Cleaner Food Systems 3 (2026) 100011

Contents lists available at ScienceDirect

Cleaner Food Systems

journal homepage: www.sciencedirect.com/journal/cleaner-food-systems

Food loss and waste in the environmental assessment of diets

Yanne Goossens *, Thomas G. Schmidt

Thünen Institute of Market Analysis, Bundesallee 63, 38116, Braunschweig, Germany

ARTICLE INFO

Keywords:
Food waste
LCA
Diet
System boundaries
Dietary data sources
Methodology

ABSTRACT

The impact of a diet can be calculated using a Life Cycle Assessment (LCA) approach. Food loss and waste (FLW) contribute significantly to the environmental impact of food products, yet this is not always adequately addressed in dietary impact studies. This paper presents a structured scenario analysis that examines how commonly used dietary data sources, system boundaries, and FLW assumptions interact and affect the calculated dietary impacts. Specifically, we examine scenarios formed by combining three methodological dimensions: (i) the dietary data used to define the diet (food intake, food expenditure, or food availability quantities), (ii) the system boundaries chosen for the environmental assessment (cradle-to-farm, cradle-to-retail, or cradle-to-consumer/farm-to-fork), and (iii) the inclusion or exclusion of FLW in the impact assessment, distinguishing between supply chain and consumer waste. To facilitate the analysis, we broke down the LCA calculations into simplified analytical formulae and investigated how the different combinations of these three dimensions (resulting in 21 possible scenarios) affected the LCA calculations. A case study on potato wedges is used as an illustrative example to demonstrate the practical implications of the different scenarios. We found that only one scenario could accurately calculate dietary impacts. For twelve scenarios, it is clear that the impacts would be under- or overestimated. For the remaining eight scenarios, it is less straightforward; we can only conclude that there is likely to be an under- or overestimation of the impacts without being able to say which. For the case study, the impacts ranged between an overestimation of 14 % and an underestimation of 88 %. The recommended approach for calculating dietary impacts is to use data representing food intake quantities (thus excluding any FLW quantities) and apply a farm-to-fork system boundary that considers FLW along the supply chain and at the consumer. If only food availability or expenditure data is available, the data must be converted to reflect food intake quantities. This paper highlights the importance of methodological choices related to dietary data and environmental assessments, and provides clear guidance to scientists in making transparent and consistent methodological decisions.

1. Introduction

Currently, approximately one third of all edible food intended for human consumption is lost or wasted throughout the food chain (FAO, 2019; UNEP, 2021). In 2020, about 1.05 billion tonnes of food were wasted globally at retail and by the consumer (including food services). This amounts to 132 kg pro capita, with the majority being lost at household level (UNEP, 2024). Furthermore, about 1.25 billion tonnes is lost in the supply chain before reaching the retail stage. According to Chen et al. (2020), the nutrients embedded in food wasted by an individual in a year could provide a nutritious diet for 18 days. The carbon and water footprints of global food loss and waste (FLW) are estimated to be approximately 3.3 billion tonnes of CO_2 eq. (excluding deforestation) and 250 km^3, respectively. Furthermore, nearly 30 % of global agricultural land (1.4 billion ha) is used to produce food that ultimately goes uneaten (FAO, 2013). The environmental impact of FLW depends heavily on the type of product lost or wasted along the chain, with animal-based products often having a greater environmental impact than plant-based products. For instance, meat accounts for less than 5 % of the global volume of FLW, but contributes over 20 % to its carbon footprint (FAO, 2015, 2013). The impact of FLW is further influenced by where along the food chain it occurs, as each product receives inputs from upstream processes. This leads to an accumulation of impacts as we move down the chain. Consequently, wasting 1 kg of vegetables at the producer level has a smaller environmental impact than if it were lost at the consumer level. Approximately 37 % of the carbon footprint of global FLW is generated at the consumption level, while this life cycle stage accounts for only 22 % of the total volume of global FLW (FAO,

* Corresponding author.
E-mail addresses: yanne.goossens@thuenen.de (Y. Goossens), thomas.schmidt@thuenen.de (T.G. Schmidt).

https://doi.org/10.1016/j.clfs.2025.100011
Received 9 September 2025; Received in revised form 18 December 2025; Accepted 23 December 2025
Available online 24 December 2025
3050-8355/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

2015, 2013).

Target 12.3 of the Sustainable Development Goals (SDGs) calls for global per capita food waste at retail and consumer level to be halved by 2030, as well as for food losses along production and supply chains (including post-harvest losses) to be reduced (UNGA, 2015). Reducing our FLW by 50 % across all food groups and stages of the food chain would mean that 10 % less food would need to be produced to cover current EU consumption levels (Sinkko et al., 2019). Reducing FLW along the supply chain and at the consumer has been proposed as one of the main solutions to reduce the impact of our diets (Foley et al., 2011; Poore and Nemecek, 2018; Springmann et al., 2018; Willett et al., 2019; WRI, 2019). While much is already being done to reduce FLW, much remains to be done to meet the SDG target of halving FLW by 2030 (Hoogeveen and Verghese, 2023; Lipinski, 2022; UN, 2022).

The environmental impact of food can be quantified using a life cycle approach. Goossens et al. (2019) calculated the environmental impacts associated with apples. They found that approximately 25 % of the climate change impacts of an apple can be attributed to apples that were lost along the supply chain (and thus never purchased) or to apples purchased but wasted by the consumer (and thus never consumed). Consequently, only 75 % of the impacts are attributable to the quantity actually consumed. Nevertheless, it appears that FLW is not always adequately addressed in LCA studies on food products, and greater transparency on this matter is required (Corrado et al., 2017). A shift in perspective from a single food item to an entire diet reveals that approximately 17 % of purchases by consumers in Germany ultimately result in food waste (Eberle and Fels, 2016). For an average US diet, food waste was found to contribute to approximately 28 % of the overall carbon footprint of a diet (Heller and Keoleian, 2014). The exclusion of the impacts of FLW from dietary impact calculations would thus result in an underestimation of the actual impact of a diet. In order to progress towards a more sustainable food system, it is essential to consider both the food that is consumed and the food that is not consumed but wasted instead. This was also emphasised by Helander et al. (2021) who examined the interplay between dietary modifications and FLW reduction strategies. On the one hand, a shift towards a healthier diet with a higher proportion of plant-based products (Foley et al., 2011; Poore and Nemecek, 2018; Springmann et al., 2018; Willett et al., 2019; WRI, 2019), could actually increase FLW (Conrad et al., 2018, 2020a, 2020b; Conrad, 2020; Conrad and Blackstone, 2021; Helander et al., 2021). On the other hand, many countries are currently consuming increased proportions of animal products (Drewnowski, 2000; Popkin, 2006) which, following their higher per unit impacts, could magnify the problem of FLW if these animal products go to waste (Porter et al., 2016). Thus, the differentiation in dietary patterns in terms of (impacts of) what is eaten, is to be complemented with (impacts associated with) what is not eaten.

The importance of considering consumer and/or supply chain waste when evaluating the environmental impact of diets is well recognised. Nevertheless, it remains unclear whether and how FLW is incorporated into studies examining the environmental impact of diets or dietary patterns (Goossens and Schmidt, 2025). For the purpose of their review study, Goossens and Schmidt (2025) analysed 12 existing review studies on methodological choices for evaluating the environmental impact of diets. Three out of these 12 review studies address the issue of how to best consider FLW. To ensure that FLW is duly considered, Heller et al. (2013), Hallström et al. (2015) and Mertens et al. (2017) all suggest using food availability estimates or adjusted consumption data rather than actual food intake quantities to calculate the environmental impact of a diet. Goossens and Schmidt (2025) however argue that this might be problematic since one could also consider FLW in the impact assessment itself, and it is not clear how this would affect the results. They therefore advocate for further investigation into methodological choices related to considering FLW in dietary impact calculations. To the best of our knowledge, no studies have yet systematically analysed how such methodological decisions interact and affect calculated dietary impacts. The present paper therefore presents a structured scenario analysis examining these interactions and their implications for dietary impact assessment. Through a theoretical scenario analysis and an illustrative case study, we aim at answering the following research question: Is using food availability data to define a diet (as suggested in literature) indeed the best approach to ensure FLW is accurately being accounted for? The paper concludes by presenting key messages and recommendations for best practice in the assessment of a diet's environmental performance, highlighting the importance of these methodological decisions and providing guidance to scientists on their appropriate application.

2. Background

As Goossens and Schmidt (2025) have highlighted, calculating the environmental performance of an entire diet requires a multidisciplinary approach that brings together environmental sciences and LCA, and public health and nutrition. Researchers conducting dietary impact assessments may therefore possess varying levels of expertise across these domains. To establish a common understanding for all readers, this background section provides a concise overview of a simplified food chain, the dietary data used to define a diet, as well as the main principles for calculating food impacts using the LCA approach.

2.1. Food loss and waste along the food chain

In this paper, we use the umbrella term FLW to refer to all food produced for human consumption that does not reach the consumer mouth, and we distinguish FLW by life-cycle stage (on-farm losses, supply chain FLW, and consumer FLW) rather than strictly following the policy distinction between “food loss” (pre-retail) and “food waste” (retail and consumption). Section (a) of Fig. 1 provides a simplified representation of a food chain, encompassing the farm stage [F], the supply chain [S], which includes storage, processing and retail, and the consumer stage [C], which includes purchase, preparation and consumption of the food. The life cycle stages (LCS) end either at the farm, retail or consumer gate, with the consumer gate referring to the moment the food is eaten. The system boundary in this study ends at the point of food consumption (the consumer gate); post-consumption processes such as human metabolism and wastewater treatment are outside the scope of the analysis. Throughout each stage of the food chain, food is lost and wasted. Losses occurring at the farm stage (i.e. on-farm losses) do not reach the farm gate and thus do not enter the post-harvest chain. FLW generated along the supply chain refers to harvested food that traverses part of the supply chain but does not reach the retail gate. This supply chain FLW can be generated during storage, processing, distribution, or any other sub-process of the supply chain. Consumer FLW refers to all food purchased by consumers that traverses part of the consumer stage but never reaches the consumer mouth (the consumer gate). This includes food that spoils during home storage, is wasted during preparation, or ends up as leftovers on plates. Both supply chain and consumer FLW are disposed of through incineration, composting, or anaerobic digestion, for example. On-farm losses, on the other hand, are often left on the field and thus do not require disposal. For analytical purposes, FLW is aggregated into three distinct flows, corresponding to the LCS at which the food leaves the system: on-farm losses (before the farm gate), supply-chain FLW (between the farm and retail gates), and consumer FLW (between the retail and consumer gates). Although FLW may occur at any point along a food's life cycle, it is measured and accounted for at three points in the present analysis as shown in Fig. 1a.

Section (b) of Fig. 1 enables us to examine the quantities of food traversing the food chain in more detail. Q_F refers to harvested food leaving the farm gate and thus excludes the on-farm losses. Since food is lost and wasted along the chain, the quantity of food Q_F harvested and leaving the farm gate is greater than the quantity Q_S leaving the supply chain at the retail gate and purchased by consumers. This quantity, in turn, is greater than the quantity Q_C that is prepared and consumed by

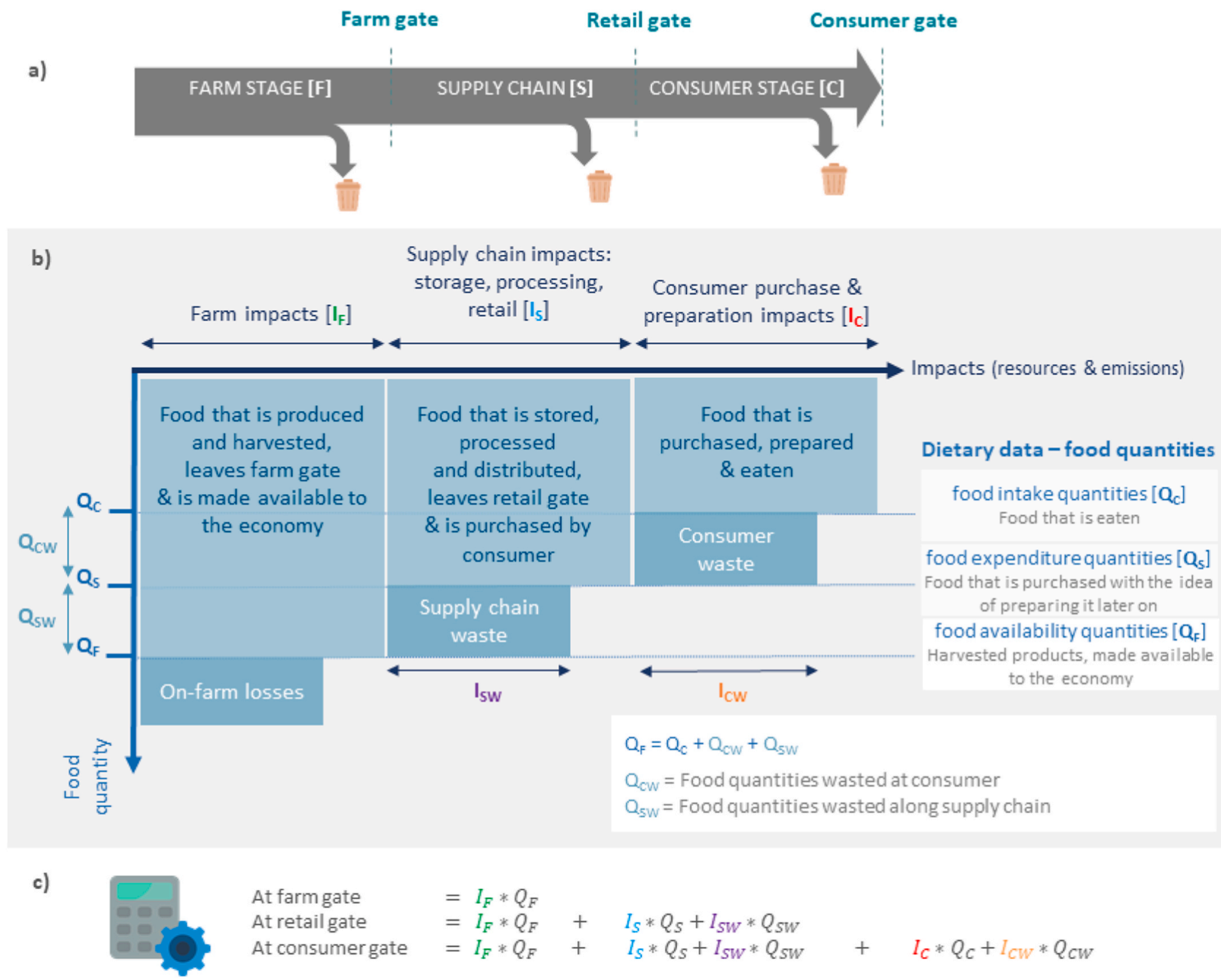

Fig. 1. Illustration of the food chain and subsequent impact calculations: a) A simplified food chain encompassing a farm stage, supply chain and consumer stage; b) Food quantities traversing the food chain (with pre-harvest losses shown outside the mass balance), related dietary data quantities and impacts generated in each life cycle stage; c) Formulae for calculating food chain impacts.

the consumer and thus reaches the consumer gate, or the consumer's mouth. The difference in food quantities can be referred to as Q_{SW} (supply chain waste) and Q_{CW} (consumer waste). Therefore, $Q_F = Q_C + Q_{CW} + Q_{SW}$ and $Q_S = Q_C + Q_{CW}$. Thus, in order to consume a quantity of food Q_C, a larger quantity of food Q_F must be harvested and traverse the food chain to account for FLW. If there were zero food waste ($Q_{SW} = Q_{CW} = 0$), the quantities of food would remain constant throughout the food chain. However, this does not reflect reality (FAO, 2019; UNEP, 2021).

2.2. Dietary data employed to define a diet

Several dietary data sources can be used to formulate a diet. As Goossens and Schmidt (2025) state, the most prevalent data sources used in literature are food intake, food expenditure, and food availability data. Food intake data, such as that derived from nutrition surveys or food diaries, refers to the quantity of food actually consumed by the individual. It excludes any food quantities that have been discarded as consumer or supply chain waste. Therefore, this represents the quantity of food Q_C at the consumer gate in Fig. 1b. Food expenditure data refers to the quantity of food purchased by the consumer. Consequently, it represents the quantity of food Q_S that leaves the retail gate, including the quantity of food classified as consumer waste. Food availability data represents the quantity of food Q_F made available to the economy at the farm gate (i.e. harvested food leaving the farm). This includes food that will subsequently become supply chain and consumer waste.

The review by Goossens and Schmidt (2025) shows that some scholars adjust dietary data to include or exclude supply chain and/or consumer waste before calculating the dietary impact. Therefore, the quantities of food actually used to define the diet may differ from those represented by the dietary data sources. Following these adjustments, the three most commonly used dietary quantities in literature are: food intake quantities (Q_C); food intake quantities complemented with consumer waste and thus equal to expenditure quantities (Q_S); and food intake quantities supplemented with both supply chain and consumer waste which are equal to food availability quantities at the farm gate (Q_F). Because only 2 % of the 301 papers reviewed by Goossens and Schmidt (2025) define diets using food intake quantities complemented with supply chain FLW (but not consumer FLW), this combination is not considered further in the present paper.

2.3. Main principles for calculating the impact of a food product

Building on the dietary quantities defined in Section 2.2 and illustrated in Fig. 1b, this section describes how environmental impacts are calculated using the LCA equations shown in Fig. 1c under different system boundaries. Throughout the food chain, the production, supply and preparation of food requires resources and generates emissions. Fig. 1b shows the per unit impacts associated with the inputs and outputs for each LCS: I_F, I_S and I_C for the farm stage, supply chain and consumer stage, respectively. Each food item we consume, carries with it the accumulated impacts of the entire food chain. To calculate these impacts, we consider each LCS by multiplying the relevant quantity of food in that LCS by the associated per unit impacts. All LCS impacts across all LCS are then summed. Note that, for simplicity, transport within and between LCS is not depicted in Fig. 1b, even though its impact would also need to be accounted for.

In the event of food waste, the food that becomes FLW traverses only a part of the food chain. Therefore, impacts are generated only along the part of the LCS, up until where the food becomes FLW. Since FLW needs to be disposed of, additional disposal impacts are generated along the supply chain or at the consumer stage. The per unit impacts associated with food waste generated along the supply chain or by consumers (indicated by I_{SW} and I_{CW}) thus consist of the impacts accumulated along part of the chain up to the point at which the food becomes waste, as well as the disposal impacts at that LCS.

The LCS that need to be considered, and thus the impacts and FLW streams that are included, depend on the chosen system boundary for the assessment. The three main system boundaries identified in the literature are: cradle-to-farm, cradle-to-retail and cradle-to-consumer (or farm-to-fork) (Goossens and Schmidt, 2025). The cradle-to-farm approach focuses exclusively on the field (or livestock) stage, with impacts calculated up to the farm gate for a quantity of food Q_F leaving the farm gate. For the environmental assessment of the farm stage, all agricultural inputs and emissions resulting in the output of both harvested produce and unharvested crops or other on-farm losses are accounted for. On-farm losses are hereby typically not modelled as separate waste flows; instead, they are implicitly considered by attributing the impacts of discarded or unharvested crops to the net yield (Corrado et al., 2017). Furthermore, for simplicity, additional disposal impacts are often considered negligible and therefore excluded (Corrado et al., 2017). The cradle-to-retail approach complements farm stage impacts with impacts generated throughout the post-harvest stages of the food supply chain, including storage, processing, packaging, distribution and retail. Consequently, impacts are calculated for a food quantity Q_S at the retail stage. Also included are impacts related to supply chain waste and their disposal. In the cradle-to-consumer or farm-to-fork approach, impacts are calculated up to the point of final intake of the food, for a quantity Q_C leaving the consumer gate (i.e. being consumed). This involves adding the impacts related to consumer transport, storage, preparation and food waste to those considered in the cradle-to-retail approach.

Since supply chain waste occurs during the post-harvest supply chain, this FLW stream can only be considered in assessments that actually incorporate this LCS, such as the cradle-to-retail or the cradle-to-consumer approach. Similarly, consumer waste can only be considered if the consumer LCS is included, which is the case for a farm-to-fork approach. In contrast, a cradle-to-farm assessment, does not allow supply chain or consumer FLW to be assessed. On-farm losses are typically accounted for in an implicit way, as discussed above.

In line with the main principles of an LCA outlined above, Fig. 1c presents the formulae used to calculate the environmental impacts of a single food product under each of the three system boundaries considered in this study. Further details are provided in Section 4.1.

3. Methods for the scenario-analysis

3.1. Scenarios under study

In order to investigate the interplay between dietary data, system boundaries and FLW, we will focus on the three variables introduced in the previous background section: (i) the dietary data quantities used to define the diet (Section 2.2), (ii) the system boundaries of the environmental assessment (Section 2.3), and (iii) the inclusion or exclusion of supply chain and consumer FLW within the assessment (Sections 2.1 and 2.3). Table 1 lists the values studied for each of these three variables. In theory, 21 scenarios could be investigated, combining all possible values of the three variables. For practical reasons, however, this paper only discusses four of these scenarios in detail (see Table 2); the analysis for the remaining scenarios can be found in the supplementary materials. However, a final assessment of all scenarios is presented in the paper.

3.2. Theoretical analysis based on LCA formulae

To facilitate the scenario analysis, we first break down the food LCA calculations into simplified analytical formulae and demonstrate how they can be applied to assess an entire diet. These formulae follow the logic explained in the background section: for each LCS, we multiply the relevant quantity of food in that LCS by the associated per unit impacts; afterwards, all impacts across the different LCS are summed. We then examine the three system boundaries considered for the environmental assessment, identify the LCS included under each system boundary, and assess the implications for the impact calculations. From there, we identify the most appropriate system boundary for evaluating a diet's environmental performance and establish this as the reference scenario.

Subsequently, we examine the quantities of food traversing the food chain for which impacts are being calculated. These quantities are determined by the dietary data used to define the diet (Section 2.2), the system boundary (Section 2.3), and the inclusion or exclusion of FLW. We therefore adapt the formulae from the first step to reflect these combinations of methodological choices and compare the resulting impacts with those of the reference scenario. This reformulation of the LCA formulae enables a consistent assessment of each individual scenario.

3.3. Case study: potato wedges

To illustrate the calculations for the various scenarios, we apply the formulae to a case study and calculate the associated carbon footprint (expressed in grams of CO_2 equivalent). For this case study, we chose fried potato wedges as this product generates distinct impacts across each of the three main LCS depicted in Fig. 1: farm stage impacts for producing the potatoes, post-harvest impacts for cutting and freezing the potatoes, and finally consumer impacts for freezing and deep-frying the wedges. Furthermore, it can easily be assumed that FLW occurs along the chain, both at the supply chain (retail losses) and at consumer level

Table 1
The variables and their respective values used in the scenario analysis.

Variable	Values under study
Dietary data quantities used to formulate a diet	- Food intake quantities - Food expenditure quantities - Food availability quantities
System boundaries for the environmental assessment	- Up to farm gate: cradle-to-farm - Up to point of sale: cradle-to-retail - Up to consumer mouth: cradle-to-consumer (farm-to-fork)
Inclusion of FLW into the environmental assessment (depending on system boundary)	- In-/or exclusion of supply chain waste - In-/or exclusion of consumer waste

Table 2
Characteristics of the four scenarios under study in the main manuscript.

Scenario	System boundaries for the environmental assessment	Dietary data quantities used to formulate the diet	Inclusion of FLW into the environmental assessment
1	Farm-to-fork	Food intake quantities	Inclusion of supply chain and consumer waste
2	Farm-to-fork	Food availability quantities	Inclusion of supply chain and consumer waste
3	Farm-to-fork	Food availability quantities	Exclusion of both supply chain and consumer waste
4	Cradle-to-farm gate	Food availability quantities	Not applicable[a]

[a] Supply chain and/or consumer waste can only be considered if the respective life cycle stages in which these waste streams are generated are included in the assessment, which is not the case for a cradle-to-farm approach.

Table 3
Formulae for calculating the food chain impacts of a single food product under each of the three system boundaries considered in this study.

System boundary	Formula for the impact calculation for a single food product
(a) Original formulae, based on LCA principles	
Cradle-to-farm	$= \textit{farm stage impacts}$
	$= I_F{*}Q_F$
Cradle-to-retail	$= \textit{farm stage impacts} + \textit{supply chain impacts}$
	$= I_F{*}Q_F + I_S{*}Q_S + I_{SW}{*}Q_{SW}$
Farm-to-fork	$= \textit{farm stage impacts} + \textit{supply chain impacts} + \textit{consumer impacts}$
	$= I_F{*}Q_F + I_S{*}Q_S + I_{SW}{*}Q_{SW} + I_C{*}Q_C + I_{CW}{*}Q_{CW}$
(b) Formulae rewritten as a function of the food quantity that leaves the respective gate	
Cradle-to-farm	$= I_F{*}\boldsymbol{Q_F}$
Cradle-to-retail	$= I_F{*}(Q_S + Q_{SW}) + I_S{*}Q_S + I_{SW}{*}Q_{SW}$
	$= (I_F + I_S) * \boldsymbol{Q_S} + (I_F + I_{SW}){*}Q_{SW}$
Farm-to-fork	$= I_F{*}(Q_C + Q_{CW} + Q_{SW}) + I_S{*}(Q_C + Q_{CW}) + I_{SW}{*}Q_{SW} + I_C{*}Q_C + I_{CW}{*}Q_{CW}$
	$= (I_F + I_S + I_C) * \boldsymbol{Q_C} + (I_F + I_S + I_{CW}){*}Q_{CW} + (I_F + I_{SW}){*}Q_{SW}$

Legend: Q_F, Q_S and Q_C denote the quantities of food leaving the farm stage (at the farm gate), the supply chain (at the retail gate) and the consumer stage (at the consumer gate), respectively; Q_{SW} and Q_{CW} denote the quantities of food that become supply chain or consumer waste; I_F, I_S and I_C represent the per unit impact (following resource use and emissions) associated with food reaching the end of a life cycle stage with impacts generated in the farm stage (F), the supply chain (S) and the consumer stage (C), respectively; and I_{SW} and I_{CW} represent the per unit impact associated with food becoming food waste along the supply chain or at the consumer stage. These impacts include both those generated along the LCS up to the point at which the food becomes waste and those associated with subsequent waste disposal.

(plate waste). The case study is used for illustrative purposes only and does not aim to represent the entire range of food products consumed within a diet.

We assume a consumer (or household) buys one bag (600 g) of frozen potato wedges with skin and fries them at home. After accounting for 10 % plate leftovers, the consumer eats 540 g ($=Q_C$) of the 600 g ($=Q_S$) purchased. Following 5 % retail losses, 632 g ($=Q_F$) of potatoes had to leave the farm gate and enter the post-harvest chain.

For the calculations, we use a dataset from Agribalyse 3.1 (ADEME-INRAE, 2022) on frozen French fries which were intended for deep frying by consumers. For simplicity, we neglect the raw-to-cook ratio which Agribalyse sets at 0.7. If this ratio were applied, only 420 g of potato wedges would be left after frying ($=0.7 * 600$ g), of which the consumer would eat 378 g while wasting 42 g. To focus the scenario analysis on avoidable consumer losses (e.g. plate leftovers), rather than unavoidable raw-to-cook losses, this ratio is not considered here. Additional adaptations to the dataset were performed (see Supplementary materials). Impact calculations were performed using SimaPro 9.5 and Excel.

4. Results and discussion

4.1. Breaking down a food LCA into formulae

In line with Fig. 1 and the background section, the formulae presented in Table 3(a) demonstrate how the impacts associated with a single food product are calculated for each of the three system boundaries under study. Since diets generally consist of various food items, these formulae are applied to each food product included in the diet, after which the impacts are aggregated to obtain the total dietary impact.

4.2. Relevance of system boundaries

As can be seen from Table 3(a), a focus solely on the farm stage (i.e. a cradle-to-farm approach) would likely result in lower impacts than a cradle-to-retail or farm-to-fork approach. The impact calculations for each of the three system boundaries would only yield the same results if all impact factors except I_F equalled zero (meaning there would be no impacts generated in the post-harvest supply chain, at the consumer stage or for food waste disposal). This could, for example, be true for food bought directly from a farm, that does not pass through the supply chain, for which no consumer transport, storage or preparation impacts are generated, and which is eaten in its entirety, without any food waste occurring. In all other cases, impacts calculated using the cradle-to-farm approach would underestimate the actual impacts of the food item under study. While certain foods consumed as part of a diet may qualify as such an exception, it is highly unlikely that all foods consumed as part of a diet would be purchased at a farm shop as raw commodities for which no post-harvest or preparation processes took place. Therefore, omitting the post-harvest supply chain stage and/or the consumer stage from a dietary assessment would result in an underestimation of the diet's environmental impact.

In literature, impacts arising during the post-harvest supply chain and the consumer stage are often omitted from assessments (Goossens and Schmidt, 2025), as it is believed that the resulting underestimation of impacts is negligible. However, the review by Goossens and Schmidt (2025) showed through a quick check of the Agribalyse 3.1. environmental database (ADEME-INRAE, 2022) that these post-harvest impacts are not always negligible. This was particularly true for plant-based products. Furthermore, Subedi et al. (2024) concluded that the production stage is definitely a critical carbon footprint hotspot for fruits, but not the only one. Furthermore, Pernollet et al. (2017) found that omitting the consumer stage led to a 30 % underestimation of the climate change impact of the French diet. Excluding both the post-harvest supply chain and the consumer stage resulted in an underestimation of 70 %. Therefore, within the context of this study, the farm-to-fork approach is identified as the most appropriate system boundary for calculating dietary environmental impacts, and the corresponding formulae in Table 3 serve as the reference for the subsequent scenario analysis.

4.3. Relevance of food quantities and consideration of FLW

The next step is to examine the food quantities for which impacts are being calculated and their respective impact factors. From a purely analytical perspective, any changes to the impact factors and/or food quantities within the reference formula would result in the impact of the food item under study being either over- or underestimated. This problem of over- or underestimation is magnified at the dietary level, as the same methodological choices are applied to all food items consumed. This highlights the importance of using food quantities and impact factors that are consistent with the chosen system boundary when calculating dietary impacts, as illustrated by the subsequent scenario analysis.

The chosen system boundary determines the gate at which impacts are calculated (farm gate, retail gate or consumer gate) and the corresponding food quantity for which impacts are calculated (respectively Q_F, Q_S and Q_C). Each formula in Table 3a can be rewritten as a function of this particular food quantity, resulting in the expressions presented in Table 3b. The food quantity for which impacts are calculated under each system boundary is indicated in bold in Table 3b. For both the cradle-to-retail and farm-to-fork approaches, the formula contains one or two additional terms that are functions of the food quantities Q_{cw} and Q_{SW}, representing food that is wasted along the chain and never reaches the gate defining the system boundary. The rewritten formulae facilitate the analysis of the effect of using different dietary data quantities to define a diet. When impacts are calculated for a food quantity other than the one in bold, that quantity is substituted accordingly. If one or both food waste streams are excluded from the environmental assessment, the respective food quantity (Q_{cw} and/or Q_{SW}) is set to zero. To facilitate comparison with the reference formula, expressed as a function of Q_C, Q_{CW} and Q_{SW}, the resulting formulae for each scenario are expressed as a function of these food quantities. The impact factors associated with each food quantity are then compared with those in the reference scenario.

Scenarios 1 to 3 are based on a farm-to-fork approach and therefore correspond to the last formulae in Table 3a or b. Scenario 4, which is based on a cradle-to-farm approach, should follow the first formula.

Scenario 1 is based on a diet defined by food intake quantities (represented by Q_C) and takes into account both supply chain and consumer food waste (= Q_{CW} and Q_{SW}). This means that the formula in Table 3 remains unchanged, ensuring that impacts are calculated correctly. Therefore, scenario 1 is equivalent to the reference scenario.

In **Scenario 2**, which is also based on the farm-to-fork approach, food availability quantities are used to define the diet, represented by Q_F (with $Q_F = Q_C + Q_{CW} + Q_{SW}$). This scenario considers both supply chain and consumer food waste (Q_{CW} and Q_{SW}). The bold value Q_c in Table 3b is therefore replaced with Q_F, while the food waste quantities Q_{CW} and Q_{SW} are retained. Next, we rewrite the formula as a function of the food quantities Q_C, Q_{CW} and Q_{SW}, as shown in Table 4. While the impact factors for Q_C remain unchanged, those associated with the two food waste streams increase relative to the reference scenario. As a result, this scenario leads to an overestimation of a diet's environmental impact.

Scenario 3 can be seen as an attempt to avoid overestimation by excluding consumer and supply chain waste from the assessment. This is based on the argument that the dietary data quantities used (food availability quantities Q_F) already include these quantities of waste. To achieve this, we need to adapt the farm-to-fork formula in Table 3(b) by setting the food waste streams Q_{CW} and Q_{SW} to zero while again replacing the bold value with Q_F, as was done in Scenario 2. The resulting formula in Table 4 shows that the resulting impact factors for the two food waste streams are not necessarily equal to those in the reference scenario, which can result in either an under- or over-estimation of the impacts. The formula would only yield correct results if both $I_C = I_{CW}$ as well as $I_S + I_C = I_{SW}$ for all foods consumed in the diet. Alternatively, correct results could arise if the overestimations for certain foods exactly offset underestimations for others. In practice, however, some degree of under- or overestimation is very likely, with the direction depending on the specific values of the impact factors. When using food availability quantities (Q_F) as dietary data, a farm-to-fork assessment may not be the most appropriate approach.

In **Scenario 4,** we examine whether combining food availability quantities (Q_F) with a cradle-to-farm approach yields more consistent results. For this, we use the formula from Table 3 for the cradle-to-farm approach. The resulting expression (Table 4) contains impact factors that are uniformly lower than those in the reference scenario, which leads to an underestimation of the calculated dietary impact.

Table 4
Formulae for the impact calculations of the four scenarios under study. The characteristics of each scenario can be found in Table 2.

Scenario	Formula for the impact calculation for each scenario under study
Scenario 1	$= (I_F + I_S + I_C) * \mathbf{Q_C} + (I_F + I_S + I_{CW})*Q_{CW} + (I_F + I_{SW})*Q_{SW}$
Scenario 2	$= (I_F + I_S + I_C) * \mathbf{Q_F} + (I_F + I_S + I_{CW})*Q_{CW} + (I_F + I_{SW})*Q_{SW}$ $= (I_F + I_S + I_C) * (Q_C + Q_{CW} + Q_{SW}) + (I_F + I_S + I_{CW})*Q_{CW} + (I_F + I_{SW})*Q_{SW}$ $= (I_F + I_S + I_C) * Q_c + (2*I_F + 2*I_S + I_{CW} + I_C)*Q_{CW} + (2*I_F + I_{SW} + I_S + I_C)*Q_{SW}$
Scenario 3	$= (I_F + I_S + I_C) * \mathbf{Q_F} + (I_F + I_S + I_{CW})*0 + (I_F + I_{SW})*0$ $= (I_F + I_S + I_C) * (Q_C + Q_{CW} + Q_{SW})$ $= (I_F + I_S + I_C) *Q_C + (I_F + I_S + I_C) * Q_{CW} + (I_F + I_S + I_C) * Q_{SW}$
Scenario 4	$= I_F*\mathbf{Q_F}$ $= I_F* (Q_c + Q_{cw} + Q_{SW})$ $= I_F* Q_c + I_F* Q_{cw} + I_F* Q_{SW}$

4.4. Application to the case study of fried potato wedges with skin

In line with the formulae from Table 3, the cradle-to-farm impact of consuming one bag of potato wedges whilst wasting 10 % as plate leftovers was found to be 58.09 g CO_2 eq., whereas the cradle-to-retail impact was 394.35 g CO_2 eq., and the farm-to-fork impact 486.22 g CO_2 eq. This means that the cradle-to-farm approach results in impacts that are 88 % lower than the reference (farm-to-fork) approach, which leads to a considerable underestimation of impacts. For the cradle-to-retail approach, the underestimation is 20 %. This example clearly demonstrates the importance of considering all stages of the product's life cycle, particularly when the product is kept frozen throughout the supply chain and at the consumer stage before being deep-fried.

Impacts can then be calculated for the four scenarios listed in Table 4. Scenario 1 (equalling the reference scenario) results in 486.22 g CO_2 eq., Scenario 2 in 555.36 g CO_2 eq., Scenario 3 in 476.81 g CO_2 eq., and Scenario 4 in 58.09 g CO_2 eq. As expected, Scenario 2 resulted in an overestimation of the impacts (+14 % as compared to the reference Scenario 1), and Scenario 4 in an underestimation (−88 %). For Scenario 3, both an over- or an underestimation of the impacts would theoretically be possible. In the case of the potato wedges, a small underestimation (−2 %) was found.

4.5. Overview of all possible scenarios

Similarly, the other scenarios (i.e. combinations of the variables in Table 1) can be investigated. A summary of the 21 scenarios is provided in Table 5. The first scenario, which combines food intake amounts with a farm-to-fork approach that considers FLW, is considered a correct calculation of the impact of a diet, as it follows the LCA formulae from Table 3 and considers all life cycle stages. As such, it serves as the reference scenario and is indicated as “REF”. The formulae representing the other scenarios were rewritten as a function of the food quantities Q_C, Q_{CW} and Q_{SW} to facilitate comparison with the reference scenario (see the Supplementary information for a detailed overview of these formulae). Table 5 shows the evaluation of the impact factors associated with each of these three food quantities, together with an overall analysis indicating whether an over- or underestimation of the dietary impacts is to be expected based on these impact factors. In some cases, the direction of the bias cannot be determined unambiguously, as it depends on the specific values of the impact factors.

As can be seen from Table 5 (Column “Resulting impact”), only the reference scenario results in the correct calculation of dietary impacts. Any other combination of dietary data quantity, system boundary, and FLW inclusion would likely lead to under- or overestimation of dietary impacts. For ten of the remaining 20 scenarios, it is evident that the impacts would be underestimated, while in two scenarios, they would be overestimated. For the remaining eight scenarios, it is less straightforward and we can only conclude that there is likely to be an under- or

Table 5
Overview of all scenarios. The impact factors and resulting impacts for each scenario were evaluated based on the formulae shown in the Supplementary Materials. The last two columns show the carbon footprint (g CO_2 eq.) associated with eating 540 g of potato wedges, as well as the percentage difference of each scenario compared to the reference scenario.

Environmental assessment		Dietary data quantity used to define the diet	Impact factors associated with each food quantity in the formula			Resulting impact	Carbon footprint (g CO_2 eq.)	Difference with reference scenario
System boundary	Inclusion of FLW		Q_c	Q_{CW}	Q_{SW}			
Cradle-to-consumer (farm-to-fork)	Inclusion of both supply chain and consumer FLW	Food intake quantities *(1)	★	★	★	✓	486.22	REF
		Food expenditure quantities	★	▲	★	△	531.52	9 %
		Food availability quantities (2)	★	▲	▲	△	555.36	14 %
	Inclusion of supply chain FLW, exclusion of consumer FLW	Food intake quantities	★	▼	★	▽	429.54	−12 %
		Food expenditure quantities	★	■	★	△▽	474.83	−2 %
		Food availability quantities	★	■	▲	△▽	498.67	3 %
	Exclusion of supply chain FLW, inclusion of consumer FLW	Food intake quantities	★	★	▼	▽	464.35	−4 %
		Food expenditure quantities	★	▲	▼	△▽	509.65	5 %
		Food availability quantities	★	▲	■	△▽	533.49	10 %
	Without any FLW	Food intake quantities	★	▼	▼	▽	407.67	−16 %
		Food expenditure quantities	★	■	▼	△▽	452.97	−7 %
		Food availability quantities (3)	★	■	■	△▽	476.81	−2 %
Cradle-to-retail	Inclusion of supply chain FLW	Food intake quantities	▼	▼	★	▽	357.10	−27 %
		Food expenditure quantities *	▼	▼	★	▽	394.35	−19 %
		Food availability quantities	▼	▼	▲	△▽	413.95	−15 %
	Without any FLW	Food intake quantities	▼	▼	▼	▽	335.23	−31 %
		Food expenditure quantities	▼	▼	▼	▽	372.48	−23 %
		Food availability quantities	▼	▼	■	△▽	392.08	−19 %
Cradle-to-farm	FLW cannot be included	Food intake quantities	▼	▼	▼	▽	49.66	−90 %
		Food expenditure quantities	▼	▼	▼	▽	55.18	−89 %
		Food availability quantities *(4)	▼	▼	▼	▽	58.09	−88 %

Scenarios marked with an asterisk (*) are standard practice for an LCA with the chosen system boundaries, while those marked with a number in brackets refer to the four scenarios studied in the main manuscript. Legend for the symbols used: Impact factors associated with the FQs (as compared to the REF. situation): ★ Impact factors are correct; ▲ Impact factors too high; ▼ Impact factors too low (or equal to zero); ■ Impact factors are different; not possible to say beforehand if the net impact factor would be too high or too low. Resulting impacts: ✓ Impacts calculated correctly; ▽ Underestimation of impacts; △ Overestimation of impacts; △▽ Over-/underestimation of impacts; net effect unclear.

overestimation of the impacts without being able to say which it would be. In the rare event that the underestimation from the low impact factors equals the overestimation from the high impact factors, the final calculated dietary impacts would be correct. However, such situation is highly unlikely. It would be even more unlikely for this event to occur for multiple food items and/or for multiple impact categories. Therefore, it would be unwise to recommend this approach for an entire diet, in the hope that underestimation in one part of the formula would be offset by overestimation in another.

To illustrate the effect of each scenario, the last two columns of Table 5 show the calculated carbon footprint of eating 540 g of potato wedges in each scenario, and how these values differ from the reference scenario. Results range from an overestimation of up to 14 %, based on food availability quantities combined with a farm-to-fork approach considering both FLW streams, to an underestimation of 88 %, based on food intake quantities combined with a cradle-to-farm approach considering neither FLW stream. The magnitude of the over- or underestimation hereby depends on the waste percentages assumed at consumer level and along the supply chain. How these affect the result for this specific case study, can be found in the sensitivity analysis in the supplementary analysis (Table S4, Table S5).

It should further be noted that the differences with the reference scenario (as shown in the last column of Table 5) depend heavily on the food product and impact category chosen and thus do not necessarily reflect the extent of over- or underestimation that can be expected when calculating the impact of an entire diet. The two last columns of Table 5 should therefore not be interpreted as valid for, or applicable to, all food products but merely illustrate the expected over-/underestimations for the case study of frozen potato wedges under the assumption of 10 % consumer FLW and 5 % retail FLW. What is applicable across food products, however, is the information provided in the “Resulting impact” column, which indicates whether an over- or underestimation is to be expected. The magnitude of this over- or underestimation then depends on the product under consideration.

Even though there is only scenario that accurately calculates the impacts, there may still be some uncertainty surrounding the calculated dietary impact. This uncertainty stems from the data that is used to calculate the impacts, namely the food quantities Q_i and the impact factors I_i. Any uncertainty in the underlying life cycle inventory or life cycle impact assessment will thus contribute to the uncertainty of the final result.

4.6. Implications for food systems research

With food systems sitting at the nexus of health, environment, climate, and justice (Rockström et al., 2025), the composition of our diet is key to moving towards a more sustainable food system. The last few years have seen an increase in the number of papers looking into the environmental impact of diets (Goossens and Schmidt, 2025). At the same time, literature emphasises the contribution of FLW to the environmental impacts of our food system (FAO, 2015, 2013). As such, it is particularly important to properly and consistently account for FLW when assessing the environmental impact of a diet.

The analysis above allows us to answer our research question on whether a diet defined by food availability data is indeed the best approach to ensure FLW is accurately being accounted for. At first sight, it seems logical that using food availability data is a good approach, since this data already includes the FLW quantities we want to consider in our assessment. However, our detailed analysis shows that this approach leads to an overestimation of dietary impacts when applying a farm-to-fork approach that considers FLW, or to an under- or overestimation when other combinations of system boundaries and FLW inclusion are used. Our findings therefore challenge the generally accepted approach for considering FLW. Instead, the analysis shows that only the scenario in which food intake quantities are used, in combination with a farm-to-fork assessment that considers both supply chain and consumer FLW, results in an accurate calculation of dietary impacts.

5. Conclusions and recommendations

Including FLW in the calculation of dietary environmental performance significantly affects the results. The exact method of including FLW depends on the chosen system boundary and the dietary data quantities used to describe the diet. The interplay between the dietary data quantities used to build the diet, the chosen system boundary, and whether or not FLW is considered in the assessment determines both which food quantities impacts are calculated for and how impacts are assigned to these food quantities.

In theory, there are different approaches to consider FLW when calculating the environmental performance of a diet: it can be included in the dietary data used to define the diet, and/or in the impact assessment itself. In dietary data, food intake quantities refer to the food actually eaten by consumers and thus exclude both consumer and supply chain waste. Food expenditure quantities refer to the quantity of food purchased by the consumer. As such, they include food that will later end up as consumer waste. Food availability quantities represent the quantity of food made available to the economy and thus include food that will later end up as consumer and supply chain waste. Whether FLW can be included in the impact assessment itself depends on the chosen system boundaries: consumer and supply chain waste can only be considered if the life cycle stages where the FLW stream occurs are included in the assessment. Furthermore, the system boundaries determine where along the chain the impacts are calculated. In a cradle-to-farm gate study, for example, impacts are calculated for a certain quantity of food at the farm gate. In a cradle-to-retail or cradle-to-consumer study, impacts are calculated for a certain quantity of food at the retail or consumer gate, respectively. Whether or not FLW is included in the assessment determines which food quantities are assumed to traverse the food chain and how impacts are assigned to these quantities. This was investigated by breaking down a food assessment into formulae and applying them to each scenario.

Excluding one or more post-harvest stages will always result in an underestimation of the actual dietary impact. Therefore, a farm-to-fork approach is considered crucial. If FLW is considered as part of the dietary data (as suggested in the literature), and in the environmental assessment, the calculations assume that an unrealistically high quantity of food enters the food chain. This results in impact factors that are too high, leading to an overestimation of impacts. Excluding FLW from environmental calculations would prevent this overestimation. However, this would not be a correct calculation and an under- or overestimation of the impact would be likely. The only way to accurately calculate the environmental impact of a diet is therefore to use food intake quantities that exclude supply chain and consumer waste, and to apply a farm-to-fork approach that considers both supply chain and consumer waste. A case study illustrates the over- or underestimation of impacts to be expected for frozen potato wedges. The magnitude of the over-/underestimation is highly dependent on the food product under consideration.

In practice, researchers often only have access to one set of dietary data. If the data base is limited to food availability or expenditure data, we recommend converting these quantities into intake quantities using food waste data. Litearature data on food waste can be used for this purpose, such as data from the Food and Agriculture Organisation of the United Nations or the United Nations Environment Programme (Gustavsson et al., 2011; FAO, 2019; UNEP, 2021), as well as national statistics on FLW. For consumer FLW, specific data may also be found in grey literature, as is the case for German households (GfK, 2021).

The present paper explores how methodological decisions relating to dietary data quantities, the environmental assessment's system boundaries, and the inclusion of FLW affect the calculation of the impact of a diet. Greater transparency regarding how FLW is considered in dietary impact calculations would enable a more accurate interpretation of study findings, including whether an under- or overestimation of impacts is to be expected. Adopting a more harmonised approach to assessing the environmental performance of diets, based on the recommendations made in this paper, would overcome this hurdle and enable more comparable study findings.

Furthermore, adopting such a harmonised approach would allow for more robust and reliable calculations of dietary environmental impact. This is particularly important when modelling or monitoring the environmental effects of dietary changes in our transition towards a more sustainable food system. Modelling or monitoring based on inappropriate methodological choices, can lead to systematic under- or overestimation of impacts, which may negatively affect policy making. Policies based on an overestimated environmental impact of our diet can lead to overly strict regulations, economic inefficiency, and public resistance, as resources may be diverted from more effective areas. Conversely, underestimating impacts can result in weak or ineffective policies, missed climate goals, and continued environmental degradation. In both cases, policy credibility suffers. Accurate, transparent and evidence-based assessments are therefore essential to design fair, effective, and adaptive food and environmental policies.

CRediT authorship contribution statement

Yanne Goossens: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Thomas G. Schmidt:** Writing – review & editing, Supervision, Conceptualization.

Supplementary information

Supplementary Information. This file contains information on the case study on potato wedges and on the formulae associated with the scenarios.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepL Write in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements and funding sources

This paper was financed with special funds of the German Federal Ministry of Agriculture, Food and Regional Identity (BMLEH), within the framework of the COPLANT project (Cohort-Study on Plant-based Diets). The funder of the project had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The graphical abstract has been designed using resources from Flaticon.com (icons from flatart_icons, Icongeek26, Freepik, iconsmeet and Cursor Creative).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clfs.2025.100011.

Data availability

No data was used for the research described in the article.

References

ADEME-INRAE, 2022. Agribalyse 3.1. Retrieved 06/10/2022 from the Agribalyse homepage at. https://doc.agribalyse.fr/documentation-en/agribalyse-data/data-access.

Chen, C., Chaudhary, A., Mathys, A., 2020. Nutritional and environmental losses embedded in global food waste. Resour. Conserv. Recycl. 160, 104912. https://doi.org/10.1016/j.resconrec.2020.104912.

Conrad, Z., 2020. Food waste, healthy diets, and environmental sustainability: a guide for nutritionists. Nutr. Today 55, 5–10. https://doi.org/10.1097/NT.0000000000000390.

Conrad, Z., Blackstone, N., Roy, E., 2020a. Diet quality and environmental sustainability are linked, but in unexpected ways. Curr. Dev. Nutr. 4, 4140137. https://doi.org/10.1093/cdn/nzaa042_002.

Conrad, Z., Blackstone, N.T., 2021. Identifying the links between consumer food waste, nutrition, and environmental sustainability: a narrative review. Nutr. Rev. 79, 301–314. https://doi.org/10.1093/nutrit/nuaa035.

Conrad, Z., Blackstone, N.T., Roy, E.D., 2020b. Healthy diets can create environmental trade-offs, depending on how diet quality is measured. Nutr. J. 19, 117. https://doi.org/10.1186/s12937-020-00629-6.

Conrad, Z., Niles, M.T., Neher, D.A., Roy, E.D., Tichenor, N.E., Jahns, L., 2018. Relationship between food waste, diet quality, and environmental sustainability. PLoS One 13, e0195405. https://doi.org/10.1371/journal.pone.0195405.

Corrado, S., Ardente, F., Sala, S., Saouter, E., 2017. Modelling of food loss within life cycle assessment: from current practice towards a systematisation. J. Clean. Prod. 140, 847–859. https://doi.org/10.1016/j.jclepro.2016.06.050.

Drewnowski, A., 2000. Nutrition transition and global dietary trends. Nutrition 16, 486–487. https://doi.org/10.1016/S0899-9007(00)00295-1.

Eberle, U., Fels, J., 2016. Environmental impacts of German food consumption and food losses. Int. J. Life Cycle Assess. 21, 759–772. https://doi.org/10.1007/s11367-015-0983-7.

FAO, 2013. Food Wastage Footprint: Impacts on Natural Resources - Technical Report, FAO. Food and Agriculture Organization of the United Nations, Rome, Italy, p. 63.

FAO, 2015. Food Wastage Footprint & Climate Change, FAO. Food and Agriculture Organization of the United Nations, Rome, Italy, p. 4.

FAO, 2019. The State of Food and Agriculture 2019. Moving Forward on Food Loss and Waste Reduction, FAO. Food and Agriculture Organization of the United Nations, Rome, Italy, p. 182.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342. https://doi.org/10.1038/nature10452.

GfK, 2021. Systematische Erfassung Des Lebensmittelabfalls der Privaten Haushalte in Deutschland: Schlussbericht 2020, GfK (Growth from Knowledge). Germany, p. 74.

Goossens, Y., Berrens, P., Custers, K., van Hemelryck, S., Kellens, K., Geeraerd, A., 2019. How origin, packaging and seasonality determine the environmental impact of apples, magnified by food waste and losses. Int. J. Life Cycle Assess. 153, 190. https://doi.org/10.1007/s11367-018-1522-0. Correction available at: 10.1007/s11367-018-1555-4.

Goossens, Y., Schmidt, T.G., 2025. Mind the method! A systematic literature review of the methodological choices used to assess the environmental impacts of diets. Clean. Environ. Syst. 18, 100289. https://doi.org/10.1016/j.cesys.2025.100289.

Gustavsson, J., Cederberg, C., Sonesson, U., 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. FAO, Food and Agriculture Organization of the United Nations, Rome, Italy, FAO. Food and Agriculture Organization of the United Nations, Rome, Italy, p. 37.

Hallström, E., Carlsson-Kanyama, A., Börjesson, P., 2015. Environmental impact of dietary change: a systematic review. J. Clean. Prod. 91, 1–11. https://doi.org/10.1016/j.jclepro.2014.12.008.

Helander, H., Bruckner, M., Leipold, S., Petit-Boix, A., Bringezu, S., 2021. Eating healthy or wasting less? Reducing resource footprints of food consumption. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abe673.

Heller, M.C., Keoleian, G.A., 2014. Greenhouse gas emission estimates of U.S. dietary choices and food loss. J. Ind. Ecol. 19, 391–401. https://doi.org/10.1111/jiec.12174.

Heller, M.C., Keoleian, G.A., Willett, W.C., 2013. Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: a critical review. Environ. Sci. Technol. 47, 12632–12647. https://doi.org/10.1021/es4025113.

Hoogeveen, h., Verghese, S., 2023. SDG Target 12.3 on Food Loss and Waste: 2023 Progress Report. an Annual Update on Behalf of Champions 12.3, WRI. World Resources Institute), Washington DC, USA, p. 11.

Lipinski, B., 2022. SDG target 12.3 on food loss and waste: 2022 progress report. Annu. Update Behalf Champ. 12.3.

Mertens, E., Van't Veer, P., Hiddink, G.J., Steijns, J.M., Kuijsten, A., 2017. Operationalising the health aspects of sustainable diets: a review. Public Health Nutr. 20, 739–757. https://doi.org/10.1017/S1368980016002664.

Pernollet, F., Coelho, C.R., van der Werf, H.M., 2017. Methods to simplify diet and food life cycle inventories: accuracy versus data-collection resources. J. Clean. Prod. 140, 410–420. https://doi.org/10.1016/j.jclepro.2016.06.111.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216. New York, N.Y.

Popkin, B.M., 2006. Global nutrition dynamics: the world is shifting rapidly toward a diet linked with noncommunicable diseases. Am. J. Clin. Nutr. 84, 289–298. https://doi.org/10.1093/ajcn/84.2.289.

Porter, S.D., Reay, D.S., Higgins, P., Bomberg, E., 2016. A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. Sci. Total Environ. 571, 721–729. https://doi.org/10.1016/j.scitotenv.2016.07.041.

Rockström, J., Thilsted, S.H., Willett, W.C., Gordon, L.J., Herrero, M., Hicks, C.C., Mason-D'Croz, D., Rao, N., Springmann, M., Wright, E.C., Agustina, R., Bajaj, S., Bunge, A.C., Carducci, B., Conti, C., Covic, N., Fanzo, J., Forouhi, N.G., Gibson, M.F., Gu, X., Kebreab, E., Kremen, C., Laila, A., Laxminarayan, R., Marteau, T.M., Monteiro, C.A., Norberg, A., Njuki, J., Oliveira, T.D., Pan, W.-H., Rivera, J.A., Robinson, J.P.W., Sundiang, M., Te Wierik, S., van Vuuren, D.P., Vermeulen, S., Webb, P., Alqodmani, L., Ambikapathi, R., Barnhill, A., Baudish, I., Beier, F., Beillouin, D., Beusen, A.H.W., Breier, J., Chemarin, C., Chepeliev, M., Clapp, J., Vries, W. de, Pérez-Domínguez, I., Estrada-Carmona, N., Gerten, D., Golden, C.D., Jones, S.K., Jørgensen, P.S., Kozicka, M., Lotze-Campen, H., Maggi, F., Marzi, E., Mishra, A., Orduna-Cabrera, F., Popp, A., Schulte-Uebbing, L., Stehfest, E., Tang, F. H.M., Tsuchiya, K., van Zanten, H.H.E., van Zeist, W.-J., Zhao, X., DeClerck, F., 2025. The EAT-lancet commission on healthy, sustainable, and just food systems. Lancet (London, England). https://doi.org/10.1016/S0140-6736(25)01201-2.

Sinkko, T., Caldeira, C., Corrado, S., Sala, S., 2019. Food consumption and wasted food. In: Galanakis, C.M. (Ed.), Saving Food: Production, Supply Chain, Food Waste and Food Consumption. Elsevier; Academic Press, London, United Kingdom.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., Vries, W. de, Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature 562, 519–525. https://doi.org/10.1038/s41586-018-0594-0.

Subedi, S., Dent, B., Adhikari, R., 2024. The carbon footprint of fruits: a systematic review from a life cycle perspective. Sustain. Prod. Consum. 52, 12–28. https://doi.org/10.1016/j.spc.2024.10.014.

UN, 2022. The Sustainable Development Goals Report 2022. United Nations, New York, USA, p. 68.

UNEP, 2021. Food Waste Index Report 2021. United Nations Environment Programme (UNEP), Nairobi, Kenya, p. 100.

UNEP, 2024. Food Waste Index Report 2024: Think Eat Save. Tracking Progress to Halve Global Food Waste. United Nations Environment Programme (UNEP), Nairobi, Kenya, p. 193. https://www.unep.org/resources/publication/food-waste-index-report-2024.

UNGA, 2015. Resolution Adopted by the General Assembly on 25 September 2015: Transforming our World: the 2030 Agenda for Sustainable Development. United Nations - General Assembly, p. 35.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., Vries, W. de, Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. Lancet 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

WRI, 2019. Creating a Sustainable Food Future: a Menu of Solutions to Feed Nearly 10 Billion People by 2050, WRI. World Resources Institute, Washington DC, USA, p. 564. https://www.wri.org/insights/how-sustainably-feed-10-billion-people-2050-21-charts.