Novafert

D2.1 – Sustainability Mapping Report

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Abbreviations

BBF: Bio-based fertiliser

CEN: European Committee for Standardization

D:Deliverable

EC: European Commission

EF : Environmental footprint

EU: European Union

EPD: Environmental Product Declaration

EPD-PCR: Environmental Product Declarations Product Category Rules

GHG: Greenhouse Gases

ILCD: International Life Cycle Data system

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

PAHs: Polycyclic aromatic hydrocarbons

PCBs: Polychlorinated biphenyls

PCDD/Fs: Chlorinated dioxins/furans

PCR: Product Category Rules

PEF: Product Environmental Footprint

PEFCR: Product Environmental Footprint Category Rules

POPs persistent organic pollutants including

OCs: Organic contaminants

SOC: Soil Organic Carbon

WP: Work package

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Executive Summary

"The 'Sustainability Mapping Report' (Deliverable 2.1) aims to enhance understanding of the current landscape of Life Cycle Assessment (LCA) guidelines and standards to assess the production and application of alternative fertilizing products. It also seeks to identify complementary non-LCA indicators to enable a more comprehensive evaluation of these products. D2.1 is part of WP2 within the NOVAFERT project, "Mapping current LCAs methods, Risk assessment + LCA of selected P/T: Environmental criteria". This initiative endeavours to contribute towards the development of a 'PEF compliant methodology' aimed at implementing LCA in the environmental assessment of alternative fertilizing products". The report presents the outcomes of tasks 2.1 and 2.2, and it will be featured in the guideline created in task 2.3, which outlines a unified, compliant methodology for implementing LCA in the environmental evaluation of alternative fertilising products.

Task 2.1, "Mapping of Available LCA Guidelines and Standards for Assessing Alternative Fertilizing Products," involved a thorough examination of key guidelines and recommendations, including the "COMMISSION RECOMMENDATION (EU) 2021/2279" by the European Commission and the "General Programme instructions for the International EPD® system" by ©EPD International AB. Additionally, PEFCR and EPD-PCR guidelines were analysed to support the development of a unified LCA methodology for biobased fertilizers. The review compared various LCA methodological guidelines, highlighting differences and considerations for developing a PEF-wise methodology. This analysis, supplemented by previous reviews and scientific publications, revealed potential conflicts and challenges in establishing a common LCA method for biobased fertilizers.

Task 2.2 "Mapping of other relevant environmental/sustainability" aimed to identify and map available standards for assessing environmentally relevant impacts not included (or not well assessed within its boundaries) in the LCA approach, such as improving soil health, soil carbon sequestration, biodiversity, and emerging pollutants. A systematic literature search was conducted, combining bibliometric analysis and manual searches, to identify key environmental concerns related to alternative fertilising products (mainly identified with the term biobased fertilizers, BBFs) during production and in-field application. The analysis involved surveying existing literature, filtering publications relevant to BBFs and LCA, and categorizing identified environmental concerns. Additionally, a comprehensive review of available models, tools, and methods for each environmental concern category was conducted, highlighting their benefits, drawbacks, and potential application in an LCA context.

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1. Introduction

1.1 NOVAFERT project

NOVAFERT, aligned with the Zero Pollution action plan, the "Farm to Fork" strategy, and the new Fertilising Product Regulation, aims to showcase the technical, economic, and environmental viability of over 25 alternative fertilising products. These products, derived from diverse waste streams, seek to replace mineral fertilisers. NOVAFERT will address environmental concerns through guidelines and consensus-based environmental assessments. Simultaneously, it will foster circular and green business models, ultimately curbing environmental impacts and reducing nutrient reliance across 6 European countries. NOVAFERT promotes the responsible use of alternative fertilizers. Additionally, it will develop support policies and legislative instruments to facilitate safe and efficient utilization of these products, contributing to informed decision-making in nutrient recovery.

1.2 NOVAFERT project and WP2

The NOVAFERT project aims to demonstrate the technical, economic, and environmental feasibility of alternative fertilising products or bio-based fertilizers (BBFs) and the safety of a wide brochure of products recovered from different waste streams. In particular Work Package (WP) 2 aims to develop a methodological guideline compliant with Product Environmental Footprint (PEF) rules. PEF is an initiative of the European Commission that aims to create LCA-based standard methodologies to unify the assessment of different products and sectors.

1.3 Objective and Development in the NOVAFERT Project

The objective of Deliverable 2.1 (D2.1) within the NOVAFERT project is to establish a "PEF compliant methodology for implementing LCA in the environmental evaluation of alternative fertilizing products". D2.1 is crafted by drawing from the insights presented in the NOVAFERT project's initial deliverable, Deliverable 1.1, titled "Report on EU Nutrient Recovery Technologies and Derived Products", and it incorporates the outcomes derived from the tasks accomplished under Project Work Package 2: "Task 2.1 Mapping of Available LCA Guidelines and Standards for Assessing Alternative Fertilizing Products", "Task 2.2 Mapping of other relevant environmental/sustainability" and "Task 2.3 Definition of a Unified Compliant Methodology for LCA Implementation in the Assessment of Alternative Fertilizing Products".

1.4 Task 2.1 Mapping LCA Guidelines and Standards

Task 2.1 Mapping of available LCA guidelines and standards for assessing the production and application of alternative fertilizing products" orchestrates the scrutiny of specialized literature and guidelines germane to LCA, which are either currently employed or have the potential to be adopted in the assessment of alternative fertilizers. This task includes a comparative analysis of these guidelines to unearth shared recommendations and divergences among them. Foremost, the primary outcome sought from Task 2.1 involves defining a universally accepted

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methodology to effectively apply LCA when assessing BBFs. The parameters of this review are aligned with the outcomes of Deliverable 1.1, wherein the most impactful or promising BBF production technologies within the European landscape are validated.

1.5 Task 2.2 Mapping of non-LCA indicators for assess environmental burden

Task 2.2 Mapping of other relevant environmental/sustainability involves investigating various environmental and sustainability assessments focusing on the methods or tools mainly used to assess the environmental impacts of BBFs, during its production, storage and application in a non-LCA approach. Task 2.2. try to cover different gaps in LCA methodology to complement the proposed "Unified Methodology for LCA Implementation" from task 2.3 to include a wider range of global and local/site-specific environmental impacts related to the alternative fertilizing products application.

2. Mapping of Available LCA Guidelines and Standards for Assessing Alternative Fertilizing Products

Life Cycle Assessment is the acknowledged method to assess environmental performance of products and organizations (EC, 2021). General guidelines to implement LCA, for the environmental assessment of production system are given by the ISO 14040 and ISO 14044 standards. However, there are many specific ISO compliant guidelines that specify additional rules to assess defined product categories. These Product Category Rules (PCRs) are mostly developed within the Environmental Product Declarations (EPD) framework (EPD, 2021), but since the launch of the EC's Environmental Footprint initiative in 2013 to achieve a European single market for green products, EC recommendation on general Product Environmental Footprint (PEF) guidelines and compliant product category rules (PEFCRs) for some product categories have been also developed. However, neither the EPD-PCRs nor the EC's- PEFCRs cover suitable categories for the production and application of bio-fertilizers. This lack of guidance affects the LCA methodological choices taken by practitioners when conducting LCA on bio-fertilizers, and thus, the obtained LCA results cannot be replicable and directly comparable even among similar bio-fertilizing products or to other fertilizer products. In this Task 2.1, specialized LCA literature and guidelines that are or could be used for the assessment of BBF products will be mapped and compared to identify common recommendations and differences.

The NOVAFERT project endeavours to demonstrate the technical, economic, and environmental feasibility of alternative fertilizing products, specifically BBFs, along with the safety of a diverse range of products recovered from different waste streams. In particular, the project's Work Package (WP) 2 focuses on the development of methodological guidelines

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compliant with the PEF rules, an initiative by the European Commission to establish LCA based standard methodologies for a unified assessment of various products and sectors.

The NOVAFERT deliverable, D1.1 "Report on EU Nutrient Recovery Technologies and Derived Products", serves as a comprehensive repository of information on nutrient recovery technologies and associated products in the European region. D1.1 guides the scope of the literature review in this task (T2.1) and the development of consistent PEF guidance for fertilizers (T2.3) in this D2.1 report.

This Task 2.1 "Mapping of available LCA guidelines and standards for assessing the production and application of alternative fertilizing products" involves scrutinizing specialized literature and guidelines relevant to LCA. This task aims to review a universally accepted methodology for applying LCA in assessing BBFs, aligning with the outcomes of Deliverable 1.1, validating impactful or promising BBF production technologies in the European landscape.

2.1 Material and Methods

Task 2.1, "Mapping of Available LCA Guidelines and Standards for Assessing Alternative Fertilizing Products," involved mapping the key guidelines and recommendations that could be utilized in developing a common LCA methodology for the biobased fertilizing product category. The most important general guidelines considered here are the "COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations" prepared by the European Commission (EC), and the internationally valid "General programme instructions for the International EPD® system" produced by ©EPD International AB.

In addition to these general guidelines, existing or under-development PEFCR and EPD-PCR (Copyright-protected Product Category Rules, PCR) guidelines were mapped, which could partially apply or support the development of the LCA methodology for biobased fertilizers. The purpose of examining the selected PEFCR and PCR documents was to analyse how they have examined or defined the Functional Unit in situations where the physical or chemical composition of the product varies within the same product category, how they have determined the definition of the system boundary for products produced from recycled materials, and how they have allocated environmental impacts from both raw material production and the end use of the fertilizer product.

As part of the EC's Environmental Footprint initiative, comprehensive work was done comparing different existing LCA methodological guidelines. The current general PEF method (EC, 2021) was formed taking into account ISO 14044 (2006) LCA – requirements and guidelines, ISO/DIS 14067: carbon footprint of product, ILCD Handbook, Ecological Footprint, GHG Protocol, French Environmental Footprint (BPX 30-323), and UK Product Carbon Footprint PAS 2050, among others. In this review, observed differences are highlighted, aiming to understand what considerations should be addressed when a PEF-wise methodology for

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BBFs is developed. This Task's review also considers other previous reviews, such as Lex4Bio literature reviews conducted by Tanzer et al. (2021a, 2021b) on the state-of-the-art situation of the LCA of biobased fertilizers, reflecting trends in LCA methodologies in recent years inside EU market area. Additionally, several relevant scientific publications are included in the review, which describes the current state of LCA modelling and makes critical notes on the general PEF method. Finally, a conclusion is drawn, reflecting on potential conflicts or shortcomings among different standards or officially accepted documents, which in turn challenges the development of a common LCA method for biobased fertilizers.

2.2 The Main existing normative rules

2.2.1 The Environmental Footprint (EF) initiative of the EC

The Environmental Footprint (EF) initiative was started and conducted by the EU Commission from the 2010s onwards (Damiani et al., 2022; European Commission, 2024). It is the base for determining the environmental impact of products or organizations on the EU market, built on LCA standards and previous EU and other guidelines. The purpose of EF is to support more sustainable choices for consumers, promote fair competition among businesses, and open opportunities for the circular and green economy. EF is a harmonized approach provided by the European Commission and stakeholders that generates environmental footprint information in a credible and consistent manner (Damiani et al., 2022).

The LCA guidelines are published as an EC recommendation, which includes separate general guidelines for Product Environmental Footprint, PEF, and Organization Environmental Footprint, OEF (EC, 2021). The EF initiative also enables the production of official Product Environmental Footprint Category Rules (PEFCRs) and Organization Environmental Footprint Sector Rules (OEFSRs), which are the main guidelines in authoritative position for determining environmental footprints. The EC recommendation 221/2279 specifically recommends EU member states to use the EF methods in their voluntary policies, and private actors to measure environmental footprints according to the EF methods (Damiani et al., 2022; COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations, 2021).

2.2.1.1 Product Environmental Footprint (PEF)

It is recommended that the generic PEF method shall be employed when no official PEFCR is available (Damiani et al., 2022). The validity of the general PEF method to study a product can thus, also be established when such a PEF study is verified against the general PEF method according to the verification guidance of the PEF method.

The phases of the PEF method mirror those of the standardized LCA methodologies. The initial phase involves defining the goal and scope of the PEF study. This scope encompasses the definitions of the *Functional unit and reference flow, System boundary, EF impact categories,*

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Additional information, and Assumptions/limitations. These considerations are particularly relevant to the Novafert project's objective, which is to create an unofficial PEF methodological guide for assessing the environmental performance of BBFs (Damiani et al., 2022).

After the initial step of defining the scope of a PEF study, the subsequent steps include compiling the *LCI (Life Cycle Inventory), conducting LCIA (Life Cycle Impact Assessment), and Environmental Footprint reporting*. The outcomes of these processes encompass an Environmental profile, Hotspot results, and additional information. Finally, the PEF study results are calculated, presenting characterized, normalized, and weighted results for each of the 16 EF impact categories and culminating in a combined single overall score. When this harmonized approach is utilized in the comparison between different BBF products, the environmental performance of each product can be compared in a valid manner (Damiani et al., 2022).

2.2.1.2 Product Environmental Footprint Category Rules (PEFCRs)

The PEFCRs play a crucial role by providing detailed specifications to the general PEF method tailored to specific product categories (European Commission, 2022). These rules focus on key aspects and parameters to enhance the relevance, reproducibility, and consistency of LCAs following the PEF method. In contrast to studies based solely on the general PEF method, which allows for discretion, comparative assertions are only permitted if the study adheres to specific sector rules. The process of creating these rules is instructed by the EC (2021/2279) in detail, involves multiple stages and is time consuming. Chaired by a technical secretariat representing at least 51% of the EU market turnover, the process engages key stakeholders and experts in the relevant products and sectors.

When modelling the environmental footprint of a product, adherence to Product Environmental Footprint Category Rules (PEFCRs) is recommended within the EU Member states (Damiani et al., 2022). These guidelines define a representative product for the product category in question and establish a benchmark environmental footprint for allowing comparisons of the environmental performance of other products in the same category. The EF initiative, led to a pilot phase from 2013 to 2018, during which the first 'EC recommendations 179/2013' and later 'Product Environmental Footprint Category Rules Guidance version 6.3 – Dec 2017' were provided. This was followed by a transition phase Started in 2018. Currently, the latest official EF methods are '*COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organizations.*' During the pilot and transition phases, a total of 19 PEFCR guidelines have been developed for various product categories. The available PEFCR guidelines are compiled in Table 1.

Table 1. Available PEFCR guidelines for different product categories. All documents have been valid until December 31, 2021, except for the PEFCR for T-shirts, which is marked to expire at the end of 2020 (European Commission, 2022).

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Beer	Packed water
Dairy	Pasta
Decorative paints	Pet Food
Household liquid laundry detergents	Photovoltaic electricity production
Hot and cold water supply pipe systems	Rechargeable batteries
Intermediate paper product	T-shirt
Feed for food producing animals	Thermal insulation
IT equipment	Uninterrupted Power Supply
Leather	Wine
Metal sheets	

Furthermore, PEFCR development is ongoing with 'Apparel&Footwear', 'Cut flowers and potted plants', 'Flexible packaging', 'Synthetic turf', and 'Marine Fish categories'. During the Novafert project, no PEFCR guidance has been available for fertilisers, let alone BBFs made from any biomass-based reused materials. In the case when PEFCR is not available for the product category to be studied, the EC stipulates that, the general PEF method for product LCA modelling is followed (Damiani et al., 2022). However, one of the goals of the Novafert project includes the aim of producing an unofficial PCR (product category rules) for the product group of BBFs that adapts to official guidelines. Therefore, it is considered relevant in this Task to review the existing PEFCR guidelines.

2.2.2 International EPD (Environmental Product Declaration) System

A Swedish limited company EPD International is the programme operator of the International EPD® System. They operate under the IVL Swedish Environmental Research Institute. According to EPD International (2021) General Programme Instructions (EPD, 2021), the International EPD® System strives to facilitate global communication of quantified environmental information throughout product life cycles. Through a program, it ensures credibility, comparability, and comprehension of environmental data, providing verified Type III environmental declarations based on ISO standards of: ISO 21930[1], ISO 14067[2], ISO 14046[3],

[1] ISO 21930:2017 Sustainability in buildings and civil engineering works Core rules for environmental product declarations of construction products and services
[2] ISO 14067:2018 Greenhouse gases Carbon footprint of products Requirements and guidelines for quantification
[3] ISO 14046:2014 Environmental management Water footprint Principles, requirements and guidelines

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ISO 14040[4]/14044[5], ISO 14025[6], ISO/TS 14027[7], and EN 15804[8]. The EPD system plays a role in standardization, advocating for life cycle-based environmental information for various applications. It promotes collaboration, establishes regional programs, and aligns with initiatives like the European Commission's Product Environmental Footprint pilot (PEF/PEFCR) and the ECO Platform. The program encompasses all product types globally, with the flexibility to decline registrations under specific circumstances. EPDs, relevant for both business-to-business and business-to-consumer communication, comply with pertinent national laws. The scope may involve a single company's product or represent the average product of companies in a specific sector and geographical area, utilizing formats such as "Sector EPDs" and "Single-issue EPDs." EPDs, grounded in Product Category Rules (PCR), may include a "pre-certified EPD" published during PCR development (EPD, 2021).

2.2.2.1 Product Category Rules (PCRs) in EPD system

Product Category Rules (PCRs) are copyrighted documents within the Environmental Product Declaration (EPD) framework, providing a structured guide for developing EPDs specific to product categories. They guide Life Cycle Assessments (LCAs) by specifying critical parameters and go beyond standard requirements outlined in the International EPD® System's General Program Instructions (GPI). PCRs, owned by program operators, contribute to standardized LCA practices, facilitating consistent assessment and comparison of products within a category. PCRs play a role in ISO 14025, enhancing transparency and comparability between EPDs. A library[9] with over 100 PCRs covering diverse product categories aids practitioners in EPD development, promoting efficiency and coherence across industries. This collaborative approach aligns with the goal of fostering sustainability and informed decision-making in environmental product assessments PCRs play a role in ISO 14025, enhancing transparency and comparability between EPD. A library with over 100 PCRs covering diverse product categories aids practitioners in EPD development, promoting efficiency and coherence across industries. This collaborative approach aligns with the goal of fostering sustainability and informed decision-making in environmental product assessments (EPD, 2021).

As per the International EPD® System (EPD, 2021), an Environmental Product Declaration (EPD) comprises two crucial components[10]. Firstly, there is the foundational LCA report, a detailed summary of the LCA project intended to aid third-party verifiers in the EPD verification process but excluded from public communication. The second element is the public EPD document, which discloses LCA results and supplementary EPD content to the general public.

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[4] ISO 14040:2006 Environmental management Life cycle assessment Principles and framework
[5] ISO 14044:2006 Environmental management Life cycle assessment Requirements and guidelines
[6] ISO 14025:2006 Environmental labels and declarations Type III environmental declarations Principles and procedures
[7] ISO/TS 14027:2017 Environmental labels and declarations Development of product category rules
[8] EN 15804:2012 Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products
[9] https://www.environdec.com
[10] https://www.environdec.com/all-about-epds/the-epd

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2.2.2.2 Difference between systems of Global EPD-PCRs and EU-Focused PEFCRs

Environmental Product Declaration - Product Category Rules (EPD-PCRs) and European Product Category Rules (PEFCRs) are integral components of the life cycle assessment and environmental product declaration processes, each with distinct characteristics in terms of scope, development, and application (Damiani et al., 2022; EPD, 2021). EPD-PCRs establish generic rules for conducting LCAs and creating EPDs within a specific product category, offering a standardized framework applicable globally to a diverse range of products within that category. Conversely, PEFCRs are uniquely crafted for the European Union's regulatory context, concentrating on a specific product category, and developed under the guidance of the European Commission to ensure alignment with EU policies. This specific focus aims to guarantee consistency and comparability of environmental information for products circulating within the EU market.

In terms of development, EPD-PCRs are typically crafted by industry associations, standardization bodies, or other stakeholders at a global or national scale, providing a globally applicable framework without regional limitations. In contrast, PEFCRs follow explicit guidelines and mandates outlined by the European Commission, requiring collaborative efforts among industry stakeholders, experts, and regulatory bodies. These distinct development approaches contribute to enhancing sustainability practices, with EPD-PCRs offering a versatile global standard and PEFCRs specifically tailored to meet European regulatory requirements (Damiani et al., 2022; EPD, 2021).

In the regulatory context, EPD-PCRs operate independently of any specific framework, lacking inherent ties to governmental mandates and not being mandated by any government or regulatory body. Conversely, PEFCRs respond to the European Commission's dedication to advancing sustainable consumption and production, aligning with the European Union's environmental policies and regulations. Adherence to PEFCRs may become a prerequisite for certain products within the EU market, highlighting the global adaptability of EPD-PCRs and the targeted alignment of PEFCRs with the regulatory objectives of the European Union (Damiani et al., 2022; EPD, 2021).

As for the comparison of the applicability, EPD-PCRs are designed for global use, providing organizations worldwide with a standardized framework to assess and declare the environmental impacts of their products. In contrast, PEFCRs have a more targeted scope, specifically crafted for application within the European Union. The primary objective of PEFCRs is to harmonize environmental information for products circulating within the EU market, contributing to the broader sustainability goals outlined by the European Union. This contrast in applicability underscores the versatility of EPD-PCRs on a global scale, while PEFCRs are tailored to meet the specific needs and regulatory context of the European market. In summary, while both EPD-PCRs and PEFCRs contribute to standardizing environmental assessments and declarations, their distinctions lie in their broad global versus targeted EU-specific scope, development approaches, and regulatory relationships (Damiani et al., 2022; EPD, 2021).

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2.2.3 Relevant ISO standards and guidelines in LCA

The '*COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organizations'* is structured compiled on standards and guidelines of:

- EN ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework
- EN ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines
- EN ISO 14067:2018 Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification
- ISO 14046:2014 Environmental management – Water footprint – Principles, requirements and guidelines
- EN ISO 14020:2001 Environmental labels and declarations – General principles
- EN ISO 14021:2016 Environmental labels and declarations – Self-declared environmental claims (Type II environmental labelling)
- EN ISO 14025:2010 Environmental labels and declarations – Type III environmental declarations – Principles and procedures
- ISO 14050:2020 Environmental management – vocabulary
- CEN ISO/TS 14071:2016 Environmental management – Life cycle assessment – Critical review processes and reviewer competencies: Additional requirements and guidelines to EN ISO 14044:2006
- ISO 17024:2012 Conformity assessment – General requirements for bodies operating certification of persons
- PEF Guide, Annex to Commission Recommendation 2013/179/EU on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (April 2013)
- ILCD (International Reference Life Cycle Data System) Handbook developed by EC Joint Research Centre
- Ecological Footprint Standards
- Greenhouse Gas Protocol - Product Life Cycle Accounting and Reporting Standard (World Resources Institute - WRI/ World Business Council for Sustainable Development - WBCSD)
- BP X30-323-0:2015 General principles for an environmental communication on mass market products (Agence de la transition écologique, ADEME)
- PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (British Standards Institution - BSI)
- ENVIFOOD Protocol.
- FAO:2016 Environmental performance of animal feeds supply chains: Guidelines for assessment. LEAP Partnership.

The compiled basic guidelines above provide a fundamental structure for the LCA methodology outlined in the PEF/PEFCR recommendation. However, in situations such as BBFs and their product group, a PEF-oriented LCA methodology that is uniformly applicable requires several specific standards and corresponding guidelines. In addition to the above-mentioned standards and guidelines used to draft the general EF method, to produce a PEF-wise method for biobased fertilizer products, additional guidelines are of interest:

- 16760:2015; Bio-based products – Life Cycle Assessment
- CEN/TR 16957:2016; Bio-based products. Guidelines for Life Cycle Inventory (LCI) for the End-of-life phase
- Life Cycle Assessment (LCA) of alternative feedstocks for plastics production; Part 1: the Plastics LCA method

Additional standards and guidelines are reviewed in following chapters.

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2.2.3.1 Bio-based products – Life Cycle Assessment EN 16760:2015

This standard addresses the LCA of bio-based products, emphasizing a holistic approach covering the entire product, although with a specific focus on the distinctive characteristics of the bio-based component. It extends additional requirements and guidelines for bio-based products, particularly concentrating on Goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation and reporting (European Standard EN 16760:2015 Bio-Based Products. Life Cycle Assessment, 2015).

EN 16760:2015 ensures that LCAs for bio-based products encompass all four phases of LCA, building upon the foundational requirements outlined in EN ISO 14044:2006. Notably, it provides further guidance tailored to the unique aspects of bio-based products, considering factors such as geographical and temporal scope, allocation procedures for co-products, resource elementary flows, and specific considerations for land use, water use, and carbon flows—both fossil and biogenic (European Standard EN 16760:2015 Bio-Based Products. Life Cycle Assessment, 2015).

In particular, this standard addresses the modelling details associated with agriculture, forestry, and aquaculture systems, along with inventory and modelling requirements for the end-of-life phase of bio-based products. Notably, the scope of this European Standard is directed toward bio-based products for industrial applications, excluding considerations for food, feed, and energy. However, the LCA guidelines and requirements articulated herein can be universally applied to any product derived from biomass, irrespective of its ultimate application. This series of European Standards sets the stage for a comprehensive and standardized approach to evaluating the environmental impact of bio-based products within industrial contexts (European Standard EN 16760:2015 Bio-Based Products. Life Cycle Assessment, 2015).

The European Standard EN 16760:2015 offers a valuable and applicable framework for evaluating the environmental impact of BBFs. Despite not being explicitly tailored to fertilizers, the standard's general approach to LCA, encompassing the entire life cycle, aligns well with the complexities of BBF production. Its specific focus on the bio-based component becomes particularly relevant for fertilizers derived from biomass, providing guidance on representing the biomass acquisition phase.

The standard addresses key considerations for BBFs, including allocation procedures for co-products generated during production, a notable aspect in fertilizer manufacturing. The inclusion of resource elementary flows ensures a comprehensive assessment of resource usage throughout the life cycle, a crucial factor for products derived from natural resources. Additionally, the standard's guidance on modelling agriculture and aquaculture systems is pertinent to BBFs closely tied to these processes.

Considering the end-of-life phase, especially in the context of BBFs applied to soil, EN 16760:2015 provides inventory and modelling requirements, contributing to a thorough assessment of the product's environmental impact. While the standard primarily targets

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bio-based products for industrial applications, its guidelines and requirements can be effectively extended to encompass BBFs utilized in agriculture and related industries. In essence, EN 16760:2015 serves a structured and standardized guidance for assessing the environmental effects of BBFs throughout their life cycles.

2.2.3.2 Bio-based products. Guidelines for Life Cycle Inventory (LCI) for the End-of-life phase CEN/TR 16957:2016

The "CEN/TR 16957:2016 – Guidelines for Life Cycle Inventory (LCI) for the End-of-life phase" is a Technical Report within the European Committee for Standardization (CEN) framework, specifically addressing bio-based products. This standard offers guidance for conducting Life Cycle Inventory (LCI) assessments focused on the end-of-life phase.

Key aspects covered by CEN/TR 16957:2016 include recommendations and methodologies for collecting and analysing data related to the end-of-life phase. This phase encompasses activities such as disposal, recycling, and other management processes that occur once a product reaches the state of end-of-life (SFS, 2016).

By providing guidelines for Life Cycle Inventory assessments in the end-of-life phase, this technical report aims to contribute to a more comprehensive understanding of the environmental impacts associated with the entire life cycle of bio-based products. This includes considerations for waste management, recycling, and other relevant processes crucial for the sustainability assessment of these products (SFS, 2016).

While the standard is not explicitly tailored to BBFs, it offers guidance for conducting Life Cycle Inventory (LCI) assessments focused on the end-of-life phase. BBFs, as a subset of bio-based products, share commonalities in their life cycle considerations, particularly in terms of disposal, recycling, and other end-of-life management processes.

2.2.3.3 Life Cycle Assessment (LCA) of alternative feedstocks for plastics production; Part 1: the Plastics LCA method

This document is a result of the Administrative Agreement (No. 34854-2017 / DG GROW No. SI2.762599) between DG GROW and the Joint Research Centre. It outlines the "Plastics LCA method," offering detailed guidelines for Life Cycle Assessment studies on plastic products from various feedstocks. Aligned with the PEF method, the "Plastics LCA method" aims to enable reproducible, consistent, and verifiable LCA studies on plastic products at the EU level. While focusing on diverse feedstocks – including recycled biomass – the method also applies to products with different biodegradability properties, like compostable plastics, regardless of the feedstock used (Nessi et al., 2021). According to Egas et al. (2023), the production of BBFs relies on the reuse of biomass generated from side or waste streams as a source of raw materials, it is important to consider this guideline.

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2.3 Methodological review

Scientific systematic literature reviews, such as Egas et al., 2023, high-profile EU-horizon projects like Lex4Bio (Tanzer et al., 2021a, 2021b), and also NOVAFERT's EU-region product, technology, and technological readiness degree surveys (Kinsella et al., 2023), indicate that the product group of BBFs is particularly complex. It is generally recognized that producing a uniform LCA methodology for fertilizers is necessary, but the challenges are manifold.

Official LCA guidelines and standards, such as ISO 14044 (2006) LCA – requirements and guidelines; ISO/DIS 14067 (2012): carbon footprint of products; ILCD Handbook – 1st Edition (2010); Ecological Footprint (2009); GHG Protocol (2011) (WRI–WBCSD); French Environmental Footprint (BPX 30-323); and UK Product Carbon Footprint PAS 2050 (2011), are thoroughly evaluated and comprehensively compared in the document 'Product Environmental Footprint (PEF) Guide '(Manfredi et al., 2012). This guideline has served as preliminary work, leading to the currently valid EC's PEF and PEFCR guidelines and recommendations. The following paragraphs compare the methodological aspects of life cycle modelling based on both official guidelines according to PEF guide generated by Manfredi et al. (2012), and a few systematic scientific reviews such as (Egas et al. (2023): 'Life cycle assessment of BBFs production systems: where are we and where should we be heading?' The review reflects general guidelines on the challenges of modelling the life cycle assessment of biodegradable fertilizers.

2.3.1 Functional Unit and Reference flow

The official LCA standards and PEF guide provide a description of the functional unit and reference flow (Damiani et al., 2022). The functional unit is defined as encompassing the qualitative and quantitative aspects of the function(s) and/or service(s) delivered by the evaluated product, addressing key inquiries such as 'what?', 'how much?', 'how well?', and 'for how long?' within this definition. Simultaneously, the reference flow is characterized as a measure of the outputs from processes within a given product system that are necessary to fulfil the function expressed by the functional unit. In succinct terms, the reference flow can be understood as the quantity of product required to satisfy the defined functional unit. However, it is crucial to acknowledge that the concepts of functional unit and reference flow are open to interpretation, varying across different sources and allowing room for diverse perspectives.

The PEF Guide (COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations, 2021) emphasizes a comprehensive approach to determining the unit of analysis (Functional Unit, FU) for a PEF study, considering the function(s) or service(s) provided, the magnitude and duration of the function or service, and the expected level of quality. According to Manfredi et al. (2012), the ISO 14044 (2006) LCA standard focuses on ensuring that the functional unit aligns with the study's goal and scope, is clearly defined, and measurable, with a subsequent definition of the reference flow. Similarly, ISO/DIS 14067 highlights the importance of a clear and measurable

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definition for the carbon footprint of a product. The ILCD Handbook emphasizes consistency with the study's goal and scope, clear definition in quantitative and qualitative terms, and the establishment of a separate reference flow for supporting data collection. The Ecological Footprint guide lacks specific guidance on functional unit definition but acknowledges several studies using the functional unit concept based on ISO 14044. The GHG Protocol stresses the significance of the magnitude, duration, and expected level of quality, with a separate reference flow to support data collection. The French Environmental Footprint (BPX 30-323) uniquely defines the functional unit at the PCR-level. In contrast, the UK Product Carbon Footprint PAS 2050 (2011) refers to the functional unit as the unit of analysis, providing limited information and guidance (Manfredi et al., 2012). ISO standard 16760:2015 Bio-based products – Life Cycle Assessment addresses the concepts of 'Function, functional unit, and reference flows.' The standard stipulates that in defining the functional unit, one must adhere to the requirements outlined in ISO 14040 and ISO 14044 (European Standard EN 16760:2015 Bio-Based Products. Life Cycle Assessment, 2015).

In the International EPD program guide (EPD, 2021), the declared or functional unit serves as the key reference for assessing a product's environmental performance. The chosen unit, whether functional or declared, depends on the product category, and is specified in the PCR. While the PCR may allow multiple units, caution is urged for using two different units within the same EPD without justification.

The EPD guide states as EC's PEF/PEFCR guide that the declared/functional unit must be clearly defined and measurable, typically representing a product's function or property quantified in SI units. For known and well-defined functions, a functional unit is recommended, such as transporting passengers or cleaning a specific area. If the function is unclear or versatile, a declared unit may be used, applicable to intermediate products or those with varied applications (EPD, 2021; COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations, 2021).

Declared units, representing quantities of the product, should align with the product's typical applications. Examples include individual items, product mass, or volume. However, using declared units may reduce comparability between EPDs, emphasizing the need to specify technical properties for improved comparability (EPD, 2021).

Pedersen & Remmen (2022) addresses in their review that challenges arise with Functional Units (FUs) defined in PEFCR. Some FUs of official PEFCRs fail to adhere to PEF method requirements, especially regarding the incorporation of performance and quality aspects. This omission undermines meaningful product comparisons, impeding fair assessments. In their review, Pedersen & Remmen gives examples, that the PEFCR for dry pasta exemplifies an inadequate FU, defining it solely as 1 kg of pasta without considering essential aspects like satiety and nutritional value, hindering fair product comparisons. In contrast, an exemplary case is seen in the PEFCR for paint, which fulfils all criteria by addressing key questions: "What,"

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"How much," "How well," and "How long." This comprehensive approach to defining the FU in certain product categories, such as paint, ensures fair comparisons. However, the challenges persist, particularly in food product categories, where consensus on the function is lacking, prompting the need for further research in developing a method for assessing the function of food.

In their review, (Egas et al., 2023) highlights the importance of defining a consistent and standardized functional unit (FU) in LCA studies, especially for bio-based products (BBF). Egas, et al. notes that while standards like ISO 14040 and ISO 14044 do not specify state-specific requirements for the definition of the functional unit, other guidelines by the European Commission and it's research center, JRC, such as the ILCD handbook (JRC, 2010), PEF guide (EC 2021/2279, and JRCPlastic (Nessi et al., 2021) recommend certain common features ("What," "How much," "How well," and "How long") for defining the functional unit. The authors observe that inconsistency exists among LCA studies for BBF, particularly in the definition of "How much." Egas et al. notes that different studies on biochar production and struvite and bio-stimulant production use varying functional units, making it difficult to compare and interpret the results. The lack of a standardized functional unit hinders direct comparisons, limits discussions, and affects the reliability of LCA results for similar BBF.

Tanzer et al., (2021a and 2021b) authored a report on LCA studies of BBFs, wherein they discussed, among other topics, the definition and characterization of the functional unit (FU). The authors investigated how FUs are defined, whether explicit definitions are provided, and the level of adherence to ISO standards 14040/14044. The study also explored the types of FUs used in LCA studies, specifically examining the prevalence of input-related versus output-related FUs. Furthermore, Tanzer et al. examined trends over time and variations in compliance rates among different regions, providing insights into the current landscape of FU definitions in LCA studies on BBFs. In their conclusion, the authors underscore a need for increased explicit definitions of FUs, with only 16% of their reviewed studies providing such definitions. The study also emphasizes a positive trend in describing the assessment of additional functional units, revealing a modest increase in recent periods. Compliance with ISO standards remains a crucial factor, and the majority of studies ensure comparability and consistency with LCA goals. The prevalence of input-related FUs, especially in studies comparing treatment technologies, is a noteworthy trend. Overall, the findings highlight opportunities for enhancing clarity and standardization in defining FUs, contributing to the robustness and comparability of LCA studies in the context of BBFs.

Functional units and reference flows in PEFCRs and EPD-PCRs: The PEFCR guidelines lack direct instructions on modelling the functional unit for fertilizers, including BBFs. However, the finished guidelines present non-analogous product categories where both physical and chemical composition variations exist. For instance, the PEFCR for Beer defines the Functional Unit (FU) as 1 hectolitre of beer, with the Reference Flow as the quantity needed for the specified function. Similar principles apply to still and sparkling wine, dairy products,

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intermediate paper products, feed for food-producing animals, dry pasta, and prepared pet food. In these cases, functional units vary from liters to kilograms or tonnes, and the reference flow represents the amount required to fulfil the defined function. But it is worth noting that a significant portion of the BBFs on the European market differ both physically and chemically, and the applications are diverse (Kinsella et al., 2023). In this case, for example tying to a chemical composition, such as the amount of NPK nutrients, is challenging if all fertilizers do not contain the most important nutrients in question in the same proportions. In addition, since the end use varies between different products (Egas et al., 2023; Kinsella et al., 2023; Tanzer et al., 2021a, 2021b), it is particularly challenging to tie the functional unit to, for example, fertility or something similar, because the use can also be landscaping or other land improvement uses, where fertility yield is secondary. The table 2 illustrates the selected PEFCR guidelines where the Functional Unit and Reference Flow are based on the mass or volume of the final product.

Table 2. Different PEFCR guidelines and their Functional unit and Reference flow definitions. Definitions collected from web archive of European Commission (2022)

PEFCR	Functional Unit	Reference Flow
PEFCR for Beer	1 hectolitre of beer	The reference flow is the amount of product needed to fulfil the defined function and shall be measured in 1 hectolitre as consumed equal to 102 litres as volume sold at the brewery
Product Environmental Footprint Category Rules (PEFCR) for still and sparkling wine	The FU is consumption of 0.75 litres of packaged wine	The reference flow is the amount of product needed to fulfil the defined function and shall be measured in litres.
Product Environmental Footprint Category Rules for Dairy Products	The appropriate functional unit shall be chosen in relation to the scope of the PEF study and the factors driving the decision-making process (e.g. buying product A versus product B). By default, the functional unit shall be per mass or per volume, depending on the reference used on the product packaging.	The reference flow is the amount of product needed to fulfil the defined function and shall be measured with specific units.
Product Environmental Footprint (PEF) Category Rules (PEFCRs) INTERMEDIATE PAPER PRODUCT	The functional unit is one tonne (1000 kg) of saleable paper grade [graphic, packaging papers or tissue] at the paper mill gate6 with no duration connected to it	The reference flow is the amount of product needed to fulfil the defined function and shall be measured in one metric tonne (1000 kg)
PEFCR Feed for food-producing animals	Feed is an intermediate product which means that no functional unit is considered as such. The declared unit (equal to reference flow) is considered instead.	The reference flow is 1 tonne of animal feed product as fed and delivered to the livestock farm (or fish farm) entry gate.
Product Environmental Footprint Category Rules for Dry pasta	The functional unit of this PCR is 1 kg of dry pasta ready to be cooked at home or at restaurant.	The reference flow is 1 kg of dry pasta being cooked, considering also the cooking and packaging end of life impact

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Prepared Pet Food for Cats and Dogs	Serving the recommended daily intake in kilocalories of metabolizable energy (kcal ME) ("daily ration") of prepared pet food to a cat or dog	The reference flow is the amount of product needed to fulfil the defined function and shall be measured in grams (g) per day

The EPD-PCR documents also provide instructions for defining a functional unit (or declared unit). The PCRs contain applicable instructions for various products, such as biochar (PCR 2021:07 Biochar; 1.0), and guidelines related to fertilizer products (PCR 2010:20 Mineral or chemical fertilizers; 3.0.2). While neither of them provides direct instructions for LCA modelling of BBFs, relevant instructions can be applied to applicable sections.

In the PCR instructions (EPD, 2021), the functional unit is declared as either 'Functional unit' or 'Declared unit.' For both biochar and fertilizer, the unit is defined as 1 metric ton of packaged product (Table 4). The PCR documents for both biochar and fertilizer do not specify the definition of the 'Reference flow'.

No EPD document for biochar related products was found during the D2.1 report's production, but there are 7 documents for different kinds of fertilizer products (Table 3). In EPD documents, the functional unit and declared unit align with EPD-PCR guidelines, except for two products. The reference flow is defined as 'The reference flow is defined at the customer gate, at the shelf or the retailer, or at the marketplace,' which deviates from the 'reference flow' concept defined in the PEF guidelines.

Table 3. Environmental Product Declaration (EPD)

EPD documents	Declared unit (or functional unit)
SCAM Organo-mineral fertilizers	The functional unit is the production and use of 1000 kg of packaged fertilizer
PUSRI Prilled Urea Fertilizer	1000 kg of urea fertilizer and its packaging
Nitrea Prilled Urea Fertilizer	1 ton of urea fertilizer and its packaging
DURAMON 26 PLUS	The declared unit is 1000 kg of product and its packaging. The reference flow is defined at the customer gate, at the shelf or the retailer or at the market place.
Microquel Amin Cuaje	The declared unit is 1000 kg of product and its packaging. The reference flow is defined at the customer gate, at the shelf or the retailer or at the market place.
DICHIARAZIONE AMBIENTALE DI PRODOTTO DI BIOSTIMOLANTI, FERTILIZZANTI E MICRONUTRIENTI ORGANO MINERALI SOLIDI E LIQUIDI	For all solid products under study, the declared unit is 1000 kg with its packaging
Mineral Fertilisers from TIMAC AGRO	The declared unit is 1 ton of fertiliser, packaging included.

2.3.2 System boundaries

System boundary is a "definition of aspects included or excluded from the study. For example, for a 'cradle-to-grave' EF analysis, the system boundary includes all activities ranging from the extraction of raw materials, through processing, distribution, storage and use, to the disposal or recycling stages." (COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations, 2021)

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In comparing the outlined instructions from various environmental standards and guidelines, notable differences emerge in the definition and application of system boundaries (Manfredi et al., 2012). The PEF Guide mandates the inclusion of all processes linked to the product supply chain for the specified unit of analysis, employing a default cradle-to-grave approach. In contrast, ISO 14044 (2006) for LCA utilizes an iterative process to define system boundaries based on the study's goal and scope, refining them through calculations and sensitivity analysis. ISO/DIS 14067 (2012) for the carbon footprint allows for both cradle-to-grave and cradle-to-gate analyses, while the ILCD Handbook (2010) adopts an iterative approach focused on the most relevant processes, including both attributable and non-attributable ones.

The Ecological Footprint (2009) lacks standardized rules for system boundary definition but emphasizes a clear delineation of all included activities, typically ranging from cradle to the point of purchase in product analyses. The GHG Protocol (2011) requires attributable processes and recommends relevant non-attributable processes, permitting both cradle-to-grave and cradle-to-gate analyses. The French Environmental Footprint (BPX 30-323) specifies exclusions such as carbon offset, R&D, and specific transportation services, while the UK Product Carbon Footprint PAS 2050 (2011) allows for cradle-to-grave and cradle-to-gate analyses, with additional supplementary requirements and exclusions related to capital goods, human energy inputs, and certain aspects of transport. These variations highlight the nuanced approaches taken by different standards in defining and applying system boundaries within the context of environmental assessments (Manfredi et al., 2012).

Tanzer et al. (2021a and 2021b) conducted a study, where system boundaries in environmental assessments of BBF were tackled, focusing on ISO standard adherence. They analysed 123 studies and found high compliance (106 studies) with comprehensive and consistent system boundaries. Waste generation was identified as a common input boundary (79 out of 123 studies). In agricultural and Anaerobic Digestion (AD) contexts, some studies defined input boundaries with crop cultivation or manure as a substrate, referred to as the "cradle." Studies that commenced with treated waste often centred on sewage sludge, neglecting wastewater treatment. Output boundaries varied depending on the context. Approximately 61% of waste management studies concluded with the fertilizer product, while agricultural and AD studies often extended to fertilizer field application.

Tanzer et al. observed that context-specific analyses were common, especially in studies comparing agricultural practices, often considering the entire cultivation process up to the farm gate. Between 2016 and 2021, a trend emerged indicating that half of waste management studies, particularly in a European context, included fertilizer field application in their system boundaries (Tanzer et al., 2021b).

Adhering to findings from Tanzer et al. (2021a, 2021b), the definition of system boundaries for biobased fertilizers could benefit from considering the incorporation of waste generation. Conducting a cradle-to-gate analysis with a focus on crop cultivation or manure as a substrate is advisable, along with context-specific analyses, especially when comparing agricultural

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practices. Trends over time suggest a growing consideration of including fertilizer field application within system boundaries for waste management studies.

Egas et al. (2023) found in their review that Cradle-to-Gate is the most preferred system boundary in biobased fertilizer studies. This preference guides the selection of the system boundary method for the PCR instructions of the PEF-wise PCR for BBFs. This method is justified since incorporating the use phase as a 'cradle' phase within the system boundary of the fertilizer product may result in overlapping calculations in the LCA of food production.

Furthermore, Egas et al., (2023) identified discrepancies in their literature review of 30 studies focused on Biomass-Based Fertilizers (BBFs). Among these, 20 studies did not report environmental burdens linked to feedstock production, suggesting an assumption that the feedstock had reached its end-of-waste state before the biorefinery, aligning with the EPD approach. The remaining 10 studies in their scope recognized biomass feedstock as a production-related input and reported associated environmental burdens. However, only three of these studies explicitly outlined the allocation criteria for upstream feedstock production. Through economic allocation, few attributed environmental burdens to agricultural and forest residues and sewage sludge, respectively. This lack of clarity, coupled with the prevailing assumption of feedstock as waste, highlights the necessity for a standardized and consensus-driven approach in evaluating the environmental impact of using reusable/recyclable waste flows as biomass feedstocks in BBF production systems, revealing a significant gap and inconsistency in the literature's reporting and application of allocation methods.

Based on the research conducted by Egas et al. (2023), a potential trend that could be applied when establishing a "PEF-Wise PCR method for BBF" is the consideration of biomass feedstock as a production-related input rather than assuming it as waste. This trend aligns with the approach highlighted in the PEF guidelines, where the end-of-waste state of the biomass feedstock is not automatically assumed.

Egas et al. (2023). revealed that out of the reviewed studies on BBFs, a substantial number assumed feedstock to be waste, omitting environmental burdens. However, acknowledging biomass feedstock as a production-related input and considering its environmental burdens is crucial for a more accurate and comprehensive assessment. By adopting this trend, the PEF-Wise LCA method can improve the precision of its calculations and better reflect the actual environmental impact associated with the production of BBFs, aligning with the PEF guidelines.

According to International EPD guidelines (EPD, 2021), a description of the EPD system boundary is “cradle-to-gate”, “cradle-to-gate with options”, or “cradle-to-grave”. The EPD system boundary of the product life cycle determines which processes are included or excluded. The applicable system boundary for a specific product category is specified in the PCR — whether it shall, should, or may be applied. EPD guide stresses that, it is crucial to include all environmentally relevant processes from the product's inception to its end, covering at least 99% of total energy use, product mass, and environmental impact.

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For products with uncertain end uses or categorized as intermediate, the system boundary may be limited to "cradle to gate." Excluding end-of-life treatment comes with specific criteria: the product must be physically integrated with other products, not identifiable at end-of-life due to a transformation process and lacking biogenic carbon.

When considering the guidelines of the international EPD system for establishing the system boundary, the life cycle of BBFs is modelled with a cradle-to-grave boundary. However, in the context of a fertilizer product, there is a potential risk of duplicative calculations, particularly when modelling cultivation related to food production. This concern arises, especially when the "grave" of the fertilizer product is represented by the field use of the product. This approach contradicts the prevailing trend in research literature (Egas et al., 2023), where the general inclination for life cycle modelling is cradle-to-gate.

2.3.3 A Life Cycle Impact Assessment (LCIA) method

According to PEF/PEFCR[11] directions and ISO 14044[12] standard, Life cycle impact assessment (LCIA) is defined as an *"phase of life cycle assessment that aims to understand and evaluate the magnitude and significance of the potential environmental impacts for a system throughout the life cycle. The LCIA methods used provide impact characterisation factors for elementary flows to aggregate the impact to a limited number of midpoint and/or damage indicators."*

When comparing various LCA guidelines, it becomes evident that each standard takes a nuanced approach, showcasing differences and commonalities (Manfredi et al., 2012). The PEF Guide advocates for a default set of 16 mid-point impact categories, with flexibility for modifications based on PEFCR specifications. It also mandates the use of provided mid-point LCIA methods. In PEF guidance, these 16 selected impact categories (Table 4) are defined for each stage of a product's life cycle or an organization's activities. These 16 impact categories, determined at each stage of the life cycle or activities, are summed up to create the total EF, demonstrating the aggregated effects of all 16 different impact categories. This same principle can be repeated across all examined products or organizations in EU markets, allowing environmental impacts to be clearly and consistently compared. (Damiani et al., 2022; COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations, 2021).

Table 4. EF impact categories (Damiani et al., 2022; COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations, 2021)

Climate change, total	Eutrophication, terrestrial
Ozone depletion	Eutrophication, freshwater

[11] European Commission. (2021). COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations.
[12] EN ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines

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Human toxicity, cancer	Eutrophication, marine
Human toxicity, non-cancer	Ecotoxicity, freshwater
Particulate matter	Land use
Ionising radiation, human health	Water use
Photochemical ozone formation, human health	Resource use, minerals and metals
Acidification	Resource use, fossils

The ISO 14044 (2006) covers numerous environmental impacts, including GHG emissions, ozone depletion, acidification, eutrophication, and photochemical ozone creation, along with other considerations like resource depletion and human health (endpoint). The ISO/DIS 14067 (2012) specifically targets the carbon footprint of products, concentrating on climate change and necessitating the reporting of all GHG emissions. The ILCD Handbook (2010) takes a comprehensive approach, addressing twelve impact categories at the midpoint and three at the endpoint, providing recommended methods for both. The Ecological Footprint (2009) uniquely measures values, such as global hectares. The GHG Protocol (2011) emphasizes climate change and GHG emissions reporting, specifying six substances under the Kyoto Protocol and recommending others. The French Environmental Footprint (BPX 30-323) follows JRC-recommended LCIA methods, with fixed impact categories by product category and mandatory use of default midpoint LCIA methods. Lastly, the UK Product Carbon Footprint PAS 2050 (2011) centres on climate change, including land use change, and requires reporting of all GHG emissions (Manfredi et al., 2012).

Egas et al. (2023) conducted a study on the Life Cycle Impact Assessment (LCIA) of BBFs. They explored commonly used LCIA methods, such as CML[13], PEF[14], ILCD[15], ReCiPe[16], and TRACI, finding the CML method most prevalent. The study revealed a predominant use of the midpoint approach, with few exceptions for both midpoint and endpoint approaches. GWP, eutrophication, acidification, and human ecotoxicity were commonly reported impact categories. Differentiation among GWP sources was lacking. The study emphasizes the diverse landscape in applying LCIA methods within BBF studies and the importance of careful methodology consideration for meaningful comparisons.

Pedersen & Remmen (2022) critique the PEF method for its rigid set of impact assessment methods, suggesting it may result in inconsistencies compared to the more flexible ISO 14044

[13] Guinée JB (2002) Handbook on life cycle assessment: operational guide to the ISO standards. Kluwer Academic Publishers
[14] EC (2018b) Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods: New methods and differences with ILCD. Publications Office of the
European Union, Luxembourg (Luxembourg)
[15] EC (2012) Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods Database and supporting information, First edit. Publications Office of the European Union,
Luxembourg
[16] Huijbregts MAJ, Steinmann ZJN, Elshout PMF et al. (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22:138–147.
https://doi.org/10.1007/S11367-016-1246-Y

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standard. They express concerns about the maturity level of some impact assessment methods in PEF, highlighting the risk of including results with high uncertainty. The authors note the inclusion of 16 impact categories in the PEF method but caution that the application lacks precautions toward method maturity. They raise reservations about the adequacy of certain impact categories for decision support in PEFCR. While acknowledging ongoing efforts to improve the PEF model, Pedersen & Remmen emphasize that changes to impact assessment methods would necessitate revising the PEFCR due to potential shifts in the relevance of impact categories. They also criticize the exclusion of biodiversity and indirect land use change, arguing that their qualitative consideration is essential for a comprehensive assessment of bio-based products.

2.3.4 Allocation for recycling

In the context of "allocation for recycling," various approaches and features are identified among different LCA guidelines (Manfredi et al., 2012). Specific guidance, including the Circular Footprint formula (CFF) and considerations for energy recovery in the context of recycling, is provided by the PEF Guide (COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations, 2021). If LCA is conducted according to the PEF guide, the use of CFF is mandatory, but it has received some critique: Pedersen & Remmen (2022) scrutinize the Circular Footprint Formula in their structured literature review. They highlight challenges, including a departure from ISO 14044, the formula's failure to account for the number of material reuse cycles, inadequate default data for recycled material quality, and. They also note that, the lack of compatible databases makes the model more time-consuming. According to them, despite these challenges, the allocation and quality parameters are seen as positive, enhancing the realism of results for recycled content and end-of-life impacts.

The ISO 14044 (2006) LCA requirements and guidelines address allocation for recycling separately, offering a general principle of avoiding allocation without specifying a rule or formula. ISO/DIS 14067 (2012), focusing on the carbon footprint of products, emphasizes the substitution of primary production of avoided products and aligns with the ISO 14044 allocation hierarchy. The ILCD Handbook (2010) recommends the substitution of market average primary production for avoided products when addressing allocation for recycling. Specific guidelines on this matter are not provided by the Ecological Footprint (2009). The GHG Protocol (2011) stipulates that allocation in recycling should use either the closed-loop approximation or recycled content method. If neither method is suitable, other methods consistent with ISO 14044 may be employed, provided they are disclosed and justified in the inventory report. The French Environmental Footprint (BPX 30-323) provides detailed guidance and equations for closed-loop recycling and open-loop recycling, with or without energy recovery, specifically addressing the allocation aspect. Contributions from the UK Product Carbon Footprint PAS 2050 (2011) include offering equations for calculating emissions,

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distinguishing between the recycled content method and closed-loop approximation recycling method, and setting criteria for when to apply 0/100 or 100/0 in the context of allocation for recycling (Manfredi et al., 2012).

2.3.5 Carbon accounting

When comparing standards and guidelines related to "Fossil and biogenic carbon emissions and removals," there are notable similarities and differences among them (Manfredi et al., 2012). The PEF Guide, ISO/DIS 14067 (2012), and the ILCD Handbook (2010) align in stipulating that removals and emissions shall be reported separately for both fossil and biogenic sources. Similarly, the French Environmental Footprint (BPX 30-323) dictates that both carbon emissions and removals from fossil and biogenic sources should be reported separately. This consistency underscores the uncertainties still remaining in the assessment of removals and the importance of distinguishing between these sources for a comprehensive assessment.

The somewhat older guidelines, ISO 14044 (2006) LCA and the Ecological Footprint (2009), provide no specific provisions regarding the reporting of removals and emissions from fossil and biogenic sources. The absence of guidelines on this aspect may introduce variability in the approach to handling carbon emissions and removals in these standards. In contrast to PEF guide and ISO/DIS 14067 (2012), the GHG Protocol (2011) takes a robust stance, mandating the inclusion of both carbon emissions and removals from fossil and biogenic sources in inventory results. This aligns with the approach recommended by the PEF Guide, ISO/DIS 14067 (2012), and the ILCD Handbook. Also, the UK Product Carbon Footprint PAS 2050 (2011) mandates reporting of both carbon emissions and removals together. However, an exception is noted for biogenic emissions and removals from food and feed, which are not mandatory for inclusion in the assessment (Manfredi et al., 2012).

In comparing different standards and guidelines regarding "Carbon storage and delayed emissions," certain commonalities and distinctions emerge (Manfredi et al., 2012). The PEF Guide explicitly states that credits associated with temporary storage or delayed emissions should not be considered in calculating the PEF for default impact categories unless specified otherwise in a supporting PEFCR. ISO 14044 (2006), while not providing specific provisions, suggests that carbon storage and delayed emissions are typically excluded from the usual scope of study based on the interpretation of the LCA definition. ISO/DIS 14067 (2012) specifies that carbon storage should be reported separately. The ILCD Handbook (2010) takes a nuanced approach, excluding carbon storage and delayed emissions from the usual scope of study but providing detailed operational guidance if included as part of the study goal. This aligns with the recommended approach in PAS 2050 for calculating carbon storage impacts, emphasizing the need to differentiate temporary storage from permanent storage. The GHG Protocol (2011) introduces a concept according to which that share of carbon, which is not released due to end-of-life treatment over the study period, is considered stored, with a recommended time period of at least 100 years. Delayed emissions or weighting factors are not included in inventory results but can be reported separately. The French Environmental Footprint (BPX 30-

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323) introduces a time-weighted average for storage/delay for up to 100 years, and the decision to apply delayed emissions is optional and determined in each PEFCR. GHG removal is considered for products with biomass from replanted forests. The UK Product Carbon Footprint PAS 2050 (2011) includes any impact of carbon storage in the inventory but requires a separate reporting (Manfredi et al., 2012).

2.3.6 Common steps to implement allocation procedures for multifunctional systems

The various LCA standards and guidelines demonstrate both shared principles and distinctions in their strategies for addressing the 'Allocation and multifunctionality hierarchy' methods (Manfredi et al., 2012). The PEF Guide prioritizes subdivision or system expansion, followed by allocation based on relevant physical relationships and, as a last resort, allocation based on other relationships. ISO 14044 (2006) emphasizes the initial avoidance of allocation through process subdivision or system expansion, resorting to physical relationships like mass or energy, and, when necessary, economic value. ISO/DIS 14067 (2012) directs users to adopt ISO 14044 principles, signifying alignment between the two standards. The ILCD Handbook (2010) builds upon ISO 14044, suggesting methods like virtual subdivision and economic allocation. The Ecological Footprint (2009) requires adherence to ISO LCA Standards. The GHG Protocol (2011) advises avoiding allocation through subdivision or system expansion; if unavoidable, it recommends allocation based on physical relationships or, failing that, economic allocation. The French Environmental Footprint (BPX 30-323) adopts ISO 14044 without significant modifications. The UK Product Carbon Footprint PAS 2050 (2011) further develops from ISO 14044, avoiding co-product allocation through subprocess division or system expansion, with economic value as a last resort (Manfredi et al., 2012).

The Bio-based products – Life Cycle Assessment, EN 16760 guidelines emphasize a detailed allocation process for inputs and outputs, requiring clearly documented and explained procedures. Following EN ISO 14044, the study identifies shared processes, applying a stepwise procedure to avoid allocation whenever possible. This includes dividing the unit process into sub-processes or expanding the product system to encompass additional functions. In cases where allocation is necessary, Step 2 recommends partitioning inputs and outputs based on underlying physical relationships, such as mass or energy content. Step 3, if physical relationships are unavailable, suggests allocation based on other relationships, like economic value, with consideration for the study's geographical scope. For bio-based products, the guidelines highlight the importance of considering biogenic carbon content, providing a value chain allocation based on carbon content when tracking greenhouse gas emissions. The guidelines stress the need for sensitivity analysis when multiple allocation procedures seem applicable to illustrate the consequences of the chosen approach. Also, the PEFCR Feed for food producing animals is recommending sensitivity analysis regarding used allocation methods.

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The International EPD General Programme Rules guide (EPD, 2021) the allocation of waste in life cycle assessments based on the 'polluter pays principle' and EN 15804. Waste processes are assigned to the product system generating the waste until the end-of-waste state, determined by criteria such as common use, market demand, technical compliance, and avoiding adverse impacts. The waste generator bears the full environmental impact until these criteria are met, often when waste has a positive market value. The allocation method aligns with legal and financial responsibilities. For recycled or reused waste, impacts are attributed to the waste generator until the end-of-waste state, then to the system using recycled materials. Landfilling impacts are assigned to the waste generator. The rules acknowledge potential environmental benefits from reuse, recycling, or recovery, allowing separate declaration in EPDs. Construction product EPDs follow the allocation guidance in EN 15804.

In the LCA allocation of a BBF produced through the recycling of waste, it is relevant to highlight the guidance provided in the EPD: 'For waste being recycled or reused, the environmental impact of processes until the end-of-waste state shall be attributed to the product system generating the waste. Processes after the end-of-waste state, if any, shall be attributed to the product system using the recycled/reused material flow.' In this frame, emissions arising from the raw material of the recycled-material-based fertilizer are considered outside the system boundary.

2.4 Conclusion

In conclusion, the examination of literature surrounding the LCA of BBFs reveals several critical points. Firstly, there's a notable absence of a clear model for comparative LCA work in this domain, indicating a pressing need for official guidance, possibly under the direction of the EU Commission, to ensure credible comparisons and steer future practices towards sustainability. While the existing PEFCR guidelines provide a foundation, their limited scope and lengthy development process underscore the challenges ahead. Furthermore, contradictions within official guidelines and research literature contribute to interpretational uncertainties, particularly given the unique complexities of BBFs arising from diverse raw materials and technological variations. The EU Commission's guidance offers clarity, suggesting alignment with PEF guidelines for robust PCR of BBFs. However, discrepancies in defining Functional Units (FUs) pose challenges, emphasizing the necessity for explicit definitions and standardization in LCA studies. Despite these hurdles, a coherent guideline can be formulated by integrating official PEF/PEFCR guidelines with diverse LCA standards, accommodating variations in raw materials and production techniques. Addressing interpretational questions, such as the status of recycled materials and defining functional units, remains pivotal. Harmonizing methodological choices and system boundary definitions is crucial for achieving consensus and ensuring compliance with standards. Ultimately, the selection of guidelines must consider contextual objectives and unique study requirements. Adherence to recommended practices, such as process subdivision and avoiding allocation whenever possible, enhances the accuracy and reliability of LCA assessments for BBFs, aligning with broader sustainability goals.

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3. Mapping of other relevant environmental/sustainability indicators and methods

The main goal of task 2.2 was to map out the available standards to assess environmentally relevant impacts not well covered by the LCA approach such as carbon sequestration, biodiversity or emerging pollutants. The outcomes of this task will be incorporated into T2.3 to enhance the suggested LCA methodology (in Deliverable 2.2) by producing and incorporating site-specific environmental impacts associated with the application of alternative fertilizing products.

3.1 Material and methods

A systematic literature search was carried out to identify the principal environmental impacts caused by BBFs. Firstly, a bibliometric analysis of global scientific production using the Scopus database was performed to reveal the main topic trends; and secondly, a manual search served to complement the results.

i) The main goal of the bibliometric analysis was to picture the present state-of-the-art and to identify the main environmental concerns of the BBF during their production and in-field application. The systematic analysis consisted of a two-step process i) surveying and critically reading existing literature and ii) summarizing and organizing the information obtained.
ii) In the first step, two queries were developed in the Scopus® database (Table 5) (3rd July 2023). The first one was dedicated to BBFs aggregating the nomenclature commonly used in scientific publications. The second one was oriented to the environmental impacts and benefits or methods. The search was limited to results that contained the title, abstract or author keywords. Publications were constrained to reviews and original articles written in English and published between the 1st of January 2000 and to 3rd of July 2023. As a preliminary result, 209 published articles were obtained. After that, a manual filtering of manuscripts was developed to exclude the papers that do not deal with BBFs, and their environmental impacts were measured by applying the LCA approach. The final list consisted of 114 publications[17].
iii) For the second step, abstracts of each publication were reviewed to identify and list the most frequently mentioned environmental concerns. The results were grouped into main categories and the results were grouped into main categories and each publication could contain more than one environmental concern reported.

[17] See complete list in annex 1

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Table 5. Terms of queries for the main sentence. For crossing both queries the operator AND was used that is, a term of each query had to be contained in the publication to be considered[18].

Terms of BBFs	Terms of environmental impacts
OR ("bio-based fertili*", "biobased fertili*", "recycling derived fertili*", "nutrient recovery", "waste-based fetili*" "alternative fertili*", "waste-to-fertili*", "nutrient recycling", "recycled fertili*", "recovered nutrient", "recover* nitrogen", "recover* phosphorous", "recover* carbon", "fertili* product", "fertili* products")	OR ("environmental impact*", "environmental assess*" "environmental indicator*", "environmental analys*", "environmental metric*")

Finally, to complete the mapping a comprehensive search was conducted to review the available modelling, tools, and methods of each category of environmental concern. The search covered publications in specialized literature (databases Scopus and Google Scholar, technical guidelines, documentation (in the case of electronic tools), technical reports and initiatives from international organizations. It developed a comprehensive list of the main global or regional initiatives, the proposed methods for the assessment, and the tools developed for each category of environmental concern. For each model, the benefits and drawbacks were detailed together with its potential use in an LCA context.

3.2 Results

3.2.1 Bibliometric analysis

The bibliometric analysis conducted in the Scopus database shows that research on BBFs has increased in recent years. After the two-step literature review, the most significant number were the research articles (96) and the review articles (18). Based on the productivity (number of publications over time) of publications, two periods can be distinguished (Figure 1). The first period (2001 to 2015) shows a low production with an average of 1.53 documents per year. Probably. It is due to less financing or a little interest in the production of fertilizers through recovery techniques. The second period (2016 to 2023) shows a continuous annual increase in the number of publications (an average of 11.38 documents per year). This growth can be associated with the introduction of the concept of CE by the European Commission (EC, 2015) and the CE package, which incentivises the use of by-products (derived from biowastes) in the fertilizer regulation. Regarding the number of citations, there is not a marked trend; the year with the highest number of citations was 2009. However, it can be considered an outlier because most of the citations correspond to a single article (Le Corre et al., 2009) (628 citations). In the following years, the average citations per article show an irregular trend. This is because articles published in recent years have not accumulated enough citations due to fewer cited years over time.

[18] The complete sentence query used in Scopus was TITLE-ABS-KEY((("bio-based fertili*" OR "biobased fertili*" OR "recycling derived fertil*" OR "nutrient recovery" OR "waste-based fetili*" OR "alternative fertili*" OR "waste-to-fertili*" OR "nutrient recycli*" OR "recycled fertili*" OR "recovered nutrient" OR "recover* nitrogen" OR "recover* phosphorous" OR "recover* carbon" OR "fertili* product" OR "fertili* products")) AND (("environmental impact" OR "Environmental assess*" OR "environmental indicator" OR "environmental analys*" OR "environmental metric*"))).

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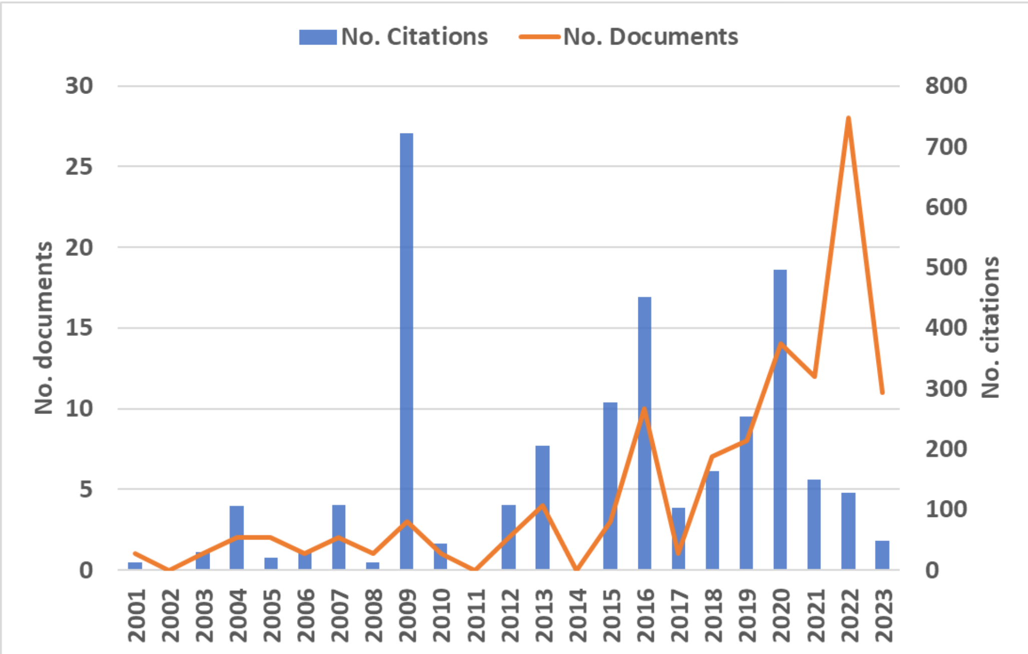

Figure 1. Overall production of scientific production about environmental concerns of BBFs.

71 % of the publications were aggregated into four subject areas. Environmental Sciences (41%) is the major subject due to the publications in this field reporting the possible environmental impacts of using these recovery technologies. The Energy (11%) and Agricultural and Biological Sciences (11%) reported the same percentage, and the publications are focused mainly on the evaluation of the new technologies and the effects caused by the application of the products respectively. Lastly, the publications on the Chemical Engineering (8%) subject area cover the feasibility of different biorefinery technologies for producing BBFs. The sources with the major number of publications were Science of the Total Environment (14), Chemosphere (6), Journal of Environmental Management (5), Bioresource Technology (4), Resources, Conservation and Recycling (4), Waste Management (4), and Water Research (4).

The geographical production analysis shows that overall scientific production is mainly concentrated in European countries (Figure 2a) most of them funded by the European Commission or national funds. The countries with the highest production in this region were Spain, Belgium and the Netherlands with 12, 9 and 8 publications, respectively. The United States of America (USA) (25 publications) is the main contributor. In the North American region and as an individual country as well, most of the publications in the region were supported by national funds related to the agricultural sector (National Science Foundation, U.S. Department of Agriculture and National Institute of Food and agriculture). In the Asian region, China was the main contributor (12 publications) and their major financing comes from two institutions the National Natural Science Foundation of China and the National Key Research and Development Program of China.

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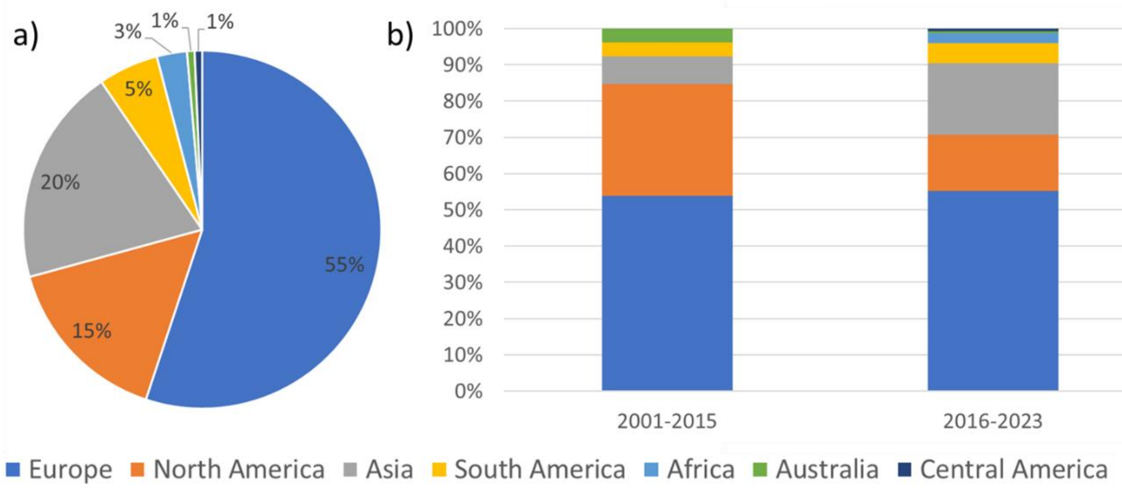

Figure 2. Geographical background of BBFs environmental impacts studies (a) divided into periods of production (b).

When comparing the two periods of production, it can be observed that European countries have maintained the proportion in the percentages of publications, which implies an increase of around four times, going from 14 to 81 publications (Figure 2b). In the first period (2001-2005), the production was led by Sweden in topics of nutrient recovery from food waste, wastewater, and organic waste. While in the second period (2015-2023), Spain led the trend focusing on N and P recovery and the effects of BBFs application in agricultural lands. In the case of the North American region, its proportion decreased in time, even though the number of publications increased from 8 to 23. USA led in both periods addressing the research on P recovery, followed by the obtention of digestates. Finally, the region of Asia increased the proportion in number (2 to 29) and in percentage because of the publications produced by China.

3.2.2 Main environmental concerns

The principal environmental issues in the non-LCA literature were recognized and summarized in Table 6. Most of the publications reviewed pointed out the positive environmental impacts of BBFs. However, for some environmental impacts such as soil properties, carbon sequestration, and biodiversity, the net effect of BBFs is controversial or under discussion. Negative and positive effects were obtained in the literature and results depend on several factors such as the product or the application site, for instance.

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Table 6. Selection of the most relevant references about the non-LCA environmental concern of BBFs.

Environmental concern		Importance	Trade-offs sign	Main references
Affections on soil properties (physical and chemical)		BBFs can induce modifications in soil properties. There are some evidence in favour: physical properties, and biological activity. However, there are also risks associated with decreasing efficiency of soil nutritional management.	Positive or negative	Adegbeye et al. 2020; Santos et al. 2018; Ren et al. 2020; Karim et al. 2022; Gillingham et al. 2022; Rizzioli et al. 2023; Kiani et al 2023; Martínez-Sabater et al. 2022; Ro et al. 2016; Bernstad et al. 2013; Hendriks et al. 2022; Hidalgo et al. 2021; Piash et al. 2023; Wester-Larsen et al. 2022; Zilio et al. 2022; Preisner et al. 2022; Raza et al. 2021; Collivignarelli et al. 2020; Maltais-Landry et al. 2019; Černe et al. 2019; Sigurnjak et al. 2016.
Heavy metals		The presence of toxic substances in livestock manure and sewage (the most common secondary raw material), can result in damage to ecosystems and human health. Thus, it is very important to develop specific frameworks and datasets to assess them to prevent environmental impacts and human risks.	Negative	Egle et al. 2015; Robles et al. 2020; Antonini et al. 2012; Wang et al. 2004; Krähenbühl; Zou et al. 2021; Siwal et al. 2021; Karim et al. 2022; Gillingham et al. 2022; Rizzioli et al. 2023; Kiani et al 2023; Zabaleta and Rodic 2015; Álvarez-González et al. 2023; Zilio et al. 2022; Preisner et al. 2022; Collivignarelli et al. 2020; Černe et al. 2019; Sigurnjak et al. 2016.
Soil carbon sink and sequestration		Soil carbon dynamics are affected by BBF application as well as various land management measures (e.g. ploughing). Therefore, should be incorporated the measuring of the different Carbon stocks in the soil and their transformation.	Potentially positive- (under discussion)	Adegbeye et al. 2020; Anex et al. 2007; Ren et al. 2020; Karim et al. 2022; Martínez-Sabater et al. 2022; Galamini et al. 2023; Liu et al 2023; Egene et al. 2022.
Biodiversity		Assessing the impacts caused by BBFs on biodiversity is crucial due to the potential effects on ecosystem stability and functioning such as changes in soil microbial communities.	Positive or negative	Stacey et al. 2019; Chelinho et al. 2019; Ren et al. 2020; Suleiman et al. 2020; Zou et al. 2021; Karim et al. 2022; Gillingham et al. 2022; Kiani et al 2023.
Others	Organic emerging contaminants	Their presence is related to the secondary raw materials quality and the transformation processess. Their application may lead to bioaccumulated soil, uptaken by the crop or leached to the groundwater, causing potentially severe risks to human health and the environment.	Negative	Egle et al. 2015; Robles et al. 2020; Albihn et al. 2007; Suleiman et al. 2020; Karim et al. 2022; González et al. 2023; Zilio et al. 2022; Preisner et al. 2022.
	Microplastics	The use of BBFs can introduce microplastics into soil and water causing important damage to human health and affecting ecosystem services. Plastics included in organic fertilisers could	Negative	Santos et al. 2018; Johansen et al. 2023.

	be linked with soil alteration, accumulation on water reservoirs and impact on biota.		
Odour	Emissions of odours from organic fertilizers, rich in organic matter, may lead to the release of compounds like ammonia, impacting air quality and causing disturbances in the nearby community. Furthermore, the detection of odours may indicate the decomposition of organic matter and the potential release of substances that could be harmful.	Negative	Riva et al. 2016; Zabaleta and Rodic 2015.

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3.2.2. Analysis one-by-one: Affections on soil properties and carbon sequestration.

The integration of soils in LCA has gained significant attention in land-use-based sectors due to their importance in the maintenance of global ecosystem functions such as carbon sequestration, nutrient cycling, water purification, provision of food and habitat for organisms among others. In this sense, soil quality is affected by land use as well as various land management (i.e., ploughing or fertiliser products) including BBF application. Hence, assessing the influence of human activities on soil health is crucial. In fact, that is the term with the widest consensus for this evaluation and it was defined by (FAO-ITPS, 2020a) as "*the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems*".

Several authors reported that the application of BBFs affects soil properties enhancing soil health. The most frequently mentioned are i) Carbon sequestration, ii) soil erosion prevention, iii) increasing soil moisture content, iv) improving soil workability and v) enhancing soil biological activity (Martínez-Blanco et al., 2013). Moreover, the most extended review on improving soil health using BBFs was conducted by Kurniawati et al. (2023).

Quantifying these impacts is challenging due to the complexity of soil processes and their spatial and temporal variability. To tackle this barrier, it is necessary to create a unified model that is suitable for each region and capable of incorporating all possible local variations by establishing archetypes. However, before establishing a monitoring system it is necessary to guarantee the sustainable management of soil. For this purpose, a global initiative from ITPS-FAO was developed "The Voluntary Guidelines for Sustainable Soil Management" (FAO-ITPS, 2017). It intends to establish a baseline of basic harmonized indicators and supplement them with additional indicators for comparison with a baseline. These guidelines provide general technical and policy recommendations on sustainable soil management for a wide range of committed stakeholders. The document is a technical reference to be applied on a context-specific basis. Based on these guidelines, stakeholders can create specific manuals or guides to ensure Soil Sustainable Management. Furthermore, a Protocol for the assessment of Sustainable Soil Management (FAO-ITPS, 2020b) was elaborated subsequently to provide a framework of a basic and additional set of indicators (with their parameters and measurement methods in farm scale) to determine if the implemented soil management practices are sustainable according to the guidelines.

Basic indicators

- Soil productivity. The ability to produce biomass (agronomical yields) indirectly indicates the soil's status. It should be measured as dry matter production on a referred surface ($t \cdot ha^{-1} \cdot year^{-1}$).

- Soil organic carbon (SOC in percentage)The most common indicator that reflects the changes (chemical, physical and biochemical) produced by the agricultural management. The standard methodology is Walkley-Black method.
- Soil physical properties. Represented by bulk density (BD) that indicates changes in soil structure, porosity and compaction. BD can be measured with the core method.
- Soil biological activity. An indicator of soil's life. Soil respiration is a reliable method for measuring biological activity in the soil.

Additional indicators

- Soil nutrients. Essential for agricultural production. Plant-available P can be used as an indicator because its mobility is limited; N, P and potassium (K) in soil can also be considered.
- Soil erosion. Soil displacement due to physical or chemical causes. It can be assessed visually or using the RUSLE model.
- Soil salinity. It can be a natural phenomenon or the result of anthropogenic activities such as the use of salt-rich water for irrigation or the adverse impacts of poorly managed irrigation in dry regions. Electrical conductivity (EC) is one of the most effective methods to measure it.
- Soil biological activity (enzymatic methods). The most recommended additional methods to estimate soil biological activity are soil microbial biomass, specific enzymatic activity methods and the Bait-Lamina[19] method.
- Soil biological diversity. The variety of living organisms in the soil. The most recommended methods for soil biodiversity include the counting and identification of macro and meso-organisms (by a trained person). A regular genomic analysis also enables biodiversity to be assessed more accurately at the microbial level.
- Soil pH. The reaction of the soil gives an important indication of plant nutrient availability, and different crops thrive at different pH values. Soil pH may be measured in the field with simple indicators, or with standard laboratory measurements.
- Available water capacity. The water held in the soil between its field capacity and permanent wilting point.
- Soil infiltration rate. How fast water enters the soil under non-saturated conditions.
- Soil penetrance resistance. For estimating the soil compaction.
- Soil pollution. Refers to the presence of contaminant(s) in the soil whose nature, location, or quantity produces undesirable effects on the environment or human health. There are several methods according to the pollutant to be measured.

3.2.2.1 Available methods, models and tools to quantify modifications in soil properties.

Quantifying changes in the physical and chemical properties of soil represents a challenging task due to the complexity of soil-forming processes (spatially and temporally) that cause a

[19] ISO 18311:2016

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high variability. The measurement methods most commonly used to assess it can be divided into three categories (below). However, is commont to find them combined as hybrid models to increase reliability and accuracy.

i) **Soil Sampling.** Soil sampling provides reliable data for the soil. However, there are a few drawbacks to comment on. One major drawback of this approach is that it requires a vast number of samples and significant effort. The spatial variability and heterogeneity of the soil are two main issues. It´s therefore, this method is time resource-consuming, and expensive. Only a limited number of countries worldwide have adopted a systematic sampling strategy to measure changes in soil properties and they are not harmonized.

ii) **Soil modelling.** It is a powerful tool to predict soil behaviour, offering valuable insights for agricultural and environmental management. Soil modelling can simulate complex soil processes, predict outcomes under various scenarios, and optimize resource use, contributing to sustainable practices. Nowadays, there are several models and tool models available capable of predicting multiple soil properties (RothC, EPIC, ECOSSE, DNDC). However, most of them need a wide range of data to run the models including topography, land cover, soil type, and soil characteristics which can be challenging to obtain.

iii) **Earth observation (EO) methods.** Several research studies have been conducted over the past five years to monitor topsoil through EO methods (Tziolas et al., 2021). This involves the use of various technologies and techniques, mostly based on satellite information and remote sensing. These techniques utilize a space-borne microwave and optical sensors to map soil physiochemical properties such as soil organic carbon, soil pH, soil fertility, and soil moisture. Most recent mapping approaches provide rasterized soil indicators (the most important is the SOC stocks) that are essential for accurate modelling of ecosystem processes, such as carbon exchange specialization towards informed arable farming and long-term ecological monitoring (Tziolas et al., 2021). Moreover, in recent years by integrating advanced EO technologies with machine learning and soil spectral libraries, it has been possible to improve the accuracy and reliability of soil property assessments (Andries et al., 2022).

Regarding the initiatives available for monitoring changes in soil properties table 7 shows the most relevant initiatives. Although most initiatives assess multiple physical, chemical, and biological properties of the soil, it should be noted that both the water content and the organic carbon of the soil occupy a relevant place in most methodologies; in fact, several have been developed exclusively for the measurement of these parameters due to their importance in nutrient cycling or as an indicator of soil health.

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Table 7. **Soil initiatives for assessing changes in soil properties.**

Type	Name	Geographical scope	Soil parameters, models or indicators	General comments	Reference
Sampling	*Agri-Environmental indicators, EU-AI (2002)*	European Union Members	A set of 28 indicators for measuring and tracking the agricultural impacts on the environment in Europe. It covers different properties such as soil erosion, farming intensity, genetics and diversity.	Indicators to evaluate and communicate the environmental performance of agriculture. These metrics provide valuable insights to scientists and policymakers, offering information on the state of the environment, the impact of various policies, and the efficiency of budget allocation in achieving environmental goals.	https://ec.europa.eu/eurostat/web/agriculture/database/agri-environmental-indicators Bockstaller et al., (2008), 10.1051/agro:2007052
	European Soil Database, European Commission (2006)	European Union Members	The geographical representation • Contains databases of Soil Typological Units (STU) specifying their properties such as texture, water regime, the stoniness. • Harmonisation of the soil data from the member countries is based on a dictionary defining each occurrence of the variables. • Soil Database consists of both a geometrical dataset and a semantic dataset.	It was a collaborative effort aimed at providing harmonized and standardized soil data to support various environmental and land management initiatives. For its representation were constructed the European Soil Database v2 Raster Library which contains raster (grid) data files with cell sizes of 1km x 1km. It is perhaps the predecessor of the Lucas survey	Panagos Panos. The European soil database (2006) GEO: connexion, 5 (7), pp. 32-33. https://web.archive.org/web/20070928022734/http://www.geoconnexion.com/uploads/europeansoil_intv5i7.pdf
	Harmonized World Soil Database (HWSD), FAO (2009)	Global scale	**Characterization of selected soil parameters.** • **SOC** • pH • Water storage capacity • Soil depth • Cation exchange capacity • Clay fraction • Total exchangeable nutrients • Lime and gypsum contents • Sodium exchange percentage • Salinity • Textural class • Particle size distribution (clay, silt, and sand content).	The database is the result of a collaboration between the FAO with IIASA, ISRIC-World Soil Information, the Institute of Soil Science, the Chinese Academy of Sciences (ISSCAS), and the Joint Research Centre of the European Commission (JRC). It presents a raster database map (21600 rows and 43200 columns) which links soil property data.	FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria. https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/

	Web Soil Survey, Natural Resources Conservation Service (NRCS), U.S. Department of Agriculture (2016)	United States of America	The website contains an online tool with the information collected through the National Cooperative Soil Survey such as: • Soil classification maps (Soil Taxonomy System) • Online databases for soil-related information • Soil maps often have various scales and measure different parameters • Historical soil surveys from 1899 • Geospatial data	The National Cooperative Soil Survey is a collaborative effort involving federal, regional, state, and local agencies, as well as private entities and institutions in the United States that provides soil data and information produced by the National Cooperative Soil Survey. The program provides soil data and information through platforms like the Web Soil Survey (WSS)	Natural Resource Conservation Service https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soil/strategic-plan-and-guidance-documents Tool https://websoilsurvey.sc.egov.usda.gov/app/WebSoilSurvey.aspx
	Long-Term Experiments Overview Map (LTE), BonaRes Data Centre, and European Join Programme of Soil. (2022)	30 different countries across Europe	Cluster information of the LTEs in different categories (management operations, land use, duration, status, etc.). The information in the dataset can be divided and displayed in categories: • Fertilization • Crop rotation • Tillage • Other	Contains information about 572 agricultural experiments with a duration of at least 20 years. The following networks are included: EJP SOIL (European Joint Programme), GLTEN (Global Long-term Experiment Network), ILTER (International Long-term Ecological Research), IOSDV (International Organic Nitrogen Fertilization Experiment), NLFT (National Long-term Fertilization Trials, Hungary), RetiBio 2 (Italy).	https://tools.bonares.de/ltfe/ https://doi.org/10.20387/bonares-40kc-2661
	Land Use and Coverage Area frame Survey (LUCAS) (2023)	25 Member States of the European Union (EU) in 2009 sampling. In 2015 the survey was expanded to 28 EU member states.	**Sampling strategy 2009** • Coarse fragments • Particle size distribution (clay, silt, and sand content). • pH • **SOC** • Carbonate • Phosphorous • Nitrogen (total) • Extractable potassium • Cation exchange capacity (CEC) • Multispectral properties • Metals (As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Sb, Va, Zn) **Sampling strategy 2015** • Electrical conductivity included.	The in-situ survey is designed to provide harmonized statistics on Land Use and Land Cover across the European Union. It is developed every three years in 28 EU member states by observing 340,000 out of one million points selected from a Master sample. The last sampling was carried out in 2022 with 400,000 points observed, half of them directly in the field and the other half through photointerpretation.	Joint Research Centre (JRC), European Soil Data Centre (ESDAC). https://esdac.jrc.ec.europa.eu/projects/lucas

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			Sampling strategy 2018 • Bulk density • Soil biodiversity (DNA metabarcoding) • Visual assessment of erosion • Measurement of thickness of organic horizon in organic-rich soil **Sampling strategy 2018** • Auxiliary variables from the Copernicus program. Prediction **SOC**		
	Global Soil Information Service, International Soil Reference and Information Centre (ISRIC)	Global scale	Harmonized resources from the entire globe are grouped in datasets. • Bulk density • Cation exchange capacity • **SOC** • Calcium • Digital soil mapping • Electrical conductivity • Nitrogen • Nutrients • pH • Salinity • Soil profiles (description)	It is the data hub of ISRIC. Provides global soil information, including datasets derived from soil sampling efforts. The World Soil Information Service offers various datasets on soil properties, and carbon content is often included. In collaboration with its partners, ISRIC has been working for over 50 years on compiling and harmonising data on soils and their properties	https://data.isric.org/geonetwork/srv/eng/catalog.search#/home
Soil modelling	*International Soil Modelling Consortium*	Global scale	**Soil physics models** • Coup Model (soil water and heat) • Criteria (water balance in crop) • DAISY (physical and biological) • RUSLE 2015 (erosion model) • SWAP (transport of water) **Crop models** • AgroC (flux of water and **SOC**) • Apex (Land management practices) • CNMM (Hydrology and nutrients C, N, P • CANDY (Carbon and nitrogen) • Cop-soil (pollutants and **SOC**)	It is an international initiative to integrate and advance soil systems modelling, data gathering, and observational capabilities led by experts in soil processes and promoting the integration of soil modelling expertise. The initiative collects in a portal different model by discipline compartments, scale and dimension.	https://soil-modeling.org/resources-links/model-portal

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			• ECOSSE (**SOC** and nitrogen) • Expert-N (nitrogen) • EPIC (physic-chemical processes) • N14CP (C, N and P dynamics) • MONICA (Carbon and nitrogen) **Biogeochemical models** • Agro C • CANDY • CNMM • Cop-soil • ECOSSE • DEMENT (organic matter decomposition) • DAYSI • DNDC (**SOC** and nitrogen biogeochemistry in agro-ecosystems • RothC (**SOC**)		
	The European Joint Programme of Soil	Europe	**Soil Quality models** • AgroMo • CASH Protocol • DAYSI • ECOPLAN • HYDRUS1D • HYDRUS 2D • Landscape DNDC • Markstruktur index • MOHID-Land • Pasim • PESERA • REPRO • STICS • STROTASIM • Terranimo • Yasso07 **Soil Carbon models** • C-TOOL • CARBINE • CITEPA	European Joint Programme on Agricultural Soil Management addressing key societal challenges including climate change and future food supply. They developed an Inventory of the use of models for accounting and policy support (soil quality and soil carbon). The soil properties considered by the models were grouped into four categories. 1) nitrogen cycle, greenhouse gas (GHG) emissions, leaching and other properties (related to soil physical properties such as soil structure and compaction, soil salinity, or other content of other nutrients). SOC models in the report are used for reporting the national GHG inventories.	https://ejpsoil.eu/ https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP2/Deliverable_2.12_Inventory_of_the_use_of_models_for_accounting_and_policy_support_-_soil_quality_and_soil_carbon.pdf

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			• Daycent • ICBM • LandscaleDNDC • RothC • Yasso07		
Earth observation methods	*Global Soil Map*	Global	**Soil properties predicted** • pH • **SOC** • Clay, silt, sand and gravel • Bulk density • Available water holding capacity (AWC) • Electrical conductivity (EC) • Effective Cation Exchange Capacity (ECEC) • Soil depth • Total profile depth	The Global Soil Map project developed a digital soil map of the world from 2009 to 2013 using state-of-the-art and emerging technologies for soil mapping and predicting soil properties at fine resolution. GlobalSoilMap produces estimates of soil property values, their uncertainty and their date of prediction at each of six specified depth increments.	https://www.isric.org/projects/globalsoilmapnet https://www.isric.org/sites/default/files/GlobalSoilMap_specifications_december_2015_2.pdf
	Soil Grids 2.0, ISRIC	Global	**Physical properties** • Bulk density • Clay content • Sand • Silt • Water content (-10, -33, -1500 kPa in 10−2 cm^3 cm^{-3}) **Chemical properties** • Cation exchange capacity • Nitrogen • **SOC** pH water	Soilgrids is a system for digital soil mapping based on a global compilation of soil profile data (WoSIS) and environmental layers. It produces maps of soil properties using state-of-the-art machine learning methods to generate the necessary models. It takes as inputs soil observations from about 240,000 locations worldwide and over 400 global environmental covariates describing vegetation, terrain morphology, climate, geology and hydrology.	https://soilgrids.org/
	ESA's Climate Change Initiative (CCI), Soil Moisture	Global	Soil moisture content	Is a project founded by the European Space Agency, it uses earth observation data to estimate soil moisture levels, which can indirectly provide insights into soil carbon dynamics. The dataset ingests soil moisture datasets derived from the sensors: ASCAT-A, -B and -C data are generated through the HSAF soil moisture project which can be accessed on the EUMETSAT HSAF soil moisture.	https://climate.esa.int/en/projects/soil-moisture/about/

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	The Agro-Ecological Zones (AEZ), methodology, FAO	Global	• Soil resources included in the model are coming from the World Soil Database (HWSD v1.2.1) [20]. • Evaluation of terrain and slope from Shuttle Radar Topography Mission (SRTM). • Lan cover data	Is a standardized framework for assessing agricultural resources and potential. It follows an environmental approach and provides a characterization of climate, soil, and other relevant factors. It involves the analysis and compilation of general agro-climatic indicators for historical, baseline, and future climates, as well as the suitability and potential yields for various crops under alternative current and future climate conditions. The Agro-Ecological Zones methodology is widely used in research and development projects to guide decision-making in agriculture.	https://www.fao.org/documents/card/en/c/cb4744en
	AussieGRASS,	Australia	• Regional drought analysis • Translating seasonal climate outlooks • Managing landscapes • Environmental analysis • Climate change • Additional data • Daily estimates of fuel load via FTP • Experimental products and customised analyses	The AussieGRASS model is used for the assessment of Australian grasslands and rangelands, particularly in the context of soil organic carbon and soil moisture validation. Research has utilized this model to evaluate soil organic carbon levels in relation to land use change, grazing management, and pasture types in Australia. The model is essentially a spatial implementation of the Queensland government model. The spatial framework includes inputs of key climate variables (rainfall, evaporation, temperature, vapour pressure and solar radiation), soil and pasture types, tree and shrub cover, domestic livestock and other herbivore numbers.	https://www.longpaddock.qld.gov.au/aussiegrass/main-features/
	Copernicus Global Land Service	Global pan-European and local	**Parameters** • Land cover • Vegetal dry matter production • Soil Water Index • Surface Soil Moisture • Land Surface Temperature	The Copernicus Global Land Service (CGLS) is a component of the Land Monitoring Core Service (LMCS) of Copernicus, the European flagship programme on Earth Observation. The Global Land Service systematically produces a series of qualified bio-geophysical products on the status and evolution of the land surface, at a global scale and at mid to low spatial resolution, complemented by the constitution of long-term time series. The	https://land.copernicus.eu/global/

[20] Nachtergaele et al., 2014

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				products are used to monitor the vegetation, the water cycle, the energy budget and the terrestrial cryosphere.	
Hybrid	*European Soil Data Centre 2.0*	Pan-European scale	ESDAC provides EU-wide datasets for 73 soil attributes (since 2006) grouped in five groups. 1. European soil database (ESDB)and World Reference Base (WRB), 2. Point data and soilproperties, 3. Soil threats (erosion, **SOC**, soil biodiversity, landslides and soil pollution), 4. Soil functions, 5. Global data. Additional group of 15 datasets limited to specific countries or regions. The LUCAS module is incorporated to improve the pan-European land cover mapping and better describe land coverand use diversity at regional level.	An web-based platform hosting a series of pan-European and global datasets, maps and soil-related documents. The methods used are a hybrid approach based on sampling, modelling and earth observation. The core business of ESDAC is to make the data from the soil data repository accessible, augmented by providing access to a large number of maps, atlases, publications, and technical reports. The scope of the ESDAC data is its use for policy development, implementation, and assessment in a number of policy areas both at EU and national scale. The data cover soil properties, soil functions, and soil threats.	https://esdac.jrc.ec.europa.eu/ Panagos et al. (2022)

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3.2.2.2 Adaptability to the LCA framework: Soil health

In the LCA, soil health has been incorporated focusing on three quantitative approaches i) land accounting, which delineates the land area associated with specific activities or crops, ii) weighted accounting, where the land amount is standardized by factors such as land productivity, (Wackernagel, 2014) and iii) the quantification of changes in specific soil attributes resulting from land interventions (Milà i Canals et al., 2007). Nevertheless, it is necessary to develop an integrated assessment method to evaluate and allocate the impacts of particular production systems (i.e. agricultural systems using BBFs), especially at the product level, on natural resources such as soil. The principal limitations for incorporating these models into LCA approach are:

Data Availability and Quality**:** Soil health models often require detailed and site-specific data, which may not always be readily available. The most profitable alternative is to develop archetypes to cover the pedodiversity.

Limited Impact Assessment Methods: Currently, there are limited methods for assessing the impact on soil (all of them are orientated to evaluate land use changes), which restricts the comprehensive integration of soil health indicators in LCA.

Model Complexity: Soil health models can be complex (specially and may lead to challenges in model implementation, calibration, and interpretation, especially for users without a background in soil science.

Limited Standardization: The absence of standardized methods for assessing soil health poses challenges. This lack of standardization complicates result comparisons across studies or regions and impedes the development of a consistent methodology.

Spatial and Temporal Variability: The wide soil heterogeneity in time and space makes it challenging to incorporate all its intrinsic dynamism, usually LCA method's simplified assumptions may not adequately capture the dynamic nature of soil properties. Dynamic LCAs try to integrate this temporal dimension and the effect of time sequencing in a defined time horizon. However, this LCA type is not an extended practice. Indeed, most of the LCAs implicitly recognise the negative effect of time and actions besides the soil modelling.

Limited Understanding of Long-Term Effects of Agricultural Management: The long-term effects of changes in soil properties may not be fully understood or accurately predicted, but they are critical in cropland and fertilizers performance. Soil health improvements or deteriorations may take time to manifest, and predicting these effects over extended time frames can be challenging.

3.2.2.3 Case studies: Soil health

Within the context of LCA, the evaluation of soil quality involves quantifying midpoint indicators that depict factors influencing soil degradation or improvement. Despite challenges in measuring soil physical, chemical, and biological properties, strides have been taken to develop a framework for quantifying indicators of impact on soil quality from a life cycle perspective. Some relevant case studies were reviewed.

Case 1: Joensuu and Saarinen (2017) assessed the Finnish crop production with LCA. Three soil quality indicators erosion (VIHMA model, Puustinen et al. 2010), soil organic matter (SOM) (Yasso07 model, Tuomi et al. 2009), and soil compaction (COMPSOIL, O'Sullivan et al. 1999) were introduced. They collected data at a parcel-specific level with a high degree of geographical detail (data collected from two conventional farms and two organic farms for 4 years) and concluded that erosion and SOM models are appropriate for the LCA framework. However, the soil compaction model resulted too difficult to use it. The main constraints of the study were difficulty in finding suitable data for soil compaction. There is insufficient data on the cultivation history of field parcels for an accurate assessment of soil carbon decline. The findings may not be directly applicable to other regions or agricultural systems and did not consider other important factors such as contamination, salinization, soil biodiversity loss, sealing, landslides, and flooding.

Case 2. Vidal Legaz et al. (2017) evaluated 11 models for soil properties in croplands. Two models were not developed specifically for an LCA context. It was found that none of the soil models currently available meet all the criteria necessary to comprehensively depict the impacts on soil properties and function. Some models offer multi-indicators, which cover various drivers of impact, while others focus on a single driver of impact but provide a more relevant impact characterization. As a result, further research is necessary to improve soil modelling and its applicability in LCA.

Case 3. Morais et al. (2018) proposed incorporating the process-based modelling approach for Life Cycle Impact Assessment (LCIA) of land use and land use change (LULUC) in LCA framework. The study was conducted in Alentejo (Portugal) using the RothC model. They suggested as necessary to go beyond the calculation of characterization factors (CFs) for generic land use (LU) classes and enable accurate and regionalized impact assessment of LULUC based on SOC depletion, mainly. They recommended the production of global CFs obtained from similar methodological approaches (similar soil models such as RothC) and data sources indicating the importance of regionalization in impact assessment models. They provide CFs for individual crops and discriminated LU classes and management practices. We additionally provide insights and indications for future work leading up to the production of global CFs using similar soil models and an updated procedure for CF calculation.

Case 4. Pereira-Andrade et al. (2022) carried out a study to identify and provide indicators that cover the important aspects of environmental sustainability regarding nutrient recovery related to N and P biogeochemical flows. The authors tested a set of 15 agri-environmental indicators to create a dashboard of nutrient recovery and environmental issues. Most of the findings were integrated in the Dashboard Indicator (DBI). Similar to LCA, they can also provide information on the potential benefits of technologies. Finally, the DBI can be used as a rapid

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comparison tool for potential technologies applied in agriculture, complementing the more detailed and comprehensive assessment provided by LCA.

3.2.2.4.-Adaptability to LCA framework: Soil Organic Carbon (carbon sequestration)

The application of BBF with a stable content of organic Carbon will contribute to enhancing the temporary storage (or release) of C in the agricultural soils. Moreover, the production of BBFs has the potential to complete the cycle of agro-food production systems, ushering in more resource-efficient and environmentally sustainable fertilizer products to the market. In consequence, C sequestration is considered one of the most promising climate change mitigations from agriculture. Therefore, it is necessary to take into account that both the production and the field application of BBFs generate environmental impacts that must be measured. One of the most used approaches is to evaluate the magnitude of these impacts of the LCA, however, has not been generated a consensus in the methodology to account for changes in the SOC dynamics due to the use of different management practices such as the use of BBFs. There are still gaps that need to be addressed to accurately account for soil carbon changes in LCA. Some of the main gaps include:

Methodology. There is not a regional or international consensus about how to include changes in soil C stocks in croplands due to fertilization or the addition of organic amendments. To incorporate the C dynamics in LCA it is necessary for an approach that combines the degradation and emissions of CO2 from the soil and the following decline in the atmosphere.

Available data. It is challenging to accurately estimate the impact of soil carbon sequestration on LCA due to a lack of data on soil C changes in all countries. For this reason, several LCA methods have tried to incorporate the data from C modelling, but the principal issue in adapting those models is that they need to be simple and limited, which avoids assessing the complex effects of stabilized matter in soil dynamics beyond carbon.

Stability (long-term stability). The persistence of SOC is still uncertain and requires continuous monitoring and evaluation. Considering the dynamic stability of soil carbon in LCA is crucial because the amount of carbon stored in the soil is subject to various factors such as land use change, soil management practices, and climate change.

Site specificity (soil type and weather conditions). The heterogeneity of soils and climatic conditions make regionalization or formation of archetypes necessary for a better interpretation of the results, which is why it is necessary to couple information systems with the LCA to improve measurements.

3.2.2.5 Case studies: Carbon sequestration

Case 1. Petersen et al. (2013) suggested a method (Bern Carbon Cycle Model common method incorporated in soil C models such C-TOOL and RothC) with different time perspectives 20, 100 and 200 years, to estimate carbon sequestration in LCA framework. They concluded that time perspective had a huge impact on the results and recommended the adoption of a 100-

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year time perspective for a more comprehensive and meaningful assessment in LCA studies. The main challenge associated with this method is estimating the carbon deficit between the baseline scenario and the new practice. This challenge stems from the dependence of turnover on soil properties and climate data, complicating the accurate determination of carbon turnover, even though many models assume independence between soil carbon turnover and carbon content.

Case 2. Goglio et al. (2015) ranked several soil C methodologies LCA, non-LCA, LCI, and related to Land Use Changes (LUC) and Land Management Changes (LMC) used in agricultural systems. The models analysed were classified into i) simple C models, which consider soil C dynamics but do not simulate crop production (e.g. C-TOOL, ICBM and RothC), and ii) dynamic crop-climate-soil models which describe interactions between crop growth, soil C and N dynamics, and environmental processes (e.g. CERES, DNDC, DAYCENT, CENTURY). Also, they provided a ranking of soil C methodologies for small-scale site-specific assessment and larger-scale site-dependent assessments. They concluded the time horizon of assessment should be at least 20 years for large-scale and 10 years for site-specific assessment, most of the methods have presented large uncertainties in calculating indirect LUC effects (sensitivity analysis can be combined to reduce it), and a common methodology needed to assess soil C dynamics in agricultural LCAs.

Case 3. Texeira et al. (2021) explored the utilization of SOC depletion in LCA studies as an indicator for midpoint impacts related to LU and LUC. They integrate a process-based modelling approach, incorporating models that account for site-specific soil conditions, soil management practices, and climatic data. This approach involves the use of CFs for SOC depletion as an indicator (Morais et al, 2021), providing globally contextualized and land-use-specific results. They separated two distinct methods for referring to the land transformation CFs calculated. "background" transformation, where CFs are established with an unknown initial LU and a known final LU. In contrast, "foreground" CFs are characterized by two known LU classes, indicating scenarios where both the initial and final LU classes are identified. They concluded that coupling both methods it is possible to obtain consistently through the same model and data sources, enhances the accuracy of impact assessments, particularly for foreground processes/elementary flows.

Case 4. Andrade Díaz et al. (2024) reviewed the interplay between bioeconomy and SOC studying the use of coproducts (pyrochar, hydrochar and digestate) to predict SOC turnover in agricultural soils (data from over 600 literature records). Comparing different modelling approaches to incorporating stabilized organic matter into soils the authors proposed average conversion coefficients from biomass C to coproduct and their inherent recalcitrance in agricultural soils, as well as its possible incorporation into LCA framework. The models included in the review were AMG, APSIM, CANDY, CENTURY, C-TOOL, EPIC and RothC, all of which have been adapted at least once for bioeconomy coproducts. They concluded that RothC is the model most used due to its simplicity and limited data requirements. However, more complex

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models may provide a more comprehensive understanding of the diverse effects of stabilized matter in soil dynamics beyond carbon.

3.2.3 Heavy metals

BBFs can contain heavy metals due to the accumulation coming from the secondary raw materials with which they are produced. The application of these metals into the soil can damage both individual species and the ecosystem's structure and function. There is evidence of a cumulative effect in the soil compartment, plants and animals. In extreme circumstances, this can cause damage to human health. Therefore, the limitation of the concentrations has been widely spread in normative rules defining limit values, depending on soil concentrations and properties as well such as the soil pH, the nature of the chemical association between the metal, the organic residual, and the soil matrix, and the plant's ability to regulate uptake of the particular element (Jensen et al., 2020). Nowadays, there is no general recommendation or standard procedure to date how to evaluate BBFs with respect to their ecotoxicological potential when producing agricultural fertilizers.

3.2.3.1 Available methods, models and tools to quantify heavy metals.

The most common methods for assessing heavy metals in BBFs include:

Near-Infrared (NIR) and Mid-Infrared (MIR) Spectroscopy. These spectroscopic methods are employed for measuring the levels of heavy metals in BBFs. They offer a non-invasive and effective approach to analysis, enabling swift evaluation of heavy metal quantities (Wali et al. 2022).

Chemical Analysis. Traditional chemical analysis methods involving digestion, titration, and distillation processes are utilized to quantify the heavy metal content. While these methods are considered accurate, they are often time-consuming and involve the use of hazardous chemicals (Albert and Bloem 2023).

Plant and Soil Analysis. Assessing the heavy metal accumulation in plants and soil, including techniques such as bioaccumulation factor and translocation factor, to understand the transfer of heavy metals from soil to plants (Abdelgawad et al., 2023).

Ecotoxicological Methods. These methods are employed to evaluate the toxicity of BBFs, which includes the analysis of the elemental composition and heavy metal content (Albert and Bloem 2023). Ecotoxicological methods in combination with fate models have been incorporated to LCA methodologies commonly used for assessing ecotoxicological impacts (i.e. USEtox, IMPACT, Eco-indicator 99, Caltox, etc.)

The initiatives, methods and indicators for assessing heavy metals in BBF are included in Table 8.

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Table 8. Initiatives for assessing heavy metals in biobased fertilisers or agricultural soils.

Name	**Geographical scope**	**Methods, indicators or tools**	**General comments**	**Reference**
Soil environmental quality. Risk control standard for soil contamination of agricultural land, China	China	Include critical values to evaluate: • Water for irrigation • Agricultural soils • Manures and amendments • Urban soils	This national standard specifies the risk screening values for soil contamination of agricultural land, as well as the monitoring, implementation and supervision requirements. The standard contains different normative references to measure the content of heavy metals. Likewise, it includes the critical values to evaluate the contamination of agricultural soils	https://www.chinesestandard.net/PDF/English.aspx/GB15618-2018 Document available in: https://www.chinesestandard.net/PDF/English.aspx/GB15618-2018
Guidelines for the Testing of Chemicals - Agricultural Chemicals OECD.	OECD Member states	The methods are grouped in five sections: • Physical-Chemical properties. https://www.oecd.org/env/ehs/testing/section1-physical-chemical-properties-replaced-and-cancelled-test-guidelines.htm • Effects on Biotic Systems. https://www.oecd.org/env/ehs/testing/section2-effects-on-biotic-systems-replaced-and-cancelled-test-guidelines.htm • Environmental fate and behaviour. https://web-archive.oecd.org/2023-07-20/63981-section3-degradation-and-accumulation-replaced-and-cancelled-test-guidelines.htm • Health Effects. https://www.oecd.org/env/ehs/testing/section4-health-effects-replaced-and-cancelled-test-guidelines.htm • Section 5: Other Test Guidelines. https://www.oecd.org/chemicalsafety/testing/section5-other-test-guidelines-replaced-and-cancelled-test-guidelines.htm	A collection of about 150 of the most relevant internationally agreed testing methods used by government, industry and independent laboratories to identify and characterise potential hazards of chemicals. They are split into five sections:	https://www.oecd-ilibrary.org/environment/oecd-guidelines-for-the-testing-of-chemicals_72d77764-en
Framework for Metals Risk Assessment, Environmental Protection Agency (EPA), USA.	USA	The conceptual model identifies issues, and their location in the health risk assessment process, and directs the remainder of the assessment: • Fate and transport models. • Media-based exposure models.	The reports developed a conceptual model representing the actual and potential, direct and indirect relationships between stressors in the environment and exposed humans (or particular subpopulations) or ecological entities. The model illustrates potential pathways originating from	https://www.epa.gov/risk/framework-metals-risk-assessment Document

		• Bioaccumulation and toxicokinetic models. mathematical representations used to describe the absorption, distribution, metabolism, and excretion of toxic substances within living organisms. • Residue-based toxicity models. • Bioaccumulation/food web model. • Dietary exposure models. • Exposure-based toxicity model. • Media-based toxicity model. • Population, habitat, ecosystem models.	metal sources and common approaches to risk assessment, such as evaluating media concentrations, calculated doses, or tissue residues.	https://www.epa.gov/sites/default/files/2013-09/documents/metals-risk-assessment-final.pdf
Impacts of nutrients and heavy metals in European agriculture. Current and critical inputs in relation to air, soil, and water quality. European Environment Agency (EEA).	Europe	To avoid the effects on environmental targets the reports review the principal limits or thresholds of heavy metals in soil. Limit values for heavy metals at national level in soils includes: • Cadmium • Copper • Lead • Zinc The values are related with the main regulations in EU: • Council Directive 86/278/EEC on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. • Regulation (EU) 2019/1009 laying down rules on the making available on the market of EU fertilising products. • Commission Regulation (EC) No 1881/2006 and commission regulation (EU) 2021/1323 setting maximum levels for certain contaminants in foodstuffs. • Council Directive 98/83/EC on the quality of water intended for human consumption.	The report covers the variation in concentrations and losses of four of the most common heavy metals present in soil: cadmium, copper, lead, and zinc and how their current inputs exceed safe levels. It assesses the impact of these heavy metals on soil quality and the environment and determines whether changes in soil levels cause any undesired effects on specific environmental targets. • Soil organisms (soil ecosystem) • Crop production (yield) and quality of crops • Quality of animal products for human consumption, • Animal health (e.g. grazing cattle), and • Quality of water leaching from the soil (including drinking water, groundwater or nearby surface water).	https://www.eionet.europa.eu/etcs/etc-di/products/impacts-of-nutrients-and-heavy-metals-in-european-agriculture-current-and-critical-inputs-in-relation-to-air-soil-and-water-quality/@@download/file/D22%201821%20M1%20and%20M2%20Nutrients%20and%20heavy%20metals%20in%20soils%2001032022%20ETC-DI_30March.pdf
Ecotoxicological methods to evaluate the toxicity of bio-based fertilizer application to agricultural soils	Europe	The review of ecotoxicological tests comprises: 1. General requirements for ecotoxicity tests 2. Preparation of BBFs for ecotoxicological evaluation 3. Test strategy for ecotoxicological evaluation of BBFs 4. Evaluation of the ecotoxicological test results	It is a literature review about the potential ecotoxicological concerns of the application on farm of biobased fertilisers. The publication analyses the main regulation applying to biobased fertilisers and the Ecotoxicological tests to evaluate it.	Albert, S., Bloem, E., 2023. https://doi.org/10.1016/j.scitotenv.2023.163076

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		5. Combination of ecotoxicological tests, chemical analysis and soil indicators for the valid evaluation of BBFs	The review included tables with the principal limit values of heavy metals in agricultural practices according EU Regulation 2019/1009 and developed a Decision tree for the evaluation of BBFs by ecotoxicological studies in combination with chemical characterization and soil indicator evaluation[21]	

[21] See decision tree on annex 2

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3.2.3.2 Adaptability to the LCA framework

Data Availability and Quality. Limited and inconsistent data on heavy metal concentrations in soil, especially for specific regions or land uses.

Spatial and Temporal Variability. Soil contamination can vary spatially and temporally, making it difficult to capture the full extent of heavy metal impacts. LCA studies may lack precision in reflecting the true environmental burden associated with heavy metals over different locations and timeframes.

Limited Fate and Transport Models. Incomplete models for the fate and transport of heavy metals in environmental compartments. Difficulty in predicting the long-term behaviour of heavy metals and their potential migration into water bodies, affecting the accuracy of impact assessments.

Bioavailability Considerations. Lack of consensus on how to account for the bioavailability of heavy metals in different soil types and under various management practices.

Integration with Human Health Impact Assessment. Limited integration of heavy metal assessments with human health impact models in LCA.

3.2.3.3 Case studies

Leclerc and Laurent (2017) developed a framework for estimating the release of harmful substances from the application of manure on agricultural land. This framework can be used to calculate the national inventories for 215 countries between 2000 and 2014. The framework has been tested for eight heavy metals (arsenic, cadmium, chromium, copper, mercury, nickel, lead and zinc) that are typically present in manure (a feedstock of BBFs). They applied the method proposed by Cucurachi et al. (2014) to estimate the input quantity of manure applied yearly in each country (data extracted from FAOSTAT 2015[22] databases) and then calculated the heavy metal content based on data previously published. Finally, to evaluate the toxicity-related environmental impacts caused by the release of heavy metals to agricultural soil they used the inventory created as input for developing an LCA (USEtox) model. Their results showed consistency with previous inventories performed for single countries however they concluded that country-specific and harmonised data on heavy metal contents is needed.

Yunta et al. (2024) carried out a quantitative analysis of the sewage sledge directive 86/278/EEC[23] at the European level using the LUCAS topsoil database 2009 (see table 7). The European reference values were established by considering both the upper value and lower value for each heavy metal (arsenic, cadmium, copper, chromium, mercury, nickel, lead, and zinc), alongside the soil pH (for cadmium, copper, mercury, nickel, lead, and zinc). Single (CRI) and integrated contamination rate indices (OCRI) were developed to pinpoint agricultural soils

[22] FAOSTAT, 2015a. Manure Applied to Soil. http://faostat3.fao.org/download/G1/GU/E
[23] Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (OJ L 181 04.07.1986). ELI, p 6. http://data.europa.eu/eli/dir/1986/278/oj

surpassing these reference values for each heavy metal. They conclude that the soil parameters extracted from the LUCAS 2009 database, including heavy metal concentrations and soil pH values, can serve as valuable tools for policy stakeholders involved in the Soil Strategy Directorate (SSD). These stakeholders can utilize this data not only to establish limit values for heavy metal concentrations in soils but also to monitor compliance levels by integrating experimental data obtained from previous and forthcoming LUCAS surveys over time.

3.2.4 Biodiversity

Biodiversity serves crucially supporting life on Earth. It is responsible for most environmental services and forms the basis for all ecological processes across the world. However, in the past 50 years, biodiversity has been threatened mainly by human activities. The direct drivers that affected the nature are changes in land and sea use; direct exploitation of organisms; climate change; pollution; and invasion of alien species according to the IPBES (2019).

Multiple global reports and initiatives have been presented to convey the current state of biodiversity, delineate the direct and indirect drivers leading to losses, and outline general methodologies for its assessment.

3.2.4.1 Available methods, models and tools to quantify biodiversity.

The different methods grouped by initiatives found are shown in the Table 9.

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Table 9. Initiatives around the world for the assessment of biodiversity losses/gains due to BBFs.

Name	Geographical scope	Methods, indicators or tools	General comments	Reference
Biodiversity Assessment Initiatives, Core initiative to measure, valuate and communicate Biodiversity	Global	**Foundational data & tools** • IBA (www.ibat-alliance.org) • Globio (www.globio.info) • Predicts (www.predicts.org.uk) **Guidelines** • Biodiversity in Standards & Labels (http://www.business-biodiversity.eu/ en/biodiversity-criteria-in-standards) • Land Use Impacts on Biodiversity in LCA (http://www.lifecycleinitiative.org/ training-resources/global-gui- dance-lcia-indicators-v-1/) • Biodiversity in Forest Restoration Assessment (https://portals.iucn.org/library/sites/ library/files/documents/2018-022-En. Pdf) **Decision Support Tools** • LC-Impact Method (http://lc-impact.eu/downloads/%20 documents/LC-Impact_report_%20 SEPT2016_20160927.pdf) • Product Biodiversity Footprint (http://www.productbiodiversityfoot- print.com/) • Biodiversity Impact Metric (https://www.cisl.cam.ac.uk/publi- cations/working-papers-folder/ healthy-ecosystem-metric-framework) • Biodiversity Performance Tool (https://solagro.com) • Agrobiodiversity Index (https://www.bioversityinternational. org/abd-index/) • ROOT (https://portals.iucn.org/library/sites/ library/files/documents/2018-031-En. Pdf)	The report collected biodiversity assessment methods useful to decision-making, from the company to the citizen that are being used by the members of the initiative. The authors developed an analytical mapping of the methods considering the scale, key features, the application, the type of valuation, and the type of pressures.	https://www.business-biodiversity.eu/en/publications/biodiversity-assessment-initiatives Neveux et al., 2018
Critical Assessment of biodiversity accounting approaches for businesses and financial institutions, EU	Global	Adapted from EU Business @ Biodiversity platform 2019: Developer / tool • CDC Biodiversité / Global Biodiversity Score 2	The platform published a methodology guideline on biodiversity accounting approaches for businesses and financial institutions in a European context. The biodiversity metrics were selected based on their relevance, rigour, replicability, and	EU Business @ Biodiversity platform 2018. Lammerant et al., 2018.

Business@Biodiversity plattform		• Cambridge Institute for Sustainable Leadership (CISL)/ Biodiversity Impact Metric • UNEP-WCMC / Biodiversity Indicators for Extractive Companies • I CARE – Sayari / Product Biodiversity Footprint • ASN Bank Biodiversity / Biodiversity Footprint approach • Biodiversity International / Agrobiodiversity Index (ABD) • Plans Up / Biodiversity Footprint Calculator • LIFE Institute / Impact Index + Positive Scoring • Platform BEE (Dutch Ministry) / Bioscope • IUCN / Biodiversity Return on Investment Metric (BRIM)	consistency. The selected metrics also have the capacity to relate to tools used by businesses and financial institutions. Table 10 shows the assessed approaches.	
Global Assessment Report on Biodiversity, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services	Global	• The report subdivided the Earth's surfaces into 17 units of analysis to assess the changes/impacts in nature. 13 "biomes" or "ecoregions" and 4 "anthromes" (Ellis and Ramankutty, 2008) (regions where the ecosystem structure and function have been severely altered through human management). • The initial discussion of IPBES indicators began in 2015 and aimed at providing common indicators for the IPBES. The criteria selection was based on its policy relevance, scientifically sound, simplicity and reliability, practicality and affordability, sensitivity, and suitability for aggregation. • A total of 30 core indicators and 42 highlighted indicators were described, and even other complementary sets of indicators were used to evaluate specific targets.	The global assessment adopted in the report includes multi-dimensional system of indicators to examine status, trends and progress towards international goals such as the Aichi Biodiversity Targets and the Sustainable Development Goals on biodiversity.	https://www.ipbes.net/global-assessment IPBES, 2019
Biodiversity and the livestock sector Guidelines for quantitative assessment	Global	The indicators coupled with the LCA approach proposed are divided into thematic issues: • Habitat protection • Habitat Change • Wildfire conservation • Invasive lien species • Pollution and aquatic biodiversity • Off-farm feed • Landscape-scale observation	Developed guidelines for quantitative assessment of the effects of livestock production on wild biodiversity, based on existing indicators and methods relevant to a range of assessment objectives, users, scales, geographical regions, livestock species and production systems. The guidelines can be coupled with LCA methods to provide a comprehensive assessment of the impact of livestock production on wild biodiversity.	https://www.fao.org/documents/card/en/c/ca9295en/ FAO LEAP, (2020).

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Living Planet Report, WWF	Global	Living Planet Index (LPI) is a measure of the state of the world's biological diversity based on population trends of vertebrate species from terrestrial, freshwater, and marine habitats. It tracks the abundance of thousands of populations of mammals, birds, reptiles, amphibians, and fish across the globe. The LPI is based on trends of thousands of population time series collected from monitored sites, and it provides valuable insights into the state of the planet's biological diversity. The index reveals a significant decline in the abundance of vertebrate populations, indicating a biodiversity crisis.	The initiative proposed the living planet index (LPI) as a valuable tool for policymakers, researchers and conservationists. LPI offers a quantitative assessment of global biodiversity trends. The index tracks the changes in the relative abundance of wild species populations over time and it was constructed by calculating an average trend for tens of thousands of terrestrials, freshwater and marine vertebrate populations from across the globe.	https://www.livingplanetindex.org/ Almond et al., 2022
Finance for Biodiversity Guide on biodiversity measurement approaches	Global	The models approach included were: • BFFI – Biodiversity Footprint Financial Institutions (CREM and PRé Sustainability, together with ASN Bank). • BIA-GBS – Biodiversity Impact Analytics powered by the Global Biodiversity Score (Carbon4Finance and CDC Biodiversité). • CBF – Corporate Biodiversity Footprint (Iceberg Datalab and I Care Consult as scientific partner) • GBSFI – Global Biodiversity Score for Financial Institutions (CDC Biodiversité). • GID – Global Impact Database, Biodiversity Impact Data (Impact Institute). • ENCORE – Exploring Natural Capital Opportunities, Risks and Exposure (UNEP-WCMC, UNEP FI & NCFA). • IBAT – Integrated Biodiversity Assessment Tool (BirdLife International, Conservation International, IUCN, UNEP-WCMC). The first five approaches (BFFI, BIA-GBS, CBF, GBSFI and GID) use a similar LCA-based approach to model a company's potential impact on biodiversity from data on their revenue, business activities, and related input and output. All the approaches were assessed with an uniform criteria based on their organisational focus area, business/finance application, asset category, maturity level, pressure, coverage, scope, metric, type of data	It's a update of the guidelines published in 2019. In this new version the guidelines include only biodiversity impact measurement approaches that: 1) are relevant to, and are currently explored or used by, the financial sector, 2) include all main drivers of biodiversity loss, and 3) are scientifically robust.	EU Business @ Biodiversity plattform https://green-business.ec.europa.eu/business-and-biodiversity_en (Impact, 2022).

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		and effort. Moreover, includes two new chapters. One of them, describing different types of data sources as well as innovations in the field of biodiversity data and the second one, dedicated to measuring marine biodiversity.		

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3.2.4.2 Adaptability to the LCA framework

The principal gaps to include biodiversity assessment in LCA studies are as follows:

Spatial Dimension: Biodiversity impact assessment in LCA faces enduring challenges, such as the inclusion of a spatial dimension. The spatial resolution of LCA assessments needs to increase as more data becomes available to better represent the spatial distribution of biodiversity impacts, (which will probably require several indicators).

Specific Data and Assumptions: A major challenge for LCA methodology is the lack of specific data, leading to the need for concessions and assumptions to represent the environment realistically. This lack of specific data and the need for assumptions pose challenges for accurately quantifying biodiversity impacts in LCA studies.

Representation of Biodiversity: While species richness remains the most usable representation of biodiversity, there is an ongoing effort to include genetic and ecosystem diversity as well. The representation of biodiversity in LCA needs to evolve to encompass a broader understanding of biodiversity beyond species richness.

Man-made Impacts on Biodiversity: The feasibility of including man-made impacts on biodiversity in the context of LCA has been a topic of discussion for over 20 years, indicating the ongoing challenges and gaps in effectively integrating biodiversity assessment into LCA studies.

3.2.4.3 Case studies

Crenna et al. (2020) reviewed existing frameworks, models, and metrics used in LCA framework for assessing the impacts caused by products and services on biodiversity. Their findings suggest limitations in operational LCA models, focusing solely on community composition. They emphasize the need for a more comprehensive evaluation that includes multiple biodiversity dimensions like ecosystem structure, composition, species traits, and populations. Ongoing advancements in the LCA community include the integration of non-LCA approaches, often developed for business initiatives and utilizing databases from LCIA methods. The authors highlighted some key considerations for incorporating these metrics into LCA: i) consistency across spatial scales, ii) consistency across system boundaries, iii) utilization of heterogeneous data, and iv) establishing a causal relationship between biodiversity loss and impacts from producing sectors.

Damiani et al. (2023) identified a total of 64 LCA-based methods and models non-LCA (beyond LCA) used to address impacts on biodiversity. Then, 23 methods (17 purely LCA and six with other complemented approaches beyond LCA) were selected to carry out a detailed analysis based on their availability of documentation, domain of application, geographical scope, potential to be used in LCA, and added value. The limitations were that some methods presented insufficient documentation for use in LCA, narrow geographical scope, and some methods do not apply to product, value chain, or company. The conclusion highlighted that no single method comprehensively captures all biodiversity drivers, but some of them perform better than others depending on the criteria or goals specified. Addressing gaps requires enhancing method completeness regarding pressures and taxonomic groups and improving descriptive power on biodiversity components such as genetic diversity, community composition, structure, and ecosystem functionality.

3.2.5 Emerging organic contaminants

The utilization of sewage and manure in the production of BBFs may result in the accumulation of organic contaminants because they have lipophilic properties and hence transfer to sewages sludge and may be present in residual concentrations within crops, soil matrices, or groundwater reservoirs causing environmental affections. Special emphasis has been placed on specific priority classes of persistent organic pollutants (POPs), including chlorinated dioxins/furans (PCDD/Fs), polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) (Clarke and Smith, 2011). All of them are recognized as potential risks when biosolids (i.e. some BBFs) are applied to land due to their persistence, bioaccumulation potential, and toxicity. However, hydrophobic non-ionic organic contaminants (OCs) tend to tightly sorb to sludge and soil organic matter, reducing their bioavailability but increasing their persistence. Risk assessments indicate minimal entry of OCs into the human food chain from biosolids land application, with low plant uptake and strong sorption to soil preventing groundwater contamination (Schowanek et al., 2007). Despite international risk assessments suggesting minimal human health risks, ongoing monitoring is essential to assess the significance and implications of emerging organic contaminants for biosolids land application (Schowanek et al., 2004).

3.2.5.1 Available methods, models and tools to quantify emerging organic contaminants.

i) *ILSI-Europe's*[24]*, A risk-based methodology for deriving quality standards for organic contaminants in sewage sludge for use in agriculture (2004)*. The authors described systematic methodology (Conceptual Framework) to derive quality standards for organic (anthropogenic) contaminants in sewage sludge added to agricultural land, in the context of revision of EU Sludge Directive 86/278/EEC and the broader Soil Thematic Strategy. The main objective was to ensure, based on a risk assessment approach, a sustainable use of sludge over a long-time horizon. The framework developed include a series of risk assessment endpoint and the suggested methodologies for assess it (Table 10).

Table 10. Suggested endpoints risk assessment and the methods for accounting organic contaminants (Source, Schowanek et al. 2004).

Endpoint	Methods
Effects on microbial systems and soil fertility	• Microbial numbers. • Microbial biomass.

[24] https://ilsi.eu/

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	• Microbial metabolic activity. • Respirometer based methods. • Molecular biology-based techniques. • Field studies.
Effects on soil flora	• Protocols to evaluate phytotoxins. • Taxonomic evaluation.
Effects on soil fauna	• Ecotoxicological tests.
Biomagnification and secondary poisoning of top predators	• Predicted no-effect concentration (PNEC). • Secondary poisoning in risk assessment.
Leaching and groundwater quality	• Several models based on physio-chemical properties (water solubility, vapour pressure, octanol–water partition coefficient, organic carbon–water partition coefficient. • The SESOIL screening-level model (http://www.scisoftware.com).
Run-off, erosion, and surface water quality	• Modelling of run-off and contaminant transport (EPIC, GLEAMS, OPUS, PRZM, ANSWERS-2000, SWAT-2000, SWATCATCH, etc).
Indirect human exposure	• Modelling of indirect human exposure to environmental contaminants.
Direct human exposure	• Soil ingestion • Exposure to airborne dust and via volatilization

ii) Stockholm Convention on POPs[25]. It is a global treaty adopted in 2001 and entered into force in 2004. It aims to protect human health and the environment from the harmful effects of POPs by regulating and ultimately eliminating their production, use, trade, and release into the environment. The methodologies included are:

- Listing of POPs. the Convention establishes criteria for identifying and listing POPs based on their persistence, bioaccumulative potential, long-range environmental transport, and adverse effects on human health and the environment. As of now, the Convention lists 30 chemicals as POPs.
- Risk Assessment. Encourages parties to conduct risk assessments of POPs to evaluate their environmental and human health impacts.
- National Implementation Plans. Outline the measures and strategies that each country will undertake to eliminate or reduce POPs, including legislative and regulatory measures, capacity-building initiatives, and public awareness campaigns.
- Best Available Techniques (BAT) and Best Environmental Practices (BEP) to minimize the release of POPs into the environment. BAT/BEP guidelines provide technical guidance to industries and governments on reducing POPs emissions and promoting cleaner production practices.

[25] https://www.pops.int/Home/tabid/2121/Default.aspx

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- Alternatives Assessment. Encourages the development and promotion of alternatives to POPs, such as safer chemicals, non-chemical alternatives, and integrated pest management approaches.

3.2.5.2 Adaptability to the LCA framework

Analytical challenges: Detecting and quantifying organic pollutants in biobased fertilizers can be technically challenging due to their diverse chemical compositions and complex matrices. Analytical methods for measuring organic pollutants in soil and organic materials may require sophisticated equipment and expertise.

Environmental fate and behaviour: The environmental fate and behaviour of organic pollutants in soil and agricultural systems are complex and influenced by various factors such as soil properties, climate, and agricultural practices. Predicting the fate and transport of organic pollutants from BBFs through soil-water systems in LCA models may introduce uncertainties.

Impact assessment limitations: Assessing the environmental and human health impacts of organic pollutants from biobased fertilizers in LCA models is challenging due to uncertainties regarding exposure pathways, toxicity, and ecological effects. Incorporating organic pollutant impact pathways into existing LCA frameworks may require further methodological development and refinement.

Comparability with traditional LCAs: Comparing the environmental performance of biobased fertilizers with traditional fertilizers in LCA may be challenging when considering organic pollutants. Traditional LCAs typically focus on conventional environmental impacts such as greenhouse gas emissions and resource use, whereas organic pollutants introduce additional impact pathways that may not be directly comparable.

3.2.6 Microplastics

Microplastics are increasingly detected in both organic and inorganic fertilizers, causing environmental concerns. In some BBFs, microplastic characteristics are primarily influenced by their feedstocks, such as solid bio-waste. Studies indicate that agricultural fertilizers, encompassing both organic and inorganic variants, significantly contribute to soil microplastic concentrations, leading to a gradual buildup over time. In fact, some chemical components derivates from plastic called "additives" can potentially migrate and undesirably lead to human exposure via e.g. food contact materials, such as packaging (Hahladakis et al., 2018). Thus, understanding and monitoring the levels of microplastics in BBFs is therefore crucial to minimize their impact on the environment and human health.

3.2.6.1 Available methods, models and tools to quantify microplastics.

Several methods have been described for quantifying microplastics in fertilisers in agricultural soils due to the inputs used in the agronomic management of the crops (i.e. BBFs). One of the most recent reviews regarding the methodologies for accounting microplastics in agricultural

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soils was developed by (Junhao et al., (2021). They reported a set of 16 methods grouped in three main categories: Sample purification, Digestion and Identification and quantification. Furthermore, by reviewing the available publications it is possible to suggest that the most applied methods are the following.

i) *Particle Separation and Analysis:* Microplastics within a specific size range are separated from biobased fertilizer samples and analysed using microscopy, spectroscopy, and chemical methods to quantify their abundance (Junhao et al., 2021).
ii) *Source Tracking:* Identifying the sources of microplastics in agricultural systems, such as biobased fertilizers, through techniques like polymer identification and tracing the distribution of specific types of microplastics (Pérez-Reverón et al., 2022).
iii) *Effects on Soil and Crops:* Assessing the impact of microplastics on soil quality and crop yield through field studies and controlled experiments, which is essential for understanding the potential effects of microplastics in biobased fertilizers on agricultural ecosystems (Quilliam et al., 2023).

3.2.6.2 Adaptability to the LCA framework

The main gaps to adapt the identification and quantification of microplastics from BBFs are:

Data availability and reliability: Limited data on the sources, fate, and impacts of microplastics in BBFs can impede accurate assessments. Reliable data on microplastics content in different types of BBFs and their environmental fate are often lacking.

Analytical challenges: Detecting and quantifying microplastics in BBFs can be technically challenging due to their size, shape diversity, and complex matrices. Analytical methods for measuring microplastics in soil and organic materials may require sophisticated equipment and expertise.

Uncertainty in environmental fate: The environmental fate of microplastics in soil and agricultural systems is complex and influenced by various factors such as soil properties, climate, and agricultural practices. Predicting the fate and transport of microplastics from BBFs through soil-water systems in LCA models may introduce uncertainties.

Impact assessment limitations: Assessing the environmental and human health impacts of microplastics from BBFs in LCA models is challenging due to uncertainties regarding exposure pathways, toxicity, and ecological effects.

3.2.6.3 Case studies

Askham et al (2023) examined the data collection and reporting methods for field and laboratory studies on micro and nano plastics exposure and effects that are relevant to LCA data inputs. They proposed the data requirements for field and laboratory studies to increase the potential for LCA studies and models to utilise data gathered in receptor-oriented studies. They suggest three levels of detail: Level 1 outlines minimum requirements; Level 2 provides

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additional data that can be easily obtained using standard equipment and methods; Level 3 requests data that sometimes require more specific and advanced analytical equipment and methods.

3.2.7 Odour

Currently, anaerobic digestion and composting are replacing incineration and landfills in waste management. These technologies recover energy and materials, contributing to a circular economy. Nevertheless, the production of BBFs implies the generation of volatile compounds released into the atmosphere, it can find ammonia, greenhouse gases (such as methane and nitrous oxide), and a heterogeneous group of Volatile Organic Compounds (VOCs). These emissions from BBFs can have a negative impact on air quality and community well-being. Thus, measuring both parameters is crucial in determining the overall environmental impact of biobased fertilizers.

3.2.7.1 Available methods, models and tools to quantify odour.

The most recent review published by González et al. (2022) regarding the methods of measurement odour in waste and wastewater treatment plants summarises several methods of assessment.

i) *Odour sampling*. Sampling methodologies vary depending on the types of sources of odour that should be conducted to observe. The most used alternatives are to cover the entire surface to capture odours, wind tunnel devices to obtain representative air samples and anemometers to also obtain the air speed and calculate the number of odours released in the preparation of BBFs.
ii) *Odor Measurement*. The European standard EN 13725:2003 and its update BS EN13725:2022—Stationary source emissions. Determination of odour concentration by dynamic olfactometry. Also, there have been recent experiences with portable field olfactometers for assessing the odour nuisance of odour sources and validating the odour dispersion modelling results.
iii) Electronic Noses. The electronic nose has the potential to serve as a portable, quick, cost-effective, and non-invasive diagnostic method for initial screening to identify odour issues. In essence, electronic noses comprise an array of nonspecific chemical sensors that interact with various volatile organic compounds (VOCs) in the sample. The signal undergoes analysis using pattern recognition and multivariate statistical techniques to distinguish and categorize samples based on their volatile composition.

3.2.7.2 Adaptability to the LCA framework

The limitations of introducing the odour assessment in the LCA approach are the following:

Subjectivity. Odour perception can vary greatly among individuals and communities, making it difficult to quantify and standardize. This subjectivity introduces uncertainty into the assessment process.

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No harmonized methods. Until now there is no standardized methodology at a global level for measuring odour during the production of BBFs, however there are European regulations that have contributed to defining a methodology. Nevertheless, methodologies to evaluate odour (with the concomitant release of volatile compounds) during the application of BBFs have been scarce.

Data availability. Reliable data on odour emissions, including Odor Threshold Values, are often limited, or outdated. This lack of data hampers the accuracy and reliability of odour impact assessments within LCA.

Chemical heterogeneity. Odours are typically composed of complex mixtures of volatile organic compounds, which can vary in composition and concentration. Assessing the environmental and human health impacts of these compounds accurately is challenging.

Spatial and temporal variability. Odour emissions can vary spatially and temporally, influenced by factors such as weather conditions, terrain, and proximity to receptors.

3.2.7.3 Case studies

Peters et al. (2014) developed a general framework to include odour into LCA framework including midpoints and endpoints impacts (Fig. 3).

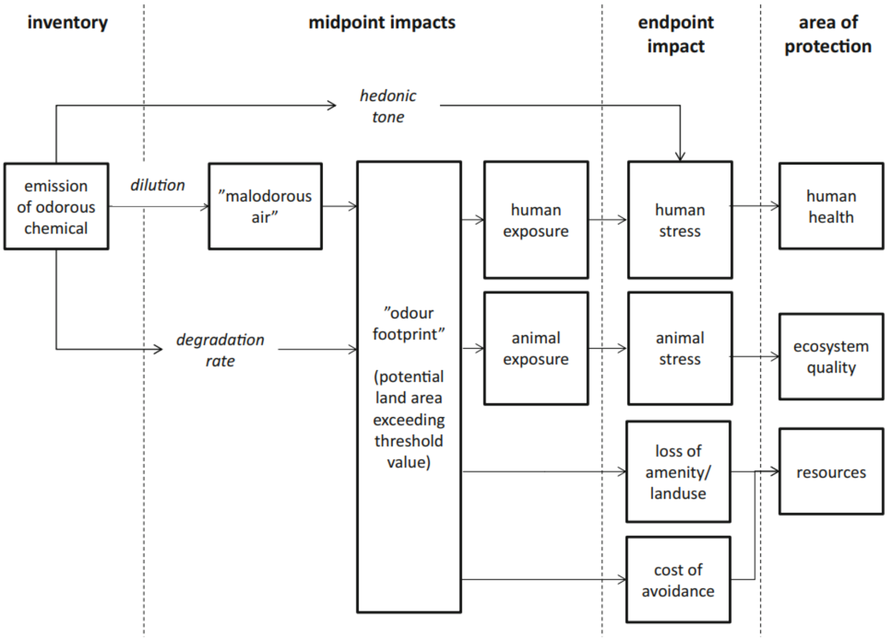

Figure 3. General framework for odour LCA. Source: Peters et al 2014.

The main conclusions were the Odor Threshold Values in LCA guiding documents have not been updated with more accurate and consistent values since the early 90s, and there has been limited effort to incorporate chemical fate considerations into odour Life Cycle Impact Assessment.

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3.3 Conclusions

BBFs demonstrate significant potential for reducing the use of mineral-based fertilizers, a trend observed across several countries including Belgium, China, Croatia, India, Denmark, France, Germany, Hungary, the Netherlands, and Spain. This preference is due to their lower cost, coupled with benefits such as enhanced soil health, the utilization of local waste streams, and reduced environmental impacts compared to mineral fertilizers. However, there is no adequate assessment approach that provides adequate information and guidance for its evaluation. These approaches often fail to adequately consider factors like seasonality, regional variations, and the intricate complexities of agricultural waste management chains and raw material sourcing during BBF production. Furthermore, gaps persist in assessing agronomic performance, particularly in terms of crop yield and soil health, with existing literature predominantly focused on production rather than field application phases.

The bibliometric analysis showed the key environmental impacts associated with BBFs including alterations in soil health, dynamics of carbon sequestration, effects on biodiversity, and heavy metal content. While these impacts have been partially addressed within the LCA framework, methodological limitations hinder comprehensive evaluations, notably in constructing Life Cycle Inventories (LCI) and establishing characterization factors reflecting local and regional environmental damages. Complementary non-LCA methodologies or indicators are deemed necessary to enhance effectiveness, a proposition to be explored further in task 2.3.

Various methods exist for assessing soil health, ranging from traditional soil sampling to modelling and earth observation techniques. Combining these methods through hybrid modelling offers promise in generating detailed datasets suitable for LCA evaluations. Similarly, the dynamics of SOC have been extensively studied, with modelling proving effective in evaluating the impact of BBF application.

Efforts to measure biodiversity loss and toxicity due to heavy metals or emerging contaminants predominantly rely on ecotoxicological methods, though challenges persist in capturing comprehensive data under varying environmental conditions. Addressing emerging contaminants like microplastics and odours presents analytical challenges, highlighting the need for standardized methodologies and frameworks for inclusion in LCA.

Augmenting LCA with additional indicators, including non-LCA metrics and circularity indicators, promises a more robust evaluation of BBFs throughout their life cycle. This integrated approach facilitates clearer communication of environmental performance outcomes and underscores the transition toward more circular systems.

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4. Main conclusions

Functional Units and Reference Flows:

- Clear and standardized definitions of functional units and reference flows are crucial in LCA studies.
- While standard guidelines exist, interpretations may vary, posing challenges in standardization and comparability.
- The PEF Guide and EPD-PCR documents provide instructions, but challenges persist, especially in defining functional units for BBFs.
- Recommendations include adherence to ISO standards and explicit definitions to improve comparability and consistency.

System Boundaries in Environmental Assessments:

- The system boundary is vital for determining environmental impact throughout a product's life cycle.
- Variations exist in defining and applying system boundaries across different standards and guidelines.
- Trends in BBF studies show a preference for cradle-to-gate boundaries, but challenges remain in handling biomass feedstock.
- Recommendations call for consensus-driven approaches and clarity in reporting to ensure robust assessments.

Life Cycle Impact Assessment (LCIA) Methods:

- LCIA aims to evaluate potential environmental impacts throughout a system's life cycle.
- Different standards adopt nuanced approaches, but criticism exists, particularly towards the rigidity of the PEF method.
- Studies on BBFs reveal diverse landscapes in applying LCIA methods.
- Methodological considerations are crucial for meaningful comparisons and comprehensive assessments.

Allocation for Recycling:

- Different LCA guidelines provide varying approaches and features for allocation in recycling.
- The PEF Guide mandates the Circular Footprint Formula, but challenges exist, including compatibility issues and methodological concerns.

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- Recommendations emphasize standardized approaches and clarity in reporting to enhance comparability.

Carbon Accounting:

- Reporting fossil and **biogenic** carbon emissions and removals separately is crucial for a comprehensive assessment.
- Variability exists in guidelines, with some lacking specific provisions regarding carbon storage and delayed emissions.
- Recommendations stress clear and consistent reporting to ensure accurate environmental assessments.

Common Steps for Allocation Procedures:

- LCA standards prioritize methods like subdivision or system expansion to avoid allocation whenever possible.
- Specific guidelines for bio-based products emphasize detailed allocation processes and sensitivity analysis.
- Allocation of waste follows the 'polluter pays principle,' but challenges remain in handling reuse, recycling, or recovery.
- Guidance for BBF production through recycling underscores the importance of clear attribution of environmental impacts.

Non-LCA indicators

- The bibliometric analysis identified 114 scientific publications assessing the environmental impacts of various BBFs using non-LCA methodologies, providing a comprehensive overview of research in this area.
- Scientific production concerning BBFs can be segmented into two distinct periods. The initial period (2001-2015) reported less than 5 publications annually, while the subsequent period (2016-2023) experienced exponential growth, attributed to the emergence of circularity concepts and global regulatory shifts promoting nutrient recovery technologies.
- A significant proportion of publications focus on evaluating environmental impacts during BBF production, showcasing diverse methodologies. Conversely, a limited number of studies explore the effects of field application, indicating an area ripe for further investigation.
- Main environmental concerns associated with BBF production and use have been identified, including alterations in soil health, dynamics of carbon sequestration and

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SOC fluxes, impacts on biodiversity, heavy metal content, and the presence of emerging contaminants such as organic pollutants, microplastics, and odours.

Main environmental concerns.

- The most suitable methods for assessing changes in **soil health** and **SOC** contents involve hybrid modelling, combining sampling techniques, modelling approaches, and soil observation methods (e.g., the LUCAS survey and ESDAC 2.0). However, integrating these methods into LCA encounters challenges such as model complexity, spatial and temporal variability, and limited understanding of long-term effects (e.g., **carbon sequestration**).
- Various methods and tools have been developed to assess **biodiversity** loss, primarily focusing on economic and social impacts. Predominantly used non-LCA methods include GLOBIO and IUCN, yet they currently lack the capacity to comprehensively capture all environmental pressures and biodiversity proxies necessary for accurate metrics. Coupling these methods with LCA requires the development of approaches that consider ecosystem services.
- Ecotoxicological methods, human risk assessment, and fate models are employed to identify potential health hazards associated with **heavy metals** and certain **organic pollutants** throughout the BBF life cycle stages.
- Emerging contaminants like **microplastics** and **odour** demand further research and standardized methodologies to develop effective models for their transport, accumulation, and allocation. This is essential for distinguishing whether these contaminants pose environmental or human health concerns.

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Annex 1

Publication list from the bibliometric analysis

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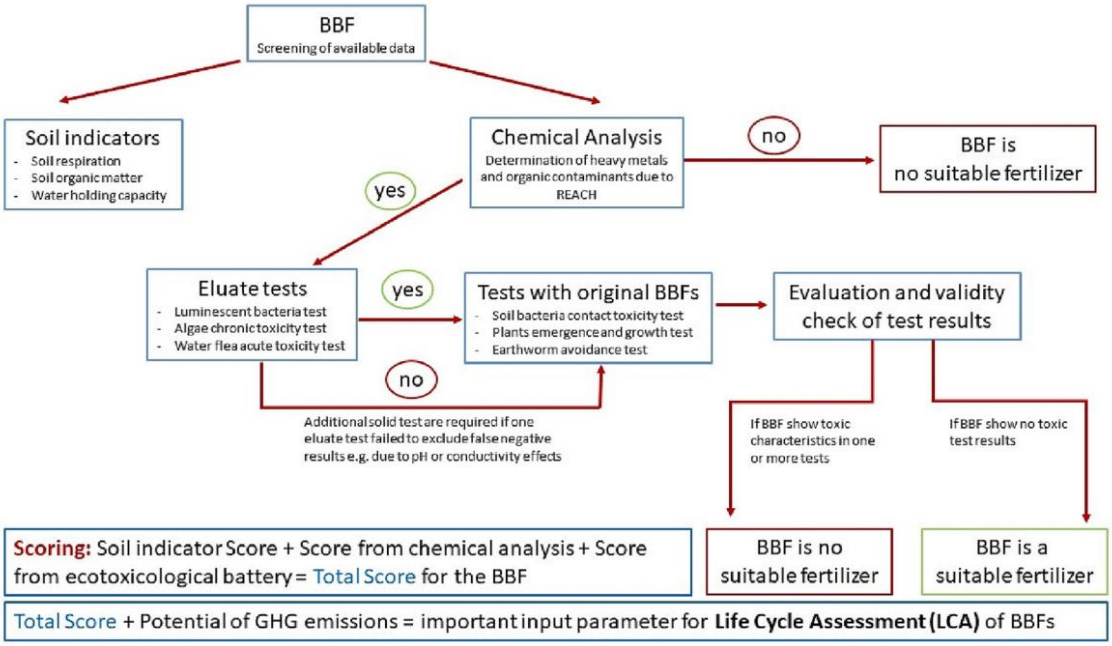
Annex 2

Decision tree developed by Albert and Bloem (2023) for the evaluation of BBFs by ecotoxicological studies in combination with chemical characterization and soil indicator evaluation.



Source: Albert and Bloem, 2023.

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