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Towards a harmonized true cost accounting methodology: Evidence from a nationwide retailer campaign in Germany

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ABSTRACT

True Cost Accounting (TCA) is an essential transparency tool for assessing the environmental and social costs of value chains. This study investigates how methodological choices in TCA shape the assessment of hidden environmental costs in food systems. It compares leading databases, impact assessment methods, and monetization approaches to test the robustness of TCA results. The analysis reveals wide variability in outcomes: for example, the external costs of conventional sausages range from €2.17 to €22.50 per kilogram depending on the method used for TCA calculation. Yet across all methods, a consistent pattern emerges: Animal-based products entail substantially higher external costs than plant-based alternatives. To translate these findings into practice, the most robust TCA estimate is applied as a harmonized TCA method (h-TCA) during a nationwide campaign with the German retailer PENNY, where nine products were sold in all 2,119 German stores with their environmental costs made visible in store and charged at checkout. The study demonstrates both the methodological challenges and the transformative potential of h-TCA, underscoring the urgent need for a harmonized framework that ensures comparability, transparency, and policy relevance.

1. Introduction

The scientific consensus is clear: a "business-as-usual" approach to agri-food systems is unsustainable given global population growth, changes in consumption patterns and the escalating climate crisis (IPCC 2019, Borsellino et al., 2020, Araújo et al., 2023). The 'FAO Strategy on Climate Change 2022-2031', identifies agri-food systems as major drivers of climate change and calls for systemic dietary transformation to ensure food security and meet the Paris Agreement (FAO 2022). To support this transformation, True Cost Accounting (TCA) offers a methodology to assess the externalities of food production, including its environmental and social costs (de Adelhart Toorop et al., 2021, Gemmill-Herren et al., 2021, Hendriks et al., 2023, Michalke et al., 2022, Riemer et al., 2023). TCA increases transparency and supports decision-making by quantifying environmental externalities of food production (e.g., agricultural land occupation, freshwater eutrophication, particulate matter formation or climate change) and thereby informs policies for more sustainable agri-food systems (FAO 2024). In this paper, this internalization of such costs/externalities through TCA will be referred to as the "true costs" of products and is crucial to correct market and policy failures in the food system. Since Pigou's early work on externalities (Pigou, 2017), it has been recognized that internalizing social, health, and environmental costs is key to correcting market failures. It can incentivize healthier, more sustainable consumption and production patterns, while supporting broader policy goals such as redistribution and social protection (FAO 2024, Hendriks et al., 2023). Moreover, it also can potentially help businesses mitigate long-term risks and respond to consumer and regulatory demands for sustainability but requires coordinated public policy and institutional support to drive systemic change (Gemmill-Herren et al., 2021, FAO 2024).

Currently, a wide range of TCA databases, methodologies, and monetization approaches exist to calculate the true cost of food. Among the most widely used life cycle (LC) inventory databases, are the Agrifootprint database, which provides global data for agricultural products (Blonk et al., 2022) and Agribalyse, a French database for food products, assessing sustainability and environmental impacts (Auberger et al., 2022). In addition, there are LC impact assessment methods like Product Environmental Footprint (PEF) and ReCiPe. The Product Environmental Footprint (PEF), developed by the European Commission offers provides a standardized Life Cycle Assessment (LCA) based

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framework for assessing product-level environmental impacts in Europe (European Commission 2021). The ReCiPe approach, developed by CE Delft, provides a comprehensive evaluation of externalities by converting emissions and value chain processes into mid- and endpoint indicators (Huijbregts et al., 2017). However, there is currently a lack of standardization and harmonization amongst these TCA methodologies, and therefore a lack of reliable and comparable results. Moreover, on top of the differences in LCA, existing monetization approaches also differ, e.g. those proposed by the German Environment Agency (Umweltbundesamt 2020, Umweltbundesamt 2024), he report on the social cost of greenhouse gases by the US Environmental Protection Agency (EPA 2023), the PEF Guide by the European Commission (European Commission 2021), or CE Delft's (CE Delft 2024) Environmental Prices Handbook. Even for CO_2eq, monetization estimates vary widely ranging from 57 to 765€ / t CO_2eq illustrating the broader lack of methodological consensus:

- UBA (Germany): Approx. €180 to €250 per ton of CO_2 using a time preference rate of 1% or 680 to 765€ using a time preference rate of 0% (from a study on the external costs of CO_2) (Umweltbundesamt 2024).
- EPA (USA): Approx. 120 to 340 $ per tonne of CO_2 depending on the discount rate 1.5 to 2.5 % (EPA 2023).
- PEF guidelines (EU): Approx. €100 to €200 per tonne of CO_2 (depending on national assessments and specific applications) (European Commission 2021).
- CE Delft (Netherlands): Approx. €57 per tonne of CO_2 using a social discount rate of 2.25% (CE Delft 2024).

These methodological variations significantly influence the calculated external costs, leading to divergent results. Therefore, systemic comparisons and robustness checks are essential to assess uncertainty and ensure the reliability of results. In the long term, the development of a standardized, stakeholder-oriented national, European, or international TCA framework is essential to establish TCA as a robust tool for transparency and decision-making in agri-food and other industry sectors (Gemmill-Herren et al., 2021, Hendriks et al., 2023, Michalke et al., 2022).To test the feasibility and implementation of TCA as a tool, it is essential to evaluate its application in practice. This paper focuses on a novel approach by comparing some of the largest and most reputable LCA-based true cost calculation approaches detailed previously. This is done to define and discuss necessary steps to create a standardized and harmonized True Cost Accounting (h-TCA) method. After conducting this harmonization of different TCA approaches, a robust middle-ground TCA methodology is applied in a practical setting to demonstrate its feasibility, communicability and implementation potential. We call this method h-TCA (for harmonized TCA) in the following, describing it as the selected choice for harmonization the methods derived from systematic robustness checks in this paper. This practical setting is the PENNY true cost campaign of August 2023 (see subsection 2.4). PENNY is a German food retailer with >2000 markets in Germany, and part of the REWE group, who is the second largest supermarket chain in Germany.

Overall, the goal of this study is dual: first, to assess differences in TCA approaches and monetization methods and find a harmonized, robust combination. Secondly, to apply this h-TCA method in a real-life setting. Therefore, the key research question is: How can a harmonized TCA methodology be derived from existing TCA methods and their implications? By addressing this question, the research aims to contribute to the discourse of a standardized, stakeholder-oriented TCA framework for the agri-food sector. In the following, the method of True Cost Calculation (section 2) is first described, then the results are presented and discussed (sections 3 and 4, respectively) and finally, conclusions for further research and practice are drawn (section 5).

2. True cost calculation

A TCA approach that combines LCA with social cost estimates was used to compute the true costs to get a broad measure of environmental externalities (de Adelhart Toorop et al., 2021, Pieper et al., 2020). Following Michalke et al. (Michalke et al., 2023), the analysis consisted of three steps. First, a Life Cycle Inventory (LCI) is created for each product by using existing databases, ingredient lists, and adjustments for farming practices (cf. subsection 2.1). The inventory comprises resource, energy, and water flows of all processes needed for the production and processing of that product. Second, Life Cycle Impact Assessment (LCIA) is used to aggregate related damages into one environmental impact with a standardized unit (e.g, tCO_2eq for climate change damages) (cf. subsection 2.2). Third, the environmental impacts are monetized by multiplying them with estimates of the social costs per unit of environmental impact (cf. subsection 2.3).

The workflow in Fig. 1 visualizes the process of this study in short: The usability of different databases and LICA methods was evaluated. Second, three different monetization methods towards these TCA approaches were analyzed. With combining these different steps and approaches, we finally arrive at the most robust, harmonized TCA approach, the h-TCA, as described in section 2.4.

The usage of these databases and methods is further described in the following subchapters.

2.1. Life cycle inventory modeling

To create and compare LCIs for the campaign products, data from two commercial LCI databases is used that are identified as the most robust data source for the herein presented case and therefore used within the h-TCA: Agri-footprint and Agribalyse, including a large set of agricultural products and markets. The life-cycle boundaries are cradle to processing gate. The stages of distribution to consumer, use by consumer, and waste treatment are excluded, as these externalities are supposed to not greatly vary between products, and data certainty decreases towards the end of a product’s life cycle. Data for raw materials extraction and manufacturing comes from the Agri-footprint database, whereas data for post-farm transport and processing comes from Agribalyse. Agri-footprint models on site processes very specifically and allows for adjustment of small level inputs (e.g., specific amounts of fertilizers) while Agribalyse offers data for a broad range of processed foods, which are helpful to model the diverse campaign products. The databases model average products. To get an estimate for a specific PENNY product, the most closely matching item available for Germany is selected and inputs are adjusted according to the ingredient list. For example, for modeling the vegan schnitzel based on wheat gluten, the process of seitan (i.e., wheat gluten) production is used. If needed, details in the modelling could be altered based on product specifications provided by PENNY. Because Agribalyse provides data only for the average French market, whereas Agri-footprint allows for a more detailed and site-specific modelling of production processes, Agri-footprint was used as the reference database for h-TCA. Agribalyse baseline data were included in the robustness check for comparison.

The modeling is done using the LCA tool SimaPro. The LCI databases assume conventional production methods. For organic products, the method developed in Michalke et al. is used (Michalke et al., 2023) to adjust yield, manure, diesel and energy use on farms. Diesel and energy use are adjusted according to data from literature that compare the use in conventional and organic cases. Pesticides and synthetic fertilizers are omitted for organic production since they are forbidden under the EU organic regulation. There is an ongoing debate about the environmental benefits of organic versus conventional agricultural production (Boone et al., 2019, Tuomisto et al., 2012). While most studies agree organic practices decrease environmental impacts per hectare (Volanti et al., 2022), there is disagreement if organic production decreases environmental output when comparing practices per kg of output (Clark and

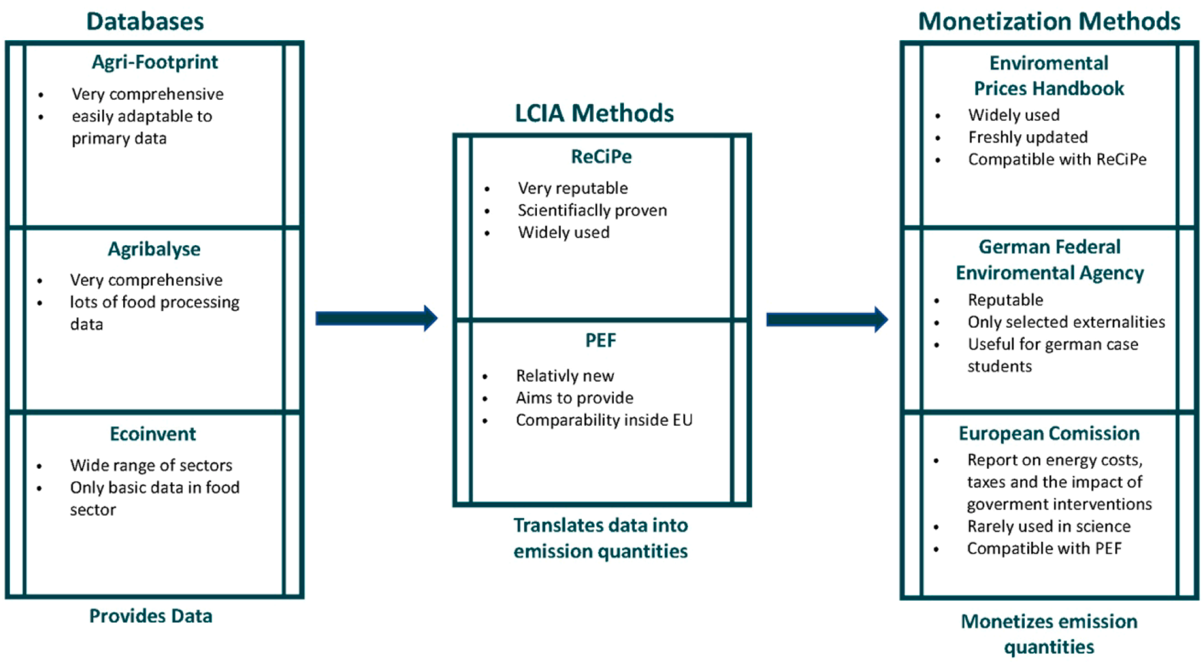

Fig. 1. Workflow-diagram of study design. The workflow links three methodological components: databases (Agri-Footprint, Agribalyse, Ecoinvent) provide data; LCIA methods (ReCiPe, PEF) translate these into environmental impact categories; and monetization methods (Environmental Prices Handbook, German Federal Environmental Agency, European Commission) assign economic values to externalities. This integrated approach allows the quantification of uninternalized environmental costs ("true costs") for the analyzed products.

Tilman, 2017, Shennan et al., 2017). This is due to a lower yield per hectare for organic farming (Smith et al., 2019, Meemken and Qaim, 2018). Our methodology accounts for this by incorporating literature-based yield adjustments.

2.2. Life cycle impact assessment

For the assessment of the modeled LCIs ReCiPe (Huijbregts et al., 2017) is used, as it is the most comprehensive LCIA method (Michalke et al., 2023) and therefore used within the h-TCA. All substance or material flows and emissions associated with the assessed product are characterized by environmental impact categories, which describe environmental mechanisms and problems. The units for the different impacts (e.g., kgtCO_2eq for climate change) are shown in Table A.1 in the appendix. As an alternative, the European Commission's LCIA impact assessment methodology PEF can be used (European Commission 2021). It serves a similar purpose as ReCiPe, but, as a relatively new method using different units than ReCiPe is only compatible with the European Union's monetization scheme (European Commission 2020) and not widely used among LCA experts.

2.3. Impact monetization

To monetize different environmental impacts and get a €-value for overall environmental externalities, social cost estimates from literature are used, following Michalke et al. (Michalke et al., 2023). For the climate change impact, the German Federal Environmental Agency's central estimate is used: €195/tCO_2eq in 2020 (the UBA 2024 version was not yet available during the 2023 TCA campaign) (Umweltbundesamt 2020). For the remaining impacts estimates from the Environmental Prices Handbook by CE Delft (de Bruyn et al., 2018) are used. The Handbook is the only source providing social cost estimates for most ReCiPe environmental impacts and is rooted in the project NEEDS (NEEDS 2009), and is therefore used for the h-TCA considering ReCiPe was previously identified as the most robust LCIA method. Note that in previous monetization schemes of environmental impact, there was no consideration of already internalized environmental costs (Pieper et al., 2020, Michalke et al., 2023). In the Environmental Prices Handbook, the upper and lower bounds represent a plausible range of monetary estimates for environmental externalities, capturing uncertainty in underlying scientific evidence, valuation methods, and normative assumptions, with the lower bound reflecting more conservative damage cost assumptions and the upper bound reflecting more precautionary, higher damage cost estimates. Accordingly, these bounds are applied in the robustness check and reflect uncertainties in valuation assumptions.

Existing TCA studies assess the environmental and social externalities of food products and their value chains, offering valuable insights into the hidden costs embedded in global food systems. However, most current studies (Michalke et al., 2023, The Economics of Ecosystems and Biodiversity 2018, Global Alliance for the Future of Food 2019) overlook the fact that certain externalities have already been internalized through regulatory frameworks, market-based instruments, or compliance costs, such as carbon pricing mechanisms. Consequently, not accounting for these internalized externalities separately can lead to inflated estimates of total externalities. The current study addresses that methodological gap by explicitly subtracting already internalized externalities through carbon prices.First, an adjustment for EU Emissions Trading System (ETS) carbon pricing is conducted. At the time of the campaign, electricity and heat generation as well as certain energy-intensive industries (e.g., oil refineries, steel works) had to acquire ETS certificates for their CO_2 emissions. These industries are identified by their name and country of origin in the inventory data. Those emissions are then multiplied with the average ETS price from May 2022 to May 2023 (the latest available data at the moment of the campaign), i.e. 83.91€/tCO_2 (see supplementary material 2, spreadsheet "ets price"). Second, an adjustment for the German carbon tax is conducted, which at the time of the campaign covered gasoline and diesel, and multiplied these emissions with the German carbon price of 30€/tCO_2. The final climate change damage estimate is the social cost net of ETS and German carbon tax pricing.

Important to note is that some of the campaign products are sold within PENNY markets in so-called "mixed boxes". This means that products with different LCI datasets and hence different true costs are sold using the same barcode and price. For these boxes, weighted averages according to the shares of the different products in the boxes are calculated. This is the case for organic cheese (Gouda, Emmental, Maasdam, and mountain cheese) and organic sausages (pork, poultry, and beef).

2.4. Applying harmonized method in practical setting

After developing the harmonization of the previously described TCA method, (2.1 through 2.3), in the following called h-TCA, the method was used within the empirical setting of the PENNY "True Cost" Campaign of 2023. This application does not constitute an empirical validation of the accounting methodology in terms of testing its numerical accuracy or predictive power. Rather, the campaign serves as an implementation case that demonstrates the practical feasibility, scalability, and communicability of the harmonized TCA approach in a real-world retail environment. The research team (consisting of Nuremberg Institute of Technology and University of Greifswald) used the herein presented TCA approach for nine campaign products from the German retailer PENNY as part of a nationwide TCA campaign. These true costs were requested at checkout for one week across all 2,119 German stores. A short summary of key findings from the campaign can be found in the current report by FAO (FAO 2024) (cf. p. 60, box 18) detailed analysis of sales data, price elasticities, and representative surveys are presented in Semken et al., (forthcoming).

As described in 2.2, Table A.1 shows the slightly different impact categories and corresponding units used in different LCIA methods. While there are many overlaps, most monetization approaches are not directly compatible with the PEF categories. As a result, PEF can currently only be used in combination with the European Commission's own, relatively new and not yet widely established, monetization method (European Commission 2020). This limitation ultimately led us to choose ReCiPe for the PENNY campaign. To facilitate the presentation of the results during the campaign and throughout this paper, the 14 environmental impacts of ReCiPe were aggregated into four groups that can easily be understood by consumers:

(1) climate change (global warming), **(2) human health** (ozone depletion, particulate matter formation, ionizing radiation, photochemical oxidant formation, human toxicity), **(3) soil** (terrestrial acidification, terrestrial ecotoxicity, agricultural land occupation, urban land occupation), and **(4) water** (freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, marine ecotoxicity)

The following results show TCA results of the different approaches used to calculate the true costs of the products later used in the PENNY campaign. All methodologies considered here capture similar environmental externalities, as ReCiPe and PEF assess largely the same impact categories. Any ambiguities in the results therefore arise solely from methodological differences. We, on the one hand, use the preliminary campaign design to inform the harmonization of the h-TCA approach, and, on the other hand, use the gathered insight to finalize the campaign design and roll out the campaign.

2.5. Quantitative robustness assessment

The results of true cost calculations based on life cycle analysis are deterministic model outputs and not stochastic samples. Therefore, inferential statistical tests are not methodologically appropriate, as important assumptions such as random sampling and statistical independence are not met (Heijungs and Huijbregts, 2004). Instead, robustness in life cycle assessment is usually evaluated using formalized sensitivity indicators that quantify how strongly the results depend on methodological decisions (Groen et al., 2017).

In this study, robustness across alternative databases, impact assessment methods and monetization approaches was assessed using three complementary indicators: (1) normalized ranges (NR), (2) coefficients of variation (CV) and (3) relative deviation indices (RDI). In addition, the stability of product rankings across methodological configurations was assessed to capture decision-relevant robustness.

Normalized range

$$NR = \frac{\max(x) - \min(x)}{\bar{x}} \quad (1)$$

Coefficient of variation

$$CV = \frac{SD(x)}{\bar{x}} \quad (2)$$

Relative deviation index

$$RDI_i = \frac{x_i - x_{ref}}{x_{ref}} \quad (3)$$

Legend. x denotes the set of monetized external cost estimates for a given product across all methodological configurations; $\max(x)$ and $\min(x)$ are the corresponding maximum and minimum values, $\bar{x}$ the arithmetic mean, and $SD(x)$ the standard deviation. x_i denotes the estimate obtained under methodological configuration i, and x_{ref} the estimate obtained with the harmonized reference method (h-TCA). NR denotes the normalized range, CV the coefficient of variation, and RDI_i the relative deviation index relative to the reference method.

3. Key results

3.1. Harmonizing the TCA approach

Below, the results of a robustness check will be presented by comparing different LCA-based TCA and monetization approaches including upper and lower bounds, using three products from TCA campaign with PENNY as an example. To ensure harmonization across all stages of the TCA, several checks were performed. For the database stage, the impact of using a different reputable database, Agribalyse, is assessed. The LCIA impact assessment was also performed using the European Commission's PEF methodology as an alternative. Additionally, the monetization approach was tested with its upper and lower bounds. This novel approach provides a comprehensive perspective.

The alternative true cost estimates compare three conventional products: fruit yogurt, Wiener sausages, and vegan schnitzel; see Fig. 2. The key finding is that the meat product has the highest external costs, while the vegan schnitzel has the lowest among the three analyzed products. Regardless of the chosen LCIA impact assessment method, database, or monetization approach, the external costs of sausages are significantly higher than those of the other products. The central estimate serves as the h-TCA and is based on the Agri-footprint database, the ReCiPe 2008 LCIA method, and a combined UBA and CE Delft monetization approach. It finds that the external costs of sausages (7.05€/kg) are 6.98 times higher than those of fruit yogurt and 10.22 times higher than those of vegan schnitzel. Detailed overviews of the individual products can be found in the appendix (Fig. A.1, A.2, A.3).

A comparison between the ReCiPe methodology and PEF 3.1 (see Appendix) results in lower true cost estimates (36 to 53% of the central estimate). However, this reduction is partly attributable to the inclusion of significantly lower PEF social damage estimates (cf. Table A.1). Because the EPH and PEF use different methods to measure and value environmental impacts, it is not possible to directly apply the EPH estimates within the PEF framework. The results are highly sensitive to the externality estimates used. To ensure harmonization, the lower and upper bounds for social costs as specified in Fig. 1 are applied. The upper bound for climate change costs is defined by the UBA cost estimate with a discount rate of 0% (i.e., equal weighting of present and future damages), while the lower bound is based on Tol (Tol, 2018) at a discount rate of 3%. The remaining social cost bounds are derived from CE Delft, adjusted for inflation (for the campaign year 2023). Please find the

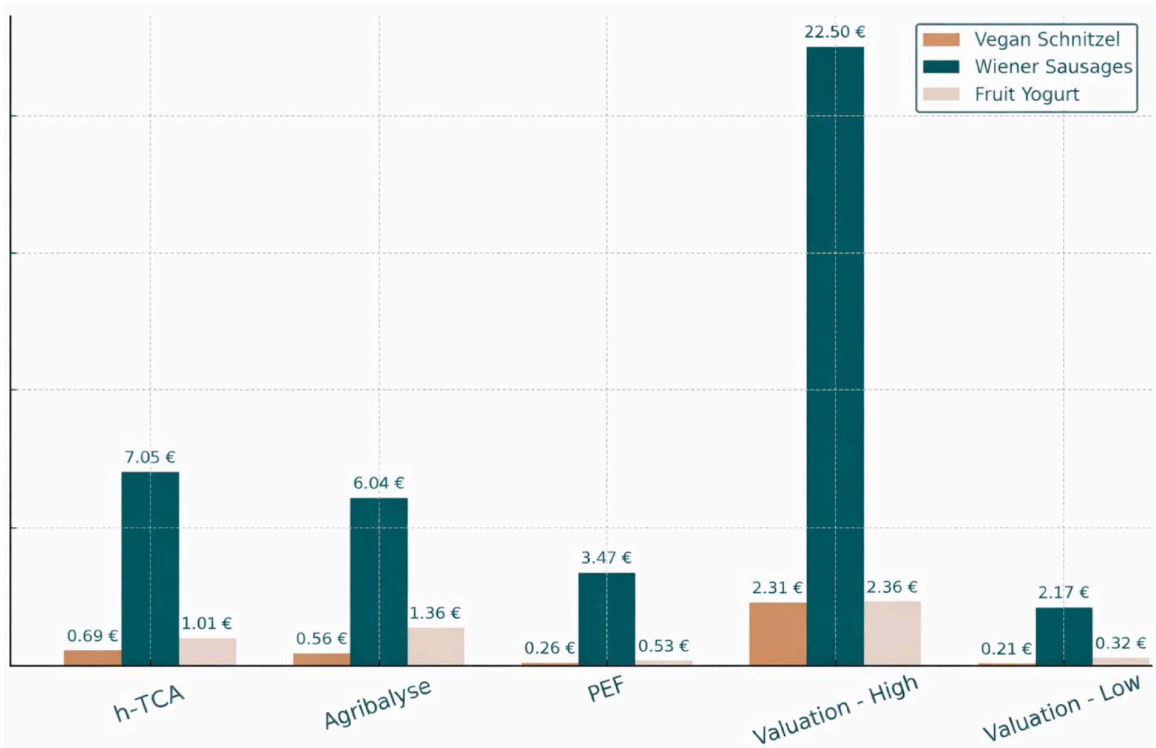

Fig. 2. Robustness check of different TCA valuation approaches regarding uninternalized environmental externalities of Wiener sausages, fruit yogurt, and vegan schnitzel (€/kg). Across all valuation methods, Wiener sausages exhibit by far the highest external costs (up to 22.50 €/kg), fruit yogurt remains in an intermediate range, while vegan schnitzel consistently shows the lowest external costs (< 1 €/kg in most cases).

displayed calculations for h-TCA estimate in Supplementary Material 1 and all other estimates in Supplementary Material 2. Using these bounds, the true costs are estimated to range from 2.17 to 22.50€/kg for sausages, 0.32 to 2.36€/kg for fruit yogurt, and 0.21 to 2.31€/kg for vegan schnitzel (see Fig. 2).

These variations highlight the influence of different valuation approaches on the environmental and social costs of food. Despite the observed variations, consistent trends emerge across robustness checks. However, certain deviations can be observed: for example, switching from Agri-footprint to Agribalyse results in lower external cost estimates for vegan schnitzel and sausages but leads to a higher estimate for fruit yogurt, due to differences in modelling approaches. Importantly, the overall pattern of externalities remains unchanged across all robustness checks: the tested meat products consistently exhibit the highest externalities by a significant margin, whereas the plant-based product consistently shows the lowest externalities.

Taken together, these results show that large valuation uncertainty primarily affects the magnitude of estimated true costs, but not the relative ranking of products: Across all monetization approaches and robustness checks, ordinal product rankings remain unchanged, even when individual estimates differ substantially. This stability of relative comparisons indicates that harmonized central estimates can support robust comparative assessments, despite wide uncertainty ranges in absolute values.

When examining the correlations between the different food products, it becomes evident that the choice of method does not affect the overall relationships. The correlation between sausages and the vegan Schnitzel is nearly perfect (0.9998), while correlations between sausages and yogurt (0.9429) and between yogurt and the vegan Schnitzel (0.9450) are also very strong. This indicates that the general pattern — sausages having the highest externalities and the plant-based Schnitzel the lowest — is robust across all methods.

Table A.2 further underscores the robustness of these results. Meat products exhibit a substantially higher environmental impact — approximately ten times that of plant-based alternatives — while yogurt causes nearly twice the impact of the vegan Schnitzel. From a calorie-based perspective, assuming a daily intake of approximately 2,500 kcal, the main findings remain consistent. Sausages and vegan Schnitzel have nearly identical caloric values per 100 g (286 and 285 kcal, respectively), so their relative environmental impacts remain similar. In contrast, yogurt provides only 94 kcal per 100 g, which results in a comparatively worse performance on a per-calorie basis. Under this approach, the coefficient of variation between yogurt and meat products decreases to 1.47–3.15, whereas the coefficient of variation between yogurt and the vegan Schnitzel increases to 3.09–7.36. Overall, a calorie-based assessment reinforces the environmental benefits of plant-based alternatives. Nonetheless, the overall ranking remains unchanged: meat products exhibit the highest externalities, dairy products occupy an intermediate range, and plant-based products have the lowest impacts.

Quantitative robustness indicators supplement the descriptive comparison (Table 1). Normalized ranges show considerable fluctuations in absolute cost estimates, particularly for vegan schnitzels (NR = 2.61) and Vienna sausages (NR = 2.47). This reflects the strong influence of valuation assumptions. The coefficients of variation indicate high methodological sensitivity for sausages and vegan schnitzels (CV = 0.99 and 1.07). Fruit yoghurt shows less variation between the valuation approaches (CV = 0.72).

Relative deviation indices with respect to the harmonized reference method show that alternative methodological choices can reduce the estimated external costs by up to about 70% or increase them by more than 200%. These differences are mainly due to valuation boundaries. Despite these pronounced level effects, the product rankings remain completely stable across all methodological configurations. Vienna sausages consistently have the highest external costs, followed by fruit yoghurt. Vegan schnitzel has the lowest costs in every scenario considered.

Because relative product rankings remain stable despite substantial

Table 1
Indicators are calculated across the methodological configurations shown in Fig. 2. RDI values are relative to the harmonized reference method (h-TCA).

Product	Mean (€/kg)	Min	Max	Normalized range	Coefficient of variation	RDI min vs h-TCA	RDI max vs h-TCA	Ranking stable
Vegan schnitzel	0.81	0.21	2.31	2.61	1.07	−69.6%	+234.8%	Yes
Fruit yogurt	1.12	0.32	2.36	1.83	0.72	−68.3%	+133.7%	Yes
Wiener sausages	8.25	2.17	22.50	2.47	0.99	−69.2%	+219.1%	Yes

valuation uncertainty, the results provide a robust basis for downstream application. In the following section, this decision-relevant robustness is translated into a real-world retail setting to assess whether a harmonized TCA estimate can be operationalized at scale.

3.2. Application

The following application shows that a harmonized TCA estimate can be implemented in a real-world retail context. Despite practical constraints such as mixed assortments and communication requirements at the point of sale, the h-TCA approach was successfully operationalized across 2,119 stores by using weighted averages and aggregated impact categories. Building on the conducted robustness checks (cf. 3.1), the true costs of the campaign products for PENNY are calculated using the h-TCA: Table 2 and Fig. 3 present the uninternalized externality estimates for the nine campaign products in €/kg (fig. 2) and in percent of the current (August 2023) sales price (tab. 2; details of calculation in Supplementary Material 1), respectively. Meat products (conventional and organic sausages) have the highest externalities (7.05 -12.12 €/kg), dairy products (yoghurts and cheese) have medium externalities (0.92 - 7.85€/kg), and the plant-based product (vegan schnitzel) has the lowest externalities (0.69 €/kg). True costs are composed of four main categories: climate, health, water, and soil impact (detailed impact categories to these main categories can be found in Table A.1). The organic sausages have higher externalities (12.12 €/kg) than the conventional sausages (7.05 €/kg) due to the difference in ingredients: the organic sausage box contains 33 percent beef sausages with very high externalities (26.38€/kg), while the conventional are pork sausages with externalities of 7.05€/kg. An analysis of the relative true cost markups (in comparison to product prices; Fig. 3) reveals that these markups are lower for organic compared to their conventional counterparts. This is partly due to higher margins at production level and, at the same time, higher average prices for organic products at the point of sale.

4. Discussion

4.1. Limitations and strengths

The results of this study confirm that monetized true cost estimates are highly sensitive to methodological and valuation-related choices and should therefore be interpreted as indicative ranges rather than precise point values. At the same time, the robustness analysis shows that relative product rankings remain completely stable across alternative databases, impact assessment methods, and monetization approaches, despite substantial variation in absolute cost levels. While the general finding that animal-based products exhibit higher external costs than plant-based alternatives is well established in the literature, the contribution of this study lies in demonstrating that these ordinal relationships remain robust even under large valuation uncertainty. By explicitly quantifying uncertainty while showing consistent relative rankings, the analysis provides a decision-relevant basis for selecting and applying a harmonized TCA estimate, rather than relying on individual point values.

The methodology applied in this study is based on data from various sources, each with inherent uncertainties. For the construction of the main LCIs, data from Agri-footprint was used. While this database provides high-quality inventory data, it represents only average conditions for Europe. However, regional differences in agricultural practices, yields, energy mixes, and fertilizer use can be significant. These variations are unlikely to affect the overall ordinal patterns observed in this study, as German production conditions broadly reflect average central European contexts. Additionally, key parameters were adjusted to precisely match the campaign products.

Despite covering a broad range of input and output flows, neither Agri-footprint nor Agribalyse can fully account for all substances involved in agricultural processes. These limitations contribute to significant variability, with differences exceeding 30% observed when modeling the same product using different LCA databases. To mitigate the risk of overestimation, Agri-footprint was selected as the baseline due to its consistent and comparatively conservative modelling assumptions (van Paassen et al., 2019).

Monetizing environmental impacts introduce additional uncertainty beyond that inherent in LCIs. The Environmental Prices Handbook (EPH) applies the damage cost approach, estimating future damages with a 2.25% social discount rate – this underlying parameter presents a source of uncertainty and sensitivity in the results. EPH values are also based on European averages and therefore ignore regional differences in healthcare costs, population density, or ecosystem sensitivity. The EPH does not provide monetization factors for all ReCiPe impact categories. Consequently, the categories mineral resource scarcity, fossil resource

Table 2
External costs of campaign products per product and impact category calculated with h-TCA [€/kg].

Campaign product	Health costs [€/package]	Water costs [€/package]	Soil costs [€/package]	Climate costs [€/package]	True Costs [€/package]	Campaign price [€/package]	Price Increase [%]
Fruit yoghurt (organic)	0,09	0,01	0,16	0,1	0,37	1,56	31
Cheese slices (organic)	0,43	0,07	0,53	0,48	1,51	3,70	69
Mozzarella (organic)	0,18	0,03	0,22	0,2	0,63	1,92	49
Sausages (organic)	0,61	0,11	0,79	0,56	2,07	5,36	63
Fruit yoghurt (conventional)	0,11	0,02	0,19	0,13	0,45	1,44	38
Cheese slices (conventional)	0,63	0,12	0,76	0,85	2,35	4,84	95
Mozzarella (conventional)	0,18	0,03	0,21	0,24	0,66	1,55	74
Sausages (conventional)	0,62	0,09	1,17	0,94	2,82	6,01	88
Vegan Schnitzel (conventional)	0,02	0,01	0,07	0,04	0,14	2,83	5

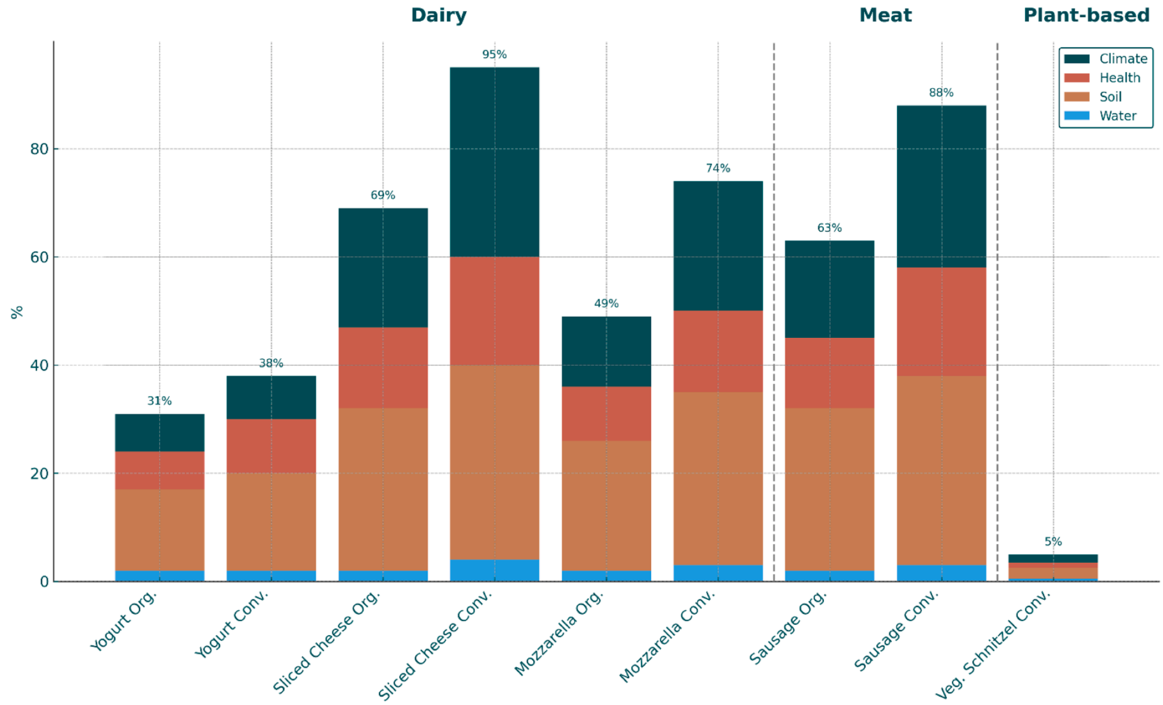

Fig. 3. TCA calculations of campaign products (with h-TCA) regarding uninternalized environmental externalities ("true costs") of all nine campaign products, price increase given in % compared to the pre-campaign price. The results show that dairy and meat products would increase in price by up to +95%, while the plant-based alternative rises only by +5%. Organic products are consistently less affected than conventional ones. Across all product categories, climate impacts dominate the true costs, followed by health and soil, with water contributing comparatively little.

scarcity, natural land transformation, and water consumption are excluded from the monetization presented in this study. These uncertainties are reflected in the wide ranges between the lower and upper estimates of EPH damage costs. For land use the high estimate (€0.685/m^2/year) is roughly 27 times higher than the low estimate (€0.0255/m^2/year). For other impact categories, the range varies by a factor of 2 to 11.

Given the sensitivity of climate damage estimates to discounting, we apply damage cost factors from the German Federal Environment Agency (Umweltbundesamt 2020), which apply a lower time preference rate of 1% compared to the EPH. This decision aligns with recent scientific literature, recommending lower discount rates to better reflect the long-term and intergenerational nature of climate damages (IPCC 2019). Additionally, the EPH uses an abatement cost estimate for climate impacts, whereas for all other impact categories they use damage costs. Therefore, using the damage cost approach of the German Federal Environment Agency is sensible. The damage estimates are adjusted for the year the damage occurs as well as for inflation. For example, the climate change cost estimate for 2023 is €211.50/tCO_2eq. The cost estimates for each impact are shown in Table A.1.

Fig. 2 illustrates the uncertainties inherent in the different TCA methodologies. Although the first three approaches considered – the h-TCA, the use of Agribalyse instead of Agri-footprint, and the application of PEF instead of ReCiPe as the LCIA method – assess the same products, differences of up to 51% (for Wiener Sausages) and 62% (for Vegan Schnitzel) can be observed, depending on the product examined. Nevertheless, these strong correlations across products indicate that relative patterns (most notably the higher external costs of animal-based products) remain consistent. Consequently, the specific choice of the Central Estimate as the harmonized and robust reference method is less decisive; alternative selections, such as Agribalyse, would also have been justifiable.

The quantitative robustness indicators (cf. Tab. 1) enable a more accurate interpretation of the results. Normalized ranges between 1.83 and 2.61 and coefficients of variation between 0.72 and 1.07 confirm that absolute estimates of monetized external costs are very sensitive to methodological and valuation-related decisions. This sensitivity is most pronounced for Vienna sausages and vegan schnitzel. For these products, alternative valuation limits lead to deviations of more than ±200% from the harmonized reference method. These results show that point estimates of actual costs should be interpreted as indicative ranges rather than precise values. At the same time, the complete stability of the product rankings across all methodological configurations provides a strong indication of decision-relevant robustness. In every scenario considered, Vienna sausages consistently have the highest external costs. Fruit yoghurt occupies an intermediate position. Vegan schnitzel has the lowest costs. This consistency shows that, despite considerable sensitivity, the central comparative conclusion of the study is methodologically robust. The robustness test therefore supports a pragmatic interpretation of the TCA results. While harmonization efforts should focus on reducing uncertainty in assessment – particularly with regard to climate and land use impacts – the current evidence base appears sufficient to inform communication, prioritization and policy discussions on relative environmental externalities. Overall, the results demonstrate that within each methodological framework, highly robust and meaningful comparisons between products and product categories are possible, suggesting that the TCA methodologies themselves are internally consistent, conceptually sound, and suitable for comparative assessments. Importantly, this study also exhibits several notable strengths. Most significantly, it represents the first study to conduct a robustness check prior to a nationwide TCA campaign in the food retail sector. By doing so, it makes the previously highly scientific discourse on methodological choices more transparent and accessible to a broader range of stakeholders. Furthermore, the study introduces an initial framework for how future true cost calculations should be conducted — emphasizing openness toward the final method and basing methodological selections on a prior robustness check. This provides a crucial foundation for the urgently needed development and implementation of a standardized approach to calculating true costs.

4.2. Practical implications

The consistently show that animal-based products incur substantially higher external costs than plant-based alternatives. Despite inherent uncertainties in the applied methodology, these results highlight the relevance of policy discussions aimed at mitigating these costs. Meat and dairy products, in particular, generate considerable uninternalized externalities that require targeted intervention. As a result, current prices for animal-based products fail to reflect environmental costs, causing market distortions and welfare loss. The findings of this study thus highlight a societal need for effective mitigation strategies addressing the environmental impacts of (animal) food production. While fully internalizing external costs may be unfeasible or undesirable due to equity concerns, measures promoting a shift away from animal-based and towards plant-based products appear warranted. Potential policy instruments to achieve this include taxes on meat or nitrogen, as well as tax incentives for products with low external costs. Adapting the VAT could be a simple but effective option to help shift consumption patterns and reduce societal costs – especially since the European Parliament (European Parliament 2022) recommended VAT adaptations to incentivize more sustainable consumption (Oebel et al., 2024, Springmann et al., 2025).

Based on TCA key findings, Oebel et al. (Oebel et al., 2024) created a scenario to adapt the current German VAT system by reducing VAT on organic vegetarian food to 0% and raising VAT on conventional meat and fish to 19%. This would lead to an overall increase of consumption of organic food by 21.83%, due to the increased taxation on conventional meat products. Moreover, the scenario would yield €2.04 billion in extra tax revenues in Germany per year due to the increased taxation on conventional meat products. Additionally, uninternalized environmental externalities of €5.31 billion would be avoided as a result of lower external climate costs due to higher shares of organic and vegetarian food.

Similarly, a study by Springmann et al. (Springmann et al., 2025) suggests a reduction of VAT for fruits, vegetables, legumes and nuts to 0% and an increased VAT for beef, lamb, pork, poultry and milk to the highest possible rates per country (between 17 and 27% depending on the member states). On average, these calculations yielded health gains of 330 averted deaths per million people, 6% lower GHG emissions and resource use, a 0.22% GDP increase in tax revenues, and a 0.18% GDP reduction in societal costs from ill health and climate damage.

Both studies show that VAT incentives can effectively shift consumption patterns, and especially when combined with TCA could be even a stronger motivator for consumers. Therefore, it is necessary to a) provide TCA approaches and b) TCA communications as stakeholder oriented as possible (Stein et al., 2024, Carlsson et al., 2025). Our example has clearly demonstrated the need for a robustness check before deciding on a TCA approach. One potential option to ensure cohesion amongst all applications, could be to have a large encompassing database in which one can tailor the LCA, or monetization approaches based on the specific objectives or availability of data.

Certification and sustainability labels also play a crucial role in making external costs visible and guiding consumer choices. A reputable certification label must balance stringent yet feasible ecological and social criteria, while ensuring transparency and verifiability (German Federal Environment Agency 2025). Such labels can effectively raise consumer awareness and support sustainable consumption decisions (Thøgersen et al., 2024). Initial TCA studies already tested such label approaches in a field experiment in a German supermarket in Berlin (Michalke et al., 2022) and with recruited Dutch participants in Amsterdam (Taufik et al., 2023). These studies revealed both a strong interest in true price information and challenges such as consumer trust, concerns about greenwashing, and questions regarding social implications of rising costs. Methodological robustness is therefore essential to support policy and business decisions and to maintain trust in labels communicating environmental and social impacts.

In addition to labeling instruments, market-based price signals such as carbon pricing represent another lever to internalize external costs in food production. Recent modeling studies indicate that integrating agriculture into carbon pricing systems, even at the national level, leads to measurable emission reductions, with stronger effects under an EU-wide approach (Stepanyan et al., 2023, Schaper et al., 2025). European cross-country simulations further highlight that appropriately designed carbon taxes can at least modestly shift consumption towards lower-emission foods (Varacca et al., 2024). However, implementation remains challenging due to diffuse emission sources, administrative and monitoring costs, as well as distributional impacts (Cabrini et al., 2024, Commission, 2023). Ultimately, carbon pricing can be effective if revenues are strategically used to promote sustainable farming practices and to compensate vulnerable households. Beyond these instruments, True Cost Accounting could, in the medium to long term, evolve into a complementary decision-making tool similar to carbon pricing — beginning with the most robust and scientifically validated indicators with highest environmental externalities, and gradually expanding as data availability and methodological reliability improve.

A final important point for the practical implication is that this study was consumer-oriented, as consumers primarily expressed interest in understanding the environmental costs of food products. Consequently, the damage cost approach was applied to quantify the externalities associated with environmental impacts. In contrast, policymakers focus on the long-term societal and ecological implications of true costs and often conduct cost-benefit analyses to inform policy decisions. For this purpose, the abatement cost approach is particularly relevant, as it reflects the costs required to mitigate environmental damage. Businesses, on the other hand, can utilize both approaches: the damage cost approach for internal and external sustainability tracking and reporting, such as compliance with Corporate Sustainability Reporting Directive (CSRD) or other requirements, and the abatement cost approach to develop future-proof business strategies that align with sustainability goals. So, depending on who the target group of the TCA is, the applied approach should be carefully considered.

4.3. Systemic challenges and need for future research

The need for a harmonized TCA approach is discussed in several studies (de Adelhart Toorop et al., 2021, Gemmill-Herren et al., 2021, Hendriks et al., 2023, Michalke et al., 2022, Holden and Jones, 2021) and by the FAO (Riemer et al., 2023), which identified "gaps in the standardization of methods, including indicators, impact pathways and valuation factors". This concern is reinforced by the findings of the present study, which reveal the high methodological sensitivity of TCA estimates. For instance, the external costs of conventional sausages varied by a factor of 10.3 (from €2.17 to €22.50 per kilogram) depending on the LCA and monetization approach. Without a harmonized framework, externality valuation remains inconsistent, complicating cross-sector and cross-country comparisons, especially for businesses and policymakers seeking to integrate true cost considerations into decision-making. Lord (Lord, 2023) estimates hidden agrifood systems costs of 12,7 trillion PPP (purchasing power parity) dollars in 2020, of which 73% stem form health impacts, while environmental costs, which are presumably undervalued, represent nearly 2,9 trillion PPP dollars in 2020, or 20% of the total. Seidel et al. (Seidel et al., 2023) attribute health costs at the product level at 32.56% due to overconsumption of meat; followed by under-consumption of whole grains (15.42%) and legumes (10.19%).

Current TCA methodologies also overlook positive externalities, such as ecosystem services (e.g., carbon sequestration through humus formation, biodiversity benefits provided by flowering areas). Additionally, social externalities, such as animal welfare and labor conditions, are also excluded in most approaches. Nevertheless, there are first approaches, e. g.: a study by Florencio et al. (Florencio et al., 2025) evaluated a first approach to monetize health effects and environmental costs of different types of fish by comparing wild-caught and cultivated fishes. Similarly, Vissers et al. (Vissers et al., 2023) published a method to measure animal welfare for dairy cattle, pigs and broilers based on the welfare quality protocol. And Baltussen et al. (Baltussen et al., 2025) confirm that TCA can support the transformation of livestock systems in the direction of sustainability. Developing and integrating valuation further methods for missing externalities, in particular for animal welfare and ecosystem services, is crucial for advancing the understanding of "true costs" in a holistic way.

Finally, for future research, it is important to note that any results generated by the methodology presented are often referred to as "true costs." However, this terminology is misleading, as the approach only captures certain aspects of the uninternalized externalities of the food production, overlooking impacts from e.g., distribution and consumption, which may represent significant contributors to overall external costs in the food system. Therefore, future research should focus especially on social and positive externalities to provide a holistic approach of "true costs". Moreover, comparable TCA studies between different emission sectors like mobility or construction and chemical industry need to be researched within the next years.

5. Conclusion

This study addresses the current challenges in calculating external costs and highlights the need for a harmonized True Cost Accounting (h-TCA) methodology. Such a novel methodology is proposed, aiming to ensure robustness and illustrating its practical applicability and communicability through nationwide implementation, which could serve as the (discussion) foundation for a harmonized approach. The findings offer key insights into external cost assessment.

More specifically, this study presents a method for calculating the social external costs of food production in the EU. It was applied to nine products, with external costs assessed in a case study conducted in collaboration with the German food retailer PENNY. Generally, external costs are substantially higher for animal-based products compared to plant-based products. These results emphasize the need for policy measures that support shifts in both consumption and production towards more plant-based diets and products.

Our robustness check of existing approaches – including Agrifootprint, Agribalyse, Ecoinvent, ReCiPe, and PEF – combined with various monetization methods and chosen time preference rates, shows significant differences in the results. This highlights the need for harmonization in the short term to ensure scientific comparability of these approaches, and in the medium to long term, to support policymakers and businesses seeking to integrate true cost considerations into decision-making. Based on this assessment, the h-TCA estimate presented in this paper was identified as the most suitable and robust approach. This was confirmed by applying this h-TCA for the case study with PENNY.

In addition to methodological robustness, the application of h-TCA demonstrates behavioral responses to true cost transparency. Evidence from the TCA intervention shows that disclosing external costs can influence consumer decisions beyond simple price-driven substitution, including reduced demand for high-externality products and changes in overall consumption levels. These findings indicate that that the relevance of the h-TCA approach lies not in an empirical validation on the accounting methodology itself, but in its ability to make the societal and environmental consequences of food choices more visible to consumers, thereby supporting changes in demand that can contribute to reducing environmental externalities.

Overall, it becomes clear that True Cost Accounting brings much-needed transparency and sheds light on the previously obscured agri-food system. The continuous expansion of this TCA approach to include social indicators, human health, ecosystem services and animal welfare plays a crucial role in shaping a more comprehensive understanding and ultimately a more sustainable food-system in the long-term.

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CRediT authorship contribution statement

Lennart Stein: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Benjamin Oebel:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Amelie Michalke:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Tobias Gaugler:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2026.101427.

Appendix

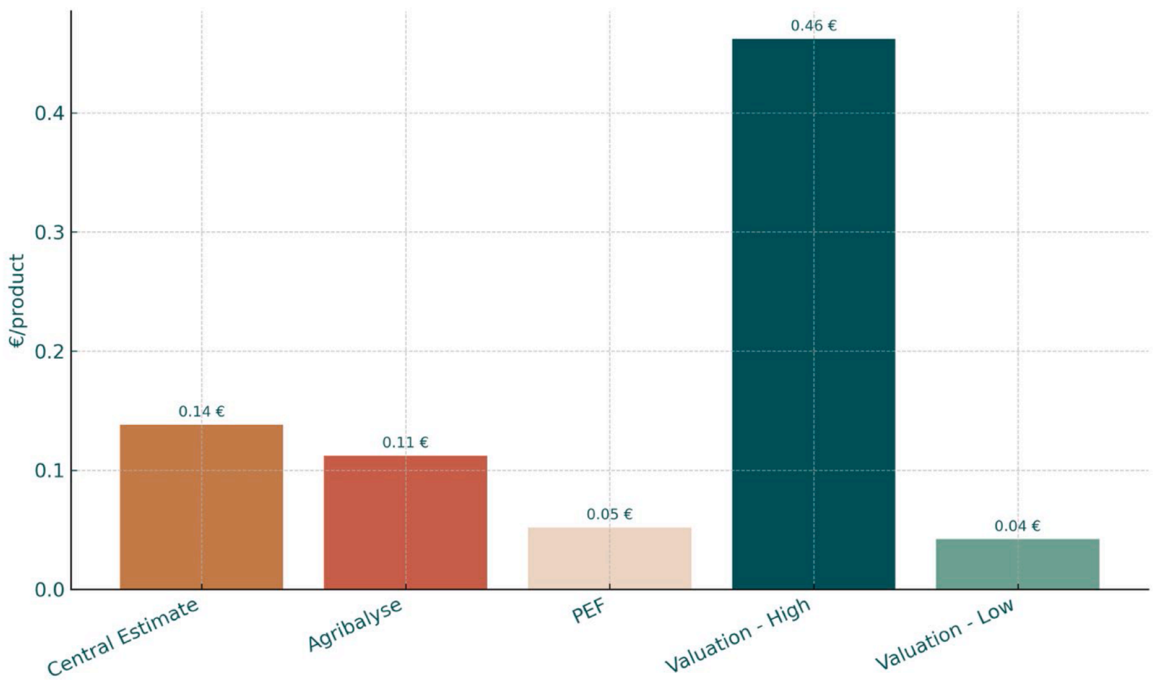

Fig. A.1. Robustness check of different TCA valuations: Comparison of external costs for vegan schnitzel (200g). Across all approaches, external costs remain very low, ranging from €0.04 to €0.46 per product. Even under the high valuation scenario, additional costs stay below €0.50, confirming that the vegan schnitzel entails only minimal uninternalized environmental externalities compared to animal-based products.

Notes: Robustness checks for the true costs of the conventional vegan schnitzel (200g). The central estimate is derived from the Agri-footprint database and the ReCiPe LCIA method. In robustness check "Agribalyse", solely Agribalyse LCIs are used for the evaluation. In "Impact assessment" the LCIA method PEF is used instead of ReCiPe. Due to the incompatibility of this method with the used monetization factors, the PEF cost factors indicated in Table A.1 had to be used for this check. In "Valuation" the upper and lower bound for the social cost estimates is used.

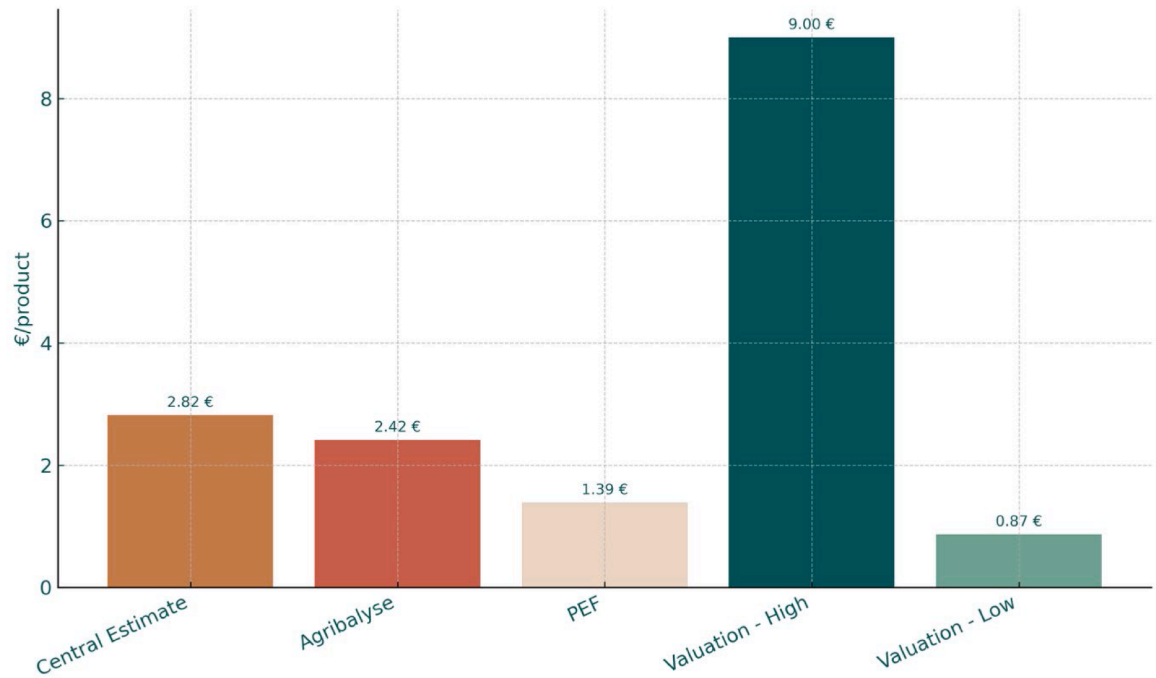

Fig. A.2. Robustness check of different TCA valuations: Comparison of external costs for conventional Wiener sausages (400g). Across all approaches, external costs are substantial, ranging from €0.87 to €9.00 per product. Under the central estimate (€2.82), external costs are an order of magnitude higher compared to valuation high scenario of plant-based product (see Fig. A.1). With high valuation scenario, costs reach €9.00 per product, underscoring the large uninternalized environmental externalities of meat products.
Notes: Robustness checks for the true costs of the conventional sausages (400g). The central estimate is derived from the Agri-footprint database and the ReCiPe LCIA method. In robustness check "Agribalyse", solely Agribalyse LCIs are used for the evaluation. In "Impact assessment" he LCIA method PEF is used instead of ReCiPe. Due to the incompatibility of this method with the used monetization factors, the PEF cost factors indicated in Table A.1 also had to be used for this check. In "Valuation" the upper and lower bound for the social cost estimates are used.

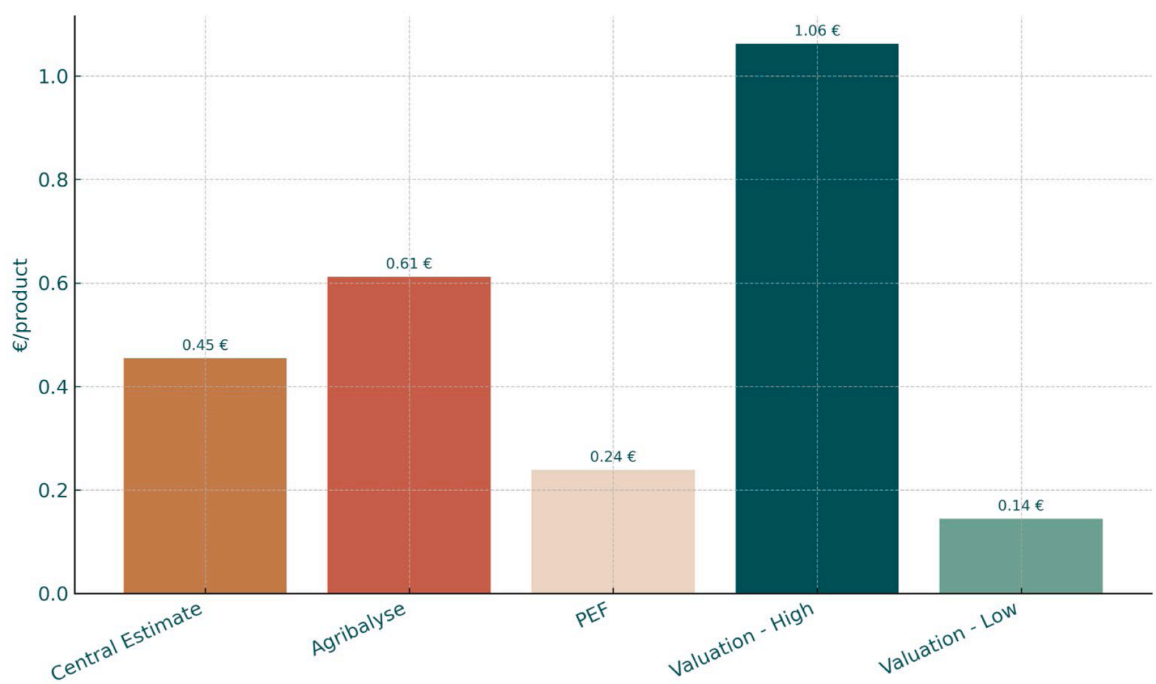

Fig. A.3. Robustness check of different TCA valuations: Comparison of external costs for conventional fruit yogurt (450g). External costs remain moderate across all approaches, ranging from €0.14 to €1.06 per product. The central estimate amounts to €0.45, positioning fruit yogurt between vegan schnitzel (very low external costs, Fig. A.1) and Wiener sausages (high external costs, Fig. A.2). Even in the high valuation scenario, additional costs stay close to €1.00, highlighting the relatively lower but still non-negligible externalities of dairy products.
Notes: Robustness checks for the true costs of the conventional fruit yogurt (450g). The central estimate is derived from the Agri-footprint database and the ReCiPe LCIA method. In robustness check "Agribalyse", solely Agribalyse LCIs are used for the evaluation. In "Impact assessment" the LCIA method PEF is used instead of ReCiPe. Due to the incompatibility of this method with the monetization factors used, the PEF cost factors indicated in Table A.1 also had to be used for this check. In "Valuation" the upper and lower bound for the social cost estimates is used.

Table A.1
True Cost Estimates: Comparison of Environmental prices handbook (EPH) and the European Commission's report on Energy costs, taxes and the impact of government interventions on investments and respective impact categories.

ReCiPe impact categories		EPH			PEF impact categories		European Commission		
Impact	Unit	Valuation [€/unit]			Impact	Unit	Valuation [€2018/unit]		
		Central	Low	High			Central	Low	High
Climate					Climate				
Climate change Human Health	kg CO_2 eq	0.2215	0.0264	0.7560	Climate change Human Health	kg CO_2 eq	0.1151	0.0688	0.2175
Ozone depletion	kg CFC-11 eq	35.4506	25.7716	53.2925	Ozone Depletion	kg CFC-11 eq	35.2730	25.6122	142.8893
Ionizing radiation	kBq U235 eq	0.0538	0.0346	0.0697	Ionizing radiation	kBq U235 eq	0.0013	0.0009	0.0518
Photochemical oxidant formation	kg NMVOC	1.3411	0.9796	2.1457	Photochemical oxidant formation	kg NMVOC eq	1.3368	0.9773	2.1344
Particulate matter formation	kg PM10 eq	45.7126	32.6519	70.4347	Particulate matter	disease inc.	880,842.8665	743,624,2080	1,353,180,0
Human toxicity	kg 1,4-DB eq	0.1156	0.0845	0.1784	Human toxicity, non-cancer	CTUh	183,607.1295	33,937.33	848,427.6656
					Human toxicity, cancer	CTUh	1,013,948,0	195,825.7370	3,133,460,1580
Water					Water				
Freshwater eutrophication	Kg P eq	2.1690	0.2915	2.4606	Eutrophication, freshwater	kg P eq	2.1568	0.2921	2.4489
Marine eutrophication	kg N eq	3.6267	3.6267	3.6267	Eutrophication, marine	kg N eq	3.6059	3.6059	3.6059
Freshwater ecotoxicity	kg 1,4-DB eq	0.0421	0.0057	0.0477	Ecotoxicity, freshwater	CTUe	4.2912E-05	2.6848E-24	2.1119E-04
Marine ecotoxicity	kg 1,4-DB eq	0.0086	0.0012	0.0098					
					Water use	m^3 water eq	0.0056	0.0047	0.2650
Soil					Soil				
Agricultural land occupation	m^2a	0.0985	0.0297	0.7988	Land use	dimensionless (pt)	0.0002	0.0001	0.0004
Urban land occupation	m^2a	0.0985	0.0297	0.7988					
Terrestrial acidification	kg SO_2 eq	5.7957	0.6134	6.6003	Acidification	mol H+ eq	0.3864	0.1977	1.8166
Terrestrial ecotoxicity	kg 1,4-DB eq	10.1337	1.3644	11.4865					
					Resource use, minerals and metals	kg Sb eq	1.8423	0	7.3365
					Resource use, fossils	MJ	0.0015	0	0.0076

Table A.2
Coefficients of variation across multiple approaches demonstrate the robustness of the main findings. Sausages exhibit the highest externalities among the assessed products (ranging from 4.44 to 13.35), while yogurt shows higher externalities than vegan schnitzel (ranging from 1.02 to 2.43).

Database	LCIA Method	Monetization method	Coefficient of variation Sausage - vegan Schnitzel	Coefficient of variation Sausage - Yogurt	Coefficient of variation Yogurt - vegan Schnitzel
Agri-footprint	ReCiPe	Environmental Prices Handbook - Central estimate	10,22	6,98	1,46
Agribalyse	ReCiPe	Environmental Prices Handbook - Central estimate	10,79	4,44	2,43
Agri-footprint	PEF	Energy costs, taxes and the impact of government interventions on investments	13,35	6,55	2,04
Agri-footprint	ReCiPe	Environmental Prices Handbook - Higher bound	9,74	9,53	1,02
Agri-footprint	ReCiPe	Environmental Prices Handbook - Lower bound	10,33	6,78	1,52

Data availability

The authors do not have permission to share data.

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