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Abstract

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The main goal of the Finnish LCAFoodPrint is to create a national Life Cycle Assessment (LCA) methodological guideline for food products and particularly, to be used in public external communication to consumers and other stakeholders. A major motivation is to significantly enhance the consistency and comparability of LCA results, which is currently limited due to varied methods across different products and categories.

To achieve this, the study systematically reviews existing LCA approaches and international standards, giving main focus on the European Commission's Product Environmental Footprint (PEF) method and the Product Environmental Footprint Category Rules (PEFCRs). Each guideline was examined for methodological consistency and differences in areas such as functional unit definition, system boundaries, allocation methods, and emission modelling. While the PEF method was designed for uniform and comparable assessments within product groups, its applicability in comparisons across product categories remains uncertain. Thus, attention was paid to the comparability of LCA results within and across product groups. In this report evaluation is made on whether the PEF method and the PEFCRs support reliable comparisons also across product categories and to identify deviations in methods causing discrepancy. Aim of this comparison is to form the basis for the development of a solid, transparent, and harmonized national LCA guideline for use in both regulatory frameworks and in external communication.

The review found that while the PEF method ensures consistency within product groups, significant methodological differences across PEFCRs could impair full comparability between food products, across product categories. Well-acknowledged issue of mass-based functional units was seen as one of the largest challenges, as they do not account for nutritional value which can be very different across food categories. System boundaries generally extended from cradle to grave, but differences exist in how the use stage is handled. Allocation methods varied widely — economic, mass-based, and biophysical allocations were found to be used mainly consistently, yet severe differences were also noticed, which would hamper comparisons. Crop production emissions were typically modelled with IPCC Tier 1 methods, while livestock modelling was more variable. Use stage modelling and land use changes were inconsistently addressed, which were seen as potentially leading to variation in interpretation. Waste treatment and end-of-life modelling were generally harmonized and use the Circular Footprint Formula (CFF), though also in this case interpretation of its use was found varying. Data quality requirements were mostly aligned with PEF, but the extent and methods for collecting primary data differed, affecting transparency and comparability.

The PEF method provides a solid basis for harmonizing food LCAs, but it was found as not fully sufficient for comparing different food products across categories due to inconsistencies found across PEFCRs. Key areas needing harmonization included functional unit definitions, allocation principles, treatment of the use phase, land use changes and modelling requirements and used Tiers. Although internal comparability within product groups is well supported, cross-category comparison remains limited. To support transparent communication of environmental information and informed decision-making, a national guideline food LCA guideline need to address these inconsistencies.

Key words: Food, LCA, harmonisation, comparability, PEF, sustainability, environmental footprint

Contents

1. Introduction

1.1. Goal and target audience

The main objective of the Finnish LCAFoodPrint project is to develop a national Life Cycle Assessment (LCA) methodological guideline that is applicable to product specific LCAs of various food products. Particularly, the focus has been on developing environmental footprint assessment which is intended to be used in public external communication to consumers and other stakeholders. The aim of the project has been to create an environmental impact assessment guideline for public communication purposes, and that the use of the guideline would lead to significantly increased consistency and comparability of LCA results. To achieve this goal, the project has reviewed different, well adapted LCA approaches, guidelines, and standards. Here, in this report, the focus is on finding the most applicable methods for food LCAs by reviewing the European Commission's Product Environmental Footprint (PEF) method and developed Product Environmental Footprint Category Rules (PEFCR; European Commission 2018, 2021).

The European Commission began work on harmonising environmental impact assessment methods for products and organisations in 2013 and the initial recommendation on use of the LCA approach as a basis for green claims was published in 2013, with the very first PEF Guide (Annex II, European Commission 2013). After this, the PEF pilot phase was initiated, and it produced the PEFCR guidance version 6.3 for development of specific PEFCRs, and several detailed instructions constructed accordingly for different product groups (European Commission 2018). The PEFCR completed during the pilot phase moved on to a transition phase which continued until the end of 2021. The transition phase between 2018 and 2021 resulted in the publication of the working documents from the European Commission's Joint Research Centre, JRC, which included suggestions for updating the PEFCR method (Zampori & Pant 2019), and the revised recommendation on the use of the Environmental Footprint method in December 2021 (European Commission 2021).

In this study, these fore mentioned PEF methods and food related PEFCRs published by the European Commission were reviewed and critically evaluated for uniformity in selected methods, but also for possible inconsistencies that may affect the comparability between the environmental footprint estimates of different food products (European Commission 2018, 2021; Technical Secretariat 2018a, 2018b, 2018c, 2018d, 2018e, 2018f, 2018g, 2018h, 2018i, 2018j, 2021). The observations made in the review of these methodological guidelines form the basis of this report.

The aim of the project has been to form a solid, consistent method for the LCA of food products and its requirements, and later also for the communication of the environmental footprint of food. The methodological guideline that will eventually be formed in the study is aimed for anyone who is implementing an LCA or environmental footprint assessments of food products, as well as for various decision-makers who utilise environmental footprint assessments of food as part of their work.

1.2. Product Environmental Footprint Category Rules (PEFCR) guidelines

To support the reliable and comparable assessment of environmental sustainability claims, the European Commission has published general guidance for the development of product group-specific assessment guidelines (European Commission 2018, 2021), as well as a number of product group specific guidelines developed in accordance with general PEF method. The aim of the PEFCRs is to achieve *comparability within the product group*. However, the PEFCRs do not aim for comparability *between product groups* (i.e., a comparison of the results of the products of two different PEFCRs). The need for harmonised methods in environmental footprint assessment, for the communication of product specific results, has been a driving force in this study. There is an increasing desire to communicate the environmental footprints of food products, but in the absence of standardised assessment guidelines, environmental claims have been made on different grounds.

The PEF guidance 6.3 and the product group specific PEFCR guidelines for food published by the European Commission, as well as other assessment standards and guidelines, such as the ISO 14040 series and 14067 and the LEAP guidelines, have been used in the implementation of this work. In addition, draft versions of the PEFCRs have been reviewed as incomplete or unofficial assessment guidelines (Table 1). The reviewed guidelines included the existing food-related pilot phase PEFCRs, which were valid until the end of 2021 for: beer, dairy products, feed, packed water, pasta, pet food and wine. Unofficial guidelines included the draft PEFCRs for marine fish, olive oil, horticultural products, coffee, and red meat. General PEF guidance, the revised PEF method and the product group specific PEFCR documents analysed in this review, are listed in Table 1.

In addition to the PEF guidance 6.3, the revised recommendation and the PEF method by the European Commission (2018, 2021, Annex I.), and the specific PEFCRs, this review also included sections, e.g., from the JRC working document by Zampori & Pant (2019), and the PAS 2050 standard (BSI 2011). The JRC working documents have provided insights for improving PEFCR method, which were taken into the revised recommendation to some extent. Yet, in this review the focus has been in the detailed product group specific PEFCRs.

Table 1. Product group specific PEFCRs and PEFCR methods, drafts and other guidelines included in the review. Short names are used in text according to this table.

PEFCR guidance and official PEFCRs (valid until 2021)		
Short name in text	**Document name**	**Reference**
PEFCR guidance 6.3	Product Environmental Footprint Category Rules Guidance	European Commission 2018
Revised PEFCR method	Commission Recommendation on the use of the Environmental Footprint methods. Annex I. Product Environmental Footprint Method	European Commission 2021
Feed PEFCR	PEFCR Feed for food producing animals	Technical Secretariat 2018a
Beer PEFCR	PEFCR for beer	Technical Secretariat 2018b
Dairy PEFCR	Product Environmental Footprint Category Rules for Dairy Products	Technical Secretariat 2018c
Packed water PEFCR	Product Environmental Footprint Category Rules (PEFCRs) Packed water	Technical Secretariat 2018d
Pasta PEFCR	Product Environmental Footprint Category Rules for Dry pasta	Technical Secretariat 2018e
Pet food PEFCR	Product Environmental Footprint Category Rules (PEFCRs) Prepared Pet Food for Cats and Dogs.	Technical Secretariat 2018f
Wine and sparkling wine PEFCR	Product Environmental Footprint Category Rules (PEFCR) for still and sparkling wine	Technical Secretariat 2018g
Other guidance and draft PEFCRs (unofficial)		
Short name in text	**Document name**	**Reference**
Horticultural products (draft)	Hortifootprint Category Rules: Towards a PEFCR for horticultural products.	Helmes et al. 2020
Marine fish (draft)	Product Environmental Footprint Category Rules (PEFCR) for unprocessed Marine Fish Products. *Draft.*	Technical Secretariat 2021
Olive oil (draft)	Product Environmental Footprint Category Rules for Olive oil – *3rd draft.*	Technical Secretariat 2018h
Red meat (draft)	PEFCR Red Meat Version 0.6. *Draft.*	Technical Secretariat 2018i
Coffee (unofficial)	Environmental footprint of coffee in Colombia.	Quantis et al. 2019
Other documents (partially reviewed)		
Short name	**Document name**	**Reference**
Suggestions for updating the PEF method	Suggestions for updating the Product Environmental Footprint (PEF) method	Zampori & Pant, 2019
Fur product PEFCR (draft)	Product Environmental Footprint Category Rules dressed (and dyed) natural fur. *Draft.*	Technical Secretariat 2018j
ISO 14040	ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework	ISO 14040 (2006)
ISO 14041	ISO 14041: Environmental Management. Life Cycle Assessment. Goal and Scope Definition and Inventory Analysis.	ISO 14041 (1998)
ISO 14044	ISO 14044: Environmental management. Life cycle assessment. Requirements and guidelines.	ISO 14044 (2006)
ISO 14067	ISO 14067: Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification	ISO 14067 (2018)
PAS2050:2011	PAS 2050:2011. Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services.	BSI (2011)

1.3. Analytical review of Product Environmental Footprint Category Rules (PEFCR)

In this report, the uniformity, and the possible differences, which would affect comparability between LCA studies or make comparison impossible, were reviewed for the different product group specific PEFCR guidelines. The focus of the review was on the climate change, the freshwater and marine eutrophication and the water use impact categories.

In this work, a critical review of the PEFCR guidance 6.3, revised PEF method and related documents according to Table 1 was conducted, to answer three research questions:

1. Are there methodological differences between the general PEFCR guidance 6.3, PEF method and the different product group specific PEFCRs?
2. Are there methodological differences between different product group specific PEFCRs? and
3. To what extent are the methods outlined in the general PEFCR Guidance 6.3, the PEF method, and specific PEFCRs applicable to the development of national recommendations for harmonised environmental life cycle assessment (LCA) of food products?

Each PEFCR, draft, and general guidance were reviewed in parallel under the headings of this report, by describing the utilised approaches. The headings follow the four phases of LCA: goal and scope definition, life cycle inventory, impact assessment and interpretation, as according to ISO standardisation of LCA (ISO 14040, 2006).

2. Goal and scope definition for LCA

According to general requirements for goal definition in LCA studies—particularly when results are intended for public use—it is essential to clearly specify the rationale and objectives of the study, the intended audience, and the anticipated application of the results (European Commission, 2018; ISO 14040). In LCA studies, key methodological choices are made in the context of the scope definition. Among the most important choices are the definition of the functional unit, the boundaries of the product system under investigation, the impact categories to be included and any key assumptions and limitations. In this section, we focus on three key LCA aspects that should be defined at the outset of the study (Sections 2.1–2.3), as they are also specified in the PEFCRs.

2.1. Functional unit

The functional unit (FU) quantifies the performance of the product system, by describing the functions and duration which the product or service under scope fulfils, answering questions about how much, how well, or for how long (European Commission 2018, 2021, ISO 14040). The functional unit is used as the LCA reference unit. According to the PEFCR method, "meaningful comparisons may only be made if products fulfil the same main function" (European Commission 2018, 2021). As the functions of different product groups presented by different PEFCRs differ, neither are the functional units of different PEFCRs are comparable with each other.

2.2. System boundaries

The principle of the PEFCR method and most PEFCRs is that the LCA of food covers the entire life cycle, from cradle to grave, starting from natural resources acquisition, and including agriculture, processing, distribution and transportation, packaging, storage, product use, disposal, and waste recovery.

No significant exceptions were identified in the system boundaries between the different product group specific PEFCRs—except for the later stages of the chain and for the use stage. Differences were also found between the PEFCRs in the accuracy with which the steps are described, which can lead to differences in interpretation between different PEFCRs. Zampori & Pant (2019) have sought to clarify this in general.

The primary production stage should in principle include, e.g., the following details: fertiliser, lime, bedding material and pesticide production chains and related transport, fuel and energy production, water use, land use change and crop and livestock production and storage. Small differences were found between the PEFCRs in these processes, e.g., manufacture of machinery and equipment, veterinary medicine and antibiotics, on-farm washing and detergent manufacturing, and refrigerants could be excluded from the system. The PEFCRs define very generally how and with what limits the various agricultural inputs should be included in the assessment.

Regarding the manufacture and processing of products, transport, packaging, retail and consumption, and the treatment of waste, the detailed system boundaries in PEFCRs are relatively product group-specific and at a fairly general level. Processing and manufacturing include, in principle, all processes in the production stages in which intermediate products and

finished products from food raw materials are processed for onward transport, for example for wholesale and retail. The system boundaries of processing and manufacturing include energy consumption, water consumption and the use of other auxiliaries and additives, and, for example, the treatment of wastewater from processing, as in principle they are part of other stages of the life cycle. Some PEFCRs describe in some detail which processes and transports should be included in the system and in the environmental footprint of the product in question. There are small differences between PEFCRs if shipments between stages of the production chain are included in the system boundary. Typically, PEFCRs include the transportation of raw materials and packaging materials from primary production to a processing plant, the transportation of a product from a production facility to a distribution center, retail, and the consumer, and transportation to a waste facility. In addition to these, the transport of inputs to primary production is included in the review according to the PEFCR for animal feed and according to the unofficial PEFCRs for red meat, marine fish, and olive oil (Technical Secretariat 2018a, 2018h, 2018i, 2021). Not all PEFCRs specifically mention the transport of inputs to primary production, so it is not clear whether this is included or not. The transport of workers to primary production has also been included in the unofficial PEFCR for marine fish and unofficial guideline for coffee (European Commission 2021, Quantis 2019).

Like the PEF method, most PEFCRs include consumer activities as part of the assessment, except for the draft of the red meat PEFCR, which excludes them (European Commission, 2018; Technical Secretariat 2018i). The inclusion of the use phase is described in more detail in section 3.1.4.

In addition, there is variation in the PEFCRs as to whether the manufacture of equipment and machinery should be included in the assessment. The manufacture of buildings and machinery and other production-related infrastructure are to be included in the assessment in accordance with the PEF method, unless they can be excluded by the cut-off rule (European Commission, 2018, 2021). In this case, an explanation must be provided to the PEFCR. PEFCRs for dairy products, beer, wine, pasta, and feed, for processing and storage, machinery and infrastructure are excluded, but in PEFCRs for beer and feed, they are included in the related crop production (Technical Secretariat 2018a,2018b, 2018c, 2018e, 2018g). According to the PEFCR draft for marine fish, infrastructure must be included but may be based on secondary data (European commission 2021a).

According to suggestions by Zampori & Pant (2019), the manufacturing of machines, equipment and infrastructure should only be included if its impact has been found to be significant in previous studies. Yet, the revised PEF method still includes the capital goods for assessment of representative products, but excludes machinery and infrastructure from all stages unless they are significant based on previous studies (European commission 2021). If the manufacture of machinery or equipment is included in the scope of the study, the assessment and related assumptions must be described very clearly and extensively (European commission 2021). So far, the machinery and infrastructure has been reported to be included only in the official PEFCR for feed, beer and in the unofficial assessment guidelines for coffee (Technical Secretariat 2018a, Quantis et al. 2019).

According to Zampori & Pant (2019), the stages of the life cycle should be defined as follows:

- Sourcing and pre-processing of raw materials should be included according to the suggestion by Zampori & Pant (2019). This includes, for example, agricultural production, pre-processing of products, transport of all raw materials to production facilities and, for example, the manufacture of packaging.

- The manufacturing stage begins when the components and raw materials of the products have entered the production site and ends when the products leave the production site. In addition to manufacturing, the production of chemicals used as auxiliaries and additives, such as detergents, and the transport of semi-finished products between different processing plants, should be included.
- The distribution phase includes the distribution and storage of products at different points in the supply chain, including transport from production facilities to warehouses and trade, storage and transport to consumers. According to this, consumer shopping trips would be included in distribution and not in use, as in most previous PEFCRs, Zampori & Pant (2019) suggests.
- The use phase describes how the product is expected to be used by the end user, typically the consumer. This step includes functions from the start of use of the product to the end of use.
- The end-of-life phase begins when the system's product and consumer packaging have been taken out of use, i.e. covering processes from transport to waste management and until the product has 'returned to the environment', for example through waste management or when the waste is transferred to another product system. This phase includes food waste and consumer packaging waste management. Waste management in other stages of the life cycle should be included within each stage of the life cycle.

In conclusion, there are mainly no significant exceptions between the different guidelines and PEFCRs. However, differences were observed for transportation and downstream, where there are significant differences, especially concerning inclusion of the use phase. The guidelines also differ in the level of detail with which the various steps are described, which can lead to inconsistencies in interpretation between different PEFCRs.

2.3. Impact categories

All the principles of PEFCR's Life Cycle Impact Assessment (LCIA) phase for different environmental impact categories were reviewed, although the focus of the project and this document on LCA and LCIA is limited to climate impact, eutrophication, and water scarcity. The climate impact is divided into four groups: the total climate impact, the biogenic and fossil climate impact, and the climate impact of land use change. The guidelines, which include both the official and draft PEFCRs, recommend the use of the 10 to 12 environmental impact categories which were in accordance with the PEF guidance or method valid at the time they were developed (Table 2).

Table 2. Included environmental impact categories in the reviewed PEFCRs.

Environmental impact category	Number of PEFCR's which include the impact category
Climate impact Note: The different components of climate impact are further subdivided in the PEFCRs: fossil, biogenic and soil	12
Eutrophication: *marine*	12
Eutrophication: *inland*	12
Water scarcity	12
Toxicity to humans: carcinogenic	10
Toxicity to humans: non-carcinogenic	10
Particles	12
Ionizing radiation	10
Ozone formation, lower atmosphere	11
Acidification	12
Ecotoxicity impact on inland waters	11
Land use	11
Resource use	11
Ozone depletion	11

In general, the impact categories and guidelines for their assessment were the same in most PEFCRs. There were a few exceptions in the older draft guidelines (olive oil and marine fish). These older guidelines recommended different impact assessment methods than the newer ones. The impact categories addressed in this report, i.e. climate change impact, eutrophication impact, and water scarcity impact, were mandatory in all the reviewed PEFCRs.

3. Life cycle inventory, LCI

3.1. Modelling requirements

The inclusion of crop and livestock emissions in LCAs requires mathematical models or emission factors, which can be globally universal, country or measure specific. The level of detail in emission modelling may vary in agricultural modelling. A hierarchical classification of different modelling options is applied for example in the IPCC's climate impact modelling. IPCC Tier 1 represents global emission factors, while Tier 2 is a method in which global factors are replaced by national coefficient values, and Tier 3 is an "alternative national assessment method". The PEFCR guidance 6.3 partly follows a similar idea in its recommendations regarding crop and livestock modelling. Yet, between PEFCRs their minimum requirements may vary. The observations made in this review regarding modelling requirements are presented in following sections.

3.1.1. Agricultural modelling

According to the PEFCR method, an overall N-balance calculation should be applied for crop production (European Commission 2018, 2021). The method to be prioritised is based on IPCC 2006 Tier 1 emission factors. If more detailed data is available, a more detailed model should be applied. Factors and formulas of an optional model are provided. The third option is still another more detailed model, in case it calculates the overall N-balance.

Even though the guidance is based on N-balance calculation by IPCC, according to PEF method, the direct and indirect N_2O emissions from synthetic fertiliser and manure should be calculated applying a general factor (0.022 kg N_2O / kg N fertiliser applied) instead of the more detailed formulas given by the IPCC (European Commission 2018, 2021).

For livestock products, the minimum requirements of the PEFCRs differ for N_2O modelling (Technical Secretariat 2018c, 2018i). Both the PEFCR for dairy products and the draft PEFCR for red meat set the Tier 2 method as the minimum requirement for enteric fermentation and manure methane emissions. The draft PEFCR for red meat also states for Tier 1 that it does not meet PEF study quality and thus is not allowed. For manure storage and manure application, for both direct and indirect emissions, the dairy PEFCR recommends set Tier 1 as a minimum requirement. In the draft PEFCR for red meat, this is a fallback option, a method inferior to the minimum requirement, which results in a lower data quality score in terms of technological representativeness. As an alternative method, Tier 3 is recommended, using the country specific method used in the national GHG inventories.

In general, the minimum requirements for emission modelling in PEFCRs represent a relatively general level of analysis that cannot record the variation in practises very well. On the other hand, a general level allows the inputs required for the assessment to be more readily available.

In conclusion, PEFCRs have rather general assessment methods. For livestock production (dairy products and meat), the methods are the same, yet there is difference in the method of modelling N_2O. For plant products, modelling is mainly recommended according to the general PEF method, which in practice means IPCC Tier 1 (uniform in all).

3.1.2. Electricity

All reviewed official PEFCRs follow PEFCR guidance 6.3 in the modelling of electricity generation. In this general guidance the electricity generation modelling is presented at three hierarchical levels (European Commission 2018). The highest level of the hierarchy is the electricity supplier's contract-based product level information on the energy sources of electricity. This can mean electricity production with a guarantee of origin, which applies to renewable energy sources. To be able to calculate life-cycle emissions of the production, information on renewable energy alone is not enough, but information on the energy sources used is also needed. Electricity suppliers are required by law to inform the customer once a year of the production distribution of the electricity they purchase, but the breakdown into fossil, renewable and nuclear power is sufficient, which is not an adequate level of precision for emissions assessments.

The second level of the hierarchy is the total distribution of electricity sold per supplier, which means practically all electricity purchased without a guarantee of origin that can be traced to energy sources, i.e., this level of hierarchy cannot include exchange electricity transmitted by the electricity supplier. The requirements of this hierarchy level must be met on the basis of legislation, which requires annual reporting of the origin of electricity sold to the customer by energy source. Yet, the same problem of roughness of distribution applies to this as to the top hierarchy level. To carry out a comprehensive assessment of emissions, an accurate breakdown by energy source must be available.

The last option is to use the electricity according to the so-called residual mix, i.e., the electricity production that is left over after deducting the electricity of hierarchy levels 1 and 2. The source for this residual distribution is the database (https://lcdn.thinkstep.com/Node/). In practice, the residual mix means exchange-traded electricity, i.e., electricity without guarantees of origin.

When self-generated solar electricity matches consumption and is not sold to a third party, it is considered self-consumption and is modelled accordingly. If electricity is sold to a third party, the residual mix is used. When self-generated electricity exceeds own consumption and surplus electricity is sold—for example, to the grid—it is recommended to separate the subprocesses. If this is not possible, substitution can be used, in which case the own electricity production substitutes the electricity production of the residual distribution.

3.1.3. Transportation and storage

In the reviewed PEFCRs, emission modelling of transport is based on information on the mass (or volume) of the goods transported, the mode of transport (truck, ship, train, etc.), the transport distance and the utilisation rate of the transport.

There are small differences between PEFCRs if shipments between stages of the production chain are included in the system boundaries. These differences are described in more detail in section 2.2.

If accurate information on all transports is not available, the default distances, modes of transportation and utilisation rates of PEFCRs can be used. For transport to the consumer's home by car, assumptions are made about the average volume of the luggage compartment of the car, and the assessment is based on the volume of the product.

In the reviewed PEFCRs, emissions from storage were included for both the distribution center and the store. If detailed data on storage is not available, PEF default values could be used: average stock/trade size in m^2 (divided into hot and cold storage), annual energy consumption per m^2, refrigeration equipment, storage capacity m^3 per m^2/week, water consumption per m^2. The product group specific PEFCRs were carried out mainly in accordance with the PEFCR guidance 6.3., yet some differences were observed in system boundaries (described in chapter 2.2).

3.1.4. Use stage

In the reviewed PEFCRs, the modelling requirements for the use stage were found to be presented in all those PEFCRs which include this stage. Most PEFCRs include a description of the use stage and more detailed modelling requirements for it, but there is considerable variation between PEFCRs.

The assessment of the use stage varies due to differences in products, how they are typically meant to be consumed and stored. Thus, the descriptions and requirements in PEFCRs vary and are completely product specific. For example, in the case of milk, the use phase is marked as relevant in the PEFCR, while in the case of cheese it is not (Technical Secretariat 2018c). Additionally, assessment of dairy products and sparkling wine should include the energy consumption of the cold storage at use stage (Technical Secretariat 2018c, 2018g) while cooking or heating are not included which are more relevant for other types of products.

If the use phase is considered relevant, there are typically default values in the PEFCR that can be used, for example, for the cold storage or preparation of food, and these are typically designed from the perspective of the average European consumption situation. Regarding cooking (e.g., pasta), it has been suggested that actual country-specific energy uses should be used in modelling and, if not available, EU average data may be used. The possible cooking/cooking time of the product should be indicated in the product manufacturer's data and if this is not the case, for example the default values given in the PEFCR for pasta are how much water is used for cooking per certain amount of dry pasta. In this case, the amount of use of a typical cooking salt is also stated, which should also be included in the assessment of the environmental footprint of the use phase of the pasta.

The environmental footprint of marine fish should also include consumption, but contrary to the above, the PEFCR does not provide advice on how emissions should be modelled for the food preparation process (European Commission 2021).

Several PEFCRs present product group-specific average consumer food waste approaches that can be used to estimate food waste in relation to the environmental footprint of waste treatment. The PEFCR for pasta states that since the manufacturer cannot influence consumer waste, it can be excluded from the assessment, and the losses are negligible for a long-lasting dry product (Technical Secretariat 2018e). It is essential that, in accordance with the PEFCR guidance 6.3, the use stage is presented in the results separately from other life-cycle environmental footprints, the revised PEF method (European Commission 2021) includes reporting of the results as part of overall results and requires separate reporting as well.

In conclusion, it was found that the use stage was included in most of the PEFCRs. Nevertheless, the modelling requirements for the stage varied since the characteristics and relevant processes of different products were different.

3.1.5. End-of-Life modelling

The PEFCR guidance 6.3 (European Commission 2018) recommends the use of the Circular Footprint Formula (CFF) in terms of decommissioning of the products (here this mainly applies to food packaging). CFF is included similarly in the revised PEFCR method (European Commission 2021). This End-of-Life (EoL) equation considers emissions from product manufacturing, emissions and environmental benefits from recycling, emissions from energy recovery and disposal, and it includes the logic of the formula and its factors for how the disadvantages and benefits are allocated for the systems which have generated and received the waste.

In all PEFCRs the EoL is implemented through CFF and can thus be considered well harmonised.

However, for intermediate products (e.g. feed) in cradle-to-gate PEF studies, the parameters related to the product's EoL (i.e. recyclability at EoL, energy recovery, disposal) are not accounted for and exclude the EoL by setting the parameters R2, R3, and Ed equal to 0 in CFF model.

3.2. GHG emissions in climate impact modelling

3.2.1. Fossil GHG emissions

According to the PEF method (2018a, 2021), fossil greenhouse gas emissions include emissions from the combustion or decomposition of fossil fuels, including emissions from landfill treatment, metabolism of farm animals, and GHG emissions from liming (calcination and carbonation) and peat (use as fuel).

3.2.2. Biogenic carbon emissions

Biogenic carbon emissions include carbon emissions related to oxidation and/or reduction of the above-ground biomass (excluding carbon exchange of native forests; European Commissions 2018) and CO_2 uptake through photosynthesis during biomass growth. According to the PEF method (European Commission 2018, 2021), the characterisation factor for CO_2 emissions from biogenic carbon stored food products is considered zero, i.e., this carbon has a short cycle and either its uptake or emissions in digestion are included in the product's total greenhouse gas emissions (European commission 2018, 2021). However, biogenic CH_4 emissions shall be included in the results. For intermediate products, the biogenic carbon content at the factory gate shall be reported.

According to the PEF method, the inclusion of biogenic CO_2 emissions in the reporting is defined separately in each PEFCR. For example, the PEFCR for dairy products requires biogenic carbon sequestration and emissions to be modelled separately, but they are not included in total greenhouse gas emissions (Technical Secretariat 2018c). In several PEFCRs, requirements for the treatment of biogenic carbon are loosely presented.

3.2.3. Land use and land use change (LULUC) emissions

According to the PEF method, biogenic carbon emissions and removals as a result of land use and land use change (i.e. LULUC emissions and removals) are modelled using the PAS2050:

2011 guideline and the supplementary document PAS2050-1:2012. It should be noted that according to these guidelines, changes in carbon stocks shall be allocated for a period of 20 years following the change in land use and for all products cultivated in that area during that period. Thus, if more than 20 years have elapsed since the land use change, the area in question is considered "old" agricultural land, and land use change emissions need no longer be taken into account in the LCA (BSI 2011). In the PEF method, land use changes are considered conversions from one land use category to another (e.g. from forest land to cropland) following the IPCC classification of land use types. It should be noted that only direct land use changes are considered according to the PEF method, and indirect land use changes shall be excluded (European Commission 2018, 2021).

According to the PEF method and PAS2050: 2011, changes in carbon stocks should not be taken into account when they are not due to direct land use changes that have occurred within the past 20 years (BSI 2011, European commission 2021). For fields undergoing direct land use changes within the past 20 years, all soil carbon stock emissions (CO_2, CH_4, CO) shall be included (European commission 2021).

The soil carbon stock accumulation (i.e. soil carbon sequestration) related to management methods (e.g. grass management and tillage methods) shall be excluded, except for the possibility to include soil carbon accumulation in a PEF study report as additional environmental information and if proof is provided (European commission 2021). The PEFCR for dairy products mentions that an increase in the soil carbon stock in grassland can be considered if there is sufficient information on this (Technical Secretariat 2018c). The PEFCR for wine mentions an increase in the soil carbon stocks to be included in the assessment of the biogenic climate impact if the soil carbon stock has been growing for more than one hundred years (Technical Secretariat 2018g). In the draft PEFCR for red meat, the soil carbon stock increase for grass is mentioned as possible additional environmental impact information. However, according to the draft PEFCR for red meat, the results must be reported without a soil carbon stock increase, or if this is reported as additional environmental information, the result and the used method must be described comprehensibly (Technical Secretariat 2018i). Similarly, the PEFCR for olive oil also mentions an increase in the soil carbon stocks as possible additional environmental information (Technical Secretariat 2018h).

In conclusion, the PEF method is based on the PAS2050: 2011 guideline and its supplementary document PAS2050-1:2012 (European Commission 2018, 2021; BSI 2011, 2012). Requirements for the treatment of biogenic carbon in several PEFCRs are loose, leaving room for deviating interpretations and approaches. The increase in soil carbon stocks has been considered in only a few PEFCR guidelines, in accordance with PEF methods (2018, 2021).

3.3. Offsets

Offsetting GHG emission must not be included in the LCA assessment according to the PEF or any other LCA guidelines (European Commission 2018, 2021). However, potential emission offsets can be used in communications, reporting them separately, as additional environmental information (European Commission 2021). PEFCRs do little to address emission compensation.

3.4. Allocation

In general, the recommended allocation methods vary between PEFCRs representing different product groups. Recommended allocation methods include 1) avoidance of allocation, 2) physical (mass, volume) allocation, 3) economic allocation, and 4) physical, biophysical allocation. The following is a brief overview of the recommended use of these methods for product groups.

Many PEFCRs recommend to avoid allocation as the first option, which is in line with ISO standards. However, it should be noted that the recommendation is based on the physical separation of sub-processes. Instead, system expansion is generally not recommended. The exception to this is the modelling of animal manure in accordance with the draft PEFCRs for red meat production and fur products, in which the compensatory effects of manure on energy production and crop production (fertilisers) should be considered (Technical Secretariat 2018i). This contradicts the guidance regarding crop production, which does not mention credits. Yet, it should be borne in mind that both guidelines are drafts and not official PEFCRs.

Within the reviewed PEFCRs, the most commonly recommended allocation methods are mass allocation and economic allocation, but the recommended use of these varies widely between different PEFCRs (Table 3). Most of the reviewed PEFCRs recommend economic allocation at least at some stage in the production chain when the different processes cannot be physically separated. This is the case for example in the feed PEFCR and the PEF method (Technical Secretariat 2018a, European Commission 2021) regarding livestock products at the slaughterhouse. The exception is the draft PEFCR for red meat, which does not accept economic allocation, even if the general PEF guidance 6.3 recommends it, and recommends the use of mass allocation (or biophysical allocation) instead (Technical Secretariat 2018i).

Even if the feed PEFCR recommends the use of economic allocation for feed raw materials, the draft PEFCR of fur products uses both economic and mass allocation for feed, however the economic allocation is more widely used (Technical Secretariat 2018a, 2018j). In the instructions of draft of fur PEFCR, it is specified for which feed fraction which allocation method is used.

Several of the guidelines in which economic allocations have been recommended also provide default values, for example, the section for slaughterhouses in the PEF method and the draft PEFCR for fur products for primary production (European Commission 2018, 2021; Technical Secretariat 2018j). However, there are differences between the PEFCRs as to whether they allow the economic coefficients to be adjusted based on primary data. For example, the general PEF method does not allow that for slaughterhouse co-products, but the feed PEFCR allows.

Physical-causal, biophysical allocation is based on the idea that the energy needs of different metabolic processes in plants and animals (and their "resulting" products) can be determined, and the allocation factors would then be determined by the proportions of these relative energy needs. Biophysical allocation is the primary method in the general PEF guidance for allocating emissions for primary livestock production (on farms), and economic allocation is recommended for allocation between sows and piglets (European Commission 2018, 2021). The PEFCR of dairy products also recommends the use of biophysical allocation (Technical Secretariat 2018c). The red meat draft PEFCR also highlights biophysical allocation as a possible recommended method in the future.

The feed PEFCR states that the consequences of the allocation choice may not be reflected if only one allocation method is used and recommends a sensitivity analysis with two alternative physical allocation methods (Technical Secretariat 2018a). A similar mention is made in the FAO LEAP feed guidelines, but not in other product group-specific guidelines. The PEF guidance v6.3 (European Commission 2018) requires a sensitivity analysis of allocation methods in the first consultation of the PEFCR draft, but this phase is not included to the same extent in the updated PEF method (European Commission 2021).

In addition, the guidelines include a Circular Footprint Formula (CFF) for the disposal of 'waste,' including an economic factor describing market demand. A coefficient is used to divide the impacts between the subject and other production systems. In other words, the impacts are allocated on economic grounds. However, it is somewhat unclear when allocations should be used and when the CFF should be used, as the guidelines do not specify what is meant by "waste." For example, the draft for the fur product PEFCR has interpreted manure as waste and within the scope of the CFF, allowing it to be credited, while the PEF method (European Commission 2018, 2021) and the PEFCR for dairy products instruct using CFF only when manure is treated as waste (e.g. landfilled). An economic allocation of the upstream burden shall be used for manure in case it has an economic value at the farm gate (European Commission 2021).

In addition, it is unclear what form of CFF is to be used and whether there is any crediting for different products based on their definition as intermediate products (e.g. feed, fertilisers) or final products (e.g. food products). Intermediate products such as cradle-to-gate PEF studies, exclude the EoL phase including for example the recyclability, energy recovery, disposal phases (European Commission 2021).

In general, the CFF can be considered to cover mainly the actual waste which ends up in waste processing. However, the PEF method specifically mentions how the formula applies to compost and digestate, for example, whose classification as waste is questionable because they are often used, e.g. in agriculture and applied on fields as residual products or may even have an economic value defined as a co-product. On the crop production side, similar credits are not mentioned and may lead to inconsistencies. As a result of interpretation and contradiction, it is possible that the negative environmental impacts of manure, for example, may not be attributed to any product.

In conclusion, allocations are a critical part of the LCA and have a significant impact on the assessment results. Allocation methods vary in different PEFCRs. The most typical allocation criteria are economic value and physical factors such as mass or volume. However, there are many exceptions. Inconsistencies in the use of allocation and Circular footprint formula can lead to contradictions, double-counting or unaccounted emissions.

Table 3. Allocation in different life cycle stages, in different PEFCRs.

	Primary Production	Processing	Processing, facility	Transportation	Use
All				Physical allocation (mass, volume, or duration and volume)	
Crop production (all PEFCRs)	economic				
Feed for food producing animals		economic	Physical (mass)		
Pasta PEFCR	economic	Economic (for flour), pasta is not allocated (or physical, mass allocation is used)			
Beer PEFCR		Economic (for raw materials, side streams not allocated)	Physical (volume)		
Wine PEFCR			Physical (volume)		
Coffee (draft)	Economic, and additionally mass allocation results shall be given	Economic (coffee, beans, peels)			According to duration of use (pot, coffee maker, number of times used; washing machine, according to volume needed
Livestock production (Dairy PEFCR, Red meat (draft))	Dairy, sheep and goats: Physical causality, biophysical (PEF method 2018a, 2021; IDF 2015; FAO LEAP 2016 guidance), sows and piglets: economic, Draft of the fur product PEFCR: economic for sheep	Dairy products; dry matter content, Red meat (draft); slaughtering with mass-allocation, biophysical recommended. PEF method, economic allocation			
Manure					
Dairy PEFCR	Manure is handled as a co-product to which emissions are allocated				
Red meat (draft)	Crediting production according to substituted fertiliser				

3.5. Data collection and quality requirements

One of the key factors affecting the comparability of LCAs, and PEFCRs, is the quality and consistency of the data. The criteria for assessing the quality of data in PEFCRs are very much in line with the wording and requirements of the PEF method (European commission 2018, 2021). Only a few PEFCRs provide more detailed or stricter requirements, which are elaborated in the following chapter.

According to the PEF method, the data is classified into that collected from primary and secondary sources. In product group-specific PEFCRs, according to the PEF method, processes that have a significant impact on the environmental footprint are considered to be those for which higher quality primary data must be collected. On the other hand, the PEFCRs approach the issue from the perspective of the company, i.e., the producer of the product, in which case primary data for the company's production chain must be collected from processes that are managed by the company and have a significant impact on the environmental footprint. These processes are described separately in the PEFCRs (mandatory company specific data). In the case of the PEFCR for fur, these stages include feed composition and production, on-farm energy production, manure treatment and rendering (Technical Secretariat 2018j).

However, for food and agricultural products, a significant part of the environmental footprint occurs outside the processes managed by the company, such as on farms. Thus, for example, the draft PEFCR for red meat includes primary data requirements for farm data, although secondary data can be used to partially supplement lacking data (Technical Secretariat 2018i).

For the collection and evaluation of non-mandatory company-specific production chain data, the PEFCRs provide the so-called Data Needs Matrix (DNM, European commission 2018, 2021). The DNM divides the source data into three categories and instructions are given for collecting the data depending on them:

1. A company-managed process for which the company has primary data available
2. The process is not managed by the company, but primary data is available
3. The process is not managed by the company and no primary data is available

To assess the quality of both primary and secondary data, the PEF method provides assessment frameworks, known as the Data Quality Requirements (DQR, European commission 2018, 2021). DQR scoring must be assessed separately for the various stages of the production chain, in accordance with the boundary conditions set by the PEFCR. Each PEFCR provides at least one DQR table for primary data and one for secondary data to assess the accuracy of the data collected (Precision, P), Time Representativeness (TiR), Technological Representativeness (TeR) and Geographical Representativeness (GR). Each criterion is given minimum requirements for a certain point level (values 1-5). Based on these, the DQR of the data can be calculated with Equation (1). The PEFCRs have determined the weakest DQR score for each process that must be at least achieved for the result to be PEF-compliant.

$$DQR = \frac{Te_R + Ti_R + G_R + P}{4} \qquad \text{(Equation 1)}$$

The DQR tables for the primary data in PEFCRs follow the formulation of the general PEF method. The PEF method limits the design so that only the time representativeness criteria can be modified. However, refinements can be given in more than one DQR table for the relevant processes.

The DQR tables for the secondary data provide criteria for the utilisation of statistical data or database data, for example (European commission 2018, Table 34; European Commission 2021, Table 24).

The average DQR for each impact category is calculated from the DQR results for the individual processes, weighting their significance to the footprint for that impact category (European Commission 2018, 2021). In the PEF environmental impact assessment, one combined environmental footprint result is also produced, so the DQR score for the entire assessment is also calculated according to the PEF method as common to all impact categories, highlighting the relevance of the impact categories.

In addition to collecting data from the production chain in accordance with the criteria, care must be taken to ensure that a representative sample is obtained from the data collection. If sampling is possible in the data collection, the principles by which sub-populations are classified for sampling need to be defined in the PEFCRs.

In some PEFCRs, a separate sampling procedure is described, according to which samples can be taken from the population (such as pasta, dairy, marine fish, feed, wine, olive oil; Technical Secretariat 2018a, 2018c, 2018e, 2018g, 2018h, 2021). On the other hand, sampling is not allowed in all PEFCRs (such as beer, packaged water; Technical Secretariat 2018b, 2018d). There are many sampling procedures, but the PEF method describes the generation of a stratified sample of classified material (European commission 2018, 2021). The advantage of this procedure is that the data collection is less demanding and can be better controlled. The classification is based on geographical location, production capacity and technologies/production methods. The basic principle should be that the sub-population is uniform, and that the dispersion of its environmental load is small. However, the challenge of forming a sub-population may be that with little prior information it is difficult. If the PEFCR allows sampling, the criteria for classification have in most cases been determined. For example, the PEFCR for dairy products mentions technological factors that allow the population to be divided into sub-populations: breed, feed procurement, feed composition, milk yield, grazing amount, and manure system (Technical Secretariat 2018c). The criteria for classification are also mentioned for olive oil: variety, density, irrigation system, organic/conventional, age of the crop, yield level (Technical Secretariat 2018h). The sample size is determined for each sub-population separately, for which the PEF method (2018, 2021) provides two approaches:

1. Based on the total production of the sub-population
2. Based on the number of plants/factories/premises in the sub-population

Sampling based on total production volumes should cover 50% of the production of the sub-population and for the second option, the number of production facilities or premises shall be determined as the square root of total number of units in sub-population (European commission 2018).

The sample size has been treated slightly differently in different PEFCRs. For dairy, the sample size directly affects the DQR score of raw milk production when the production is a process managed by a company (Technical Secretariat 2018c). In this case, the data covering more than 50% of the production reaches the best TeR level, and the data covering less than 10% of the production receive the weakest rating. The geographical representativeness of the data will also be better if the data covers several of the areas where the milk is produced. The PEFCRs for beer, pasta and wine provide guidance on sampling as described in the general PEF method (Technical Secretariat 2018b, 2018e, 2018g; European commission, 2021). For marine fish and feed products, the sampling procedure is in line with the general PEF

guidance, but also note that the sampling procedure is voluntary and, alternatively, data can be collected from all establishments or farms (Technical Secretariat 2018a, 2021).

Regarding data quality requirements, all PEFCRs follow the same principle based on the classification of production chain processes (company-managed and non-company-managed), the data needs a matrix and set criteria for time representativeness, technological and geographical representativeness. In addition to being driven by the companies and the processes run by them, also the processes that significantly impact the product's environmental footprint are considered when the need for primary data is determined.

4. Environmental footprint impact assessment

4.1. Classification and characterisation

In the classification, emissions are classified according to the environmental impact class they affect. Greenhouse gases such as carbon dioxide, methane and nitrous oxide contribute to the effects of climate change and phosphorus and nitrogen emissions to eutrophication. In the characterisation, on the other hand, the different emission components are related to each other, the effect of climate change in relation to carbon dioxide, eutrophication in inland waters in relation to phosphorus and in marine areas in relation to nitrogen. The calculated results are expressed in carbon dioxide, phosphorus, and nitrogen equivalents.

The characterisation factor describes the impact of the emission component, i.e., the impact of that greenhouse gas emission component on a kilogram of carbon dioxide equivalent in terms of the impact on the climate.

In the comparison of the PEFCRs, depending on the time the studies have been developed and released, the utilised characterisation might vary. This is due to the PEF method's requirement to use the Environmental Footprint reference packages in characterisations, which are stored online and updated regularly on the website of European Platform on LCA (EPLCA). The recent update in 2022 (EF3.1) has included new characterisation factors by the IPCC (2021) for methane and dinitrogen oxide (GWP_{100} for biogenic methane 27, fossil methane 29.8, dinitrogen oxide with feedback 273). Thus, studies which were conducted prior to 2022, have used different characterisation factors according to AR5 (IPCC, 2013), and are no longer comparable to new studies.

Even though the EF reference package has been updated in 2022, to follow the AR6 IPCC (2021) characterisation for GWP_{100}, all official PEFCRs and PEF methods (2018, 2021) list IPCC 2013 as a recommendation for the LCIA method. This might lead to confusion and inconsistency as to which characterisation factors should be used.

The characterisation methods for GHG emissions according to IPCC (2013, 2021) with feedback for nitrous oxide are presented in Table (4).

Table 4. Characterisation factors for climate impact according to IPCC (2013, 2021).

Emission component	Characterisation factor, GWP100	
	IPCC 2013	IPCC 2021
CO_2 fossil	1	1
CO_2 biogenic	0	0
CH_4 fossil	36.75	29.8
CH_4 biogenic	34	27
N_2O	298	273

PAS 2050 is the recommendation for calculating greenhouse gas emissions from land use change (BSI 2011). For the water scarcity impact, the AWARE methodology is recommended (Boulay et al. 2018). For water eutrophication, only the Eutrend model, which distinguishes eutrophication in inland and marine areas, is recommended for use in the PEFCR (Struijs et al. 2009).

4.2. Normalisation and weighting

According to the general PEF method, an impact assessment includes four phases: classification, characterisation, normalisation and weighting (European Commission 2018, 2021). When environmental footprint information of a PEF study is communicated, "the results for all impact categories (characterised, normalised, and weighted) shall be available to the public through freely accessible information sources" (European Commission 2018) and reporting of the characterised, normalised and weighted results are mandatory in the PEF study and public PEF report (European Commission 2021). Besides the characterised, normalised and weighted results for each impact category, results must be calculated and reported as a single overall score based on the weighting factors (European Commission 2021).

Normalisation and weighting are especially important when a PEFCR of a product group is developed as the PEF method includes the definition of representative product, in which most relevant impact categories are determined based on normalised and weighted results. These are used in benchmarking of following PEF studies of the product group.

Normalisation is needed to assess the significance of the characterised emissions. This is done by proportioning the emissions to the so-called normalisation factors found in PEFCRs. Calculated in this way, each impact category is represented by one numerical value that describes its magnitude relative to the normalisation factor.

It is possible to relate the normalised values to each other using weighting factors. These are also included, e.g., in the PEF method. This is an important step in terms of being able to assess which categories of environmental impacts are significant and which are insignificant. An example is a wastewater treatment process in which, after normalisation and weighting, the eutrophication is more significant than the climate impact. Zampori & Pant (2019) mention that normalisation and valuation steps are necessary steps in life cycle research.

5. Interpretation

5.1. Most relevant impact categories, life cycle stages and processes

In the final stage of the PEF study, it is assessed whether the study has been conducted in accordance with the objectives set for it. The impact of delimitations, data quality and allocation methods, as well as possible uncertainties, on the results are evaluated and recommendations for possible improvement are made.

The identification of key life cycle stages and impact categories is also part of this phase. As the relevance of the life cycle stages varies from product to product, also the listed impact categories, life cycle stages and processes may vary (Table 5; Table 6). Some PEFCRs also provide guidance for possible comparisons between products in the same product group.

Of the most important impact categories, only climate change impact was included in all of the official PEFCRs (dairy products, beer, pasta, wine, feed and packed water), while the other most relevant impact categories (acidification, eutrophication, land use, particulate matter, resource use and water scarcity) were listed in most but not all. The most relevant impact categories should include those that together account for at least 80% of the product's total environmental impact, starting with the largest contributor. Only the dairy PEFCR included water scarcity impacts among the most relevant impact categories, above the required 80% limit as an additional category.

Table 5. Most relevant impact categories in the reviewed official PEFCRs.

	Climate change	Acidification	Eutrophi-cation	Land use	Particulate matter	Resource use, fossils	Resource use, minerals, and metals	Water scarcity
Beer PEFCR	yes	yes	no	no	yes	yes	yes	yes
Dairy PEFCR	yes	yes	yes	yes	yes	yes	no	yes
Feed PEFCR	yes	yes	yes	yes	yes	no	no	yes
Packed water PEFCR	yes	no	no	no	no	yes	yes	no
Pasta PEFCR	yes	yes	yes	yes	yes	yes	no	no
Wine PEFCR	yes	Still: yes *Sparkling: no*	no	yes	yes	yes	yes	*Still: no* Sparkling: yes

Depending on the product and the most relevant impact categories, the different PEFCRs also listed the most relevant life cycle stages which contribute to different impact categories. PEFCRs differ in the level of detail provided: some offer only a list of life cycle stages across all impact categories, while others include detailed tables showing the percentage contribution of each stage and process for every impact category. For example, the PEFCR for wine reports relevance separately for all the most relevant impact categories and separately for still and sparkling wine. The comprehensive list demonstrates well how stages are differently important for different impact categories. For example, the grape production stage is most important for acidification, land use, particulate matter and resource use of minerals and metals, yet for climate change impact packaging is the most relevant for both still and sparkling

wine. As data collection is to be directed based on the relevance of the life cycle stages and processes, a more detailed description can increase consistency between studies.

Table 6. Most relevant life cycle stages in the reviewed official PEFCRs.

	Ingredient production/cultivation (main)	Other ingredient production	Processing and manufacturing	Packaging	distribution	Use	End-of-Life
Beer PEFCR	yes	yes	yes	yes	no	yes	yes
Dairy PEFCR, liquid milk	yes	no	no	yes	yes	yes	no
Dairy PEFCR, cheese	yes	no	yes	no	no	no	no
Feed PEFCR	yes	no	no	no	no	no	no
Packed water PEFCR	no	no	no	yes	yes	yes	yes
Pasta PEFCR	yes	no	yes	no	no	yes	no
Wine PEFCR, still, e.g. climate change	yes	no	yes	yes	no	no	yes
Wine PEFCR, sparkling, e.g., climate change	no	no	yes	yes	no	no	yes

As data requirements and data collection are guided according to the most important impact categories, stages and processes, the differences between PEFCRs and within PEFCRs for different products can cause inconsistencies between PEF studies.

6. Discussion

The PEF method published by the European Commission has been developed to support a harmonised, comparable, and reliable product group-specific environmental impact assessment. The aim of the PEF method has been to produce a consistent method, especially for harmonised communication on environmental sustainability. Although the PEF method significantly harmonises LCAs with previous standards, their purpose in not to provide comparability between products in different product groups. The PEFCRs have been prepared so that an internal comparison within the product group is possible as the assessment methods are consistent and transparent. In addition to being able to compare environmental footprints within a product group, there is an increasing need to be able to compare different products. In this review, the aim has been to evaluate how well the PEF and PEFCRs provide the possibility to compare the environmental footprints of different products, also between product groups. The key conclusions from the point of view of the comparability of PEF studies and found differences are summarised below.

The definition of a functional unit is one of the basic starting points for LCA. For each assessment, the functional unit shall be defined in such a way that the estimated environmental footprint against it provides the best indication of the environmental performance of the system under investigation and allows comparison. The product group-specific guidelines (PEFCRs) base the functional units mainly on the quantity of the product produced. Comparability is thus achieved within the product group, but the situation is different between different product groups. Since functional units do not take into account the nutritional functionality of food products, a quantity-based functional unit alone does not enable a full comparison of the environmental footprints of different products. From the comparability point of view, it would be essential to take the nutritional function into account if different food products are compared. On the other hand, PEF's starting point has been to report the key environmental footprints of the product per product unit, not per nutritional response. It would be important to investigate how the communicated environmental information is understood, used, and interpreted by end users, and whether the functional unit based on physical characteristics is adequate.

In terms of system boundaries, the basic idea of PEF is to include the whole system from cradle to grave, including the stages of retail, distribution, and consumption. No exceptions were found in the various guidelines for system boundaries until the end of the chain. Significant differences were found especially for the use phase.

The environmental impact categories were examined from the perspective of how many were included in the different assessment guidelines. In general, the environmental impact categories and guidelines for their assessment were the same in most PEFCRs. There were a few exceptions to the older drafts of the guidelines (e.g., for olive oil and marine fish).

The level of precision of the emission quantification methods was also examined between different guidelines. In general, the IPCC's roughest hierarchical (Tier 1) methods were used to assess crop production. In livestock production (milk and red meat), the methods were mainly consistent, but there were differences in hierarchical levels regarding the modelling requirements for nitrous oxide emissions. The methods used in the assessment for plant products were mainly in accordance with the PEF methods. The climate impact assessment conducted should therefore be carried out in accordance with the lower tier of the IPCC methods or with the methods of the national greenhouse gas inventory. It should be noted that the national GHG inventory methods of different countries have been developed for

national monitoring, and comparability between GHG inventory methods of different countries cannot be guaranteed.

Significant differences which might affect comparability were observed in terms of the **use phase and modelling**. In general, the use phase is not included in all PEFCRs, and even if it were, the activities to be included (storage, manufacturing, visits to grocery store, etc.) varied and are product specific.

The production chains of different products also generate different waste streams, whose **end-of-life modelling** is guided according to the circular footprint formula, CFF. End-of-life modelling was found to be consistent across guidelines. However, in general, it is somewhat unclear when the CFF should be applied to grant credits and when allocations should be used instead excluding such credits from the actual assessment. A precondition for a uniform assessment is that it is precisely defined in which situations the credits can be calculated. The good thing about the guidance is that the inclusion of use of the CFF formula in all cases of material and energy recycling harmonises the calculation. The downside is that, for example, the standardisation of variables based on recycling rates: if these constants are used, the modelling is less accurate than when, for example, country-specific and even product specific recycling rates are used.

Similarly in all assessed PEF and PEFCR documents, the changes in land-related carbon stocks, including soil, shall be considered only when they are due **to direct land use changes within the past 20 years**. Therefore, the effects of land use changes older than 20 years and effects of land management on soil carbon (e.g. different cultivation practices) shall be excluded from the assessment. However, it is possible to include the **accumulation of soil carbon stocks** as a supplementary information to the climate change impact result. Nevertheless, the increase in soil carbon stocks has been taken into account in only a few PEFCR guidelines and the methods to be used for soil carbon accumulation are loosely presented.

Emission offsets refer to various activities designed to produce negative emissions outside the production system of the actual product to compensate for emissions from production. Emission compensation must not be included directly in the LCA in accordance with PEF or any other LCA guidelines. However, potential emission offsets can be used in communications, reporting them separately, as additional environmental information. PEFCRs do little to address emission compensation.

Allocations are a critical part of LCAs and have a significant impact on the assessment results. The review found that allocations vary between PEFCRs. The most typical allocation criteria are economic value and mass or volume. However, there are many exceptions. A step-by-step review of the life cycle found that for primary production, the economic allocation for plant-based products was used in all. For animal products, the method varied, but the official PEFCRs (dairy products and PEF method) used biophysical or economic allocations. The allocation of the processing stage was typically economic, but differences were found between different PEFCRs to which they were allocated. For example, in the case of beer, the allocation only applies to raw materials, but not to by-products. In the case of pasta, the allocation of flour is also economic, but no allocation of pasta is required, or mass-based allocation must be used. Regarding the processing of animal products, the PEF method provides default factors for the use of economic allocation, while the unofficial draft guideline for the assessment of red meat suggests a mass allocation. The impacts of the processing plant were observed to be quite uniformly based on physical allocation. For transport, no differences were observed between the PEFCRs (physical allocation). The allocation of the use phase was only instructed in the unofficial guidelines for coffee.

In terms of **data quality requirements**, the PEFCRs were very consistent and largely followed the format and requirements of the PEF method. In addition to the need for primary data from the processes managed by the company, processes that are of great relevance for the product's environmental footprint are also taken into account. In the PEFCR guidelines, these essential processes for which primary data must be collected are described separately. In the case of food products, a significant part of the emissions is generated in primary production, which means that the requirement for primary data is extended beyond the processes managed by the company. However, differences were found in the extent to which primary data had to be obtained, whether part of the primary data could be replaced by data from the national databases or whether sampling was allowed in the collection of primary data. With regard to sampling, the PEFCRs had varied information on the principles by which subsets could be formed. The precondition for consistency would be an equal requirement for primary data, the availability of national databases and defined principles for sampling. For secondary data, the PEFCRs provide a list of approved, harmonised databases from which the data can be used. According to the revised PEF method, EF-compliant datasets are required; when unavailable, EF-compliant proxies may be used with certain limitations. Significant differences may arise between different products only in the selection of alternative processes for acceptable secondary data. It is important that such secondary data processes are used which are as close as possible to the production to be described, although the secondary data should only be used to supplement life cycle modelling. This is also considered in the data quality assessment (DQR) included in the PEF method.

7. Conclusions

In this review, the PEF method and PEFCRs were reviewed in parallel with a focus on evaluating the comparability of the life cycle assessment results when using the methods. Comparability was evaluated especially between different PEFCRs. Due to the harmonised PEF method, most PEFCRs mainly follow the same methods and requirements. Yet, methodological differences were found between different PEFCRs. In addition to the functional unit, the most significant differences were observed in allocation, and system boundaries, especially in the definition of the use phase, and in the hierarchy levels of the modelling. It should be noted that this comparison was kept at a relatively general level. A more detailed examination could refine these results and the differences between the PEFCR could be better identified. The comparison is challenged by the fact that PEFCRs also vary in quality and documentation. For the development of a unified LCA guidance for food products, the PEF method was found to be largely applicable; however, harmonisation and clear definition of existing inconsistencies are still needed.

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