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ORIGINAL PAPER

Harmonizing and aligning life cycle assessments of bio-based fertilizers towards environmental footprint methods

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Introduction

Bio-based fertilizers (BBFs; Table 1 includes a description of abbreviations and acronyms used in this article) are made from biomass feedstocks and can help reduce the need for mineral fertilizers by providing a circular and more sustainable alternative in food production. BBFs encompass a variety of products that can be defined by origin (e.g., sludge, manure), process (e.g., composting) and final product's chemical composition (e.g., nutrient content) (Frick et al. 2025). BBFs have been widely assessed with main concerns on the content of heavy metals and other pathogens (Egle et al. 2015) but also their beneficial role in soil structure and health (Chojnacka et al. 2020; Kurniawati et al. 2023). However, studies on the environmental performance of BBFs are not easily comparable due to the many methodological differences (e.g., considering system boundaries, functional units (FUs) or allocation methods) (Egas et al. 2023; Manoukian et al. 2023; Miao et al. 2024; Orlandella & Fiore 2025).

There are several policy drivers that support the production and use of BBFs to supplement mineral fertilizers, including the EU Regulation on Fertilizing Products (EC 2019a), the EU Green Deal (EC 2019b), and the Farm-to-Fork Strategy (EC 2020). Despite the growing interest of markets and supporting policies, the development of BBFs is hindered by the lack of methodological standardization in determining their environmental footprints. Currently, there is no Product Environmental Footprint Category Rules PEFCR or EPD-PCR (Environmental product declaration–Product Category Rules) guidance available for fertilizers let alone BBFs made from any biomass-based reused materials. This can be due to the major diversity in raw materials, production processes, nutrient content and application (Egas et al. 2023), which needs to be addressed in the PEFCR.

The harmonization of assessments for BBFs is challenging as they are intermediate products and a very heterogeneous and large product category (Egas et al. 2023; Manoukian et al. 2023; Miao et al. 2024; Orlandella & Fiore 2025; Zarauz et al. 2025). The EU fertilizing products regulation (EC, 2019c) divides fertilizing products into 7 main categories and multiple different sub-categories based on their Product Function Categories (PFC, Appendixes A Table 4). In addition, all these categories can consist of 11 different component materials (e.g., compost, food industry by-products) listed in the regulation component materials categories (CMC, Appendixes A Table 5). Furthermore, to produce recycled fertilizers in many different categories, these 11 different components have many raw material alternatives and manufacturing technologies, which are presented by Wester-Larsen et al. (2022) and Hernandez-Mora et al. (2024).

Considering the relative importance of fertilizers in the life cycle assessment of cultivation, one can justify harmonizing BBF-specific methodological aspects for all BBF products. Thus, a standardized approach is needed that improves the consistency of life cycle modeling and the comparability of the environmental impacts of BBF products.

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Table 1 List of abbreviations and acronyms used in this article

Abbreviations	Explanation
BBF	Bio-based fertilizer
CFF	Circular footprint formula
DU	Declared unit
EC	European commission
EF	Environmental footprint
EU	European union
EPD	Environmental product declarations
LCA	Life cycle assessment
PCR	Product category rules
PEF	Product environmental footprint
PEFCR	Product environmental footprint category rules

This study aims to provide insights for assessing the environmental impact of BBFs in a more uniform manner by identifying key methodological challenges and providing solutions to the challenging methodological issues. By synthesizing existing literature and guidelines, this study will focus on the challenging methodological issues in producing PCR (product category rules) for the product group of BBFs. This work was supported by the *Novel procedures and sustainable guidelines to enhance the use of alternative fertilising products* (NOVAFERT) project, funded by the European Union's Horizon 2020 research and innovation program under grant agreement ID: 101,060,835. Some of the results presented in this study are consistent with the results to be reported in the forthcoming final NOVAFERT project report (Vikki et al. 2025) by the end of year 2025.

Materials and methods

The workflow for this study is shown in Fig. 1. The first step was to define the scope of the study. Secondly, data on guidelines for assessing LCA of bio based products were sought through a review from official LCA standards and international guidelines. Thirdly, a critical analysis of selected peer-reviewed publications was conducted by identifying how the LCA modelling of fertilizers produced from recycled materials had been implemented in previous research. The next steps were to address the challenging methodological issues and propose a criteria tailored to BBFs which would be consistent with the structure of official LCA standards and international guidelines.

More specifically, the scope of this study was defined to provide methodological suggestions as guidelines for harmonizing a consistent approach to conducting the environmental impact assessment of BBFs. Methodological

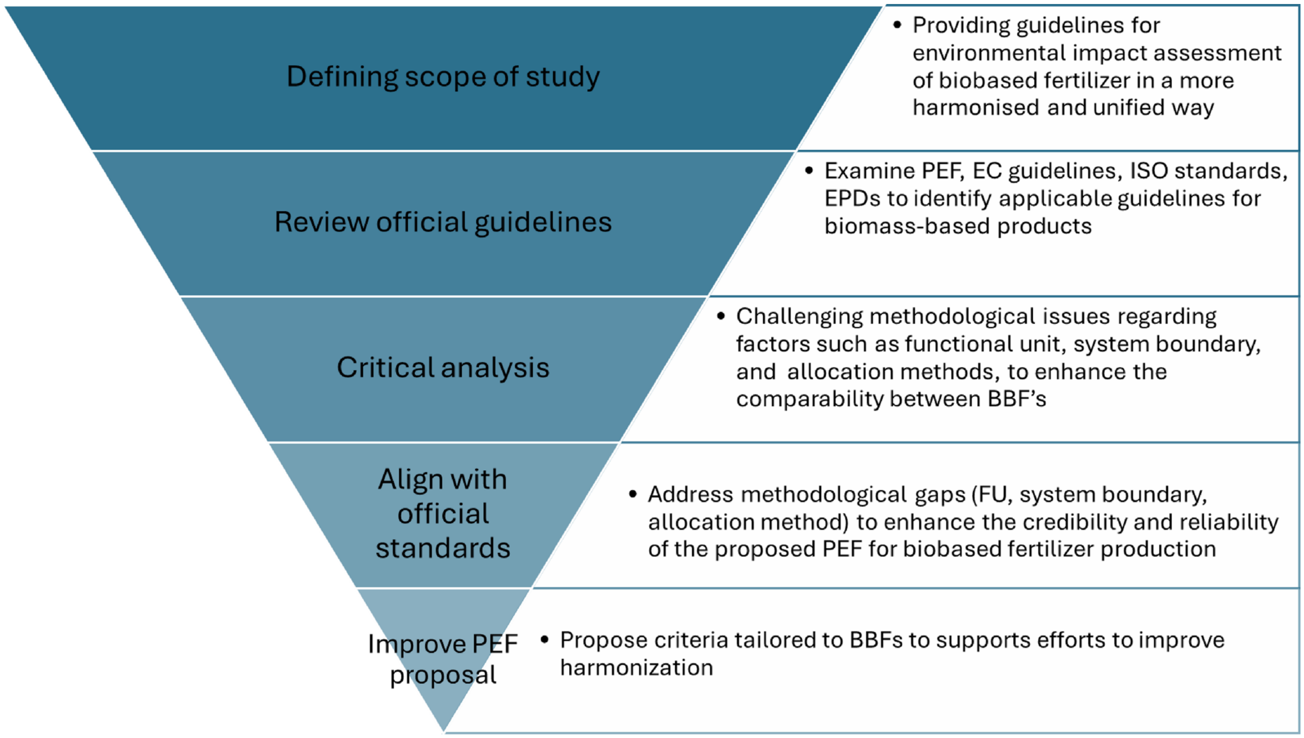

Fig. 1 Methodology for the development of the PEF-wise PCR method (Results of this study to be published also as part of Novafert final project report (Vikki et al. 2025))

standardization is necessary to enhance the comparability between BBFs and potentially also between BBFs and conventional mineral fertilizer products (with the same functionality) when evaluated under consistent methodological assumptions. Further specification at the product category level is needed to reduce methodological variability, which can lead to inconsistent results.

Following the scope definition, a narrative review of official guidelines was conducted. This review was conducted in a targeted manner without a pre-defined systematic method. The goal of the review was to evaluate LCA modelling practices relevant to BBFs and to identify applicable standards and best practices. The guidelines reviewed included the Product Environmental Footprint (PEF) Guide (Manfredi et al. 2012), the Environmental Footprint (EF) initiative of the European Commission (EC 2021), ISO standards 14040 (2006a) and 14044 (2006b), and additional methodological resources such as EPD guidelines. More specifically, the generic PEF guide by Manfredi et al. (2012) serves as preliminary work to the current European Commission's PEF and PEFCR guidelines (EC 2021). Manfredi et al. (2012) systematically analyzed and compared key LCA standards and guidelines at the global and EU levels. This formed the basis for the method comparisons presented in the PEF Guide (Manfredi et al., 2012), which show the similarities and differences between the methods. Based on this work, harmonized guidance for assessing the environmental impact of products with LCA methods has been created within the EF initiative of the European Commission (EC 2021) to provide more reliable and comparable results to be communicated externally. To ensure consistency and comparability in the assessments, the PEFCR guidelines provide specific rules and requirements for conducting an environmental assessment for a particular product category (EC 2021). However, despite the number of guidelines, they do not offer comprehensive technical rules to ensure that LCA studies for BBFs are more reproducible, consistent, robust, verifiable and comparable. In other words, there is currently no product-specific guideline (official PEFCR guideline or EPD-PCR) for BBFs, which limits the comparability and reliability of BBF assessments. Consequently, it is recommended that only the generic PEF method by Manfredi et al. (2012) be used (Damiani et al. 2022). In the present study, as there was no PEFCR for BBFs, we aimed our work to be consistent with the generic PEF method by Manfredi et al. (2012) as well as with the structure of PEFCRs, as specified in Annex II, part A of the EF guidelines (EC 2021). This is to improve harmonization and ensure alignment with official standards.

After the review process, a critical analysis of selected scientific literature was conducted for the purpose of finding the challenging methodological issues regarding the BBF LCA assessment. The research literature shows that the life cycle modelling of nutrient products made from recycled materials as alternatives to mineral fertilizers, still suffers from significant methodological challenges. According to comprehensive literature reviews by Tanzer et al. (2021a, 2021b), Egas et al. (2023) and Kinsella et al. (2023), studies on the environmental performance of BBFs are not easily comparable due to the many differences such as in defining the system boundaries of a product's life cycle, functional units (FUs) or how to allocate emissions between different inputs and outputs. Still, according to the latest research, the problems are particularly related to the ambiguity of the nutrient replacement method, the variation in system boundaries and FUs, and the lack of documentation and sensitivity analyses (Manoukian et al. 2023; Miao et al. 2024; Orlandella & Fiore 2025). The varying coverage of databases and the neglect of the conditions prevailing at the site of use, which are essential in LCA modelling, also weaken the reliability of the results (Tao et al. 2025; Mulya et al. 2025).

After the critical analyses, defining the system boundaries of BBFs life cycle, FUs or how to allocate emissions between different raw materials and outputs were addressed as the key challenging methodological issues.

Finally, a criteria tailored to BBFs was proposed for it to be consistent with the structure of PEFCRs as specified in Annex II, part A of the EF guidelines (EC 2021). This is to improve harmonization and ensure alignment with official standards. Sect. "Results and discussion" expands on this aspect in further detail.

Results and discussion

The results of this study tackle the key methodological issues on FU, system boundaries, and allocation methods for multifunctional processes considering PEFCR development for BBFs and PRC in general. The proposed solutions aim to guide the assessment of the environmental effects of BBFs in a more uniform manner.

Functional unit

According to ISO standards (2006) and the EF method (EC 2021), a FU encompasses "the qualitative and quantitative aspects of the function(s) and/or service(s) delivered by the evaluated product". This definition addresses key inquiries such as "What?", "How much?", "How well?", and "For how long?" (Damiani et al. 2022).

However, according to the EF method (EC 2021), the FU is more difficult to define for intermediate products (e.g., fertilizers) than for finished products because intermediate products often fulfill multiple functions, and their entire life cycle is not always known.

Nevertheless, the concepts of the functional unit and reference flow are open to interpretation and can vary depending on the source, which allows for different perspectives.

Declared unit (DU) as a mandatory default

In the EF method, a declared unit (DU) is equal to the reference flow and shall be applied for intermediate products in PEFCRs instead of FU. The reference flow is characterized by ISO 14044 standard (2006) as a "measure of the outputs from processes within a given product system that are necessary to fulfil the function". For intermediate products, a declared unit should be applied, for example, mass (kilogram) or volume (cubic meter) (EC 2017; Zampori, 2019; EC 2021; Damiani et al. 2022). Therefore, this study proposes a mandatory default DU of one kilogram of fertilizer product for agricultural use on field.

However, using DUs may reduce comparability which emphasizes the need to specify technical properties to improve it (EPD International 2025). Reporting the environmental footprint of 1 kg of fertilizer is not informative or useful if fertilizers do not contain the same proportions of the most important nutrients. In fact, many BBFs on the European market differ in both physical and chemical properties, and they have diverse applications (Kinsella et al. 2023). Thus, it is unlikely that different BBFs can be directly compared as their production technologies and nutrient contents differ (e.g., some fertilizers are NPK fertilizers, some are nitrogen sources, and some provide other nutrients).

Complementary FUs

To improve comparability and define the function of the fertilizer product, the FU could be made more specific by basing it on nutrient content and application parameters. This would consider the time frame and align units with industry standards.[1] Providing more information on the fertilizer product's functionality may increase the results' reliability and comparability between studies. More specific FUs may be communicated together with the mandatory default DU.

In the present study, we suggest that complementary FUs in addition to the common DU of 1 kg of BBF are chosen based on the most relevant ones considering the functionality of the BBF under study. These could be, for example, the most common FUs used in the research literature (Egas et al. 2023):

- Per mass of nutrient, e.g., per kg N*, per kg P, per kg K;
- Per mass of raw material input;
- Per mass of product;
- Per capita load of raw material input;
- Per hectare of application;
- Per size of application facility, and volume of product.[2]

*In this study, we recommend the amount of nitrogen available to plants, i.e., soluble nitrogen, in the case of the BBF to be comparable to the nitrogen contained in mineral fertilizer. More specifically, total nitrogen in organic fertilizers consists of nitrogen bound to organic matter and soluble nitrogen. Soluble nitrogen is mainly in the form of ammonium (NH_4). While this soluble nitrogen is directly available to plants, the organic nitrogen must first be released into the soil.

Targeting the environmental impact per complementary FUs instead of the common DU of 1 kg of BBF reflects the functionality and application stage of the BBF as well as comparability between fertilizing products in a more uniform manner. For example, a study by Vikki et al. (2026) compared the carbon footprint of different separated digestate fractions (7.9–9.9 kg CO_2eq /kg $N_{(soluble)}$) to mineral fertilizer (13.6 kg CO_2eq/kg$N_{(soluble)}$) with FU of 1 kg of soluble N directly available to plants. If the results are examined in terms of total nitrogen, the emissions of digestate as a BBF product appear to be significantly lower (5.7–6.4 kg CO_2eq /kg $N_{(total)}$) than those of mineral fertilizer (13.6 kg CO_2eq/kg$N_{(total)}$). Furthermore, if these results are converted per kg of fertilizer product, the carbon footprint of digestate freactions would be multiple times lower (0.03–0.04 kg CO_2eq/$kg_{(digestate)}$) than that of mineral fertilizer (1.43 kg CO_2eq/$kg_{(mineral\ fertilizer)}$). This is because the soluble N content of the digestate fractions (0.04%) is multiple times lower than the total N content of the mineral fertilizer (27%). In other words, comparing the impacts of fertilizer products per total weight of the product (kg) hinders comparability because it does not consider the functionality of fertilizer nor reflect its effectiveness, which is determined by the actual amount of plant nutrients they contain rather than the total weight of the product (i.e., the amount of nitrogen available to plants). For example, fertilizer with lower nutrient content requires greater application rates to provide the same level of nutrients to plants. The relative environmental efficiency of production systems can change on the basis of FU employed, which has been perceived also by other studies examining other product groups (Haas et al. 2001; O'Brien et al. 2012).

Nevertheless, fertilizers can often fulfil multiple functions and have major differences in the nutrient content and in fertilization efficiency. Determining the FU based on chemical composition, such as NPK nutrients, is challenging since

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[1] Present study outcomes to be published also as part of Novafert final project report (Vikki et al. 2025).

[2] Results of this study to be published also as part of Novafert final project report (Vikki et al. 2025).

fertilizers do not always contain nutrients in the same proportions. Also, intended uses vary by product, and the FU is not easily tied to, for example, soil fertility, as some uses are related to landscaping or another form of land improvement where the crop yield is not the main focus (Tanzer et al. 2021a, 2021b; Egas et al. 2023; Kinsella et al. 2023).

Despite the somplementary FUs presented above, there is still a need to further develop a common FU and investigate whether it possible to develop a common FU for all BBFs. For example, the study by Santolin et al. (2024) presented a methodology developed to integrate N, P, and K ratios in one functional unit for BBFs. Also one option would be the final function of the product, e.g., the growth of the plant that is cultivated and utilizing BBFs and volume of yield. However, there was no consensus or certainty whether e.g. "plant growth" as FU would work as this changes depending on the product and BBFs have many different functionalities.

System boundaries

'Cradle-to-Gate' as the default guideline

The system boundary determines which life cycle stages are included in the assessment. The EF method (EC 2021) provides guidance for PEFCR developers to use the 'Cradle-to-Gate' system boundary for intermediate products, because these can often fulfil multiple functions and the whole life cycle of the product is not known. Therefore, it is proposed that the default system boundary guideline for intermediate products of the EF method is used in case of BBFs.

Consequently, the following life cycle stages and processes shall be included in the 'Cradle-to-Gate' system boundary: (i) production of raw material defined as a co-product with an economic value (see more in Sect. "Allocation criteria for the definition of the status of the nutrient's sources: waste, residual or co-product") and pre-processing (including the production of parts, components and packaging production); (ii) the transportation and collection systems of the raw material until the manufacturing location, including all the reverse logistics, intermediate storages and other processing steps such as concentration or pre-treatment that could be integrated; and (iii) the manufacturing process (BBF processing at the manufacturing plant), including storage and packaging before loading and distribution to the retailer or consumer (e.g., farmer). Due to the "cradle-to-gate" boundary, the following are not included in the system boundary: (v) distribution to the retailer/consumer (e.g., farmer), (vi) use/application on the field, and (vii) end of life (including packaging recovery or recycling). See Fig. 2.

Table 2 describes the life cycle stages and the processes that are recommended for inclusion in future PEF-wise PCR methods for BBFs: raw material acquisition, the processing of BBFs at the manufacturing plant, and distribution of BBFs to the farm.

Unless they can be excluded by the cut-off rule (EC 2021), the manufacture of buildings, machinery and other production-related infrastructure are to be included in the assessment. A screening study is recommended to identify processes that may be cut off evidence from previous studies.

According to literature reviews, Egas et al. (2023) noted that 'Cradle-to-Gate' is the most commonly used system boundary in BBF studies. The 'Cradle-to-Gate' system boundary for intermediate products is also accepted by other standards and guidelines. ISO 14044 (2006) guides the definition of boundaries according to the objective and scope of the study by Egas et al., and they are refined through calculations and sensitivity analysis. For a carbon footprint assessment, ISO/DIS 14067 (2012) allows both approaches. According to the EPD system (EPD International 2025), in the case of intermediate products or where the end use is uncertain, the boundary can be restricted to "cradle-to-gate". Under certain conditions, the end stage can be omitted: the product must be integrated with others, unrecognizable at the end of its life cycle and free of biogenic carbon (EPD International 2025).

For example, Vikki et al. (2026) conducted a case study that compared the life cycle climate impacts of three different digestate products with those of mineral fertilizer. The study results demonstrated that significant environmental impact differences can be shown between fertilizers with the same functionality when viewed from a "Cradle-to-Gate" perspective, including raw material acquisition, transportation, manufacturing processes (0.0–0.5 kg CO2eq/ kg$N_{(soluble)}$) with those of mineral fertilizer (5.3 kg CO2eq/ kg$N_{(soluble)}$).

'Cradle-to-Grave' as an additional information

By also considering the distribution of BBFs, use/application on the field, and end of life, the system boundary from 'Cradle-to-Grave' would expand the 'Cradle-to-Gate' perspective presented in the previous chapter 3.2.1. However, this is not recommended by the EF method and it also increases risks for double accounting, and poses problems for the reliability and comparability of the LCA studies for other agricultural products. The reason for this is that there already are published PEFCRs for other agricultural products (foods, feed and ornamental flowers) that give guidance on how to assess and include fertilizer application and field use in the agricultural production stage assessment. In other words, fertilizer application and field use emissions are already included in other PEFCRs for agricultural products.

However, this study recommends including information on the BBF application stage as "an additional technical information" such as the content of heavy metals, pathogens

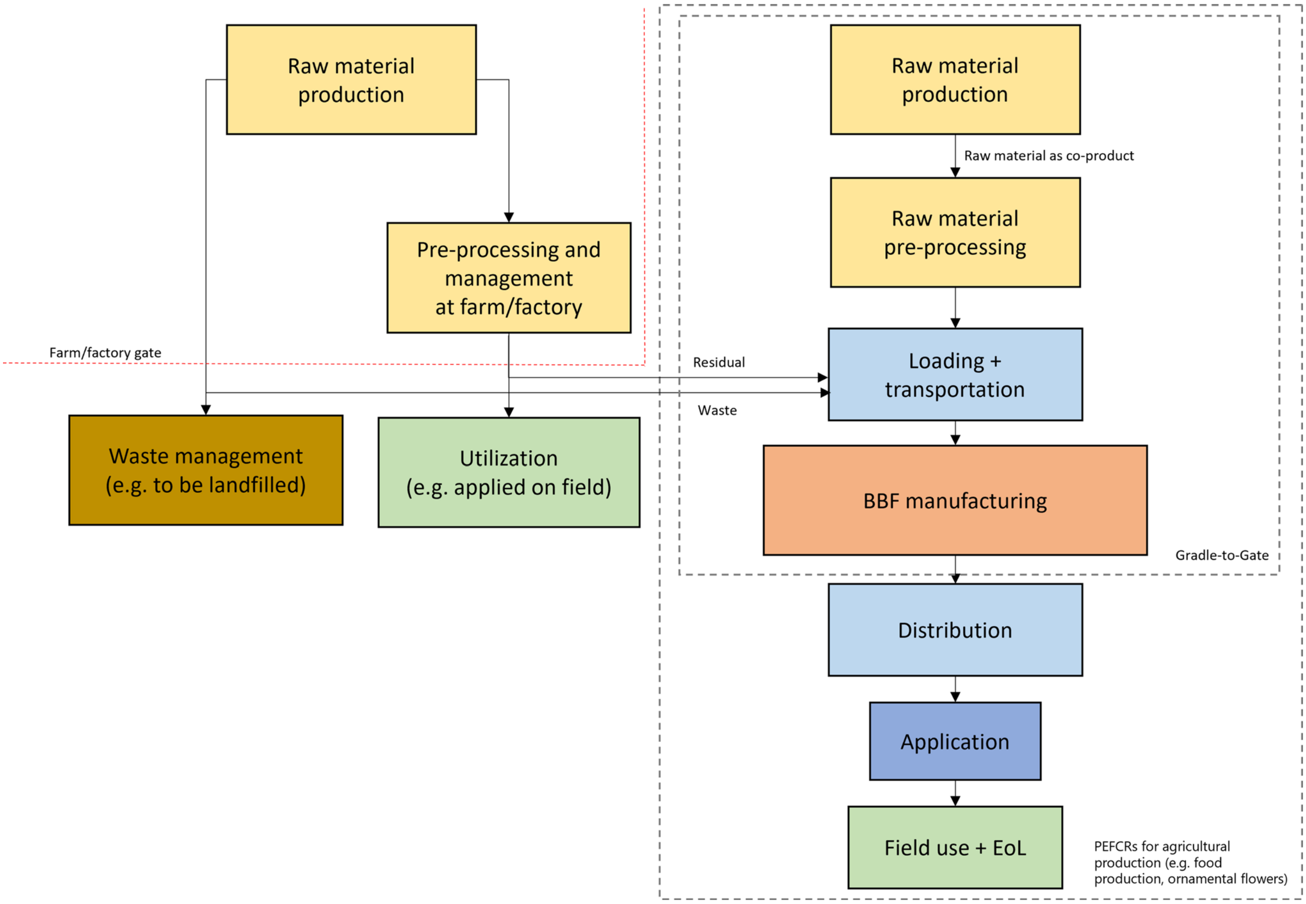

Fig. 2 System boundaries of BBFs as 'Cradle-to-Gate'. Raw materials defined as waste and residual are excluded outside the system boundary (see more in Sect. "Allocation rules with multifunctional properties".) (Results of this study to be published also as part of Novafert final project report (Vikki et al. 2025)

Table 2 Life cycle stages to be included in the assessment

Life cycle stage	A short description of the areas included
Raw material acquisition	Biomass production (only if defined as a co-product or main product with a market value), production of packaging materials and possible production of other components to be used as raw materials in the manufacturing of the main BBF product at the manufacturing plant
Transport	The delivery of all the BBF raw materials to the BBF production plant is part of the BBF's life cycle. It can consist of a variable number of transportation steps (from in-situ treatments without transportation to a more complex reverse logistic system)
Manufacturing BBF at the manufacturing plant	The production stage begins when the product components from other production chains enter the main BBF production site (manufacturing plant) and ends when the finished product leaves the production facility The manufacturing of BBFs is the main processing phase of a BBF product and is separate from other value chain processes. It may include several process steps (e.g., separation of biomass, composting of different biomass streams collected from other value chains, granulation of biomass, and adding different components (Ammonium sulfate (AMS), urea etc.)

Results of this study to be published also as part of Novafert final project report (Vikki et al. 2025)

or other xenobiotics. In addition, one potential option might be to perform a differential calculation on environmental impacts so that the results are presented separately from the 'Cradle-to-Gate' perspective and 'Cradle-to-Grave'. This enables the first part to be utilized in calculations for other agricultural products (foods, feed and ornamental flowers) according to PEFCR guidance. The latter on the other hand is to give an additional information of the total life cycle perspective of BBF specific sustainability without any risk of double accounting.

For example, according to the results in a case study by Vikki et al. (2026) the climate impacts of different digestate product scenarios from 'Cradle-to-Gate' (0.0–0.5 kg CO_2eq/kg$N_{(soluble)}$) increased significantly when the system boundaries were expanded from 'Cradle-to-Grave' to include the distribution of BBFs and their use/application in the field (end of life) (7.9–9.9 kg CO_2eq/kg$N_{(soluble)}$). This outcome emphasizes the importance of including additional information about environmental impacts during fertilizer use on field, as it provides significant insight into the product's total sustainability, and also in relation to mineral fertilizer emissions (13.6 kg CO_2eq/kg$N_{(soluble)}$).

However, the distribution and application of fertilizing products is very context dependent and can vary greatly regardless of how the product is produced, e.g., distance to farm and field, application rates, environmental conditions, soil type, and local conditions which are very challenging to assess comprehensively as part of BBF environmental footprint calculations by different chain actors, e.g., by the BBF manufacturer to whom the end use is uncertain.

Allocation rules with multifunctional properties

According to the EF method (EC 2021), "if a process or facility provides more than one function, i.e., it delivers several goods and/or services ('co-products '), it is 'multifunctional'. In these situations, all inputs and emissions linked to the process shall be partitioned between the product of interest and the other co-products in a principled manner."

Allocation rules

The present study guides one to follow the ISO decision hierarchy for systems involving the multi-functionality of processes according to the EF method. ISO/DIS 14067 (2012) directs users to adopt the principles of ISO 14044 (2006), which emphasize initial avoidance of allocation through process subdivision or system expansion. Only after this should they resort to physical relationships, such as mass or energy, and, when necessary, economic value.

However, as the aim of the EF method and PCRs is to communicate the environmental footprints of products in a unified and comparable way, subdivision is rarely possible and system expansion is not adequate for LCA studies which aim at external communication, as it usually leads to non-consistent, non-harmonized crediting and/or substitutions which hamper comparability.

In addition, the various raw materials used in manufacturing BBFs and their co-products have different physico-chemical characteristics (e.g., digestate and biogas, manure and live animals) and variable end use on the market, and therefore using physical relationships for allocation would not be suitable. For example, a study by Timonen et al. (2019) demonstrates an unbalanced distribution of emissions between biogas and digestate when an allocation method based on physical factors such as calorific value or mass is employed: in the first case, almost all emissions are allocated to biogas and in the latter to digestate. The biophysical allocation has been criticized for favoring one co-product over the other (Rice et al. 2017; Timonen et al. 2019; Nemecek and Thoma 2020; Kyttä et al. 2022).

The economic value of inputs and outputs is considered the most feasible and meaningful relationship which could reflect the valuable characteristics of inputs and the variable end use of the BBF products on the market. According to Kyttä et al. (2022), economic allocation is commonly used when co-products have very different physical properties or end uses in the market. A study by Timonen et al (2019) shows a more balanced distribution of environmental impacts among co-products (biogas and digestate) with different physiological characteristics when different allocation methods are used in relation to the economic allocation method. The choice of economic allocation is also accepted by some other LCA standards and guidelines which, according to Manfredi et al. (2012), share common principles but differ in their approach to allocation and multifunctionality. For example, the ILCD manual[3] is based on ISO 14044 but recommends virtual subdivision and economic allocation. Though the GHG Protocol[4] favors avoiding any allocation, if an allocation is necessary, physical relationships or economic value are favored. The French Environmental Footprint Method (BPX 30–323)[5] and PAS 2050[6] rely on ISO 14044, with the latter developing it further by emphasizing the avoidance of allocation and resorting to economic value only as a last resort.

Therefore, the present study suggests that though following the ISO allocation hierarchy the environmental burdens

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[3] European Commission—Joint Research Centre—Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook–General guide for Life Cycle Assessment—Detailed guidance. First edition, March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union, 2010.

[4] GHG Protocol (2011) Product life cycle accounting and reporting standard. World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI) https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-Accounting-Reporting-Standard_041613.pdf

[5] Association Française de Normalisation [AFNOR] (2011). *Principes généraux pour l'affichage environnemental des produits de grande consommation – Partie 0: Principes généraux et cadre méthodologique* (Norme BP X30-323–0). AFNOR.

[6] BSI (2011) PAS 2050:2011—specification for the assessment of life cycle greenhouse gas emissions from goods and services. British Standards Institute, London http://clearcarbontech.com/data/upload/image/20210815/1629020896125747.pdf

Table 3 Allocation rules and instructions by EC (2021) applied in this study and identified for main processes during the life cycle of BBFs

Process	Allocation rule	Modeling instructions
Raw material processes	Physical/ economical	Raw materials with similar physicochemical characteristics shall be allocated with a biophysical allocation method: "Allocation based on a relevant underlying physical relationship refers to partitioning the input and output flows of a multi-functional process or facility in line with a relevant, quantifiable physical relationship between the process inputs and co-product outputs (for example, a physical property of the inputs and outputs that is relevant to the function provided by the co-product of interest)." (EC 2021) Raw materials with different physicochemical characteristics shall be allocated with economic allocation: "Economic allocation refers to allocating inputs and outputs associated with multi-functional processes to the co-product outputs in proportion to their relative market values. The market price of the co-functions should refer to the specific condition and point at which the co-products are produced." (EC 2021). See more in Sect. "Allocation criteria for the definition of the status of the nutrient's sources: waste, residual or co-product"
Transport	Physical	"Allocation based on a relevant underlying physical relationship refers to partitioning the input and output flows of a multi-functional process or facility in line with a relevant, quantifiable physical relationship between the process inputs and co-product outputs (for example, a physical property of the inputs and outputs that is relevant to the function provided by the co-product of interest)." (EC 2021)
BBF processing operations at the manufacturing plant	Physical/ economical	Products coming out of a bio-based fertilizer manufacturing plant with similar physicochemical characteristics and functionality shall be allocated with a biophysical allocation method: "Allocation based on a relevant underlying physical relationship refers to partitioning the input and output flows of a multi-functional process or facility in line with a relevant, quantifiable physical relationship between the process inputs and co-product outputs (for example, a physical property of the inputs and outputs that is relevant to the function provided by the co-product of interest)." (EC 2021) Products coming out of a bio-based fertilizer manufacturing plant with different physicochemical characteristics and functionality shall be allocated with economic allocation: "Economic allocation refers to allocating inputs and outputs associated with multifunctional processes to the co-product outputs in proportion to their relative market values. The market price of the co-functions should refer to the specific condition and point at which the co-products are produced." (EC 2021). See more in Sect. "Allocation criteria for the definition of the status of the nutrient's sources: waste, residual or co-product"

related to raw material production and multiple different products coming out of a bio-based fertilizer manufacturing plant are allocated by mainly using the relative economic value (market price) of the material if the physicochemical characteristics of the raw material and other products of the same system are very different. Only in the case of transportation shall physical allocation be used. Allocations shall be conducted according to Table 3.[7]

The disadvantages of economic allocation are market fluctuations and context dependence, equations and context dependence. Moreover, prices might depend on who the buyer is and the purpose of the product (Kyttä et al. 2022). Economic allocation also easily indicates the by-products with the lowest market value as those with the least environmental impact (Pelletier and Tyedmers 2011; Pelletier et al. 2015). Furthermore, an increase in demand and prices would result in higher environmental impacts being allocated to recycled products that originally had a zero market price and zero environmental impact. This would result in situations indicating that utilizing or recycling materials would not be beneficial from an environmental perspective (Kyttä et al. 2022).

Allocation criteria for the definition of the status of the nutrient's sources: waste, residual or co-product

The present study further proposes that environmental impacts are allocated between products based on whether a material is defined as a waste, residual, or by-product. Classification of materials to co-product, residue or waste is based on its market value and utilization rate (e.g. applied to the field or landfilled; see Fig. 3).

This approach is similar to the one described in the EF method (EC 2021), which provides guidance on allocating emissions between exported manure and other farm outputs (e.g., beef and milk) based on the economic value of the manure at the farm gate. For example, if exported manure does not have an economic value at the farm gate, it is

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[7] Results of this study to be published also as part of Novafert final project report (Vikki et al. 2025).

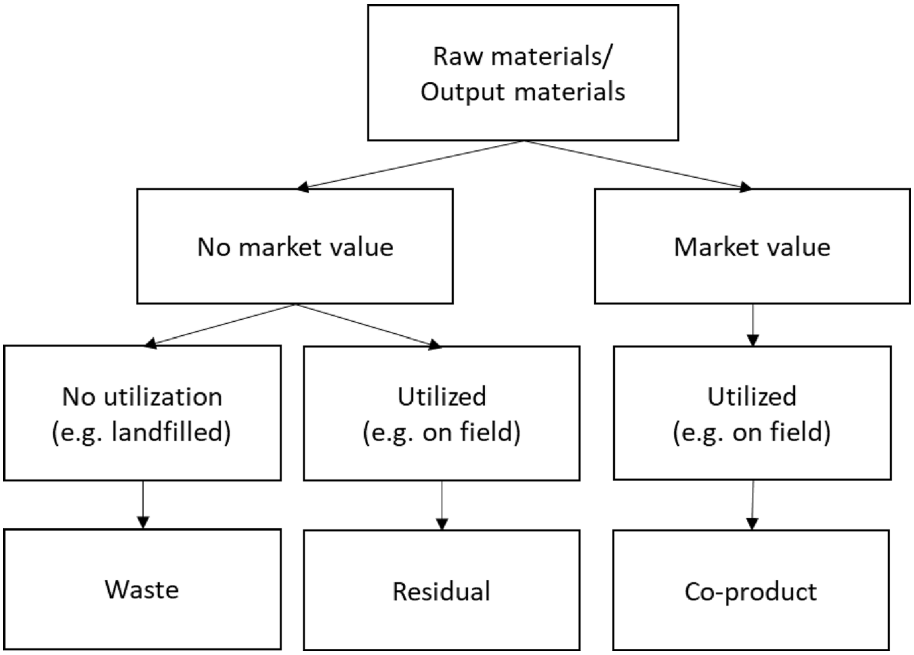

Fig. 3 Definitions of "waste," "residual," and "co-product"

regarded as residual without any allocation of an upstream burden and the emissions are allocated to the other farm outputs (e.g., beef and milk) where manure is produced. If manure does not have any economic value at the farm gate but is treated as waste (e.g., landfilled) the Circular Footprint Formula (CFF) is recommended. This is similar to EPD approach, where the environmental impacts of waste going to recycling or reuse are allocated to the waste-generating system up to the point of disposal, after which the impacts are transferred to the user of the material. In this framework, the raw material emissions from fertilizers based on recycled materials remain outside the system boundaries. However, the material is generally classified as waste here, even when it is recycled and reused, which differs slightly from the classification done using the EF method (EC 2021). According to Egas et al. (2023), many BBF studies assumed raw materials to be waste and did not allocate environmental impacts to them, which is consistent with the EPD approach. In some cases, impacts were allocated to residues without any clear definition of allocation criteria but some defined the allocation through economic allocation. For example, a study by Vikki et al. (2026) applied a similar approach to the one described in the EF method (EC 2021) and assumed that some of the raw materials of anaerobic digestion to be residual or waste with no market value and did not allocate environmental impacts to them according to the economic allocation rules.

Based on the guidance for exported manure in the EF method (EC 2021), the present study proposes the following allocation guidelines for raw or output materials classified as one of the following[8]:

- **Co-product** if raw material has an economic value at the farm/plant/factory gate before being transported to the BBF manufacturing process, it is considered as a co-product with an allocation of an upstream burden. Consequently, the output will enter the following production system (BBF manufacturing process) with environmental burdens assigned by its system of origin. Thus, the user of these flows will account for a share of the production of the raw material environmental burdens. The biophysical allocation shall be applied if the physicochemical characteristics of the raw material and other co-products of the same system are quite similar. If the physicochemical characteristics of the raw material and other products of the same system are very different (e.g., biogas and digestate), an economic allocation shall be used for output by using the relative economic value of the output compared to other co-products at the farm/factory gate. For example:

  If the manure has an economic value at the farm gate, it is regarded as a co-product and an economic allocation of the upstream burden shall be used for manure and other co-products (e.g., live animals) at the farm gate.
- If the digestate has an economic value at the farm gate, it is regarded as a co-product and the burdens allocation

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[8] Results of this study to be published also as part of Novafert final project report (Vikki et al. 2025).

of the upstream burden shall be allocated for digestate by using the relative economic value of digestate compared to energy produced by anaerobic digestion.

- **Residual** if raw material does not have an economic value at the farm/plant/factory gate before being transported to the BBF manufacturing process, it is regarded as residual without any allocation of an upstream burden. The emissions related to raw material production and management up to the farm/factory gate are allocated to the other farm/factory outputs where raw material is produced. For example:
- If the manure does not have an economic value at the farm gate, it is regarded as a residual without any allocation of an upstream burden. The emissions from manure production and management (e.g., storage, separation) up to the farm gate are allocated to the other farm outputs (e.g., beef, milk) where the manure is produced.
- If the digestate does not have an economic value at the plant gate, it is regarded as a residual without any allocation of an upstream burden. The emissions from anaerobic digestion and digestate management (e.g., storage, separation) up to the farm gate are allocated to the other outputs (biogas) where the digestate is produced. Though a biogas plant may be connected to a farm, it is considered a separate production system with a marketable output (e.g. not part of manure management operations). If the digestate is further produced as a BBF product with added value through different processing alternatives (e.g., granulation) not part of conventional biogas plant operations, the emissions shall be allocated to the final BBF product.
- **Waste** if raw material does not have any economic value at the farm/plant/factory gate and is treated as waste (e.g., landfilled) and not utilized, the Circular Footprint Formula (CFF) shall be applied (EC 2021). For example:
- If the manure does not have an economic value at the farm gate and it is landfilled, it is regarded as waste and CFF is applied.

Circular footprint formula (CFF)

EF method (EC 2021) gives guidance that the end of life stage shall be modelled using the CFF method which divides the environmental burdens of recycling, including collection, sorting, and transportation, between the original producer of the waste and the new user of the recycled material.

The CFF is modelling both energy recovery and recycling with substitution: it quantifies environmental benefits by granting credits for the material and energy that are not needed due to recycling and energy recovery (Ekvall et al. 2021). If material is used in energy recovery processes (e.g. anaerobic digestion) it is assessed under the 'energy' part of Eq. 3 in CFF (EC 2021). In this equation B = 0 means that no environmental burden or credit is assigned to the energy recovery process from the material at its end-of-life (Ekvall et al. 2021). If material is recycled it is assessed under the 'material' part of Eq. 3 in CFF (EC 2021). Specific guidance is given for compost and digestate to be recycled: "… compost, anaerobic digestion/ sewage treatment: compost, including digestate coming out of the anaerobic digestion, shall be treated in the 'material' part of CFF like recycling with A = 0.5." (EC 2021).

For intermediate products and "Cradle-to-Gate" PEF studies, the EoL is excluded by setting the parameters R2, R3, and Ed equal to 0 for the products in scope (EC 2021). The 'material' part of Eq. 3 in CFF (EC 2021) takes the following form:

$$\mathrm{CFF} = (1 - R1)E_v + R1 \times (\mathrm{AE}_{\mathrm{recycled}} + (1 - \mathrm{A})E_v \times Q_{\mathrm{sin}} \;\; Q_{\mathrm{sin}} Q_p - 0ptQ_p$$

The acquisition and pre-processing emissions from virgin material (Ev) are set to zero if recycled material is made of circular biomasses (e.g. of manure, digestate, compost and sludge). If the amount of virginal material is zero, the CFF takes the following form:

$$\mathrm{CFF} = R1 \times \mathrm{AE}_{\mathrm{recycled}}$$

Environmental burdens through the recycling process of waste material ($\mathrm{E}_{\mathrm{recycled}}$), including also collection, sorting and the transportation process, are shared between the producer of the waste flow and the user of the reusable/recyclable waste flow through its "A" factor.

However, CFF is seen to favor energy recovery over material recycling, since the benefits of energy recovery are modeled with 100% credit to the producer of the material, and the benefits of recycling (by avoiding the primary production of a material) only with 50% (Schrijvers et al. 2021). CFF has also been critized on it's potential inconsistencies in modelling energy recovery and waste recycling, risk of creating unrealistic incentives, formulas reliance on average rather than marginal data, general lack of alignment and significant data requirements (Schrijvers et al. 2021). In the present study, it is seen that applying the CFF formula to makes calculations complex for individual LCA practitioners.

Further recommendations

Fertilizer products with different methodological assumptions, such as different FUs, system boundaries, or allocation methods, cannot be compared with each other. Since BBFs are intermediate products and a heterogeneous product category, this study recommends using the "cradle-to-gate" system boundary according to the PEF guidance and the economic allocation method as the most practical option for co-products with different physical properties. Conversely, this study recommends using one and same DU but in addition to this several complementary FU options, which could be challenging to operationalize. Therefore, this study recommends applying a similar PEFCR structure for dairy products, grouping several different product categories together while maintaining their individual assessment requirements and operational units. Additionally, traditional mineral fertilizers could be included in the same PCR document, improving comparability between products and supporting consistent assessments within relevant categories.

Recommendations tailored for different stakeholders:

- LCA practitioners: a standardized framework represents a professional standard for assessing and communicating environmental impacts, particularly within the context of EU policies and regulations.
- BBF producers: to identify environmental "hotspots" in their supply chains, benchmark their performance against competitors, and collaborate on developing more sustainable solutions. A standardized framework helps companies evaluate the environmental performance of their products, pinpoint areas for improvement, and share their sustainability initiatives with stakeholders. It also supports compliance with environmental regulations and can drive innovation in product design and sourcing.
- Consumers (BBF utilizers, e.g., farmer): a standardized framework for providing reliable information about the environmental impact of products, allowing them to make more sustainable purchasing choices.
- Policymakers: a standardized framework for assessing and comparing the environmental performance of products, which can inform the development of effective environmental policies and regulations.

Limitations and future research

A major limitation of this work is the limited review study mainly focusing on PEF and EC guidelines with specific literature studies. Since a systematic literature review following a predefined criteria was not conducted, more comprehensive and diverse studies for comparison and assessment were not provided. Also, the study itself focused more on providing methodology, rather than applying the method. Thus, we did not provide a quantitative comparison of multiple different BBFs and mineral fertilizers or sensitivity analyses. In addition, this study was not able to compare different studies due to methodological differences which is the essential problem and challenge in the study literature to date and what this present study is trying to solve.

Since methodological harmonization for BBFs is challenging as they are intermediate products and a very heterogeneous product category, this raises the question of what the optimal product category should be. Although a product category which is too narrow does not allow the comparison of different options, a category that is too large makes setting a PCR difficult. One solution to the challenge could be the structure of the PEFCR for dairy products (European Dairy Association 2025) with several different product groups, e.g., milk, yoghurt, butter and cheese, grouped together but with each having its own assessment requirements and operational units defined. Indeed, a common framework in such a broad PCR allows for the harmonization of assessments while maintaining product-specific precision. A similar model could be applied to BBF fertilizers, which could be grouped according to their main function.

Moreover, traditional mineral fertilizers could also potentially be included in the same PCR document. Consequently, this would improve comparability between different products and support a more consistent assessment within the relevant product category.

Conclusion

This study provides insights in assessing the environmental impact of BBFs in a more harmonized and uniform manner to enhance the comparability between BBFs and potentially also with equivalent substitute mineral fertilizer products following the same methodological guidelines.

Instead of relying solely on the DU of 1 kg of BBF, this study recommends adopting complementary FUs (e.g., kg soluble N), which better capture the different nutrient content, fertilization efficiency and functional diversity of BBFs. In case of a system boundary, the EF method provides clear guidance for PEFCR developers to use Cradle-to-Gate system boundaries for intermediate products, e.g., fertilizers and BBFs. However, it is proposed that one provides an insight into the environmental impacts of BBFs for agricultural use as "additional technical information", such as the content of heavy metals, pathogens or other xenobiotics. Presenting results separately for BBFs as 'Cradle-to-Gate' and 'Cradle-to-Grave' avoids risks for double-counting in the life cycle assessment of the final agricultural products in which BBFs are used without posing problems for reliability and comparability. Regarding allocation, economic allocation is the most practical and accepted option when co-products have very different physical relationships or end use on the market and for LCAs used for external communication.

As BBFs are intermediate products and a very heterogeneous product category, methodological harmonization and setting a PCR for them is challenging. As one solution to such a challenge, this study recommends applying a similar structure of the PEFCR for dairy products with several different product groups grouped together, albeit with each having its own assessment requirements and operational units defined. In addition, traditional mineral fertilizers could also potentially be included in the same PCR document, thus improving comparability between different products and supporting a more consistent assessment within the relevant product category. A common framework in wider PCR allows for the harmonization of assessments while maintaining product-specific precision.

Achieving globally comparable LCA beyond just the EU level, requires harmonized calculation principles, uniform system boundaries and functional units as well as comprehensive databases. Methodological harmonization for BBFs is beneficial for both industry and policy makers since it can provide a credible basis for environmental assessments, improving market trust and product differentiation, as in the case of PEFCR for dairy products. For policy makers and policy uptakes, methodological harmonization for BBFs can provide consistent and comparable data to inform regulations, sustainability initiatives, as well as unlock new opportunities for BBF market expansion and increased adoption.

Table 5 Component Material Categories (CMCs). Designation of CMCS (EC 2021)

1	Virgin material substances and mixtures
2	Plants, plant parts or plant extracts
3	Compost
4	Fresh crop digestate
5	Digestate other than fresh crop digestate
6	Food industry by-products
7	Micro-organisms
8	Nutrient polymers
9	Polymers other than nutrient polymers
10	Derived products within the meaning of Regulation (EC) No 1069/2009
11	By-products within the meaning of Directive 2008/98/EC

Table 4 Product Categories (PFCs) of EU fertilizing products. Designation of PFCS (EC, 2019c; EC 2021)

1. Fertilizer	A. Organic fertilizer	Solid organic fertilizer		
		Liquid organic fertilizer		
	B. Organo-mineral fertilizer	Solid organo-mineral fertilizer		
		Liquid organo-mineral fertilizer		
	C. Inorganic fertilizer	Inorganic macronutrient fertilizer	Solid inorganic macronutrient fertilizer	Straight solid inorganic macronutrient fertilizer
				Compound solid inorganic macronutrient fertilizer
			Liquid inorganic macronutrient fertilizer	Straight liquid inorganic macronutrient fertilizer
				Compound liquid inorganic macronutrient fertilizer
		Inorganic micronutrient fertilizer	Straight inorganic micronutrient fertilizer	
			Compound inorganic micronutrient fertilizer	
2. Liming material				
3. Soil improver	A.Organic soil improver			
	B.Inorganic soil improver			
4. Growing medium				
5. Inhibitor	A. Nitrification inhibitor			
	B. Denitrification inhibitor			
	C. Urease inhibitor			
6. Plant biostimulant	A. Microbial plant biostimulant			
	B. Non-microbial plant biostimulant			
7. Fertilizing product blend				

Appendixes A

(See Tables 4, 5)

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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