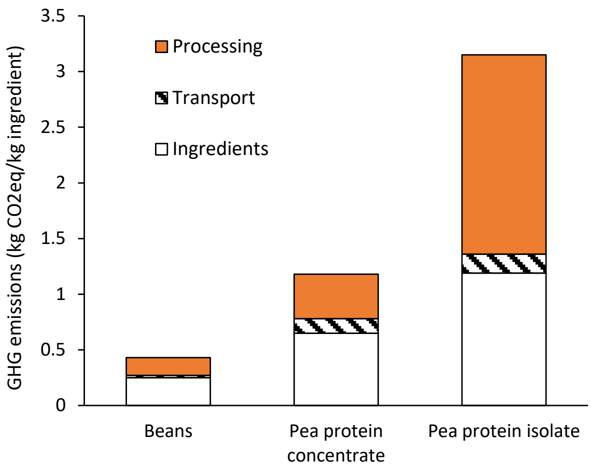


Figure 36 ***GHG emissions of the different plant-based protein sources expressed per kg of ingredient. Data obtained from*** (Broekema & Smale, 2011)***.***

Next to the GHG emissions, the energy consumption of the burgers and canned beans were analysed (Figure 37). The trends differ a bit from the GHG emissions. It can be seen that the difference between beef burger and chicken burger is smaller for the energy consumption with a factor 2.3 instead of a factor 3 for the GHG emissions. This could be explained by the large excretion of nitrous oxide (N_2O) via cattle manure and methane (CH_4) directly excreted by the cow specifically contributing to the GHG emissions of beef (Blonk et al., 2008). To convert nitrous oxide and methane to CO_2-eq, they are multiplied by their global warming potential (GWP), which are 298 and 25, respectively. The energy consumption of the beef burger has no direct link to nitrous oxide and methane, which explains why relative contribution of the GHG emissions of beef is larger than the energy use compared to the other products. Although, the energy consumption of the beef ingredient is still significant and is mainly attributed to the agriculture and processing of the feed including artificial fertilizer (Blonk et al., 2008). For the chicken burger, also the feed is the main contributor to the ingredient's energy consumption. The energy consumption of the chicken burger and pea isolate burger are similar. The contribution of packaging is larger for the pea isolate burger (and concentrate burger) than for the chicken burger due to the extra cardboard sleeve around the plastic tray. Furthermore, the energy consumption of ingredients of the pea isolate burger is relatively large. The pea protein isolate production process is related to a high energy consumption (39.7 MJ/kg pea protein isolate (Table A.17)), whereas for the pea protein concentrate this is much lower (11.1 MJ/kg pea protein concentrate (Table A.17)). Also, other ingredients, although added in smaller quantities, have a high associated energy consumption, such as the rice protein and the beetroot colourant (Table A.17). For the pea concentrate burger and the canned beans, the packaging is the main contributor to the energy consumption.

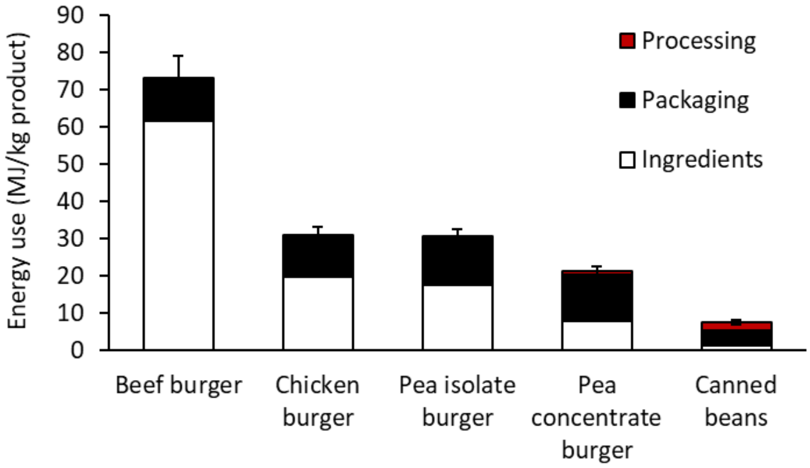
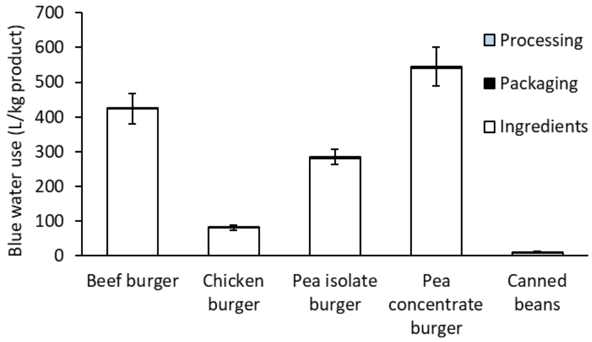


Figure 37 ***Energy consumption of the different burgers and the canned beans per kg of product.***

Lastly, the water footprints of the different products were compared, as presented in Figure 38. For the blue water footprint, the pea concentrate burger resulted in the highest water usage. This is mainly attributed to the use of olive oil in the recipe of the pea concentrate burger. The production of olive oil is water intensive and heavily relies on irrigation with 10,593 L blue water/kg olive oil produced in Spain. The pea isolate burger uses rapeseed oil from Denmark as main oil source which does not use blue water during cultivation but fully relies on green water. The blue water footprint of the pea isolate burger is mainly attributed to the use of rice protein. Rice itself is a water demanding crop, particularly in green water use. In addition, the yield of rice protein is low as to produce 1 kg rice protein 11.6 kg of rice is needed and all environmental impact is attributed to the rice protein. Replacing the olive oil and rice protein with other ingredients could reduce the water footprint. This is however out of scope for this case study.

The green water footprint of the pea concentrate burger is mainly determined using olive oil, followed by the pea protein concentrate. For the pea isolate burger, the green water footprint is mainly attributed to the rice protein, followed by the canola oil and pea protein isolate. The beef burger has the highest green water use of all products. This is explained by the feed conversion rate of cattle, i.e. 31.7 kg feed/kg edible weight, and most of the feed is cultivated with rainwater. The chicken burger has a relatively low blue and green water footprint. The feed conversion ratio for chicken meat is 4.2 and much lower than for beef. Note that the feed conversion ratio is not a direct measure for the water footprint as it also depends on the type of feed (e.g. grass, grain etc.) given to the livestock animals.



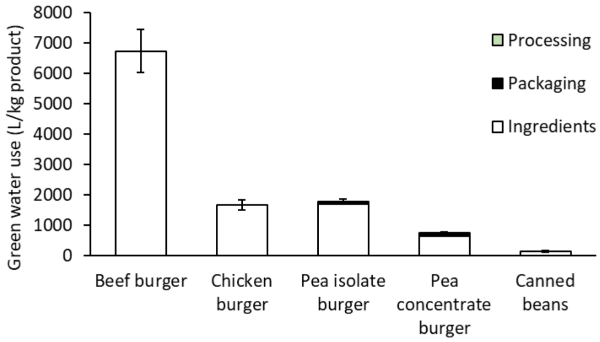


Figure 38 ***Water consumption of the different burgers and the canned beans per kg of product, with (left) blue water footprint and (right) the green water footprint.***

3.5.5.3 Workshop with teachers

This case study was implemented during a workshop at SVO vakopleiding Food, an institute dedicated to training of young professionals in the food sector. The objective was to explore the educational potential of the ACE calculator.

The workshop started with an introduction outlining the significance of environmental impact assessment tools in the food industry. Following this, participants (teachers) were guided through a practical exercise using the ACE calculator. Working individually on their computers, they conducted comparative analyses of the environmental impact associated with plant-based, chicken, and beef burgers, using data drawn from the presented case study on protein sources.

The teachers expressed strong interest in the calculator, highlighting its effectiveness in conveying the environmental implications of food choices. Several participants indicated that such a tool could be highly valuable in their curricula, enabling students to better understand and visualize some environmental sustainability aspects of different food products.

Given the critical role of sustainability in the future of the food industry, integrating such tools into education is seen as an important step in preparing students to consider environmental impacts in their professional decision-making. For this purpose, the ACE calculator would require further development to enhance its usability and ensure its suitability for education.

3.5.5.4 Conclusion

The chicken burger and plant-based options have are a lot lower resulting impact values than the beef burger, with canned beans having the lowest environmental impact. The chicken burger and pea isolate burger compete closely with each other on sustainability. The energy consumption is similar, whereas GHG emissions of the chicken burger are higher and water consumption of pea isolate burger is higher. The pea protein concentrate burger was the most sustainable burger in terms of GHG emissions and energy consumption, which is partly explained by the less refined protein. The plant-based burgers also contain other ingredients aside from the pea protein concentrate/isolate, which also impact the environmental impact. The water footprint was mainly influenced by the presence of the other ingredients as both olive oil and rice protein require a lot of water during agricultural production. For comparison, the GHG emissions were also expressed per kg of protein. The GHG emissions of the canned beans are now larger than the pea concentrate burger and similar to the pea isolate burger.

Based on the findings, the following recommendations are provided to reduce the environmental impact, and improve sustainability during the development of meat alternative products:

- Choosing more wholesome ingredients, such as beans, chickpeas, and peas, when possible, especially when high protein is not required. Products with less refined ingredients typically have lower protein content (e.g., as a result the bean burger contains half the protein of the burger using isolates).
- Avoiding refined ingredients with higher footprints, e.g., try finding alternatives for ingredients such as protein isolate which, even not being the main ingredient, contributes significantly to the footprint.

3.5.6 A case study on pulses: packaging, energy source and agriculture type

Pulses can be found in the consumer market in many different forms, like conventional and organically-grown pulses, cooked or dried and in different packaging like glass, can, plastic etc. This case study describes a sustainability assessment of brown beans. An advice on the more sustainable choice regarding CO_2-equivalents, energy and water will be made by considering the agricultural production, processing history and packaging. This case study compares different scenarios (Figure 39):

- Conventional or organic cultivated brown beans.
- Preserved brown beans in different packaging: can, glass, Tetrapak or pouch (from aluminium/plastic).
- Dry beans packed in plastic.

In the case studies described in this report, the system boundary usually ends at the retail or at the factory gate. For this case study, the factory gate is the system boundary, with results presented in 3.5.6.2, but for comparison also the extension with cooking at home option was evaluated, presented in 3.5.6.3.

A factsheet summarizing the pulses case is available here: https://edepot.wur.nl/689362 (Siccama & Broeze, 2025).

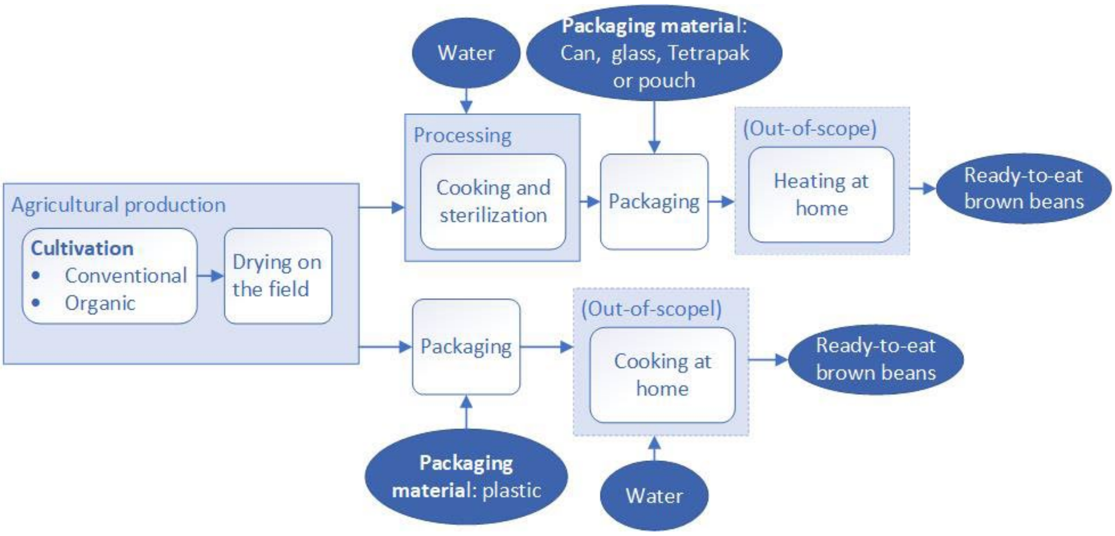


Figure 39 Process chains of preserved brown beans (top) and dry brown beans (bottom) to produce 1 kg of ready-to-eat brown beans.

3.5.6.1 Assumptions and data

The functional unit in this case study is 1 kg of ready-to-eat brown beans, considering the drained weight for preserved beans and the cooked weight for dry beans, both with 30% dry matter content. Thus, the starting volume is the amount of beans that is required that 1 kg consumable product is realised. The system boundary covers agricultural production to factory gate (Figure 48). The brown beans are cultivated conventionally or organically in the Netherlands. The environmental impact of the conventional and organic brown beans can be found in

Table A.19. Transportation from field to factory was out of scope due to short and equal distances in each scenario. It is assumed that the beans are dried on the field, thus no energy is consumed in the drying process. However, note that drying in the factory could be necessary when weather conditions do not allow drying on the field. For the production process of the preserved beans, the beans are cooked and sterilized in the factory and packed. The energy demand for the industrial cooking and sterilization process is 1.807 MJ/kg of natural gas (for heating) and 0.0654 MJ/kg of electricity (Broekema & Smale, 2011).

The analysis is based on ~ 250 g beans per package, this is important as the ratio between packaging material and product varies with portion size, i.e. a package of 1 kg requires relatively less packaging material than a package of 250 g for example. The type of packaging also influences the weight needed, for example a plastic package is much lighter in weight than glass. The dry beans are packed in transparent plastic (0.02 kg/kg dry beans). The preserved beans are packed in a glass jar, steel can, plastic/aluminium pouch (bonen in zak) or Tetrapak (bonen in pak). The packaging weights (kg/kg beans) are 0.79 for glass, 0.30 for steel can, 0.04 for pouch and 0.07 for Tetrapak. The environmental impact of different packaging materials can be found in

Table A.20. The packaging of dry beans and preserved beans are different from each other as the preserved beans require stronger packaging material due to the high temperature in the process.

Furthermore, the impact of home cooking was calculated for dry beans (60 min) and preserved beans (2 min). 500 g of ready-to-eat beans (equivalent to 180 g dry beans) was cooked at once on a small natural gas burner.

3.5.6.2 Results until factory gate

The GHG emissions (Figure 40) and energy consumption (Figure 41) are lower for the conventional beans than for the organic beans. This can be explained by the lower crop yield of organic beans, assumed at 7.5 ton/ha versus 13 ton/ha for conventional (J. Bos et al., 2014). Organic beans require therefore relatively more diesel use and other energy use of machinery, as also illustrated in Figure 42 obtained from (J. Bos et al., 2014). Higher energy consumption of organic produce is also observed for other crops (leek, strawberry, lettuce, bunched carrot). Although the primary production of organic beans is associated with higher impacts, the effect on the total GHG emissions and energy use remains relatively small due to the impacts of the glass packaging and of the processing.

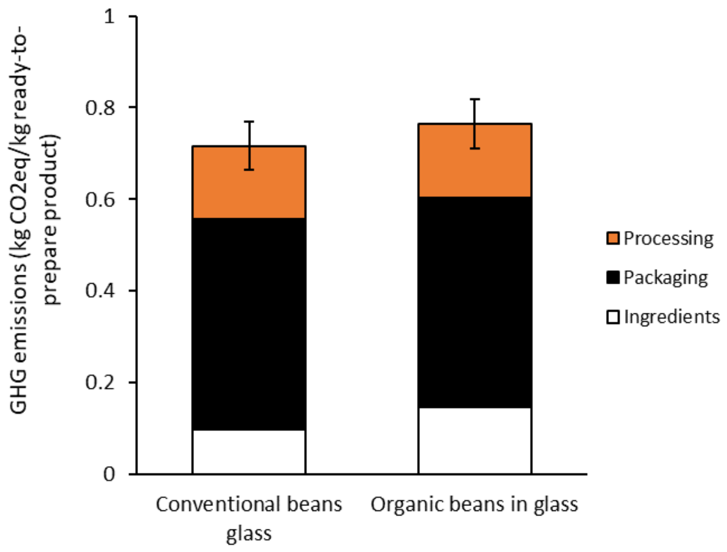


Figure 40 GHG emissions of conventional and organic brown beans in glass.

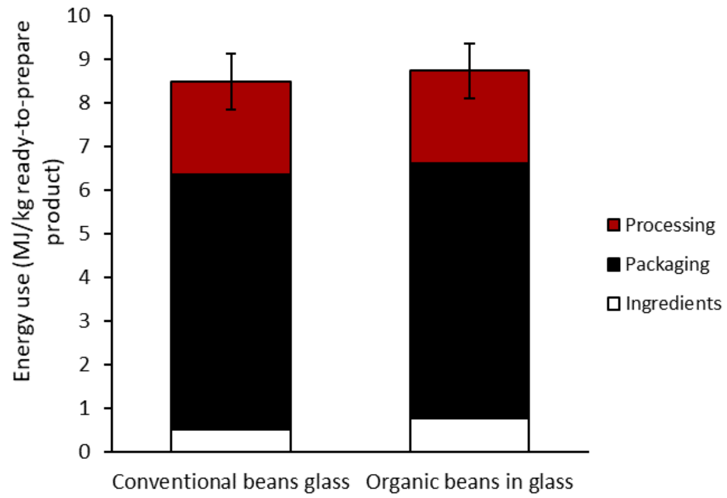


Figure 41 Energy use of conventional and organic brown beans in glass.

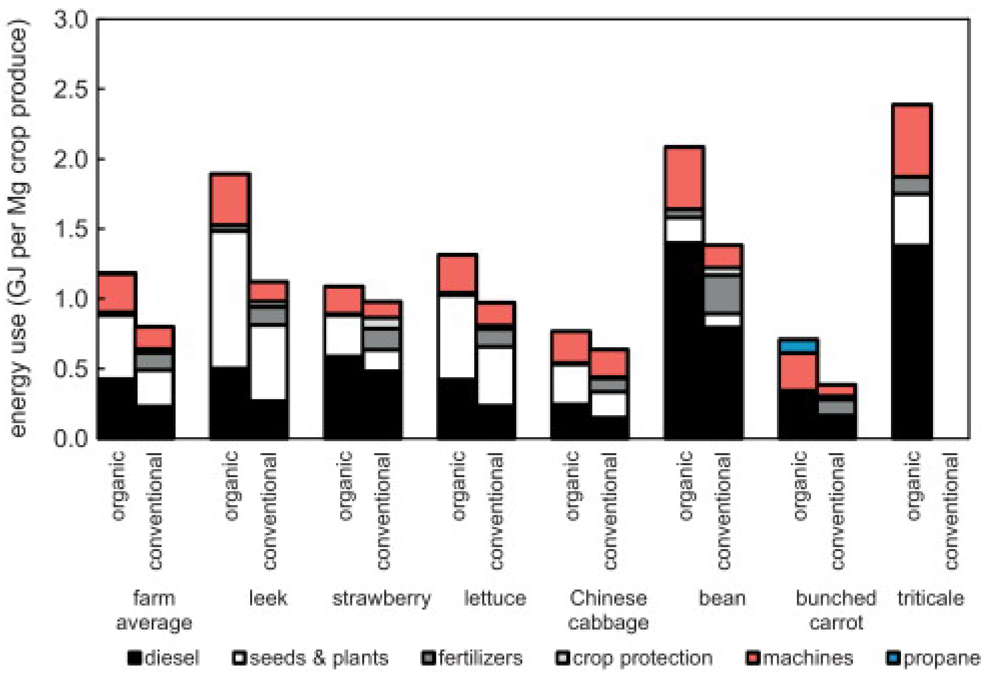


Figure 42 Energy consumption (GJ per ton crop produce) on the organic and conventional vegetable farms. Figure obtained from *(J. Bos et al., 2014)***.**

Figure 43 presents the effect of choice of packaging material on the GHG emissions. The steel can induces the highest GHG emissions. Although glass packaging is heavier per kg of beans, the higher GHG emissions from steel had a greater impact on total emissions. The Tetrapak and pouch appear to have the lowest GHG emissions. The total GHG emissions can be reduced by at least a factor two when choosing for Tetrapak or pouch instead of a can. For energy consumption a similar trend is observed (Figure A. 13).

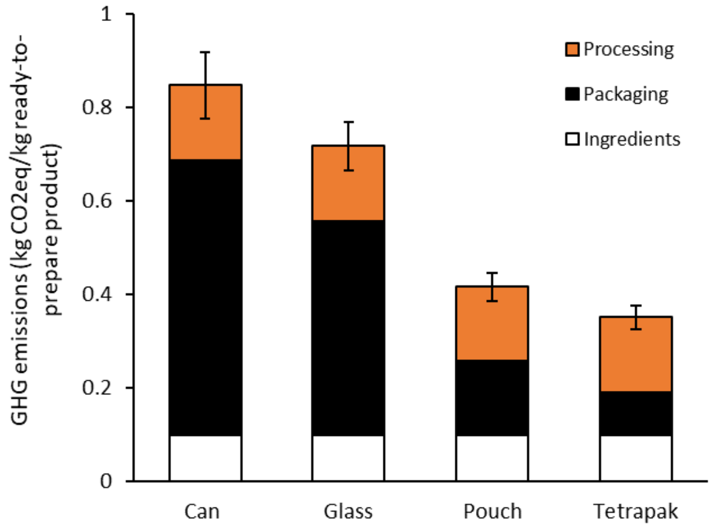


Figure 43 GHG emissions of conventional brown beans in different packaging.

The water consumption is also affected by the choice of packaging material. For blue water (Figure 44) the pouch has the lowest water consumption and the can the highest. The water used in the processing, i.e. added to the can, is considered an ingredient, therefore no water use in processing is reported. Other water used in the process (e.g. rinsing, sterilization water) was excluded from the analysis. For the green water (Figure 45) only the Tetrapak uses green water in packaging. This is because the Tetrapak is made of paper, and the trees use green water for growth. Whereas the other packaging materials containing plastic, glass, aluminium and/or steel do not rely on rainwater.

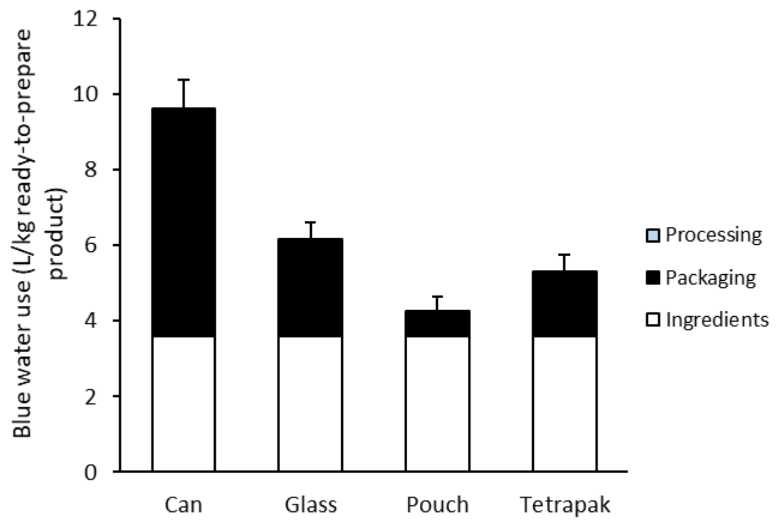


Figure 44 Blue water consumption of conventional brown beans in different packaging.

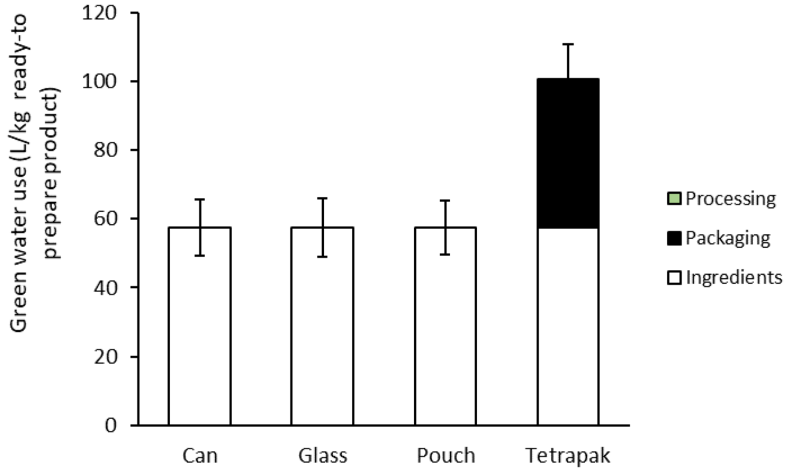


Figure 45 Green water consumption of conventional brown beans in different packaging.

The dry beans in plastic are compared with the beans in can or Tetrapak, representing the highest and lowest GHG emissions footprint (see Figure 43). The packaging of the beans is not identical, as the preserved beans require a stronger package to withstand the high temperatures of the processing. The GHG emissions of the dry beans are much lower than of the beans in can and beans in Tetrapak (Figure 46).

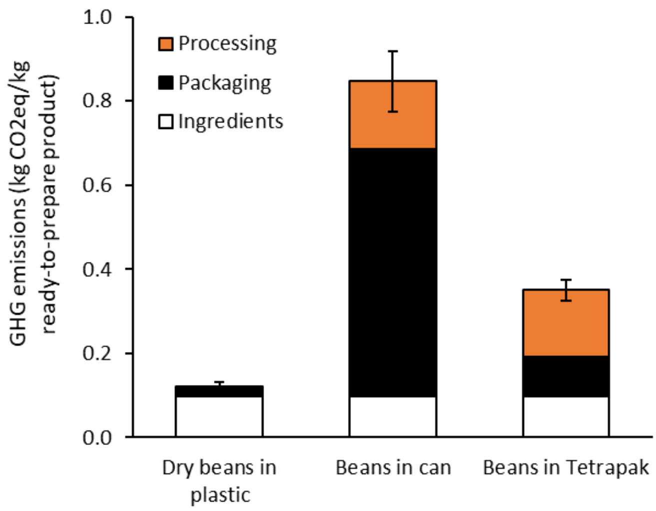


Figure 46 GHG emissions of dry and preserved beans.

3.5.6.3 Results including preparation at home

With cooking at home included (Figure 47), the GHG emissions of the dry beans increase significantly, with total emissions in between beans in can and beans in Tetrapak. When comparing the processing energy of the preserved beans with the cooking energy of the dry beans, which are similar processes it can be concluded that the cooking of the dry beans at home is not as efficient as the cooking process of the preserved beans in the factory. This can be both linked to less efficient heat transfer in a pan at home as well as lower relative energy use in industry because of the different processing scale. For cooking at home, only natural gas was considered. Cooking on electricity will change the GHG emissions. For grey electricity they will roughly double, which will make the dry beans the least sustainable choice. However, for green electricity the GHG emissions will be 0. Note that the Dutch grid provides a mix of grey and green electricity. In 2024, the share of green electricity was 54% of the total (Energieopwek.nl, 2025).

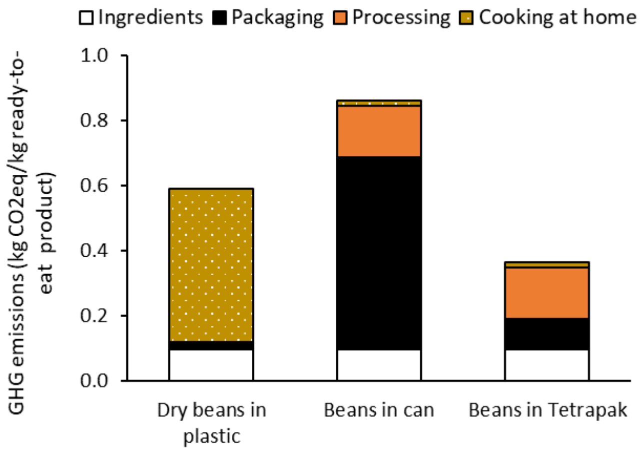


Figure 47 GHG emissions of dry and preserved beans including cooking/heating at home.

3.5.6.4 Conclusion

For agricultural production, the conventional brown beans have a lower climate impact per kg product than the organic beans, which is mainly explained by the higher crop yield. For packaging, steel cans and glass jars induce higher GHG emissions than Tetrapak and pouches. When comparing dry beans to preserved beans, the dry beans have a lower impact than preserved beans when analysed until factory gate. However, when cooking at home is included, the GHG emissions of dry beans increase significantly and its impact becomes larger than beans in Tetrapak or pouch, but remains lower than beans in glass or can.

Based on the findings, the following conclusions are made:
- Conventional brown beans are somewhat more sustainable in terms of GHG emissions than organic beans. But please keep in mind that for other crops the sustainability of conventional vs organic could be different.
- Tetrapak has the lowest impact in terms of packaging and can cut the overall GHG emissions by half compared to a can.
- The system boundary is important. When cooking at home is included in the analysis, the GHG impact of the dry beans increases significantly, whereas for the preserved beans the impact of home cooking is minimal.

3.6 Reflection on perceived sustainability improvements from case studies

In this section we summarise the learnings from the case studies by presenting the case specific conclusion regarding the domains introduced in Section 3.2, and the hotspots and the parameters most affecting the results. The parameters that influence the impacts the most represent those aspects in the chain and processing configurations that can lead to impactful improvements in sustainability.

Please note that the conclusions are case dependent and that they only cover GHG emissions, energy use and water use as selected sustainability indicators.

3.6.1 Value chain length and organisation

Three case studies are linked to the domain value chain length and organisation, and are reflected upon in this subsection.

Decentralised – centralised processing
It was observed in the case study on the production of a ready-to-sell or ready-to-eat bread that decentralised processing, in which (part of) the processing takes place at smaller scale and closer to the point of purchases, is not always the more sustainable configuration compared to centralised processing. An exception was making your own bread at home with a bread machine which had the lowest GHG emissions, energy and water use of all studied scenarios.

Hotspots of the GHG emissions and energy use are the production of the ingredients and the processing in the factories. The GHG emissions of the production of the ingredients ranges from 40 to 70% of the total GHG emissions in the different scenarios and the energy use ranges from 25 to 60% of the total energy use in the different scenarios. The ingredients are responsible for the blue (potable) and green (irrigation) water footprints, with a factor 100 higher use of green water compared to blue water.
Factors that influence the impacts the most are wheat flour production footprints and weight loss during baking for GHG emissions and energy use. The wheat flour production footprints can potentially be reduced by developments in agricultural methods and flour production. However, the weight loss during baking is a requirement to produce bread of intended quality. The wheat flour production water use footprint is also the most relevant parameter for the blue and green water uses.
The case on pulses shows that when cooking at home is included in the analysis, the GHG impact of the dry beans increases significantly, whereas for the preserved beans the impact of home cooking is minimal. Or in other words: central cooking of pulses resulted in lower GHG impact compared to cooking at home due to the relative long cooking times needed for pulses.

Longer and shorter, or local, chain
In the case study on apple juice from apples from a Dutch orchard packed in glass bottles or from apple juice concentrate imported from Poland packed in Tetrapak it was observed that the juice obtained from apples grown and processed in The Netherlands had slightly higher GHG emissions and energy impacts than the juice produced from the concentrate. This was also the case for the blue water (potable water) use. The green water (irrigation) use was larger in the scenario on the juice from concentrate.
The major hotspot in the GHG emissions, energy and water use is the impact of the agricultural production of the apples. The choice of the packaging, the glass bottles or Tetrapak, as well as the recycling rate, are also responsible for a large part of the impacts. The different processing configurations resulted in an approximately twice as high impact due to processing the juice from concentrate compared to the locally produced juice.
The process yields are factors that influence the GHG emissions and energy use the most. In case of juice from a concentrate, the concentration and (related) dilution factor is of major influence. In case of juice obtained directly from the apples the sorting yield of the incoming apples and the energy consumption of glass production are the most influential factors for the GHG emissions and the energy use. The water footprints are most affected by the sorting yield of the apples in both scenarios.

Frozen versus chilled chain
In the case study of French fries a comparison was made between the production, processing and subsequent distribution chain of frozen of chilled French fries ready for sale in retail. Despite the lower product losses for frozen fries the GHG emission and energy use are slightly lower for chilled fries. The GHG emissions are 15% higher and the energy use is 11% higher from the frozen fries in comparison to the chilled fries. In blue (potable) and green (irrigation) water use the frozen and chilled fries hardly differ.
The hotspots for the GHG emission and energy use are the footprints of the ingredient production, in which both potatoes and other ingredients are considered, and of the processing. The ingredients footprint is 40-45% of the total GHG emissions and 30-33% of the total energy use, with the potato and oil the largest contributors. The processing impact is 40-47% of the total GHG emissions and 46-53% of the total energy use. The differences in the processing cause the differences in footprint due to the higher energy consumption for the frozen fries in processing and storage. Within the processing the par-frying stage consumes the most energy. The blue water (potable water) footprint is approx. 6% of the green water (irrigation) footprint.

Generalising from the above case studies, it is not a given that a shorter chain, decentralised processing or less intense processing imply a more sustainable product since aspects such as ingredient footprints and impact of the chosen packaging and processing may be dominant in comparison to for instance transport distances or product losses in the chain.

3.6.2 Circularity, resource use efficiency

In the apple juice case the impact of waste management as part of the domain 'circularity and resource use efficiency' was addressed. Choices in waste stream management towards waste valorisation following the food hierarchy and waste management can have significant effect on the associated impact of the material streams and thus on the impact of the product. Also, the allocation strategy choice to assign the impacts to material streams, such as on volume, on economic value or by product replacement, affects the resulting impacts.

The results for the case of apple juice production showed that the most preferred options in the food hierarchy do not lead necessarily to a more sustainable scenario in terms of GHG emissions. For the apple juice from concentrate the waste valorisation / management options affected the GHG emissions, but differences were small. For the apple juice produced directly from the Dutch apples producing biogas from the apple pulp resulted in a lower GHG emissions impact in comparison to use of the waste stream in food or feed. This is a direct consequence of that the resulting biogas has an associated positive CO_2 impact. With the pulp appearing from the pressing process, the pressing yield is the most relevant factor. Other relevant factors include the apple sorting yield after sorting and washing and the filtration yield.

In this example of apple pulp as a side stream, biogas production turned out to be more environmentally sustainable than using it as food or feed due to the allocation strategy. This shows that it is important to be transparent about the allocation strategy for impacts to main and side streams and the effect it has on the impact analyses. The best waste valorisation strategy depends on the composition of the waste stream and the price of the product of interest. Therefore, the selection of the best waste valorisation option is case specific and should be evaluated for each case separately. Nevertheless, food loss and waste prevention and reduction is the preferred strategy for sustainable food processing chains.

3.6.3 Protein source / transition

In the case study on different protein sources it was found that the impacts of ready-for-sale meat and plant-based burgers produced from minced meat or from plant-based ingredients depend on multiple factors. The burgers were also compared with brown beans as a more direct source of protein.
Next to the main protein source, in this case study different types of meat or protein-rich materials from peas, also other ingredients and the packaging can have significant impacts. The ingredients are the hotspot for the GHG emissions, energy use and blue (potable) and green (irrigation) water use in this case study. For the plant-based burgers and the brown beans the packaging has a relative larger share in all impacts than is the case for the meat burgers. For energy use it is noteworthy that the energy use associated with the packaging is estimated at 14% for a beef burger, 33% for a chicken burger, 40% for the pea isolate burger, 64% for the pea concentrate burger and 73% for the canned beans. This shows that packaging is an energy use hotspot for these plant-based products. The burger processing itself has only a small contribution to the impacts. The plant-based burgers blue or potable water use was estimated to be of similar order as water use for beef burgers. This results mainly from olive oil as ingredient in the pea concentrate burger and from rice protein as ingredient in the pea isolate burger. Green, or irrigation, water use for the meat burgers was approx. 20 times the blue water use, associated with the feed production.
Furthermore, this case study illustrated that choice of functional unit influences the impact comparison. With protein a main nutrient in meat, impacts could also be expressed as function of the protein content instead of the mass.

Generalising on impacts of protein sources it is concluded that GHG emissions of plant-based products is expected to be lower than that of meat products. However, how large the differences are and if the meat product always has a higher GHG emission footprint compared to the plant-based product depends on the type of meat and on the ingredients used in the plant-based product. In terms of energy use, packaging of meat and plant-based products has significant impact. Water uses are also highly dependent on the choice of ingredients. The relative differences between impacts of possible products are influenced by the functional unit choice. Choices in formulation of plant-based products are required to ensure lower impacts of these products.

3.6.4 Packaging materials

In the apple juice case study large differences between impacts of packaging type and recycling rate were observed (see the description on the previous page). Recyclable glass bottles had a high energy demand in the production process of glass, resulting in high GHG emissions. Selecting deposit glass instead of recyclable glass bottles reduced the GHG emissions and energy consumption of glass bottles significantly because the washing process is much more energy efficient. Alternatively, the use of Tetrapak reduced the GHG emissions and energy consumption of the apple juice chain even further.

Another example of packaging variations was found in the pulses case. Brown beans can be obtained in many different types of packaging; the case study included can, glass, pouch and Tetrapak and this was exactly the order of high to low GHG emissions as estimated by the ACE calculator. By choosing brown beans in pouch or Tetrapak you reduce the GHG emissions twofold as compared with glass and can. Can and glass also had the highest blue water footprint and only Tetrapak was found to have a green water impact (for growing the trees for the paper).

Generalising on impacts of packaging materials we conclude that GHG emissions of can and glass are higher than of pouch and Tetrapak. However, how large the differences are between different kinds of packaging depends on the materials used for the pouch and Tetrapak style containers. Additionally, the use of deposit glass instead of single-use glass will reduce the GHG emissions of glass packaging.

3.6.5 Agricultural production system

The case study on pulses included a scenario where two different cultivation systems were applied: conventional and organic growth of brown beans. The total share of the ingredients is only about 25% of the total emissions, with packaging having the largest share (about 50%) and processing the other 25% of the share. Looking at the ingredients, the GHG emissions and energy consumption of organic cultivation were about twice as high as that of conventionally grown brown beans. This is also observed for other crops. The water use during cultivation did not differ between organic and conventional production.

In general it is observed that the cultivation of organic crops consumes more energy and has higher GHG emissions due to lower yields and therefore more energy and other resources are required to obtain a similar yield as conventional cultivated crops.

3.7 Knowledge dissemination

Companies were very interested in the approach and results of the project. The results of the case studies were presented in 2 webinars which were inspiring, although generalizing findings of case studies to other domains or food systems remains challenging. However, in the discussions with companies the value of the tool was evident; it showed where environmental sustainability hotspots are in the chain and in their own operations. The calculator could handle different interventions to show what improvement can be made when choosing for example another raw material, another packaging material, crops from a different origin or by changing technology and could thereby support early decision making for new investments. There is a need for quantitative environmental sustainability tools that can help companies in decision-making for reducing their impact and the ACE calculator can be part of the solution.

The protein choices case was used in a workshop to evaluate the educational potential of the ACE calculator with teachers at SVO vakopleiding Food as described in Section 3.5.5.3. The teachers expressed a strong interest to implement such a calculator in their curricula, enabling students to better understand and visualize several environmental sustainability aspects of different food products. Given the critical role of sustainability in the future of the food industry, integrating such tools into education is seen as an important step in preparing students to consider environmental impacts in their professional decision-making. For this purpose, the ACE calculator would require further development to enhance its usability and ensure its suitability for education.

The case studies on apple juice, protein choice, pulses, French fries and bread were also summarized and presented in factsheets as listed below. The factsheets were promoted on WFBR and individual LinkedIn pages.

- Berghout, J. A. M., & Siccama, J. W. (2024). Local or long chain foods: what is the more sustainable choice? A case study on apple juice.
- Rodriguez Illera, M., & Siccama, J. W. (2025). Uncovering the different environmental impacts of protein choices.
- Siccama, J. W., & Broeze, J. (2025). Pulses in many forms: what is the more sustainable choice? A case study on brown beans.
- Siccama, J. W., & Rodriguez Illera, M. (2025). Frozen or chilled: what is the more sustainable choice? A case study on French fries.
- Berghout, J. A. M., & Siccama, J. W. (2025). Centralized or decentralized: what is the more sustainable choice? A case study on bread.

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Two other publications from the project are:

- Vernooij & Vollebregt (2025) Perceived sustainability enablers, barriers and measures over time for the Dutch food processing industry: Info sheet and visualisations.
- Vollebregt, H. M., & Broeze, J. (2025). Data naar impact: duurzaamheid in ketens en verwerking. Voedingsindustrie, vol. 32, no1, February 2025, p48-51.

4 Conclusions and recommendations

Efforts and initiatives to improve the sustainability of food processing in the agri-food chain are increasing. The project started with research questions like which strategies are most effective, under which conditions and for which products, and which main opportunities and barriers can be leveraged and addressed to increase sustainability of food processing at a national level. Increasing the sustainability of processing within agri-food chains presents challenges due to the complexity of the food system, the diversity of products and processes, the interdependencies among chain actors, and the need for supportive conditions across market, policy and other external domains. To effectively compare the sustainability impacts of alternative food systems, it is essential to assess their cumulative effects across the entire chain. This requires the development of robust methods to evaluate which interventions contribute to measurable sustainability improvements.

This project compared different food processing scenarios using an environmental sustainability assessment framework for various case studies relevant to the Dutch food processing industry. What is the more sustainable choice, what interventions lead to measurable sustainability improvements? The assessment framework is based on the AgroChain greenhouse gas Emissions (ACE) calculator that was further developed in this project to be able to handle all different case scenarios. The ACE calculator provided insight into sustainability hotspots in the chain and showed the effect of different interventions on environmental sustainability impact expressed in GHG emissions, energy use and water use. The calculator analyses facilitate early analyses of interventions by companies to support decision making and business plans. Such dedicated use does however require case specific data, although analysis on the incorporated data does provide useful first indications of hotspots and effects of interventions on GHG emissions, energy use and water use.

The results of the case studies are case specific and dependent on certain assumptions. Even though an attempt was made to generalize the findings of the case studies to the meso level of food systems or domains. We showed that the choice of food packaging can have a large contribution to the environmental impact of the consumable product, but the exact materials determine the final outcome. We found that it is not a given that local food products are more environmentally sustainable than food products that have a longer food chain organisation and that waste management is important for decision-making in every value chain. We found the small difference in environmental sustainability between frozen and chilled French fries to be caused by the freezing process and longer storage times of the frozen fries (making it more energy-intensive compared to chilled fries). The slightly higher product loss at retail of the chilled fries (2% compared to 1% for frozen fries) has a negligible impact on the environmental sustainability. It was evident that plant-based meat alternatives outperform beef (and not the chicken burger) in terms of GHG emissions, but we also showed that by applying fewer refining steps for plant based burger production even more reductions in GHG emissions would be possible. We also found that organic cultivation of brown beans had a slightly higher environmental impact (in the agricultural phase) than conventional cultivation of brown beans, but this may be different per crop category and per impact category outside of the ones addressed in this study.

Companies were very interested in the approach and results of the project. The results of the case studies were presented in 2 webinars which were inspiring, although generalizing findings of case studies to other domains or food systems remains challenging. However, in the discussions with companies the value of the tool was evident; it showed where hotspots are in the chain and in their own operations. The calculator could handle different interventions to show what improvement can be made when choosing for example another raw material, another packaging material, crops from a different origin or by changing technology. There is a need for quantitative environmental sustainability tools that can help companies in decision-making for reducing their impact and the ACE calculator can be part of the solution. The workshop with teachers at SVO vakopleiding Food demonstrated the educational potential of the ACE calculator in supporting sustainability-focused learning. As sustainability becomes increasingly central to the food industry, such tools can play a vital role in preparing future young professionals. However, further development of the ACE calculator is necessary to improve its usability and ensure its effective integration into educational settings.

Within the project a comprehensive overview of near-term and expected future enablers, barriers, and potential measures for enhancing sustainability within the Dutch food processing industry based on a literature review and a series of expert consultations was realised. The result is a structured roadmap that identifies short-, medium-, and long-term opportunities and challenges across three stakeholder domains: industry, government, and society (Vernooij & Vollebregt, 2025 for more details). A broad range of measures has been identified to support the transition toward sustainability in the Dutch food processing industry, many of which are actionable in the short term. These include targeted training programs to build expertise in circular economy principles, investments in upgrading equipment and infrastructure to improve resource efficiency, and fostering collaboration across companies to enable circular supply chains. The development and implementation of harmonised sustainability performance indicators and transparent labelling systems, such as a European-wide food sustainability label, are mentioned as critical to guiding both industry decision-making and consumer choices. Policy measures complement these efforts through pilot projects promoting circular supply chains, tax incentives, regulation of green claims, and the removal of conflicting incentives. Looking further ahead, structural reforms such as true pricing mechanisms, tax adjustments, and enhanced regulatory frameworks are considered important to embed sustainability in the industry's economic model. Effective progress will depend on coordinated, multi-stakeholder approaches, adaptive policymaking, and continuous monitoring to ensure that measures remain relevant and impactful over time.

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Annex 1 Additional information ACE calculator

Data available in the ACE calculator

Topic	Data and source	Remark
Country of origin	List of sourcing countries from (Porter et al., 2016)	To obtain values for primary production and electricity conversion factors from Porter (2016) and other sources
Emissions – primary production	1. (Porter et al., 2016) 2. FAO data for high emissions crops 3. Scientific literature for different production systems	1. Parts of continents, various product categories 2. All countries (milk, meat, rice, cereals, eggs) 3. For all product categories available; some to individual products
Emissions – transport	1. EcoTransit.org; Clean cargo (2020) 2. For sea shipping: averages from 4th IMO GHG Study 3. For air cargo: (Klein et al., 2020) and (*Ecological Transport Information Tool for Worldwide Transports Methodology and Data Update 2018 Ifeu Heidelberg INFRAS Berne IVE Hannover Berne-Hannover-Heidelberg, 4 Th*, 2018) 4. Estimates for cooling reefer containers are based on a.o. (Ljs & De, n.d.)	- Rule of thumb: refrigeration adds 20% of energy transport, does not apply to reefer containers - Use of biodiesel (direct = 0, indirect = 0.5 kg CO_2-eq./kg (CO2emissiefactoren.nl) - Use of biodiesel results in -90% GHG emissions, bioethanol: -80%, bio-LNG (instead of marine diesel or fuel oil): -70% (CO2emissiefactoren.nl)
Emissions – processing	1. Expert specification: amount of natural gas or electricity used in the process per kg of input or per kg of water removed. 2. Country specific emission factors for electricity sources from multiple sources (a.o. European Environmental Agency and IEA). 3. Own database based on specification sheets from companies of equipment and on generic processing (Piccinno et al., 2016). 4. Cooling: 1 kWh/ton/day, expert adjustments possible (estimated from J. A. Evans et al. (2014) and DLV, 2015 and Tachajapong et al. (2022)).	
Emissions – ingredients	Values from scientific LCA literature and databases (such as AgriFootprint, Agribalyse, RIVM database (environmental footprint of food products))	
Emissions – packaging	CO_2 of various packaging materials, values extracted from various sources, different sources with comparable values, end-of-life specific values. - Steel: typical value based on Garofalo et al. (2017), APEAL (2012), Worldsteel Association (Worldsteel 2018) - Aluminium: average of (B. Simon et al., 2016) (assuming 50% recycling), (Stotz et al. 2017) - Paper and carton: RISE, 2019 - Plastics: ETC/WMGE (2021) - Glass: (Schmitz et al., 2011); UK Government GHG Conversion Factors for Company Reporting	
Emission – end-of life	- Default data from US inventory (Environmental Protection Agency et al., 2019): various waste management options, based on US data . - CE Delft (2020) estimates average GHG emissions from commercial waste collection in NL around 4 to 10 kg CO2-eq. per ton waste (*OUTLOOK BEDRIJFSAFVALINZAMELING*, n.d.). - CE Delft (2021) estimates GHG emissions from organic waste management options in NL (Delft, n.d.).	End of life options: left on field (zero emissions), landfilling, incineration (with and without energy recovery), composting (aerobic -> minimal methane production, negative CO_2 emissions), anaerobic digestion (biogas + compost, negative emissions).

Topic	Data and source	Remark
		The actual GHG emissions depend on the end-of-life solution, but also on specific properties of the solution and situation, e.g. • waste collection system and transport distances, • specific technology choice of the waste treatment (like open or closed composting system, landfill with either or not landfill gas recovery, etc.) • specific application of derived products (such as biogas and compost)
Emissions – renewable electricity options	(*Ketenemissies Elektriciteit Actualisatie Elektriciteitsmix 2019 Ø*, n.d.)	Renewable energy sources (like wind, solar, biogas) are often considered climate-neutral. However, this is disputable: • solar panels: when taking into consideration solar panels production and installation, GHG emissions of solar energy is estimated around 0.05 kg CO2-eq./kWh (Müller et al., 2021). • wind energy: wind mills production and installation: typically 0.014 kg CO2-eq./kWh. • biogas: depending on the situation, leakage of methane gas may be associated to the generated electricity. Based on data from co2emissiefactoren.nl, this effect is estimated at 0.2 kg CO2-eq/kWh.
Food loss and waste	- Default data source on product specific regional values for all chain stages: (Porter et al., 2016) - Case specific values used from (among more): - Aphlis (www.aphlis.net): FLW various chain stages, Africa - ISU project: FLW various chain stages, worldwide https://sippoc.esalqlog.com.br/en/home	
Transport distances	- Estimates for overseas transport from sea-distances.org, airmilescalculator.com, inland transport from google maps route planner. - A long-list of (estimated) values is provided by Bertoli et al. (2016): CERDI-sea distance database (Bertoli et al., n.d.)	
Water footprint	Crop water footprints as reported by Twente Water Centre (Mekonnen & Hoekstra, 2011a), datasets in https://www.waterfootprint.org/publications/).	Processing water use is highly dependent on specific situation and requires user data.
Energy use footprint	Data for a selection of EU crops (Paris et al., 2022)	Direct and indirect use of energy in postharvest chains is incorporated.
Impact allocation – mass		Requires mass balances in main products and side streams
Impact allocation – economic		No data incorporated, use actual market information and feed price calculations
Impact allocation – system expansion		Based on chemical composition for feed product replacement, the impact of the replaced feed product is used

Interventions in the ACE calculator

The ACE calculator supports scenario analyses on a wide variety of interventions that can potentially lower the footprints and contribute to more sustainable food chains.

Supported interventions include:

1. Alternative end products, such as a dry product or a slurry, or a product with and without packaging.
2. Alternative ingredients, such as substitution of ingredients with other ingredients.
3. Energy sources, such as effect of using different sources of energy.
4. Alternative packaging, such as use of different kind of packaging.
5. Alternative processing, such use of different processing technologies for the same transformation.
6. Alternative storage, such as use of ambient, refrigerated and frozen storage.
7. Modality shift, such use of different trucks with different capacity, electric vehicles, truck/train/sea/air.
8. Alternative sourcing, such sourcing of ingredient/raw material from a different country or from a different growing system.
9. Different chain configuration for comparison of chain designs, for instance with a different order decoupling point.
10. End-of-life options for side streams and waste stream management, including higher valued use of side streams.

Annex 2 Perceived sustainability improvements – brief introductions

5.1 Value chain length and organisation

A preference for local food is associated with shorter supply chains. In practice, the term long supply chains possess one or both of the following two characteristics: 1) long in terms of distance between production and consumption, 2) long in terms of large numbers of intermediaries between production and consumption (Castelein, 2022).

As Figure 48 below shows, there is a certain but relatively limited overlap between Dutch food production and consumption, with the agri-food industry in the middle. This indicates that currently our landscape is dominated by relatively long supply chains at least in terms of distance, with majority of produced goods not consumed in the Netherlands, and majority of consumed goods not originating from the Netherlands (Muilwijk et al., 2020). In terms of intermediaries this differs per product chain and production region.

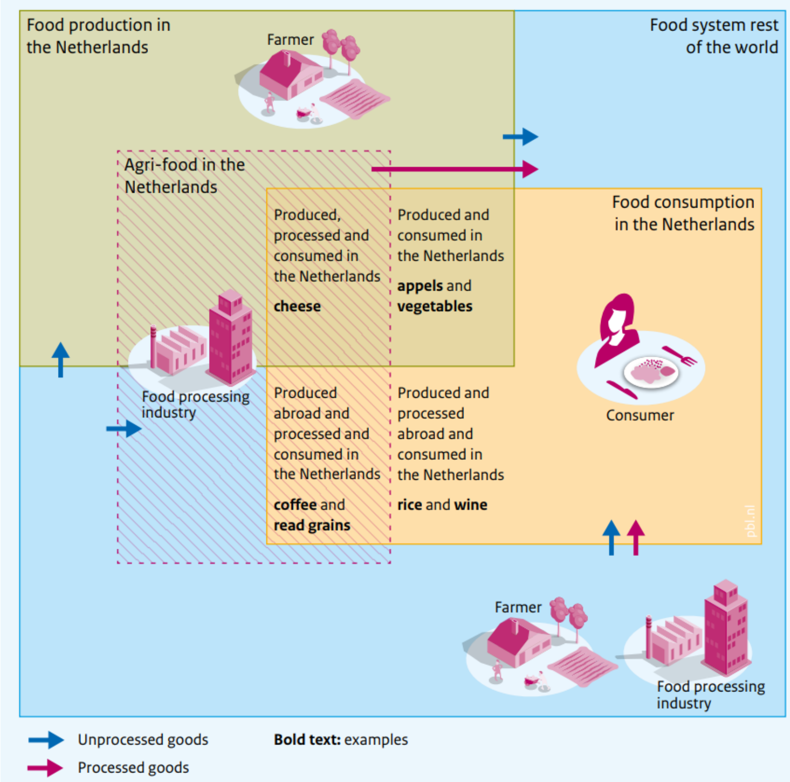

Figure 48 There is a certain but limited overlap between Dutch food production, the agri-food industry, and consumption *(Muilwijk et al., 2020)*.

According to Castelein (2022: 54) short food supply chains: "…are hypothesised to be a more sustainable, resilient and equitable alternative to long, industrialised, often international food supply chains dominated by large corporate actors." There are three broad types of short food supply chains: 1) face to face, in which consumers directly purchase from producers for example through farm shops, markets, roadside sales and delivery, 2) proximate short food supply chains, where consumers and producers are connected via a limited number of intermediaries, for example via cooperatives, markets and certain retailers, 3) extended short food supply chains, which can span larger distances but the origin of the food product is still clear for example via labels and certification schemes, presenting a source of value for consumers. The first two types of short food supply chains can still be part of local food systems in which production and consumption are geographically close to each other (Castelein, 2022).

There is also the aspect of relational proximity which addresses supply chain power dynamics, and is indicative of the type of intermediaries and their relations. Long supply chains with relatively many intermediaries can be characterised as having a number of powerful intermediaries such as retailers and processors that can to a large extend, for example, set market prices. There are also various supply chains with smaller scale intermediaries that experience limited power over, for example, prices. Depending on these power dynamics, supply chains actors can feel relative proximity or distance to other supply chain actors (Castelein, 2022).

In terms of effects on sustainability of longer and shorter supply chains, both have advantages and disadvantages. Final sustainability benefits are highly context and product dependent, and almost always consist of trade-offs between various sustainability aspects, such as water and energy use and biodiversity. Relatedly, the scale of major retailers offers both potential and constraint for sustainability. Large chains can leverage their reach to promote more sustainable supply chains, yet their internal complexity and commercial pressures often hinder more ambitious action. Smaller organic retailers may take the lead in innovation but lack market penetration.

When speaking of supply chain length in relation to sustainability, the topic of transparency is not far away. It is worth mentioning that Corporate Sustainability Reporting Directive (CSRD) is driving chain wide changes. CSRD is a comprehensive EU directive that requires companies to disclose detailed environmental, social, and governance information not only about their own operations but also throughout their entire supply chains (European Union, 2022). This means that longer, more complex supply chains must become more transparent, enabling stakeholders to better understand and manage sustainability risks and impacts at every stage. As a result, companies are incentivized to collaborate more closely with suppliers, improve traceability, and adopt more sustainable practices, ultimately fostering greater accountability and progress toward sustainability goals across the entire value chain. In 2025, the European Commission proposed amendments to the CSRD regulation aimed at reducing administrative complexity and regulatory requirements to enhance the EU's competitiveness, of which a selection has been adopted.

Strongly related to supply chain length, the location of processing varies within supply chains and can roughly be typified as either: centrally organised, or distributed and decentralized. Considering that processing takes place in between production and consumption, this can be approached both from how access to raw materials from agriculture is organised in relation to processing, and how certain consumer markets are served in relation to processing.

Centralized processing methods have increasingly been implemented in the food industry. Centralized processing means that a relatively small number of relatively large processing plants process raw materials from high numbers of producers, or serve many (inter)national consumer markets. Distributed or decentralized processing is smaller scale and located closer to costumers, as visualised in Figure 49 in relation to end users.

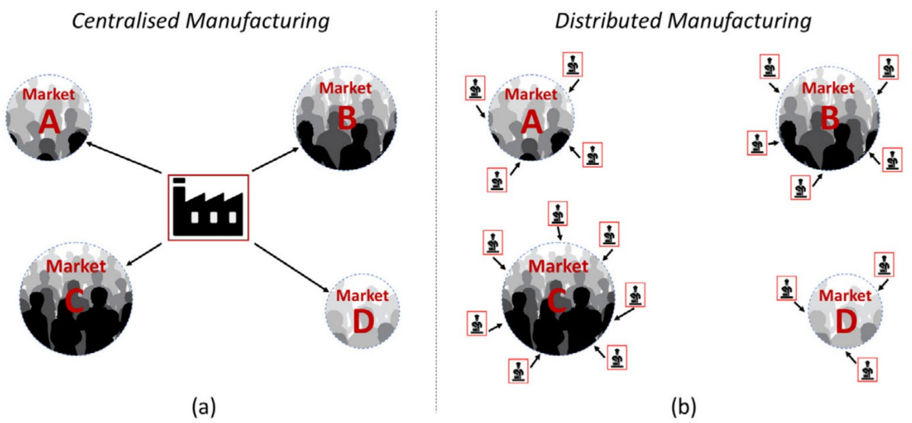

Figure 49 **Food product supply chain. (a) Centralized Manufacturing (processing) vs. (b) Distributed Manufacturing (processing). In (b) a net of manufacturing (processing) facilities replaces a big plant in (a) for supplying the demand of a product in four different markets** *(Almena et al., 2019)*.

Advantages of centralized processing are cost-effectiveness due to advantages of economies of scale, although centralization typically involves rigid and lengthy supply chains with high environmental and cost impacts (Almena et al., 2019). The dairy sector is an example from the Netherlands where there is convergence at processor level, with one company processing 75% of total milk volumes. The cocoa sector is also relatively centralized, as is visualised in Figure 50 with high numbers of producers and consumers but only a handful of processors (Muilwijk et al., 2020).

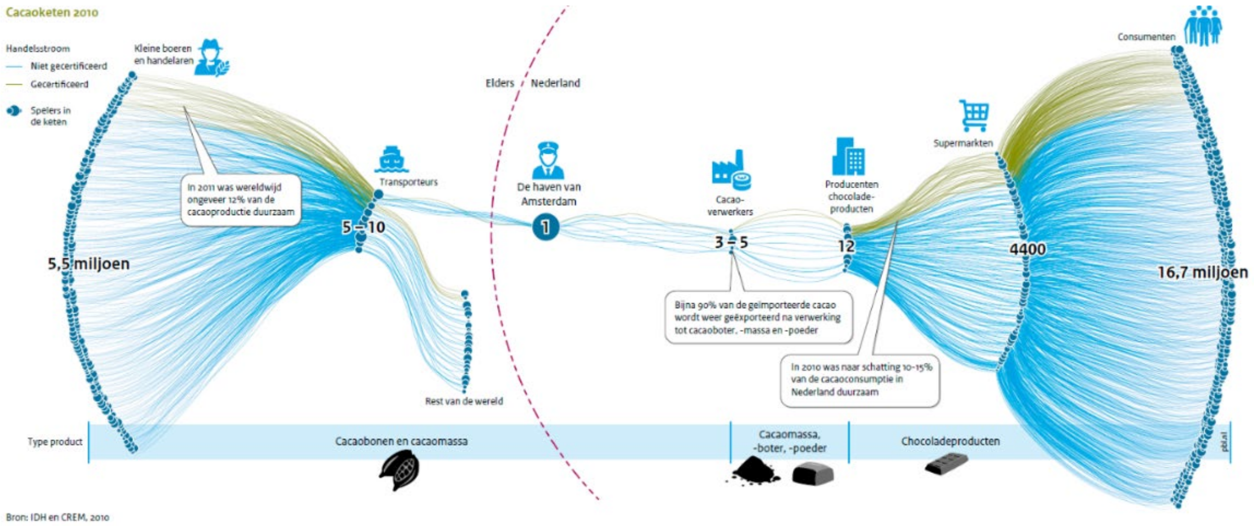

Figure 50 Cocoa chain in 2010 showing relatively high market concentration with processors (IDH & CREM, 2010, in Muilwijk et al., 2020).

Despite the trend of consolidation, there is an opposing trend with focus on local produce and products, local breweries and urban agriculture (Muilwijk et al., 2020). Distributed or decentralized processing represents an alternative to centralized processing with potential environmental and social benefits. Drivers for change towards decentral processing include new technologies, rising logistics costs, changing global economies and changing consumer preferences towards more differentiated and personalised food products, which pose challenges to centralised processing (Almena et al., 2019). These challenges include inflexibility, high logistics dependence and costs, vulnerability to global economic shifts, and limited ability to meet demand for diverse, localised, and personalised food products. With a growing, yet still niche, consumer preference increase for locally sourced and organic foods, decentral processing close to production locations in the Netherlands is becoming more economically interesting for entrepreneurs. Examples are (organic) dairy farms that offer a range of dairy products that are processed on the farm, such as cheese and yoghurts.

Social and environmental benefits of decentralised versus centralised processing is highly context, company and product dependent. A modelling example of a dried food in the UK shows the differentiated effects of centralised versus decentralised food processing: when management cost is moderate decentralised processing could be more profitable than centralised processing and can provide competitive operating cost, but for energy use and carbon load, artisanal scenarios are not advantageous compared to industrial processing (Almena et al., 2019).

5.2 Circularity

Currently our agri-food system is predominantly linear (produce-consume-waste) instead of circular. Figure 51 illustrates the distinction between linear and circular economies, and shows that a circular economy requires fewer new resources because resources that are disposed in linear systems serve as inputs (again) in circular systems.

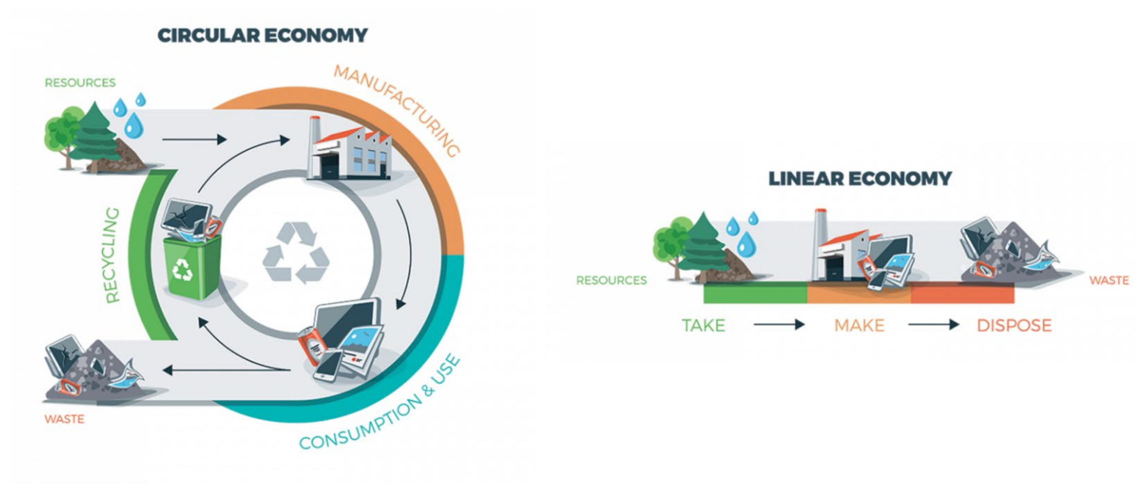

Figure 51 Linear and circular economy and the (re)use of materials** (WUR Weblog, 2019)**.

Linear economy has led to pollution, waste, and resource depletion (Meshram, 2024). Recognizing the need for a more sustainable approach, the Dutch government strives for a circular economy. However, currently high value closed cycles are uncommon, and cycles focus on low value/low priority applications from the food waste hierarchy (De Laurentiis et al., 2024). This results in an insufficient recycling of nutrients. A more circular system increases nutrient availability, including nitrogen. Currently, the Netherlands, and Western Europe import nutrients (mainly as fertilizers) to grow foods, whereas countries in the Global South are becoming depleted in terms of nutrients (Hidalgo et al., 2021).

Recent studies have shed light on important considerations and proposed steps towards achieving closed cycles in the context of food waste management. Teigiserova et al. (2020) point out the importance of transparent valorisation, where waste materials are effectively transformed into valuable resources through recycling, upcycling, and other sustainable processes. Their research emphasizes the role of food waste in the circular economy and highlights the necessity of clear frameworks to efficiently manage and minimize food waste. Figure 52 illustrates their views. The study of Moshtaghian et al. (2021) emphasizes the importance of addressing consumer perception and acceptability to ensure the successful implementation of upcycled food initiatives (Moshtaghian et al., 2021). Furthermore, they emphasize the need for education and awareness campaigns that promote the value and safety of upcycled foods, in which the Dutch food processing sector could take a role. Kowalski et al. (2021) discuss that there is a potential for improved sustainability and resource utilization within the food processing industry when waste management and resource utilization practises are implemented.

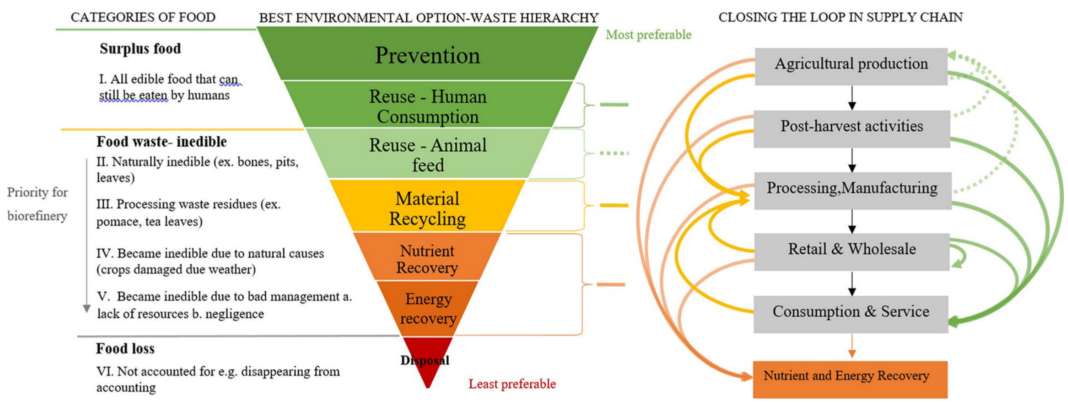

Figure 52 Hierarchy for food surplus and food waste; and framework for closing loops in the supply chain** (Teigiserova et al., 2020)**.

There have been debates about the role of animals in circular agricultural systems. Moving towards plant-based diets (see Section 2.1) can fit in a circular system. Simon et al. (2024) show that farm animals do have a place in a circular food system if we use them for converting by-products from the food system and grass resources into valuable food and manure (Simon et al., 2024). According to the authors, in this way, they can contribute significantly to human food supply, while at the same time reducing the environmental impact of the entire food system. The current number of livestock and their current use and purpose will however still have to change. Figure 53 visualises the role of farm animals in a circular food system, namely to convert by-products from the food system and grass resources into food and manure, thereby recycling biomass and nutrients (back) into the food system.

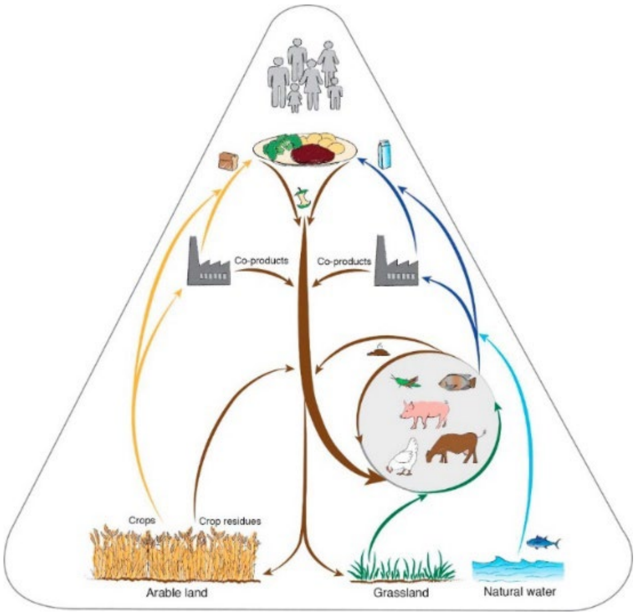

Figure 53 The role of farm animals in a circular food system *(Van Zanten et al., 2019)*.

5.3 Protein source

For the production of animal-based protein, much land, water and energy is needed, compared to plant proteins. For a large part this can be attributed to the natural resources needed to grow animal feed in combination with the relatively low efficiency of the animal to convert this to animal proteins. For example, for beef cattle, typically around 6 to 10 kg of feed dry matter per kg of live weight gain is needed, depending on the production system, genetics, and feed quality (Alexander et al., 2019). The Netherlands Nutrition Centre advises in general an intake of 0.83 grams protein per kilo of bodyweight, with some populations needing more such as children and pregnant people (Voedingscentrum, n.d.). The Protein Monitor of the Netherlands shows that in 2024 on average 40% of consumed protein are plant based, and 60% animal based (Onwezen et al., 2025). On average daily protein intake consisted of 25.2 grams plant based, and 38.3 grams animal based protein (total protein consumption of 63.5 grams), which suggests a reduction of total protein intake compared to the Protein Monitor in 2023 when 74.4 grams of proteins were consumed on daily average. In 2021, the total meat consumption per person in the Netherlands was estimated to be 75.0 kg (see Figure 54, in Dutch) .

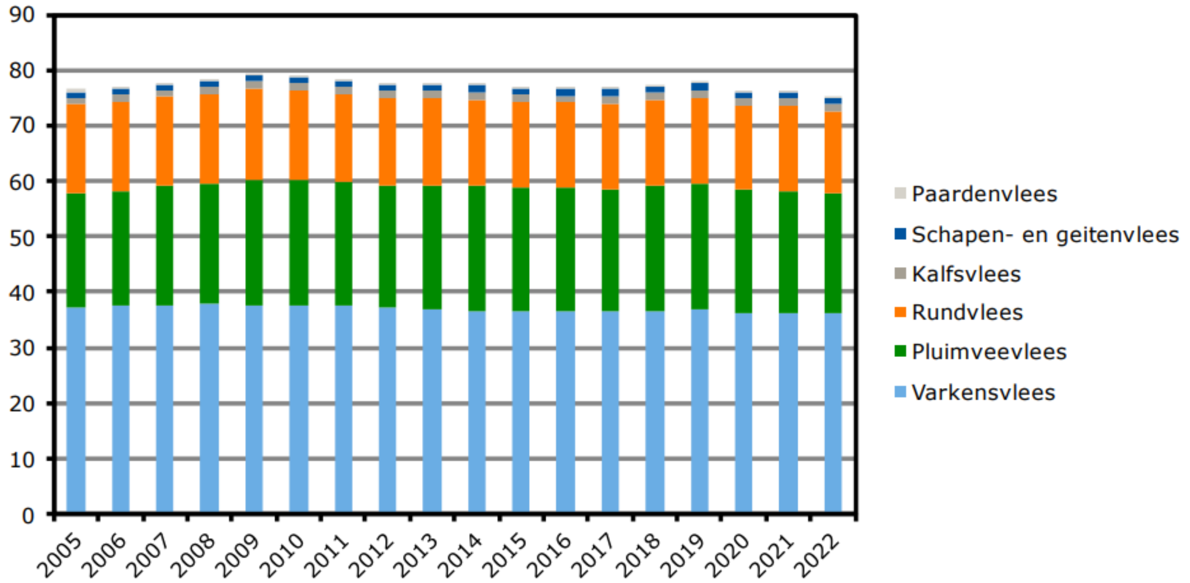

Figure 54 ***Meat consumption per person per year in the Netherlands from 2005 until 2022 in kg*** *(Dagevos et al., 2023)***.**

Various initiatives are aiming to reduce our total protein intake, and to increase the share of plant protein compared to animal-based protein. These initiatives include the Green Protein Alliance and the 'Transititieagenda Nederland Circulair', and strive to bring back the share of plant protein in our diets to 60% such as in the 1960s, as opposed to the current 40%, and strive for an overall protein intake reduction of 10 to 15% (Muilwijk et al., 2018). The Dutch ministry of Agriculture, Fisheries, Food Security and Nature has also formulated the ambition for 50-50% animal and plant based protein consumption in 2030 (Onwezen et al., 2025). Estimations about what a sustainable diet in a circular food system can look like indicate a share of about 33% to 40% animal-based proteins (Simon et al., 2024; Van Zanten et al., 2019).

Specifically relevant for the processing sector is that the protein transition is partly happening via the rise of plant-based meat substitutes. Compared to typical transition dynamics in for example energy and mobility, transition dynamics in the Dutch food processing sector differ due to particularities in required technological knowledge and government intervention. An effective role of government and policy in this is to stimulate innovation and support a new norm towards less animal-based – and more plant based proteins, which can lead to growing markets for sustainable products (Tziva et al., 2020). This is crucial, especially considering the gap between the 50-50% animal and plant based proteins ambition for 2030 and the current (2025) 60-40% division (Onwezen et al., 2025).

5.4 Packaging materials

The packaging sector accounts for about 40% of the total demand for plastics in Europe. The food and beverages sector uses more than two-thirds of all packaging materials used, including plastics, and is therefore an important user of plastics and driver of plastic waste (Kowalski et al., 2021). Plastic production reached almost 350 million tonnes in 2017. Figure 55 shows the global trends in plastic waste recycling, incineration and discarding. Improving the collection of plastic helps with increasing recycling, but with every recycling cycle, there is loss of quality and quantity of plastic. Therefore, first and foremost, it is important to reduce the use of plastic (Kosior, 2020).

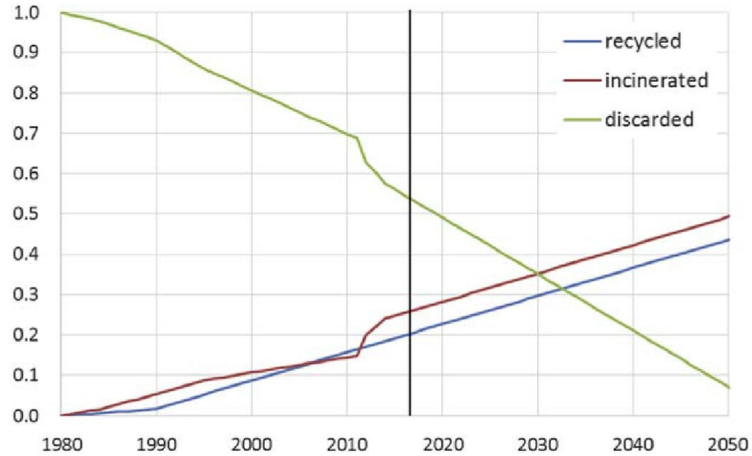

Figure 55 Projection global trends in recycling, incineration and discarding of plastic waste 1950 – 2050 (up to 2017: historical data)*(Kosior, 2020)***.**

Not all packaging can and should be removed; some packaging for example protects the products from damaging, contamination and/or drying, thereby preventing food waste. However, not all packaging material is necessary, and sometimes it can be replaced by less, limited or no packaging at all. Alternatively, other packaging materials can be chosen. For example, biobased packaging materials. These materials are derived from renewable resources such as plant-based polymers or biodegradable materials. Biobased packaging offers the advantage of reduced reliance on fossil fuels and can have lower carbon footprints compared to conventional plastics. Additionally, some biobased materials have improved recyclability or compostability, contributing to a more circular economy. However, one should be careful about choosing the right biobased resource, to prevent using food resources for packaging purposes. Moreover, the functionality and safety requirements of the packaging should still be fulfilled. In a circular economy it is preferable to use side streams such as stems and leaves as packaging material. It is important to choose the right type of packaging; if a package is biodegradable then it might also not be the best option to, for example, keep out moisture and prevent spoilage. Stark and Matuana (2021) conducted a mini review about trends in sustainable biobased packaging materials. They observe a movement towards sustainable packaging, specifically away from fossil based products towards biobased products. It is expected that the future will both need an improvement of current biobased packaging materials such as paper, as well as the further development of new biobased materials such as biopolymers. For overall market acceptance they conclude that improvements in packaging recycling, innovative new materials, designing for sustainability and the implementation of new and existing certifications will contribute.

5.5 Agriculture

The food processing sector is dependent on raw materials and therefore on agriculture. Current agricultural production is dominated by intensive methods which are now questioned for their impact on our natural resources and climate change. There are also ethical debates about whether as a relatively small country we should continue to wish to produce food for large parts of the rest of the world.

Similar to agricultural production, the food processing industry partly operates through import- and export-oriented business models. In 2021, 70% of total agricultural imports was exported again. 43% was directly exported without any (heavy) processing, and 27% after processing in the Netherlands. Of the 30% agricultural imports that remained in the Netherlands, 17% was directly destined for consumption, and 13% was first processed in the Netherlands. This means that of all the agricultural imports, 40% was processed, as summarised in Figure 56 (Jukema et al., 2022).

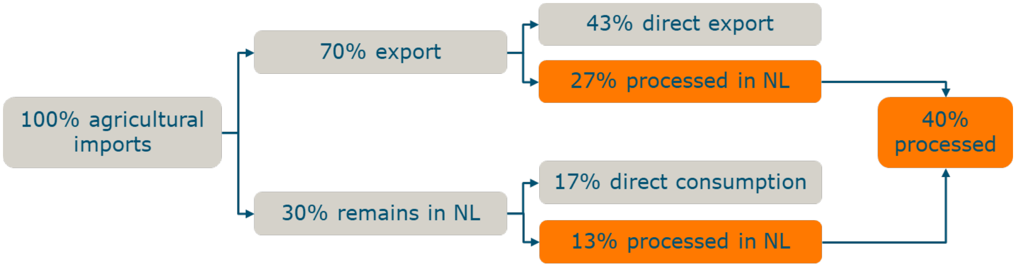

Figure 56 ***Processing of agricultural imports in the Netherlands in 2021. Includes agricultural goods only, excludes agriculture-related goods such as fertilizers. Author's figure based on data in Jukema et al. (2022).***

Approximately 3 million hectares of farmland is used for growing food and animal feed for Dutch consumption, Almost ¾ (74%) is located outside the Netherlands, which means that the direct effects on the environment largely happen outside of the Netherlands (Muilwijk et al., 2018). Because of the complex structures of current business models and supply chains, it is often difficult to establish precisely where, from which farmers and production systems, the raw materials originate from, also called the traceability. This complicates tracing the environmental impacts and consequently sustainable sourcing for the food processing industry.

Regarding agricultural production in the Netherlands, the main Dutch vision and policy document guiding agriculture development in the Netherlands is striving for circular and nature-inclusive agriculture (*kringlooplandbouw, natuurinclusieve landbouw*) (Dutch Ministry of Agriculture, Fisheries, Food Security and Nature, 2018) (Ministerie van Landbouw, 2018). An example of a market and communication tool that has been developed are labels, which guarantee for example organic production of the raw materials or quality of life of animals at a slightly better production price than conventional and intensive production. This requires transparency of production systems and supply chains of products.

Despite the complexity, there remains increasing pressure for transparency in supply chains for various sectors such as wood and textiles, and certainly also including food. This is partly driven by consumer awareness, sustainable business initiatives and by ongoing policy developments at national and EU level. For example, since 2023, the EU Deforestation Regulation was introduced which requires companies in cattle, cocoa, coffee, oil palm, rubber, soya and wood including products derived from these commodities to ensure that the goods do not result from recent deforested or degraded forest areas, or where local environmental and social laws were breached (European Union, 2023). This is expected to affect the food industry.

Annex 3 Supplementary data Case studies

Table A.1 LCA data of the bread ingredients

Ingredient	Country of origin	Indicator	Values	Reference(s)
Wheat flour	France	*GHGe (kg CO2eq-/kg)*	0.58	(Carbon Cloud, 2024d)
		Energy use (MJ/kg)	3.37	(Paris et al., 2022)
		Water use blue (L/kg)	3	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	591	(Mekonnen & Hoekstra, 2011a)
Water		*GHGe (kg CO2eq-/kg)*	0.001	(RIVM, 2019)
		Energy use (MJ/kg)	0.002	(van der Schans et al., 2015)
		Water use blue (L/kg)	1.096	(Fresán et al., 2020)
		Water use green (L/kg)	0	Assumption
Salt		*GHGe (kg CO2eq-/kg)*	0.156	Own calculation
		Energy use (MJ/kg)	3.1	(Alix et al., 2022)
		Water use blue (L/kg)	8	(Zhang et al., 2022)
		Water use green (L/kg)	0	(Zhang et al., 2022)
Yeast	Europe	*GHGe (kg CO2eq-/kg)*	3.21	(Carbon Cloud, 2024a)
		Energy use (MJ/kg)	16.1	(Dunn et al., 2012)
		Water use blue (L/kg)	80	(Xu et al., 2015)
		Water use green (L/kg)	0	(Xu et al., 2015)
Bread improver (wheat gluten)	Europe	*GHGe (kg CO2eq-/kg)*	2.925	(Broekema et al., 2009)
		Energy use (MJ/kg)	35.28	(Broekema et al., 2009)
		Water use blue (L/kg)	11	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	3064	(Mekonnen & Hoekstra, 2011a)

Table A.2 LCA data of packaging material for bread

Packaging	Indicator	Values	Reference(s)
Plastic	*GHGe (kg CO2eq-/kg)*	3	(Plastics Europe, 2014)
	Energy use (MJ/kg)	63.2	(Camaratta et al., 2020)
	Water use blue (L/kg)	13.7	(Li et al., n.d.)
	Water use green (L/kg)	0	(Li et al., n.d.)

Table A.3 Energy consumption and yield <u>central scenario</u>. Data is obtained from** (Zisopoulos et al., 2015)**, except when stated differently.

Unit operation	Energy consumption (MJ/kg input)	Yield	Settings	Additional information
Mixing industrial	0.015	1.6	t = 10 min, T = 20ºC	Water is added (36.1% of the dough is water). Same for all chains. Raw materials at ambient temperature, water is colder. ΔTmix = 8 ºC
Fermenting industrial	0.111	1	t = 60 min, T = 28ºC	Same for all industrial chains. Fermenters with capacity of 200 breads, each fermenter consumes 6.2 kW. During fermentation 2% of simple sugars are converted into ethanol and CO2.
Dividing industrial	0.002	1		Same for all industrial chains. Electricity consumption for cutting dough is 0.6 kW per 1000 units (one unit is 0.8 kg)
Proving industrial	0.111	1	t = 60 min, T = 28ºC	Same for all industrial chains. Proving has the same conditions as the fermentation step.
Baking at industrial bakery	1.931	0.96	t = 35 min, T = 235ºC	10% of water is evaporated during baking. 10% of bread becomes crust. Energy distribution in oven: 25% used to bake product, <u>15% steam usage</u> and 60% heat loss. Oven is heated by natural gas. Steam at 123.3ºC and 220 kPa is produced.
Cooling at industrial bakery	0.243	0.972	t=30 min, T=20ºC	Cooling of baked bread using three fans (400 W each) for 40 kg of bread. 0.028 kg water/kg bread is removed.
Packaging	0.008	1		Breads are packed in polyethylene bags. It is assumed that the capacity for packaging white bread is 30 units/min (single unit packaging), machine electricity consumption is 2.8 kW.
Waste at retailer		0.89		11% according to data FLW brood Nederland

Table A.4 ***Energy consumption and yield <u>central par-baking scenario</u>. Data is obtained from*** *(Zisopoulos et al., 2015)****, except when stated differently.***

Unit operation	Energy consumption (MJ/kg input)	Yield	Settings	Additional information
Mixing industrial	0.015	1.6	t = 10 min, T = 20ºC	Water is added (36.1 % of the dough is water). Same for all chains. Raw materials at ambient, water is colder. ΔTmix = 8ºC
Fermenting industrial	0.111	1	t = 60 min, T = 28ºC	Same for all industrial chains. Fermenters with capacity of 200 breads, each fermenter consumes 6.2 kW. During fermentation 2% of simple sugars are converted into ethanol and CO2.
Dividing industrial	0.002	1		Same for all industrial chains. Electricity consumption for cutting dough is 0.6 kW per 1000 units (one unit is 0.8 kg)
Proving industrial	0.111	1	t = 60 min, T = 28ºC	Same for all industrial chains. Proving has the same conditions as the fermentation step.
Par-baking industrial bakery	1.468	0.97	t = 30 min, T = 160ºC	8% of water is evaporated during baking. 5% of bread becomes crust. Energy distribution in oven: 25% used to bake product, <u>15% steam usage</u> and 60% heat loss. Oven is heated by natural gas. Steam at 123.3ºC and 220 kPa is produced.
Freezing at industrial bakery	0.885	0.99	t=120 min, T=-40ºC	Bread mass reaches -15ºC where 70% of water freezes and 3% of the water content is removed.
Packaging par-baked	0.001	1		The frozen breads are put in returnable polyethylene crates (CBL crates), each 0.06 m3 with a capacity of 8 breads per crate for transportation. The energy consumption for this process is 1.5 kW with a capacity of 15 crates/min.
Baking off at retailer	0.889	0.99	t =10 min, T =220ºC	2% of water is removed and no additional steam is added.
Waste at retailer		0.95		5% according to data FLW brood Nederland

Table A.5 ***Energy consumption and yield <u>decentral bakery scenario</u>. Data is obtained from*** *(Le-bail et al., 2010)****. No information on energy consumption of mixing and fermentation of the dough was provided. Therefore, same values were assumed as in*** *(Zisopoulos et al., 2015)****.***

Unit operation	Energy consumption (MJ/kg input)	Yield	Settings	Additional information
Mixing industrial	0.015	1.6	t = 10 min, T = 20ºC	Water is added (36.1 % of the dough is water). Same for all chains. Raw materials at ambient, water is colder. ΔTmix = 8ºC
Fermenting industrial	0.111	1	t = 60 min, T = 28ºC	Same for all industrial chains. Fermenters with capacity of 200 breads, each fermenter consumes 6.2 kW. During fermentation 2% of simple sugars are converted into ethanol and CO2.
Dividing industrial	0.002	1		Same for all industrial chains. Electricity consumption for cutting dough is 0.6 kW per 1000 units (one unit is 0.8 kg)
Baking	1.975	0.96	t = 20 min, T = 230ºC	Value reported is 1.58 MJ/kg *dough* and mass loss during baking was 20%. However, the same value as from Zisopoulos was used for water evaporation (i.e. 10% of water is evaporated during baking) - to be in line with the other scenario. Baking was done in a batch oven equipped with a sole made of "stone". The volume of the oven was 0.253 m3 and the internal surface 1.02 m2. Oven runs on electrical energy and 0.5 L of steam was added at start of baking. The share of steam was not mentioned, we assumed same ratio as in paper Zisopoulos.
Cooling	0	0.972		No active cooling, thus no energy consumption. 0.028 kg water/kg bread is evaporated during cooling.
Waste at retailer		0.925		7.5% (5-10% according to ambachtelijkebakkerij.nu)

Table A.6 ***Energy consumption and yield <u>decentral home scenario</u>. Data is obtained from*** (Real Bread Campaign, 2024)***. No information on energy consumption of mixing was provided. Therefore, same values were assumed as in*** (Zisopoulos et al., 2015)***.***

Unit operation	Energy consumption (MJ/kg input)	Yield	Settings	Additional information
Mixing	0.015	1.6	t = 10 min, T = 20ºC	Water is added (36.1 % of the dough is water). Same for all chains. Raw materials at ambient, water is colder. ΔTmix = 8ºC
Baking at home in electric oven	7.2	0.9		Reported as 1.6 kWh/loaf per use. Assumption you bake one loaf of bread, which is s 0.8 kg (Zisopoulos 2015). The same value as from Zisopoulos was used for water evaporation (i.e. 10% of water is evaporated during baking) - to be in line with the other scenarios.
Bread baking machine	1.62	0.9	t = 3 h 18 min	Reported as 0.36 kWh/loaf. Baking machine also includes mixing & fermentation. Assumption a loaf is 0.8 kg (Zisopoulos 2015).
Waste at retailer		1		Assumed there are no unsold bread ingredients at the retailer.

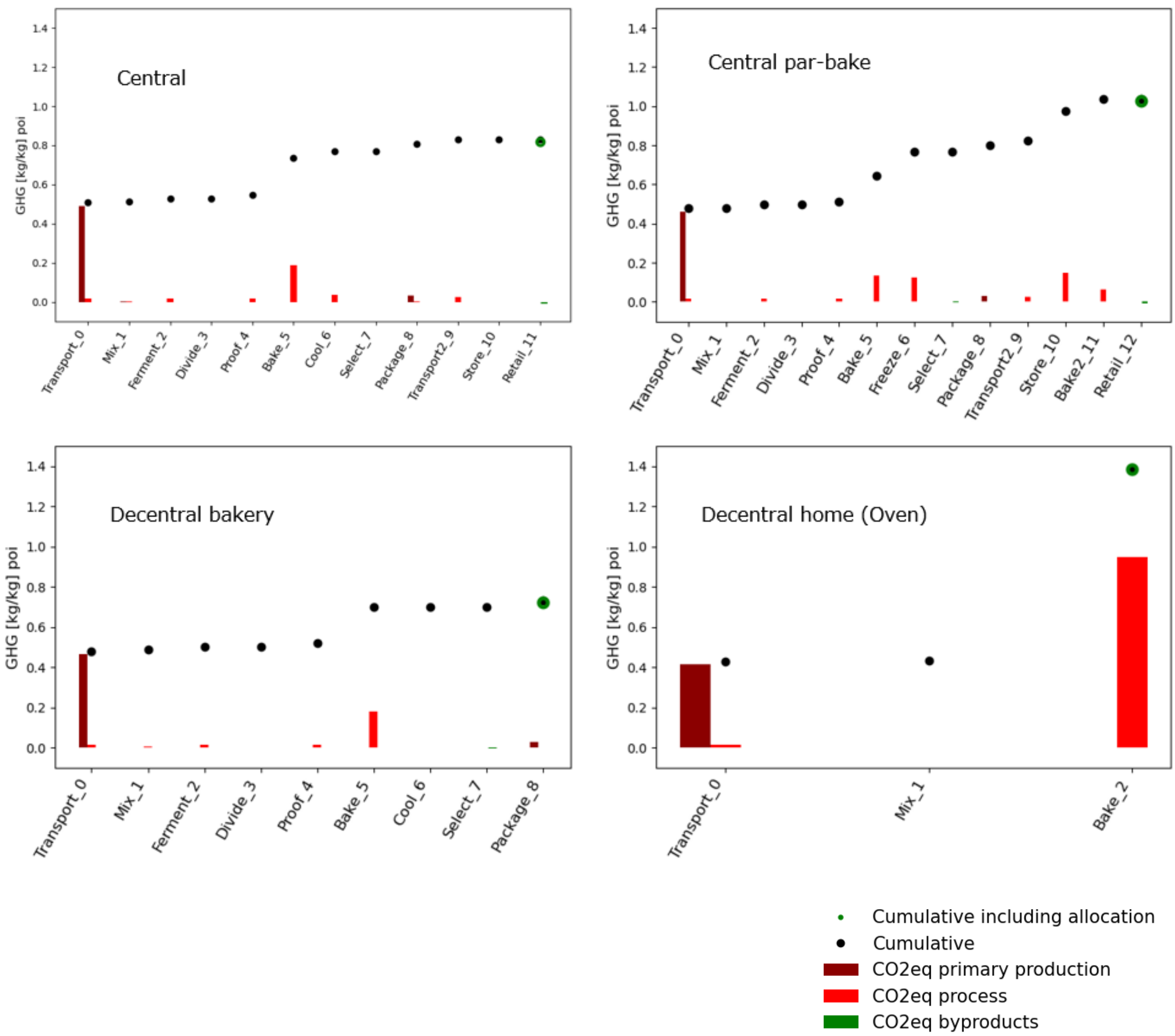

Figure A.1 GHG emissions of ready-to-eat bread for different bread case scenarios along the processing chain.

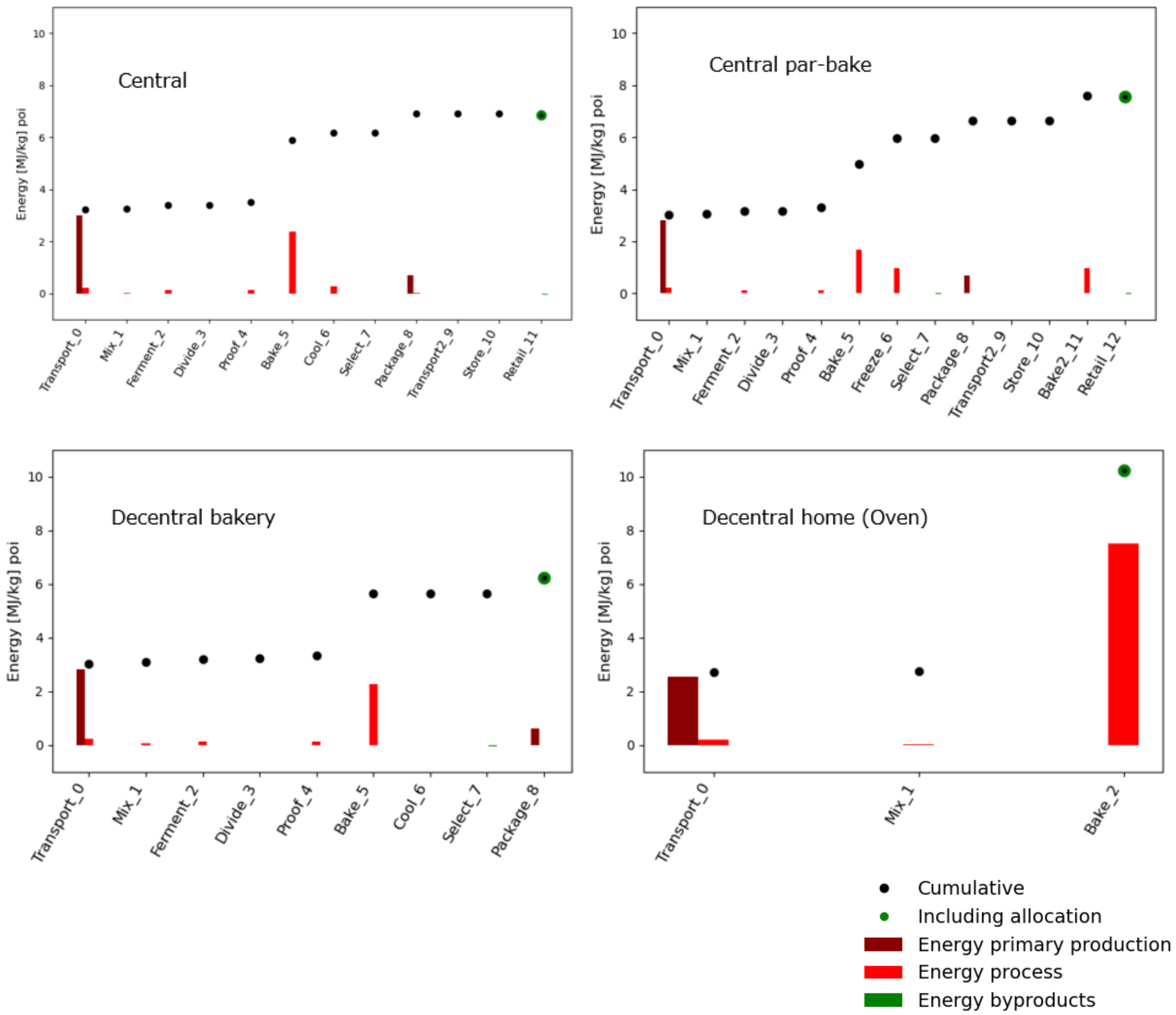

Figure A.2 Energy consumption of ready-to-eat bread for different bread case scenarios along the processing chain.

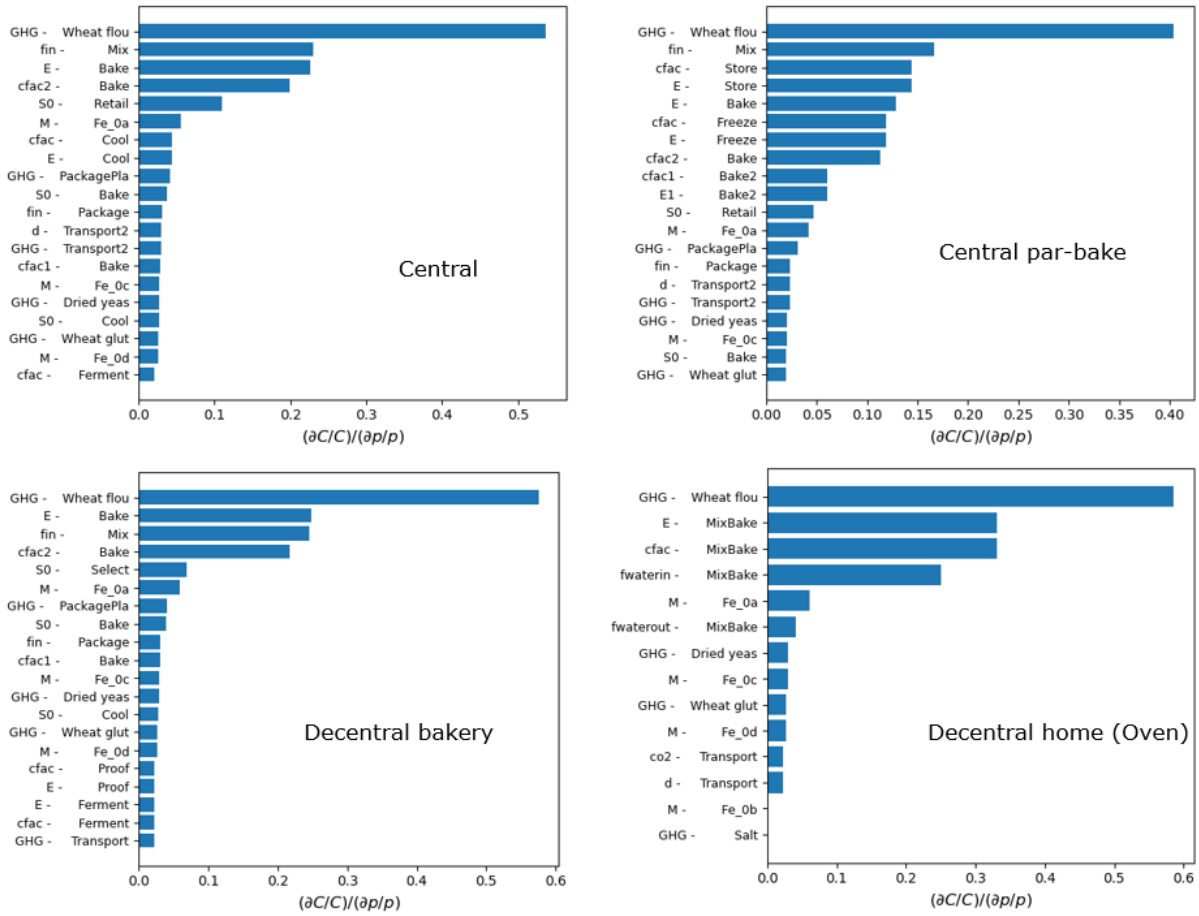

Figure A.3 Sensitivity analysis of GHG emissions of ready-to-eat bread for different bread case scenarios. Note: the sensitivity analysis of energy consumption gives similar sensitive parameters.

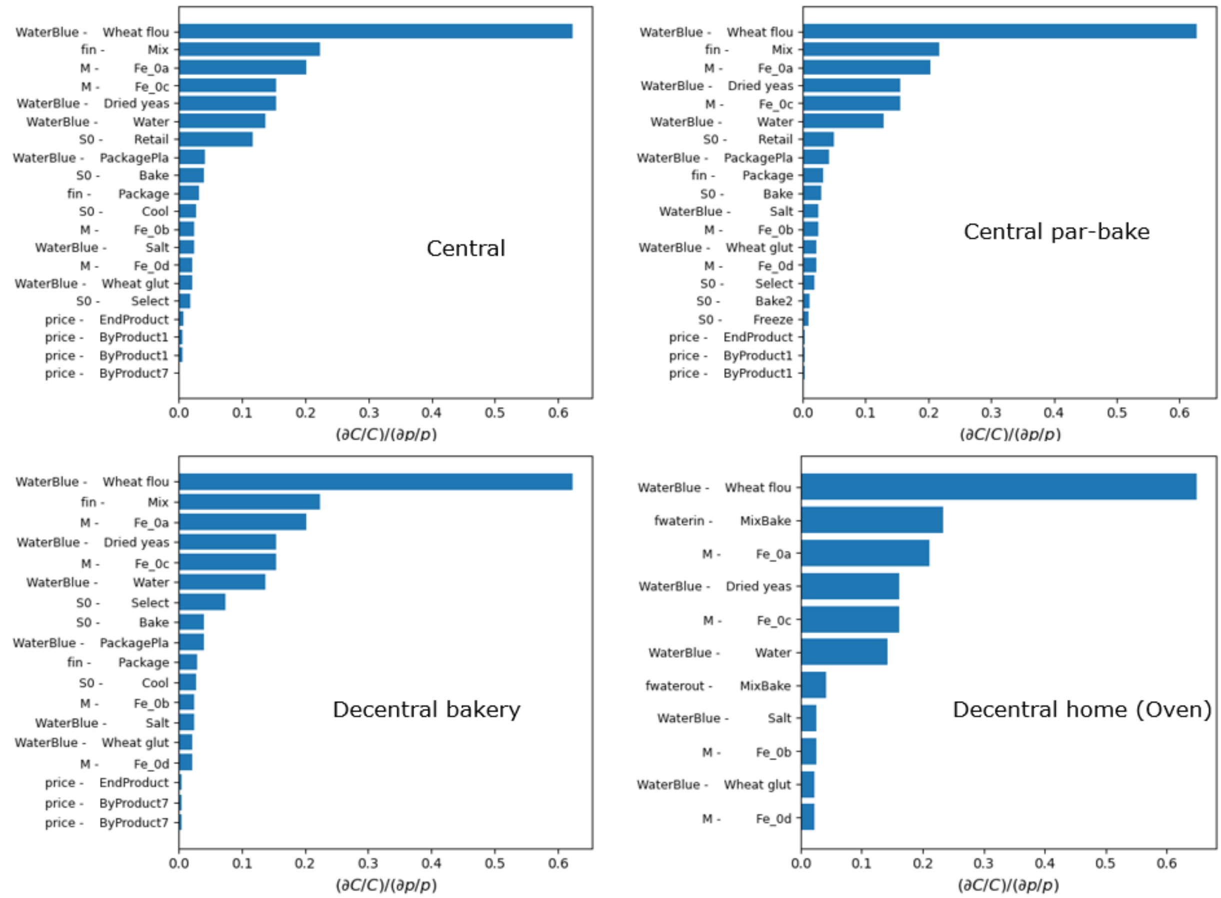

Figure A.4 ***Sensitivity analysis of blue water footprint of ready-to-eat bread for different bread case scenarios. Note: the sensitivity analysis of the green water footprint gives similar sensitive parameters.***

Table A.7 ***LCA data of the apples from Poland and the Netherlands***

Ingredient	Country of agriculture	Indicator	Values	Reference(s)
Apples	Poland	*GHGe (kg CO2eq-/kg)*	0.25	(Porter et al., 2016)
		Energy use (MJ/kg)	1.2	(Paris et al., 2022)
		Water use blue (L/kg)	2	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	425	(Mekonnen & Hoekstra, 2011a)
Apples	Netherlands	*GHGe (kg CO2eq-/kg)*	0.25	(Porter et al., 2016)
		Energy use (MJ/kg)	1.2	(Paris et al., 2022)
		Water use blue (L/kg)	26	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	192	(Mekonnen & Hoekstra, 2011a)

Table A.8 ***LCA data of packaging material for apple juice***

Packaging	Indicator	Values	Reference(s)
Tetrapak	*GHGe (kg CO2eq-/kg)*	1.32	(Stramarkou et al., 2021)
	Energy use (MJ/kg)	27.3	Calculated[1]
	Water use blue (L/kg)	24.3	(Li et al., n.d.)
	Water use green (L/kg)	617	(Li et al., n.d.)
Glass (recycled)	*GHGe (kg CO2eq-/kg)*	0.58	(Schmitz et al., 2011)
	Energy use (MJ/kg)	7.4	(Schmitz et al., 2011)
	Water use blue (L/kg)	3.22	(Gerbens-Leenes et al., 2018)
	Water use green (L/kg)	0	(Gerbens-Leenes et al., 2018)
Glass (deposit)	*GHGe (kg CO2eq-/kg)*	0.18	(Ferrara et al., 2021)
	Energy use (MJ/kg)	1.07	(Ferrara et al., 2021)
	Water use blue (L/kg)	1.01	(Ferrara et al., 2021)
	Water use green (L/kg)	0	(Ferrara et al., 2021)

[1] Energy consumption calculated on composition Tetrapak: 75% paper, 20% plastic and 5% aluminium foil (Georgiopoulou et al., 2021) and energy consumption of separate packaging materials by (Camaratta et al., 2020) and (Laurijssen et al., 2010).

Table A.9 Energy consumption and yield of unit operations in the local chain

Unit operation	Energy use (MJ/kg input)	Yield	Additional information	Reference energy use
Storage	0.05	1	5 days 0.01 MJ/kg/d	(Evans & Brown, 2012)
Sorting manual	0	0.93		(Dijkink, 2023)
Washer	0.01	1	Washing at 40ºC for 5 min 2 L/kg apples	(Dijkink, 2023)
Sorting manual	0	0.98		(Dijkink, 2023)
Juice press	0.17	0.75		(Dijkink, 2023)
Filter	0	0.95		(Dijkink, 2023)
Pasteurization	Electricity: 0.147 MJ/kg Natural gas: 0.473 MJ/kg	1	Using a hot filling packaging system. Water use is 0.17 L/kg Boiler efficiency of 95%	(Manfredi & Vignali, 2015)
Cooling	0.063	1		(Dijkink, 2023)
Packaging	0.01	1		(Dijkink, 2023)

Table A.10 Energy consumption and yield of unit operations in the long chain

Unit operation	Energy use (MJ/kg input)	Yield	Additional information	Reference energy use
Storage	0.02	1	2 days 0.01 MJ/kg/d	(Evans & Brown, 2012)
Sorting manual	0	0.93		(Dijkink, 2023)
Washer	0.01	1	Washing at 40ºC for 5 min 2 L/kg apples	(Dijkink, 2023)
Sorting manual	0	0.98		(Dijkink, 2023)
Mill	0.026	1		(Schutyser & van der Goot, 2011)
Enzyme treatment	0.036	1	Assuming a mixing liquid step on industrial scale	(Piccinno et al., 2016)
Juice press	0.03	0.75		(Dijkink, 2023)
Solids centrifuge	0.03	0.99	Based on 0.01 kWh/kg energy uptake	(Dijkink, 2023)
Ultrafiltration	0.025	0.96	In range of 0.014-0.036 MJ/kg water removed	(Ramírez et al., 2006)
Concentrate	0.52	0.18	5 stage evaporator	(Dijkink, 2023)
Cooling	0.325	1		(Dijkink, 2023)
Dilution	0.003	6	Based on incoming feed, 6x diluted during this process step mixing for 1 min	(Dijkink, 2023)
Pasteurization	Electricity: 0.205 MJ/kg Natural gas: 0.151 MJ/kg	1	Using an aseptic packaging system. Boiler efficiency of 95%	(Manfredi & Vignali, 2015)
Cooling	0.063	1		(Dijkink, 2023)
Packaging	0.01	1		(Dijkink, 2023)

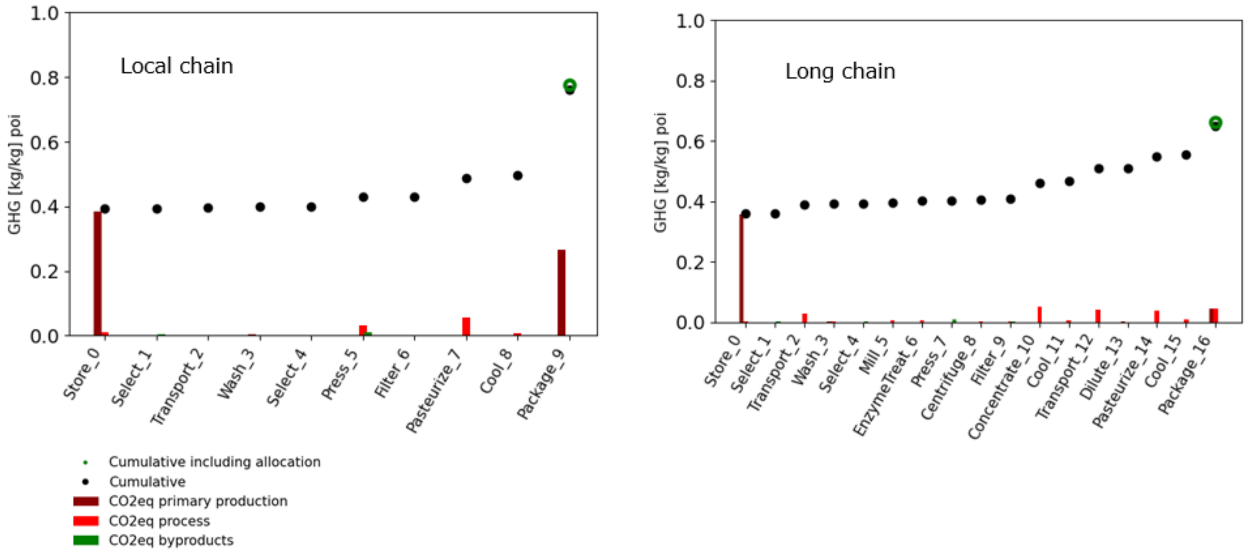

Figure A.5 GHG emissions of apple juice for local and long chain along the processing chain.

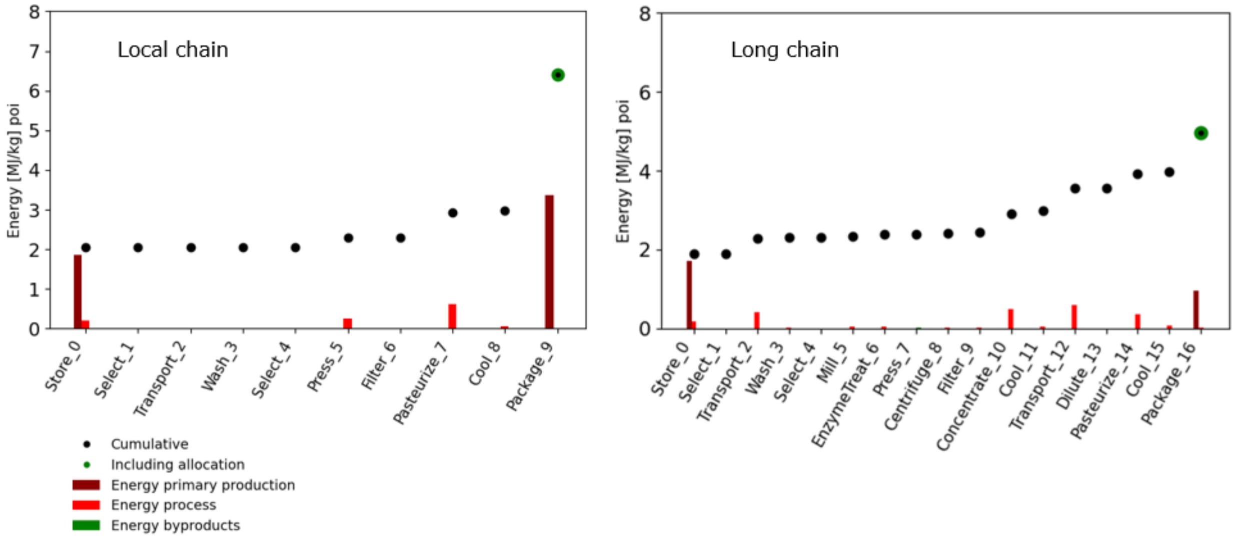

Figure A.6 Energy consumption of apple juice for local and long chain along the processing chain.

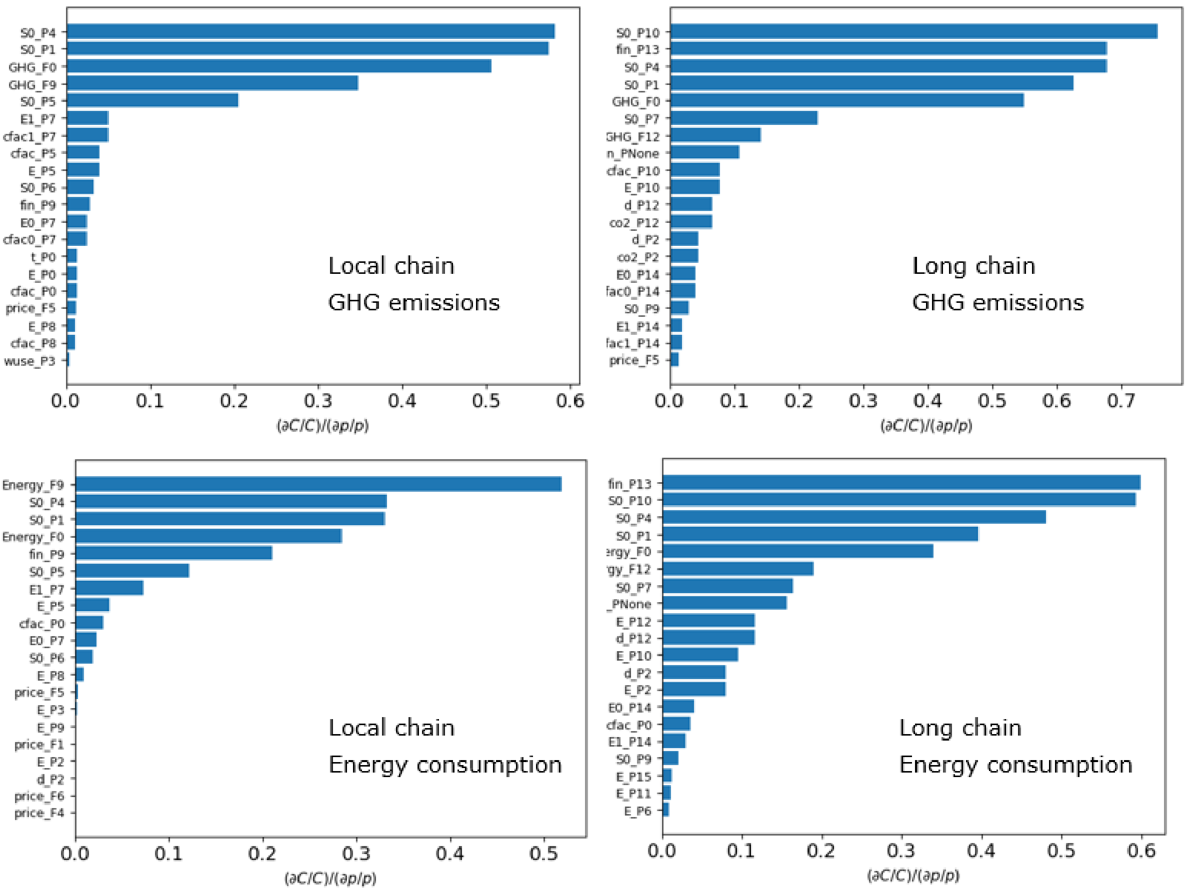

Figure A.7 Sensitivity analysis of GHG emissions and energy consumption of apple juice from the local and long chain.

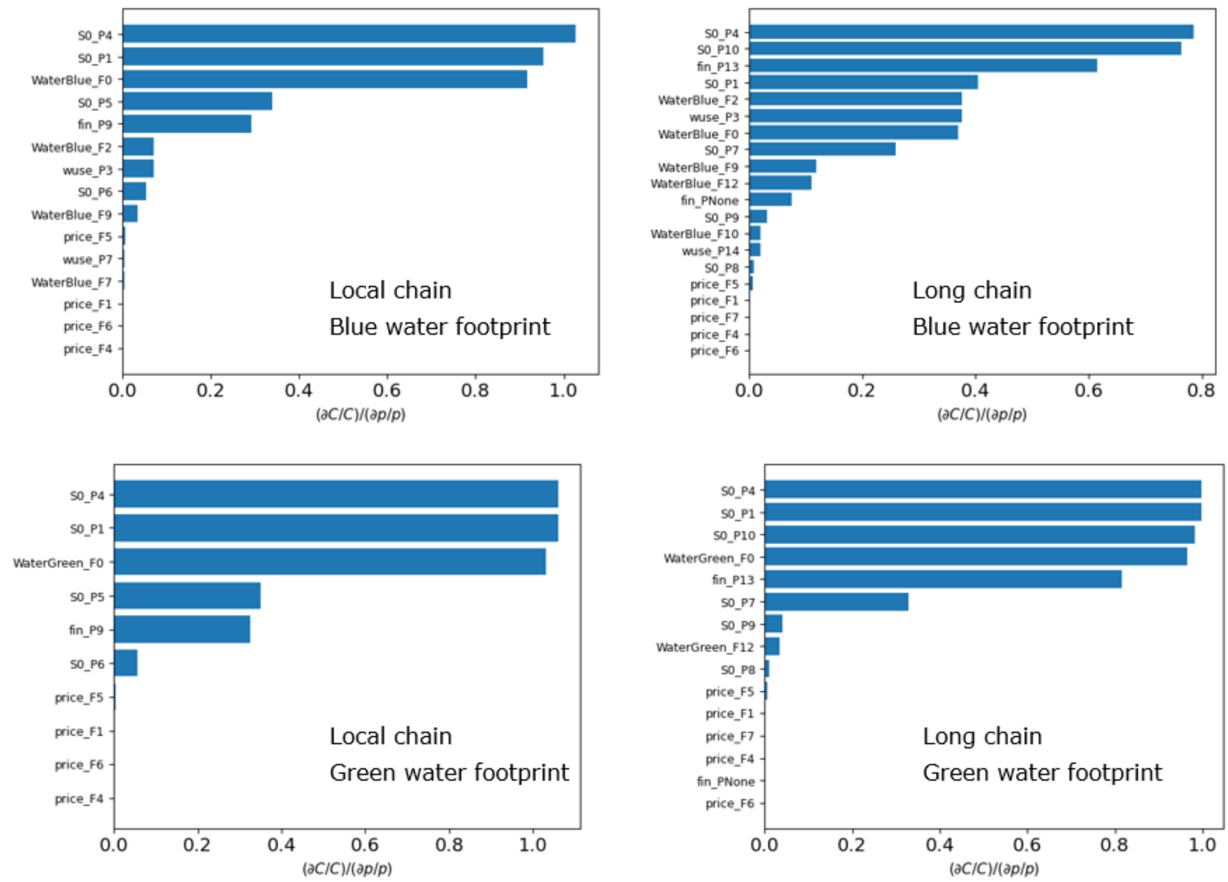

Figure A.8 Sensitivity analysis of blue water footprint and green water footprint of apple juice from the local and long chain.

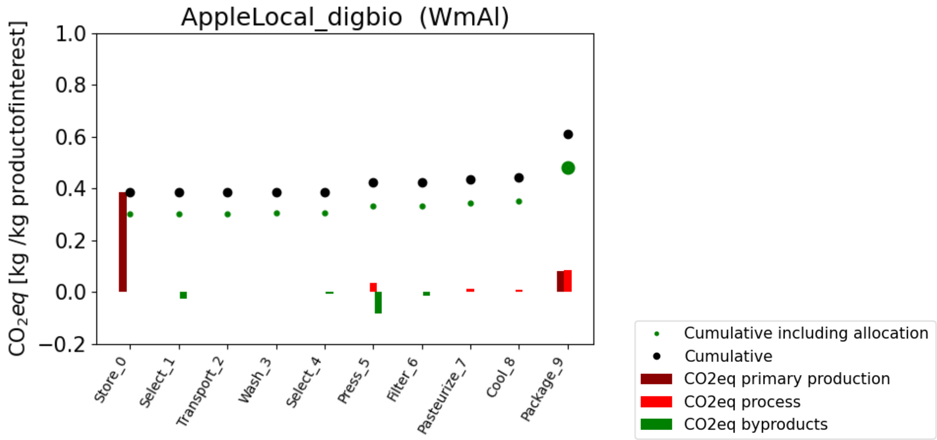

Figure A.9 GHG emissions of the apple juice local chain with the digestion to biogas as waste valorisation scenario.

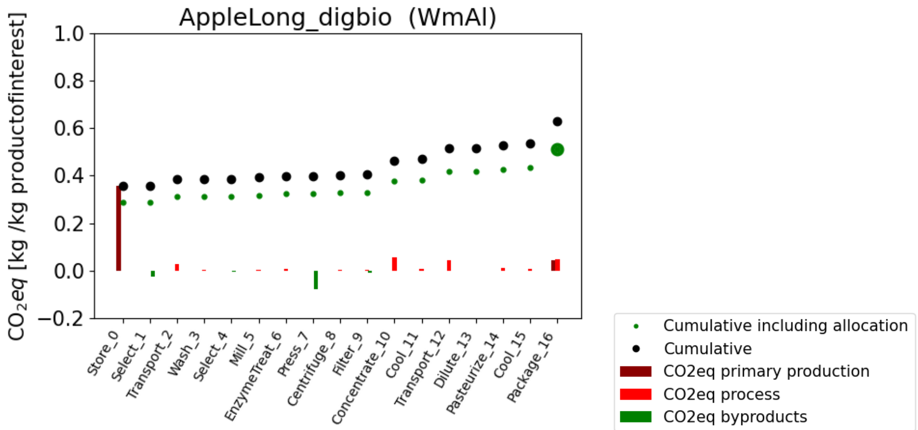

Figure A.10 GHG emissions of the apple juice long chain with the digestion to biogas as waste valorisation scenario.

Table A.11 LCA data of the French fries ingredients

Ingredient	Country of origin	Indicator	Values	Reference(s)
Potato	Netherlands	*GHGe (kg CO2eq-/kg)*	0.12	(Novidon 2020)
		Energy use (MJ/kg)	0.92	(Paris et al. 2022)
		Water use blue (L/kg)	3	(Mekonnen & Hoekstra, 2011c)
		Water use green (L/kg)	76	(Mekonnen & Hoekstra, 2011c)
Rapeseed oil	Denmark	*GHGe (kg CO2eq-/kg)*	2.22	(Schmidt, 2010)
		Energy use (MJ/kg)	13	(Fridrihsone et al., 2020)
		Water use blue (L/kg)	0	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	2318	(Mekonnen & Hoekstra, 2011a)
Sodium acid pyrophosphate (SAPP) derived from sodium bicarbonate process		*GHGe (kg CO2eq-/kg)*	1.13	(AGRIBALYSE, 2022)
		Energy use (MJ/kg)	14.72	(AGRIBALYSE, 2022)
		Water use blue (L/kg)	5	(Hungaro Yoshi et al., 2022)
		Water use green (L/kg)	0	Assumption

Table A.12 Energy consumption and yield of unit operations in the frozen French fries

Unit operation	Yield process step	Heat (from gas) (MJ/kg input)	Electricity (MJ/kg input)	Water (L/kg input)	Additional information	References
Steam peeling	0.975	0.29		0.15		(Somsen et al., 2004) (Walker et al., 2018)
Washing	1		0.0005	6.5		(Walker et al., 2018)
Cutting and sorting	0.8		0.007		Sliver (5%) and defect (15%) removal	(Somsen et al., 2004) (Walker et al., 2018)

Unit operation	Yield process step	Heat (from gas) (MJ/kg input)	Electricity (MJ/kg input)	Water (L/kg input)	Additional information	References
Blanching	0.9977	0.24	0.003	0.25		(Walker et al., 2018)
Dipping in SAPP	1.01					Personal communication
Drying in hot air	0.98		0.0452		Yield based on own calculation	(Mouron et al., 2016)
Par-frying in deep oil	0.7953	1.236	0.6		Oil uptake based on Mouron 2016, water evaporation based on Somsen 2004, energy consumption par-frying based on Walker 2018	(Somsen et al., 2004) (Walker et al., 2018) (Mouron et al., 2016)
Freezing	1		0.618			(Walker et al., 2018) adapted
Frozen storage factory	1		0.21		0.0014 MJ/kg·day for 150 days	(Evans & Brown, 2012)4
Packaging	1.0341				0.0041 kg plastic and 0.03 kg cardboard per kg fries	(Mouron et al., 2016)
Frozen transport to retailer	1				Medium truck Frozen (27% more fuel consumption than ambient). Travel distance 100 km	(CE Delft, 2021) (Tassou et al., 2008)
Storage retailer	0.99		0.538		0.1345 MJ/kg·day for 4 days	(Evans & Brown, 2012)

Table A.13 Energy consumption and yield of unit operations in the chilled French fries that are different from the frozen French fries.

Unit operation	Yield process step	Heat (from gas) (MJ/kg input)	Electricity (MJ/kg input)	Water (L/kg input)	Additional information	References
Cooling	1		0.333			(Walker et al., 2018) adapted
Refrigerated storage factory	1		0.001425		0.00095 MJ/kg·day for 1.5 days	(Evans & Brown, 2012)
Refrigerated transport	1				Medium truck Refrigerated (20% more fuel consumption than ambient). Travel distance 100 km	(CE Delft, 2021) (Tassou et al., 2008)
Storage retailer	0.98		0.155		0.1034 MJ/kg·day for 1.5 days	(Evans & Brown, 2012)

Table A.14 Nutritional value of "Krokante friet" and "Verse friet".

Nutrient	AH Krokante friet (ref. frozen fries) g/100g	AH verse friet (ref. chilled fries) g/100g
Fat	3	4.1
Carbohydrates	21	23
Fibre	2.5	2.2
Protein	2.5	2.5
Salt	0.1	0.05

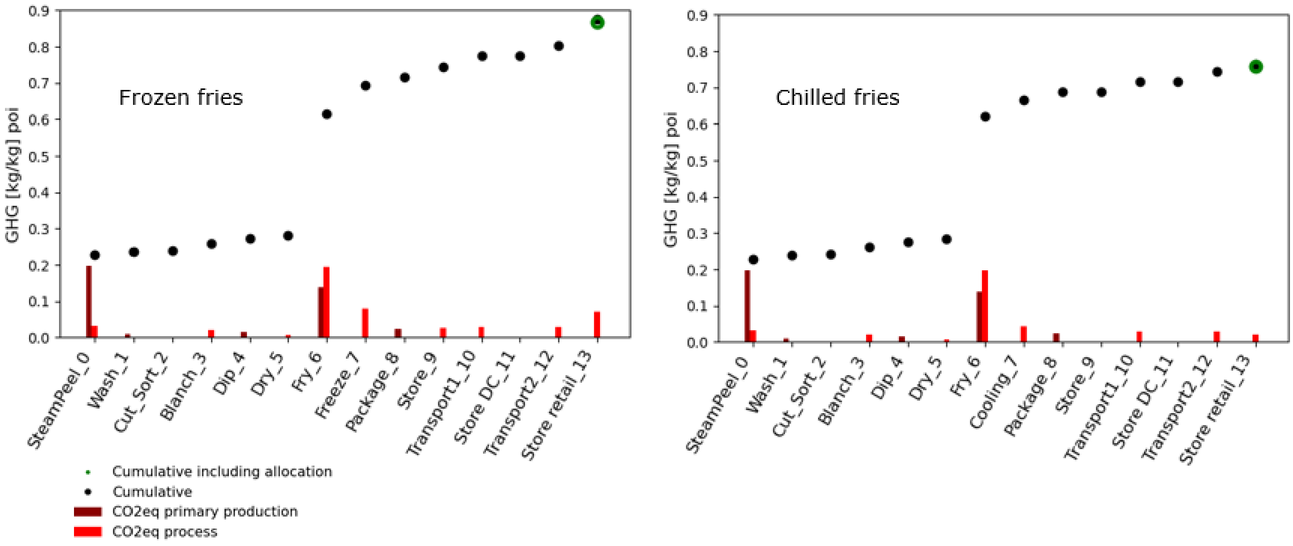

Figure A. 11 ***GHG emissions of frozen fries and chilled fries along the processing chain.***

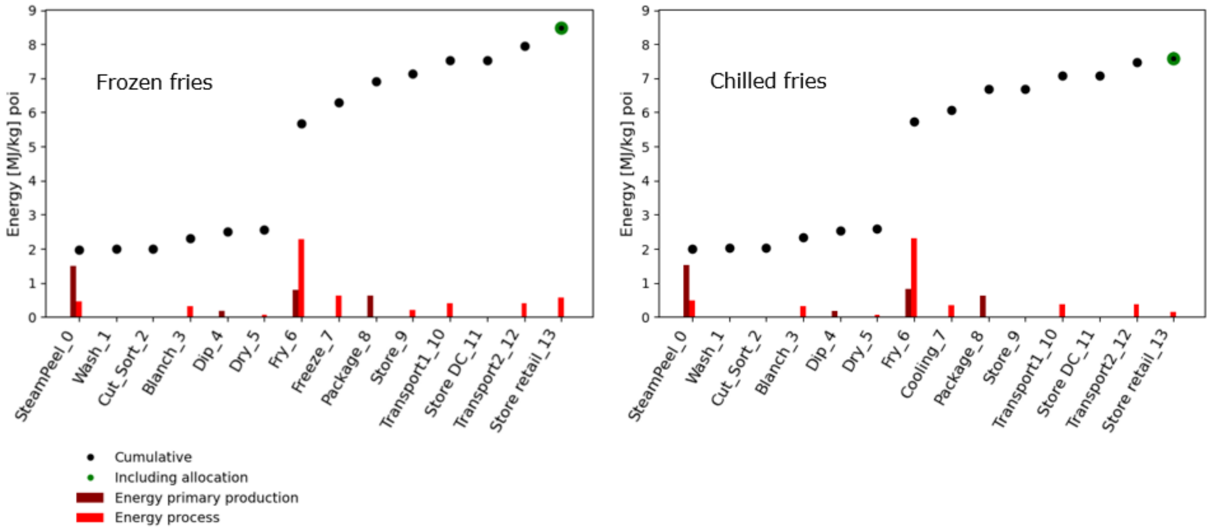

Figure A. 12 ***Energy consumption of frozen fries and chilled fries along the processing chain.***

Table A.15 ***Ingredients of the pea protein isolate burger "Beyond Burger". The quantities are calculated based on information on the label and nutritional composition.***

Ingredient	**Quantity (g/100 g)**
Water	50
Pea protein isolate	16
Canola oil	14
Coconut oil	5
Rice protein	4
Dried yeast	3
Potato starch	3
Methyl cellulose	2
Beet root colourant	1
Vinegar	1
Salt	1

Table A.16 Ingredients of the pea protein concentrate burger "Heura Burger". The quantities are calculated based on information on the label and nutritional composition.

Ingredient	Quantity (g/100 g)
Water	56.7
Pea protein concentrate	24.5
Olive oil	4.9
Shea butter (modelled as coconut oil)	3.9
Dried yeast	3
Potato starch	3
Methyl cellulose	2
Beet root colourant	1
Vinegar	1

Table A.17 LCA data of the ingredients used in meat burgers, plant-based burgers or canned beans.

Ingredient	Country of origin	Indicator	Values	Reference(s)
Beans brown	Netherlands	*GHGe (kg CO2eq-/kg)*	0.25	(Broekema & Smale, 2011)
		Energy use (MJ/kg)	1.49	(Broekema & Smale, 2011)
		Water use blue (L/kg)	8	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	158	(Mekonnen & Hoekstra, 2011a)
Beef minced	Netherlands	*GHGe (kg CO2eq-/kg)*	18.98	(RIVM, 2024)
		Energy use (MJ/kg)	61.8	(Blonk et al., 2008)
		Water use blue (L/kg)	423	(Mekonnen & Hoekstra, 2011b)
		Water use green (L/kg)	6744	(Mekonnen & Hoekstra, 2011b)
Beet root colourant		*GHGe (kg CO2eq-/kg)*	11.42	(Thomsen et al., 2023)
		Energy use (MJ/kg)	125.6	(Mekonnen & Hoekstra, 2011a)
		Water use blue (L/kg)	122	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	2785	(Mekonnen & Hoekstra, 2011a)
Chicken minced	Denmark/Germany	*GHGe (kg CO2eq-/kg)*	6.1	(Saerens et al., 2021)
		Energy use (MJ/kg)	19.8	(Saerens et al., 2021)
		Water use blue (L/kg)	80	(Mekonnen & Hoekstra, 2011b)
		Water use green (L/kg)	1667	(Mekonnen & Hoekstra, 2011b)
Coconut oil	Philippines	*GHGe (kg CO2eq-/kg)*	1.47	Own calculation
		Energy use (MJ/kg)	16.5	(Yani et al., 2022)
		Water use blue (L/kg)	0	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	5454	(Mekonnen & Hoekstra, 2011a)
Methyl cellulose		*GHGe (kg CO2eq-/kg)*	3.4	(Carbon Cloud, 2024b)
		Energy use (MJ/kg)	31.6	(MelaColl, 2021)
		Water use blue (L/kg)	55	(MelaColl, 2021)
		Water use green (L/kg)	0	Assumption
Olive oil	Spain	*GHGe (kg CO2eq-/kg)*	3.055	(Broekema et al., 2009)
		Energy use (MJ/kg)	35.29	(Broekema et al., 2009)
		Water use blue (L/kg)	10593	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	2571	(Mekonnen & Hoekstra, 2011a)
Pea protein concentrate	Netherlands, France & UK	*GHGe (kg CO2eq-/kg)*	1.10	(Broekema et al., 2009)
		Energy use (MJ/kg)	11.1	(Broekema et al., 2009)
		Water use blue (L/kg)	56	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	1054	(Mekonnen & Hoekstra, 2011a)
Pea protein isolate	Netherlands, France & UK	*GHGe (kg CO2eq-/kg)*	3.15	(Broekema et al., 2009)
		Energy use (MJ/kg)	39.7	(Broekema et al., 2009)
		Water use blue (L/kg)	74	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	1394	(Mekonnen & Hoekstra, 2011a)
Potato starch		*GHGe (kg CO2eq-/kg)*	1.015	(Broekema et al., 2009)
		Energy use (MJ/kg)	13.37	(Broekema et al., 2009)

Ingredient	Country of origin	Indicator	Values	Reference(s)
		Water use blue (L/kg)	14	(Mekonnen & Hoekstra, 2011b)
		Water use green (L/kg)	402	(Mekonnen & Hoekstra, 2011b)
Rapeseed oil	Denmark	*GHGe (kg CO2eq-/kg)*	2.22	(Schmidt, 2010)
		Energy use (MJ/kg)	13	(Fridrihsone et al., 2020)
		Water use blue (L/kg)	0	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	2318	(Mekonnen & Hoekstra, 2011a)
Rice protein		*GHGe (kg CO2eq-/kg)*	9.4	(Carbon Cloud, 2024c)
		Energy use (MJ/kg)	137.7	(Aghaalikhani et al., 2013; Broekema & Smale, 2011)
		Water use blue (L/kg)	5236	(Akter et al., 2020; Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	16364	(Akter et al., 2020; Mekonnen & Hoekstra, 2011a)
Salt		*GHGe (kg CO2eq-/kg)*	0.15	Own calculation
		Energy use (MJ/kg)	3.09	(Alix et al., 2022)
		Water use blue (L/kg)	8.16	(Zhang et al., 2022)
		Water use green (L/kg)	0	(Zhang et al., 2022)
Vinegar	Europe or Brazil	*GHGe (kg CO2eq-/kg)*	0.128	(Budsberg et al., 2020)
		Energy use (MJ/kg)	2.56	(Budsberg et al., 2020)
		Water use blue (L/kg)	0.96	Based on dilution (4%)
		Water use green (L/kg)	0	Assumption
Water		*GHGe (kg CO2eq-/kg)*	0.001	(RIVM, 2019)
		Energy use (MJ/kg)	0.002	(van der Schans et al., 2015)
		Water use blue (L/kg)	1.096	(Fresán et al., 2020)
		Water use green (L/kg)	0	(Fresán et al., 2020)
Yeast (dried)		*GHGe (kg CO2eq-/kg)*	3.21	(Carbon Cloud, 2024a)
		Energy use (MJ/kg)	16.1	(Dunn et al., 2012)
		Water use blue (L/kg)	80	(Xu et al., 2015b)
		Water use green (L/kg)	0	(Xu et al., 2015b)

Table A.18 Energy consumption and yield of unit operations in the production of the different burgers and canned beans

Unit operation	Yield process step	Heat (from gas) (MJ/kg input)	Electricity (MJ/kg input)	Water (L/kg input)	Additional information	References
Extrusion pea proteins	0.95		0.936	0.24	5% loss during extrusion	(Saerens et al., 2021)
Mixing ingredients	1		0.12			Calculation based on power consumption and capacity of planetary mixer
Patty shaping	1		0.1			Calculation based on power consumption and capacity of patty forming machine
Packaging	1		0.07			Calculation based on power consumption and capacity of packing machine for hamburger boxes
Freezing	1		0.12			(Heller & Keoleian, 2018)
Cooking and sterilization beans	1	1.807	0.0654			(Broekema & Smale, 2011)
Frozen storage factory (plant-based burger)	1		0.0294		0.0014 MJ/kg·day for 21 days	(Evans & Brown, 2012)
Refrigerated storage factory (meat burgers)	1		0.002850		0.00095 MJ/kg·day for 3 days	(Evans & Brown, 2012)
Ambient storage (canned beans)	1		0		0 MJ/kg·day for 21 days	Assumption

Table A.19 LCA data of the brown beans

Ingredient	Country of origin	Indicator	Values	Reference(s)
Brown beans conventional	Netherlands	*GHGe (kg CO2eq-/kg)*	0.27	(J. Bos et al., 2014)
		Energy use (MJ/kg)	1.38	(J. Bos et al., 2014)
		Water use blue (L/kg)	8	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	158	(Mekonnen & Hoekstra, 2011a)
Brown beans organic	Netherlands	*GHGe (kg CO2eq-/kg)*	0.40	(J. Bos et al., 2014)
		Energy use (MJ/kg)	2.08	(J. Bos et al., 2014)
		Water use blue (L/kg)	8	(Mekonnen & Hoekstra, 2011a)
		Water use green (L/kg)	158	(Mekonnen & Hoekstra, 2011a)

Table A.20 LCA data of packaging material for brown beans

Packaging	Indicator	Values	Reference(s)
Plastic	*GHGe (kg CO2eq-/kg)*	3	(Plastics Europe, 2014)
	Energy use (MJ/kg)	63.2	(Camaratta et al., 2020)
	Water use blue (L/kg)	13.7	(Li et al., n.d.)
	Water use green (L/kg)	0	(Li et al., n.d.)
Steel can	*GHGe (kg CO2eq-/kg)*	1.96	(Broekema & Smale, 2011)
	Energy use (MJ/kg)	25.2	(Broekema & Smale, 2011)
	Water use blue (L/kg)	20	(Choudhury et al., 2023)
	Water use green (L/kg)	0	(Choudhury et al., 2023)
Tetrapak	*GHGe (kg CO2eq-/kg)*	1.32	(Stramarkou et al., 2021)
	Energy use (MJ/kg)	27.3	Calculated[1]
	Water use blue (L/kg)	24.3	(Li et al., n.d.)
	Water use green (L/kg)	617	(Li et al., n.d.)
Glass (recycled)	*GHGe (kg CO2eq-/kg)*	0.58	(Schmitz et al., 2011)
	Energy use (MJ/kg)	7.4	(Schmitz et al., 2011)
	Water use blue (L/kg)	3.22	(Gerbens-Leenes et al., 2018)
	Water use green (L/kg)	0	(Gerbens-Leenes et al., 2018)
Pouch (aluminium/plastic)	*GHGe (kg CO2eq-/kg)*	3.95	Calculated[2]
	Energy use (MJ/kg)	63.33	Calculated[2]
	Water use blue (L/kg)	16.23	Calculated[2]
	Water use green (L/kg)	0	Calculated[2]

[1] Energy consumption calculated on composition Tetrapak: 75% paper, 20% plastic and 5% aluminium foil (Georgiopoulou et al., 2021) and energy consumption of separate packaging materials by (Camaratta et al., 2020) and (Laurijssen et al., 2010).

[2] Sustainability indicators are calculated based on Stazak 250 ml (Blok Packaging): 12 micron PET, 7 micron aluminium and 110 micron PE. Based on densities the ratio is: 12% PET, 13% ALU and 75% HDPE.

GHG emissions: (Stramarkou et al., 2021) (B. Simon et al., 2016) And (Plastics Europe, 2014)

Energy use: (Camaratta et al., 2020)

Water use: (Li et al., n.d.)

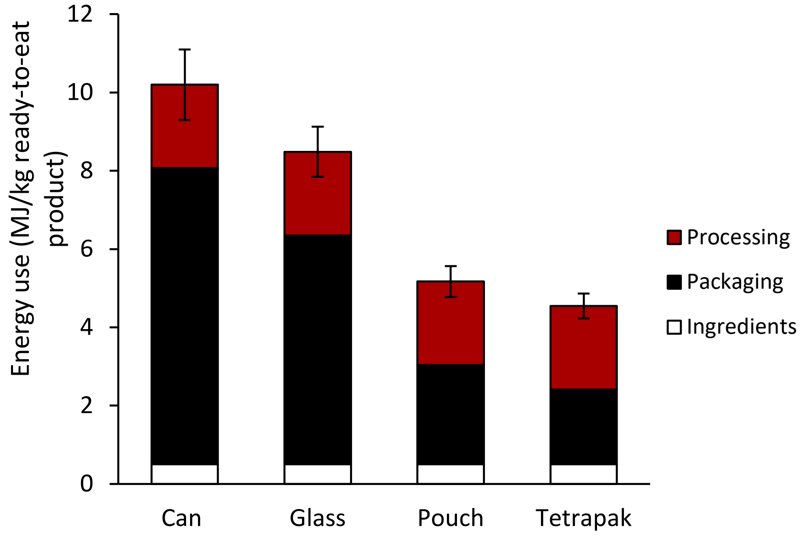

Figure A. 13 Energy consumption of conventional brown beans in different packaging.

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