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# A Review on the current Status of Food Waste Life Cycle Analysis and the used Methodology

**Deliverable D1.1.1**

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D1.1.1: Comparability of Life Cycle Analysis Studies on Food Waste and Food Products. A Review on the current Status of Food Waste Life Cycle Analysis and the used Methodology


### Authors

Kevin Kaltenbrunner, Daniel Orth,
Christian Pladerer, Victoria Menedetter

Austrian Institute of Ecology
Seidengasse 13, 1070 Vienna

### Reviewed by

Eva Lienbacher

Fachhochschule Salzburg GmbH
Urstein Süd 1, 5412 Salzburg, Austria

Christine Vallaster

Paris Lodron Universität Salzburg
Churfürststr. 1, 5020 Salzburg, Austria

### Layout

Anna Schliesselberger

Fachhochschule Salzburg GmbH
Urstein Süd 1, 5412 Salzburg, Austria

### Illustrationen

Sophie Wehmeyer
www.sophiewehmeyer.com


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# Index

# 1. Introduction

## Why is the assessment of ecological impacts caused by food waste necessary and how can it help to address systemic flaws in the food industry?

The mitigation of human-made climate change is one of the most pivotal challenges of our day and age. The severe effects of the collapse of our known climate-system and biodiversity which are already felt (Mooney et al. 2009) are giving us a preview of the serious decline of safety and liveability on our planet. A transformation of our food system, which is currently responsible for a third of global anthropogenic greenhouse gas emissions (Crippa et al. 2021), will have to play a major role in stopping these developments. While the greatest share of these emissions comes from meat and dairy products (Poore und Nemecek 2018), there is a common theme among all food categories, which is the wastage and loss of food along all stages of its value-chain.

To systemically reduce food waste and choose the quickest and most effective prevention strategy, food waste streams and their impacts need to be assessed. This is where Life Cycle Analysis (LCA) methodology emerges as a powerful tool for evaluating the ecological footprint of food waste (Dominguez Aldama et al. 2023).

By employing LCA, we gain insights into the resource-intensive processes, greenhouse gas emissions, and ecological impacts tied to food waste (Cucurachi et al. 2019). This knowledge is instrumental in identifying the critical stages where waste occurs, which, in turn, informs the development of targeted prevention and mitigation strategies (Shamraiz et al. 2019). With a deeper understanding of the environmental ramifications of food waste, we are better equipped to implement sustainable practices, reduce inefficiencies, and therefore create a more resilient food system (Sridhar et al. 2021).

**LCA is a comprehensive method used to assess the environmental impact of a product or system throughout its entire life cycle, from raw material extraction to production, transportation, use, and eventual disposal (life cycle assessment). When applied to food waste, LCA provides a holistic understanding of the environmental consequences of wasting food, enabling policymakers, businesses, and individuals to make informed decisions for waste reduction and sustainability (Dominguez Aldama et al. 2023).**

By applying LCA methodology to food waste, it is possible to gain a deeper insight into the environmental consequences of food production and consumption habits. Furthermore, this analysis helps in developing targeted interventions and policies aimed at reducing food waste and its associated environmental impacts (Abbate et al. 2023). For instance, it may highlight the benefits of composting, diverting food to food banks, or optimizing supply chain logistics to minimize spoilage (De Oliveira et al. 2021).

Ultimately, as we confront the challenge of climate change and work to make our food system more sustainable, the application of LCA to food waste is an indispensable tool. It not only quantifies the environmental consequences of our wasteful habits but also guides us toward more effective strategies for reducing food waste and lowering its ecological footprint. In this way, LCA plays a critical role in forging a more sustainable and responsible path for our European and global food system.

### Definition: Food waste

"Food waste refers to the decrease in the quantity or quality of food resulting from decisions and actions by retailers, food service providers and consumers" (FAO 2023).

# 2. Life Cycle Assessment: Definitions and Standards

**How do Life Cycle Assessment processes look like, and which standards and norms exist to build a common basis and facilitate comparability?**

## 2.1. Introduction to the LCA methodology

In the realm of food waste and the application of Life Cycle Assessment (LCA) methodology, a well-established framework is adhered to. This approach comprehensively evaluates the entire life cycle of food products, encompassing stages from raw material extraction to production, distribution, consumption, and eventual disposal. Within this holistic evaluation, LCA quantifies resource consumption, energy utilization, emissions, and waste generation associated with each distinct stage. This meticulous analysis enables a thorough assessment of the environmental impacts tied to food waste (Finkbeiner et al. 2006).

In order to promote consistency and comparability in the field of food waste LCA, the International Organization for Standardization (ISO) has crafted the ISO 14044 series (ISO 2024). This series provides essential guidelines and principles for conducting LCA studies, thus establishing a shared framework. The ISO standards foster transparency, reliability, and precision in LCA assessments, promoting the exchange of vital information among researchers, policymakers, and stakeholders. Ultimately, the ISO norm forms a cornerstone for practitioners of LCA in the context of food waste, enhancing credibility and facilitating a harmonized approach to environmental impact assessments on a global scale (Finkbeiner et al. 2006).

The life cycle stages of a food product or process (which are illustrated in Figure 1) serve as the bedrock of the LCA methodology in the realm of food waste analysis. This methodology considers the entire life cycle, encompassing a sequence of distinct stages (Finkbeiner et al. 2006). These stages include:

**01** **Raw Material Extraction & Acquisition**
This initial stage involves the procurement of raw materials for food production.

**02** **Material Processing**
In this stage, raw materials undergo processing to prepare them for food production.

**03** **Product Manufacture**
In this stage, the processed materials are transformed into the final food product.

**04** **Use Phase**
In this stage, consumers use the food product, resulting in environmental impacts such as energy consumption or emissions.

**05** **End-of-Life Stage**
The final stage deals with the recycling or disposal of the product.

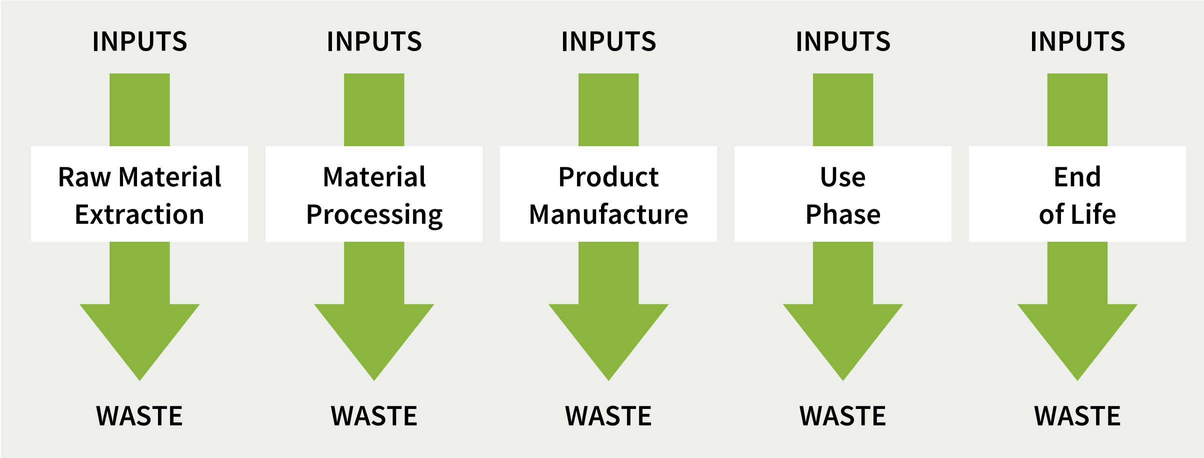


Figure 1: Simplified visualization of the life cycle stages of a product, process, or service.


Throughout these life-cycle stages, various inputs, such as energy, water, transportation services, and others, come into play. Simultaneously, outputs in the form of intermediate products and waste (in the following graphic summarized as waste) are generated. For a simplified visual representation of these life cycle stages and their respective inputs and outputs, please refer to Figure 1.

According to the voluntary international Standard ISO 14040, the process of conducting an LCA has four phases (European Commission - Joint Research Center 2010; ISO 2024). The first phase (1) is the **Definition of a Goal and Scope for the LCA**, where the primary objectives and boundaries of the assessment are established. This phase involves setting clear goals, defining the purpose of the LCA, and determining the scope of the study, including the system boundaries, functional unit, and the environmental impact categories to be considered. It is essential to identify what specific environmental aspects will be assessed, what data will be collected, and what functional unit or reference flow the analysis will be based on.

Following this, (2) an **Inventory Analysis** is conducted to quantify all the inputs and outputs within the defined system boundaries. This second stage involves collecting detailed data on resource consumption, emissions, and waste generated throughout the life cycle of the product, process, or service being assessed. The inventory analysis aims to provide a comprehensive understanding of the environmental flows associated with the system, ensuring that all relevant information is gathered.

The next phase (3) is **Impact Assessment**, where the potential environmental impacts are evaluated. During this stage, the inventory data is translated into environmental indicators and assessed in relation to predefined impact categories, such as Global Warming Potential (GWP), acidification, eutrophication, and others. This step helps identify which environmental aspects have the most significant impact and allows for the comparison of different products or systems in terms of their environmental performance.

The final phase (4) is **Interpretation**, where the results of the impact assessment are analysed and communicated. This stage involves making sense of the data, drawing conclusions, and, if necessary, suggesting improvements or mitigation strategies based on the findings. Interpretation also includes reporting the LCA results in a clear and transparent manner to inform decision-making and stakeholders.

When conducting an LCA of food products, it is essential to consider various aspects to gain a comprehensive understanding of the food's environmental impact. One of the first important factors is **the way agriculture is practiced** (Cucurachi et al. 2019). The use of pesticides and fertilizers influences the evaluation, as the use or pollution of water may impact the environment greatly. In addition, **the size of the cultivated area** must also be considered. The land used as agricultural area influences the regional flora and fauna and might impact the sensitive balance of the biodiversity prevailing there (Dominguez Aldama et al. 2023). Another important factor in the preparation of an LCA is the **packaging of food** (Skunca et al. 2018). Different types of packaging (e.g. disposable or reusable) can increase or reduce the environmental impact. All these and many more factors must be considered (FoodDrinkEurope 2022).

**Given these extensive assessment processes, conducting an LCA is defined as an iterative process with multiple feedback loops to ensure accuracy and comprehensiveness. It requires constant data refinement and adjustments to account for various variables (European Commission - Joint Research Center 2010). Recognising the interconnectedness of these factors and the need for iterative feedback loops, LCA ensures a holistic assessment that helps in making informed decisions to reduce the environmental impact of the food industry.**

## 2.2. Environmental Footprint Impact Categories

The European Commission has proposed a set of methods to homogenise LCA methodology in the European Union as a common way of measuring environmental performance (European Commission 2021). Its stringent standards allow for more international comparability while being aligned with ISO 14044 requirements. A so called impact category, in accordance with ISO 14044, serves as a grouping that captures environmental concerns to which the outcomes of life cycle inventory analysis can be ascribed, encompassing diverse factors contributing to the overall environmental impact of a product or process (ISO 14044:2006).

A list of 16 impact categories was brought forward by the European Commission's Joint Research Centre after extensive consultation with experts, stakeholders, and the scientific community to ensure robustness, transparency, and relevance in capturing the key environmental impacts associated with products across their life cycle. The 16 impact categories brought forward by the European Commission to calculate the Product Environmental Footprint (PEF) are as follows (e.g. Sala et al. 2018):

- **Climate change**
- **Ozone depletion**
- **Human toxicity, cancer effects**
- **Human toxicity, non-cancer effects**
- **Particulate matter**
- **Ionizing radiation, human health**
- **Ecotoxicity freshwater**
- **Photochemical ozone formation, human health**
- **Acidification**
- **Land use**
- **Water use**
- **Eutrophication, terrestrial**
- **Eutrophication, freshwater**
- **Eutrophication, marine**
- **Resource use, minerals and metals**
- **Resource use, fossils**

For a fully-fledged environmental assessment of a product, process or service the European Commission recommends taking all Product Environmental Footprint (PEF) impact categories into account. Given the wide variety of product and industries a specific selection and weighting of these categories may depend on the specific objectives, scope, and context of the LCA study. Flexibility in the application of the PEF framework allows for customisation based on the particularities of the product or industry under assessment (European Commission 2021).

## 2.3. Challenges of LCAs on Food Waste

In the pursuit of conducting LCAs on food waste, several challenges arise, demanding thoughtful consideration and innovative solutions. The first significant challenge lies in **defining the scope of the assessment** (Finkbeiner et al. 2006). LCAs on food waste can be approached from various angles, encompassing different stages of the food production and consumption lifecycle. The choice between evaluating the entire journey from "farm to table" or focusing solely on the "farm to gate" can yield substantially different results. Additionally, deciding whether to include or exclude the preparation stage of food adds another layer of complexity to the assessment, as it may lead to varying environmental impact profiles.

Another critical challenge in conducting LCAs on food waste is the **inherent variability** in data (Shamraiz et al. 2019). The vast and intricate nature of food supply chains, coupled with differing agricultural practices, make it exceedingly challenging to acquire consistent and precise data. This variability extends to factors such as water use, energy consumption, and waste generation at different stages of the food lifecycle. As a result, conducting LCAs on food waste necessitates a nuanced approach that accommodates this data variability while ensuring that the assessment remains reliable and credible. (Shamraiz et al. 2019)

The challenges concerning the **variability of data** continue with what methodology should be used in the LCA approach. If the analysed LCA results need to have high comparability and reproducibility a rather strict approach on data gathering has to be carried out. On the other hand, if the given data is not sufficient or future scenarios and strategies have to be analysed, a more flexible approach has to be used to ensure the robustness of the conclusions and recommendations (European Commission - Joint Research Center 2010).

Furthermore, there exists a notable challenge **regarding the selection of impact categories** in food waste LCAs. The choice of which environmental impact indicators to prioritize can significantly influence the outcomes of the assessment. This variability in chosen impact categories, whether focusing on greenhouse gas emissions, water use, or other environmental parameters, calls for standardized practices that accommodate a diverse array of stakeholder interests and policy objectives (Morone et al. 2019).

Lastly, the **availability of comprehensive and up-to-date data** presents a persistent challenge. Data accessibility is paramount for the accurate assessment of food waste, and the scarcity of real-time, high-quality data can impede the effectiveness of LCAs. To overcome this challenge, collaborative efforts among stakeholders, policymakers, and industry players to enhance data collection and sharing are crucial (Saavedra-Rubio et al. 2022).

Considering these differences in approaches, the field of LCAs on food waste is lacking comparability and harmonization. Addressing these obstacles necessitates a multidisciplinary approach that leverages advanced data collection methods, standardization of impact categories, and harmonized assessment scopes. These solutions, combined with a commitment to data transparency and sharing, can empower the food industry to make more informed and sustainable choices in the face of a global food waste crisis.

# 3. Literature Review

**Available literature on LCA methodology for food products and by-products and meta-analyses were examined to determine the status of homogenization in food waste LCA methodology and find existing barriers.**

The conducted literature research contains 31 documents, which mainly consist of articles from scientific journals. The goal was to review as much of the current key literature as possible on the topic of LCA in the food sector. In doing so, attention was paid to commonalities and differences in order to understand the set priorities. Special attention was paid to categorise the literature based on three criteria:

1. the scope used
2. the standards adhered to
3. the impact categories used

For the literature review, an online search was carried out using Google Scholar, which was restricted to the years 2010 to 2023. The year 2010 was chosen as cutoff-point for the search to find a sufficiently large number of articles, because more recent years have not yielded enough results. The following keywords were used to search for suitable articles: LCA, life cycle assessment, impact assessment, environmental impact, food production, food waste, food loss, methodology.

This literature review delves into 31 papers that explore LCA applications in the context of different types of food and food waste. A substantial portion of the reviewed papers focuses on the environmental footprint of food production. Studies on the cultivation of crops, livestock, and aquaculture systems provide detailed insights into resource consumption, greenhouse gas emissions, and land use. These LCA studies reveal the critical role of food choices and production methods in shaping our ecological footprint.

The issue of food waste and loss is a growing concern worldwide, with significant environmental consequences. By quantifying the environmental benefits of waste reduction initiatives, these studies highlight the potential to minimise the carbon and resource footprint associated with discarded food.

This literature review underscores the vital role of LCA in assessing the environmental impacts of food and food waste. It highlights the complexities and interconnectedness of various aspects of the food system, from production and transportation to dietary choices and waste management. The findings from these studies contribute to a growing body of knowledge that can guide policymakers, food producers, and consumers in making informed decisions to reduce the environmental footprint of the food we produce and consume. As we continue to address the challenges of sustainability in the food sector, the insights gained from these LCA studies will be crucial in shaping more responsible and eco-friendly food systems.

Table 1 offers a summary of the literature review and the 31 included papers:

| Author | Year | Description |
|---|---|---|
| Ahamed et al. | 2016 | LCA of food waste management technologies concerning environmental and economic impact perspectives. |
| Amicarelli et al. | 2021 | Analytical review of Global Warming Potential (GWP) of food waste with LCA |
| Brancoli et al. | 2017 | LCA of supermarket food waste |
| Djekic et al. | 2014 | LCA of various dairy products |
| Edwards et al. | 2018 | LCA of seven contemporary food waste management systems |
| Faust | n.d. | Greenhouse gas emissions of organically and conventionally produced foods |
| Finkbeiner et al. | 2006 | Description of changes to the ISO 14040 and 14044 standards |
| Finnegan et al. | 2018 | Review of LCA´s concerning cheese production |
| González-García et al. | 2013 | Environmental LCA of yoghurt |
| Herndl | n.d. | LCA of GWP of dairy products, including an analysis and strategies |
| Kalhor et al. | 2016 | LCA of GWP of chicken meat production |
| Kulak et al. (a) | 2015 | LCA of bread including several alternative food networks in Europe |
| Kulak et al. (b) | 2016 | Case study of possible improvments due to LCA in french bread supply |
| Lam et al. | 2018 | Life-cycle assessment on food waste valorisation |
| Maga et al. | 2019 | Review of LCA´s concerning different meat packaging materials |
| Martin-Gorriz et al. | 2020 | LCA of fruit and vegetable production |
| Mattsson et al. | 2000 | Case study including LCA concerning three vegetable oil crops |
| Mühlrath et al. | 2019 | Description of innovative thinking for a sustainable agriculture and food industry |
| Notarnicola et al. (a) | 2017 | Review of LCA´s role in supporting sustainable agri-food systems |
| Notarnicola et al. (b) | 2017 | LCA approach for EU national breads focusing on energy flows and GHG |
| Peters et al. | 2010 | LCA and result comparison for red meat production |
| Reinhardt et al. | 2020 | Ecological footprints of food and dishes in Germany |
| Roy et al. | 2009 | Review of LCA data on several food products |
| Schopf | 2014 | LCA of austrian pork production |
| Skunca et al. | 2018 | LCA of the chicken meat chain |
| Smetana et al. (a) | 2015 | LCA of most known meat substitutes |
| Smetana et al. (b) | 2021 | LCA of meat substituition in burgers |
| Sridhar et al. | 2021 | LCA on conversion of food waste to energy |
| Stratmann et al. | 2008 | Environmental impacts of different food diets |
| Üçtuğ et al. | 2019 | LCA of various dairy products |
| Wolbart | 2019 | Comparison of greenhouse gas emissions of Austrian diets |

Table 1: Summary of the literature review 2024 (AIE own illustration)

The reviewed studies employ a range of methodologies, reflecting diverse approaches to assessing the environmental and social impacts of food products and systems, and food waste. These studies differ on **various methodological aspects**. For the analysis the following categories were used to filter out the differences between assessment approaches: **scope, functional unit, system boundaries, impact categories and standards**.

Concerning these different approaches and standards Herndl (2014), Gonzales-Garcia et al. (2013), and Peters et al. (2010) for example, among the majority, adopt a comprehensive approach by considering the entire life cycle of a food product (cradle-to-grave), from production to consumption and disposal, while others (Djekic et al. 2014; Martin-Gorriz et al. 2020) focus on narrower **system boundaries**, such as cradle-to-gate or just looking at production or distribution phases.

The choice of **functional units** varies among studies as well. Some use consumer-oriented functional units, which are relevant for addressing consumer choices (e.g. Smetana et al. 2021) while others employ weight-based or economic units (e.g. Notarnicola et al. 2017b), potentially leading to different interpretations of results.

We observed that there were many differences in the approaches used to prepare an LCA, but there were even more similarities. The **scope** used was often very similar. According to the conducted literature research the most commonly chosen scopes were firstly “cradle to grave” followed by “cradle to gate”. However, there were also some more unusual approaches such as” cradle to production/processing facility” or the system boundary money, as everything was converted into monetary costs.

However, with the multitude of possible **standards** that could be chosen to perform an LCA, there were few surprises. According to the literature research done for this deliverable, a large majority of the life cycle analyses were performed adhering to the ISO 14044 / ISO 14040 standards. In addition, however, there were analyses based on PEF (Product and Environmental Footprint), ILCD and GEMIS data.

Nevertheless, the greatest diversity was seen in the choice of impact categories. Some analyses were limited to a handful of categories, while others evaluated the entire range of **impact categories** specified by ISO 14044. The following impact categories occurred particularly frequently in the individual articles:

- Abiotic depletion
- GWP in $CO_2$ equivalents
- Water use
- Land use

The frequent choice of impact categories such as abiotic depletion, GWP in $CO_2$ equivalents, water use, and land use in food product and food waste LCA is driven by their direct relevance to assessing the sustainability of food systems. Abiotic depletion underscores resource scarcity, GWP measures greenhouse gas emissions, water use addresses freshwater resource impact, and land use assesses agricultural consequences. These categories offer a comprehensive overview of vital environmental concerns associated with food, aligning with sustainability goals (e.g.: SDG 12: United Nations 2024).

**In summary, the field of food LCA exhibits a variety of methodological approaches, but some commonalities exist. Cradle-to-grave analysis, consumer-oriented functional units, and frequently chosen impact categories demonstrate shared priorities among researchers. Standards like ISO 14044, ISO 14040, ILCD, and GEMIS data serve as common frameworks. This diversity underscores the dynamic and interdisciplinary nature of food (waste) LCA, emphasizing the need for transparency, data quality, and continued collaboration among researchers to advance the methodology in this context.**

# 4. Discussion

**The differences in scope, standards, and regional factors in food waste LCAs are discussed and the complexities in overcoming existing barriers and possible solutions are considered.**

## 4.1. Methodological Differences and Barriers to Comparability

The availability of LCA data concerning food waste is extensive, reflecting the growing interest and concern about the environmental impact of our food consumption. However, despite the wealth of available data, comparing LCA findings on food waste is not always a straightforward task. Several factors contribute to the complexity of these comparisons. First and foremost, differences in scope can significantly impact the results. LCA studies may focus on various stages of the food supply chain, such as production, distribution, or household consumption. Consequently, the environmental impact of food waste can vary depending on which stage is being analysed, making it challenging to draw direct comparisons. (Reinhardt et al. 2020)

Moreover, the use of different standards and methodologies in LCA studies further complicates the comparability of data. Various organisations and researchers may employ distinct models and assumptions, affecting the way they quantify and assess the environmental impacts of food waste. This inconsistency can lead to disparities in results, making it challenging for policymakers, businesses, and consumers to make informed decisions based on LCA data. (Peters et al. 2010)

**Another complicating factor is regional differences.** Environmental factors, agricultural practices, and waste management systems can vary significantly from one region to another. Therefore, LCA data on food waste may not always be directly applicable or transferable from one geographical area to another. These regional discrepancies add another layer of complexity when attempting to compare LCA data on food waste. (Finnegan et al. 2018)

While the availability of LCA data concerning food waste is extensive and invaluable for understanding the environmental implications of our food choices, the differences in scope, standards, and regional variations make it difficult to compare this data directly. Efforts to standardise methodologies and improve data consistency will be essential to harness the full potential of LCA in addressing the European and global issue of food waste. (Roy et al. 2009)

## 4.2 Standardisation of Data and Methods

The standardisation of underlying data and data collection as a first step is a challenging task for many reasons. Looking at the case of Agribalyse (2024), a large-scale programme founded by the French Agency for the ecological transition (ADEME 2024), the national research institute for Agriculture, Food and the Environment (INRAE 2024), and a number of French technical institutes for agriculture and food industries, enormous financial efforts were undertaken to create a standardised and comparable platform to assess the ecological footprints of food products available in French supermarkets.

In order to harmonise methodology beyond current PEF and ISO standards, a comparison of the different approaches in different product categories, national and regional differences (e.g. functional units), the choice of impact categories and their underlying methodologies, and selected system boundaries is needed.

Current literature shows that even the efforts to harmonise LCA methods of single food product streams are facing many barriers and are still working on building a common frame (Goglio et al. 2023). Given the complex and fragmented landscape of LCA methods for food waste, it is imperative to explore and adapt existing tools and approaches that can facilitate harmonisation.

One promising approach is the development of sector-specific databases and guidelines for food waste LCA (Goglio et al. 2023; Notarnicola et al. 2017a). These databases can serve as centralized repositories for data on food waste throughout the Alpine Space region, offering standardized data sources that practitioners can reference. Moreover, the adoption of consistent reporting formats and data quality standards, such as those outlined in the Food Loss and Waste Accounting and Reporting Standard (Hanson et al. 2016), can promote uniformity in data collection and reporting. By drawing from these resources and encouraging cross-border cooperation, the Alpine Space region can foster a more harmonised and comprehensive approach to food waste LCA, contributing to sustainable food systems and resource conservation.

# 5. Conclusion

**The differences in scope, standards, and regional factors in food waste LCAs are discussed and the complexities in overcoming existing barriers and possible solutions are considered.**

The extensive availability of LCA data related to food waste represents a significant step in understanding the environmental consequences of our food consumption habits. Nevertheless, the complexities associated with comparing LCA findings on food waste cannot be understated. These complexities arise from differences in scope, standards, and regional variations, all of which hinder straightforward data comparisons.

Diverse scopes of LCA studies, focusing on various stages of the food supply chain, create variability in results, making direct comparisons challenging. The use of different standards and methodologies among researchers and organisations further adds to the challenge, resulting in disparities in data and making it difficult for decision-makers to derive consistent insights.

Regional disparities in environmental factors, agricultural practices, and waste management systems introduce yet another layer of complexity. Despite these hurdles, the importance of harnessing the full potential of LCA in addressing global food waste cannot be overstated.

The standardisation of data and methods is an essential step forward, but also a challenging one. The significant financial investments and efforts required, as demonstrated by programs like Agribalyse, emphasize the need for substantial commitment to create standardized and comparable platforms. Harmonizing methodologies beyond current standards necessitates a comprehensive comparison of various approaches, product categories, regional differences, impact categories, and system boundaries. While challenges exist in achieving a common framework, progress is being made.

One promising avenue to address these challenges is the development of sector-specific databases and guidelines for food (waste) LCA. These centralised repositories, along with consistent reporting formats and data quality standards, offer opportunities to facilitate harmonisation. Encouraging cross-border cooperation and knowledge-sharing, particularly in the Alpine Space region, can pave the way for a more harmonised and comprehensive approach to food (waste) LCA. This harmonisation, in turn, will contribute to sustainable food systems and resource conservation, ultimately benefiting both the environment and society.

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