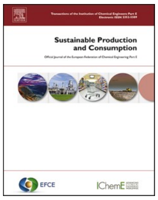
Sustainable Production and Consumption 56 (2025) 460–476

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc



Assessing environmental impacts of various biofertilizers in Europe: A step toward circular economy transition

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ARTICLE INFO

Editor: Dr. Cecile Chéron-Bessou

Keywords:
Compost
Biofertilizer
Biostimulant
Life Cycle Assessment
Environmental impacts
Comparative analysis
Circular economy

ABSTRACT

Composts, biofertilizers, and biostimulants are emerging as key solutions for sustainable agriculture, contributing to nutrient cycles closure and resource efficiency. This study evaluated the environmental impacts of three composts, three biofertilizers, and two biostimulants produced in Ukraine, Denmark, and Sweden using a life cycle assessment approach. The analyzed products include low and high biology compost, vermicompost, insect frass, digestate, biochar, fish hydrolysate, and compost tea. Environmental impacts were assessed from production to farm gate delivery, using functional units based on nitrogen, phosphorus, and potassium contents. To date, no comparative studies have evaluated biofertilizers, biostimulants, and composts based on their nutrient content, highlighting the novelty and innovative nature of this research.

The results revealed that digestate is the most environmentally favourable option for mitigating climate change impacts per tonne of nitrogen and potassium, while vermicompost is optimal for phosphorus due to its high intrinsic content. Fish hydrolysate has the highest impact on acidification, with potassium being the nutrient contributing more to this impact. Compost tea is the most water-consuming biostimulant, and it has the highest impact on eutrophication and land use per tonne of nitrogen, compared to the other products. Interestingly, biochar emerged as the least impactful in terms of acidification, eutrophication, land use, and water use across all three nutrients. Low biology compost, high biology compost, and insect frass are environmentally friendly options, demonstrating low impact across all categories. The sensitivity analysis results highlight the impact of nitrogen and phosphorus mineral fertilizer equivalents on environmental outcomes. Significant changes were observed in land use, freshwater eutrophication, and acidification, while climate change and water-use impacts remained stable.

Selecting the appropriate composts, biofertilizers, and biostimulants can enhance circularity and minimize environmental impacts. This study provides valuable insights to help decision-makers advance sustainable agricultural practices.

Abbreviations: BSF, Black Soldier Fly; C, Carbon; CHP, Combined Heat and Power; DBF, Digestate Biofertilizer; DLR, Direct Leachate Recirculation; GHG, Greenhouse Gas; K, Potassium; KMFE, Potassium Mineral Fertilizer Equivalent; LCA, Life Cycle Assessment; MFE, Mineral Fertilizer Equivalent; N, Nitrogen; NMFE, Nitrogen Mineral Fertilizer Equivalent; NPK, Nitrogen, Phosphorus, Potassium; NUBiP, National University of Life and Environmental Sciences of Ukraine; P, Phosphorus; PEF, Product Environmental Footprint; PMFE, Phosphorus Mineral Fertilizer Equivalent; SFS, Soil Fertility and Structure; SLU, Swedish University of Agricultural Sciences; TSP, Triple Super Phosphate.

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https://doi.org/10.1016/j.spc.2025.04.012
Received 8 November 2024; Received in revised form 6 April 2025; Accepted 14 April 2025

1. Introduction

The global population is expected to increase by 35 % over the next 40 years (Penuelas et al., 2023), driving a 70 % rise in food production demands to sustain this growth (Jamaludin et al., 2022). To meet these challenges, the agricultural sector has increasingly relied on synthetic fertilizers, which are essential for boosting crop yields in a world where fewer individuals are engaged in farming (Rachel Bailleau, 2023). Approximately 113 million tonnes of fertilizers per year are applied in agriculture across 110 countries (Liu et al., 2015). Between 2019 and 2021, EU-27 countries imported an average of 26 million tonnes of mineral fertilizers annually from Russia, Egypt, Algeria, Morocco, and Belarus, linking agricultural productivity with international trade and geopolitical factors (European Commission, 2022a). The rising costs of natural gas, a key input in nitrogen fertilizer production, led to a 70 % reduction in ammonia production within the EU, causing a sharp increase in fertilizer prices and raising concerns about affordability and global food security (European Commission, 2022a). However, this reliance on synthetic fertilizers has significant environmental impacts, with each tonne of mineral fertilizer produced emitting an average of 9.7 TCO_2eq in Europe (European Biogas Association, 2015). Additionally, scientific literature show that only about half of the applied fertilizers are absorbed by crops, while the rest contributes to pollution, including climate change, eutrophication of freshwater systems, biodiversity loss, and soil acidification (Liu et al., 2015).

The increasing demand for agricultural products has also led to the generation of massive amounts of biowastes, expected to reach 3.4 billion tonnes globally by 2050 (including waste from forestry and the processing industry) (M. N. H. Sani et al., 2023). Approximately three-quarters of this biodegradable waste is disposed of, with 37 % deposited in landfills and 33 % in open dumps (M. N. H. Sani et al., 2023). These disposal practices are recognized as significant environmental hazards due to the emission of various greenhouse gases (GHGs) (Bigdeloo et al., 2021), hence the need for innovative treatments of this residue. This biowaste can be used as a key raw material to produce biofertilizers, as it can be processed into nutrient-rich organic matter that enhances soil fertility and supports agricultural practices.

The transition toward a circular economy presents a transformative approach to addressing these issues. In a circular model, waste is not merely discarded but is viewed as a valuable resource for other activities (European Commission, 2022b). Biowaste, when converted into biofertilizers, plays a crucial role in the circularity of the nutrients by recycling organic waste into valuable agricultural inputs (Chojnacka et al., 2024).

This perspective aligns with the European Commission's Green Deal and the Farm to Fork strategy, both of which emphasize sustainable agricultural practices (Boix-Fayos and de Vente, 2023). Biowaste, which can be rich in organic matter, nutrients, bioactive compounds, and microbes, is particularly well-suited as a sustainable input in agriculture (M. N. H. Sani et al., 2023). Recent studies have highlighted the potential of converting biowaste into biofertilizers (M. N. H. Sani et al., 2023), biostimulants (Caradonia et al., 2022; Muniswami et al., 2023; M. N. H. Sani et al., 2024), or compost (Visconti et al., 2023), offering a solution to reduce reliance on synthetic fertilizers, lower waste treatment costs, and sustainably enhance agricultural productivity.

Before the introduction of biostimulants, biofertilizers were defined in 2005 as products containing living microorganisms that enhance plant growth and improve crop yield (Puglia et al., 2021). The definition has since been refined to include substances with live cells of nitrogen-fixing, phosphate-solubilizing, and plant-growth-promoting organisms (Puglia et al., 2021). Biofertilizers encompass a diverse range of products derived from biomass feedstocks, typically as co-products, residuals, or by-products. These products vary by their source (e.g., wastewater, sewage sludge, animal manure, or agro-industrial residues), production method (e.g., composting, fermentation, anaerobic digestion), and chemical composition (e.g., nutrient concentration, organic or inorganic content) (Novafert, 2024).

The development of biostimulants represents a significant advancement in sustainable agriculture. These products enhance natural processes, improving nutrient uptake, nutrient use efficiency, resistance to abiotic stress, and quality traits, in contrast to synthetic fertilizers, which directly supply nutrients (Ali et al., 2021). Biostimulants come in various formulations, including humic substances, seaweed extracts, beneficial microbes, chitosans, protein hydrolysates, and inorganic elements such as silicon (du Jardin, 2015;M. N. H.; Sani et al., 2021). The global plant biostimulant market, valued at $2.19 billion in 2018 (Landeta and Marchant, 2022), is expected to grow to $5.6 billion by 2026 (Albrecht, 2019), with Europe holding 42 % of the market share (Landeta and Marchant, 2022). Compost, likewise, plays a vital role in sustainable agriculture by converting organic waste into nutrient-rich material that improves soil health, reduces erosion, enhances water retention, and reduces GHG emissions. Despite being a long-established technology, composting is gaining renewed interest as an effective and beneficial waste management strategy (Bernal et al., 2009).

While biofertilizers, biostimulants, and composts hold potential for reducing environmental impacts, is necessary to validate their environmental effectiveness. In this context, Life Cycle Assessment (LCA) is an extensive method for quantifying the environmental impacts associated with processes or products throughout their life cycle (European Commission, 2022c). To the best of our knowledge, no comparative studies have been conducted on biofertilizers, biostimulants, and composts based on their nutrient content.

Therefore, this study aimed to conduct an environmental evaluation comparing different types of compost, biofertilizer, and biostimulants based on their nutrient content. The selected case studies for compost include low biology compost, high biology compost, and vermicompost. For biofertilizers, the case studies include biochar, digestate, and insect frass. For biostimulants, the case studies include fish hydrolysate and compost tea.

The fish hydrolysate assessed was produced by the Research and Production Centre «FOREL» in Ukraine. The other products were developed under the supervision of various institutions: vermicompost, compost tea, and biochar by the National University of Life and Environmental Sciences of Ukraine (NUBiP), low biology compost and high biology compost by the Department of Plant and Environmental Sciences at the University of Copenhagen (UCPH), insect frass by the Swedish University of Agricultural Sciences (SLU) and digestate by the Gasum Jordberga biogasanläggning plant in Sweden.

1.1. Literature review

Different studies have investigated the environmental impacts of composting (Serafini et al., 2023; Boldrin et al., 2010). For instance, a study conducted in Malaysia developed by Keng et al. (2020a, 2020b) demonstrated that the finished compost met Malaysia's organic fertilizer standards, highlighting the feasibility of this low-cost process. The LCA showed that using composting to replace landfill for food waste, and substituting chemical fertilizers with the produced organic compost, can significantly reduce environmental impacts, particularly concerning global warming potential, ecotoxicity, eutrophication, and fossil fuel depletion.

Composting has also been compared with anaerobic digestion in several studies (Le Pera et al., 2022;Hansen et al., 2006). These studies found that anaerobic digestion is more environmentally beneficial than direct composting of the feedstock. However, there is a lack of research on the environmental impacts of low-biology compost, and high-biology compost. A review article by Upadhyay et al. (2024) explores the combined role of bio-waste degrading microbes and plant growth-promoting microbes in enhancing bio-based fertilizers that boost plant growth while supporting a bio-circular economy. The review highlights the need for research to identify potential bacteria that can efficiently decompose bio-waste and convert it into substrates for fertilizers and other valuable products. In addition, the study showed that pelletizing and drying agro-biowaste compost improves its technical, financial, and environmental performance by enhancing storage, handling, and utilization efficiency. This study optimized process parameters to improve pellet density, crushing energy, and moisture diffusion, while also evaluating its impact on soil, plant growth, and the environment. The optimized pellet improved nutrient release, enhanced sweet basil growth, and reduced environmental impact by over 63 % by preventing methane emissions from untreated compost (Sarlaki et al., 2021).

For vermicomposting, its environmental impact has not been extensively studied. Only three studies have assessed its impact on organic waste management, using feedstock as the functional unit. A study by Dey Chowdhury et al. (2022) demonstrated that vermicomposting technology has the potential to significantly reduce GHG emissions compared to conventional waste processes, positioning it as an environmentally friendly alternative. A study by Komakech et al. (2016) on manure found that vermicomposting is more effective in reducing global warming and eutrophication potential compared to the open dumping of untreated manure. Additionally, Komakech et al. (2015) conducted a study on biodegradable waste, comparing anaerobic digestion, composting, vermicomposting, and fly larvae waste treatment using LCA. The study assessed impact categories such as energy use, global warming potential, and eutrophication potential. The results showed that anaerobic digestion performed best across all categories. However, effective management of the anaerobic digestion process is essential, as methane losses must be carefully minimized to prevent contributing to global warming. Concerning biochar, several studies have assessed its impact using different functional units, focusing either on upstream flow, such as the amount of biomass utilized (Hamedani et al., 2019), or on downstream flows, such as the biochar produced (Hammond et al., 2011). These studies employed various system boundaries and allocation methods (Keng et al., 2020a, 2020b), including system expansion (Bernal et al., 2009) (Boldrin et al., 2010) and the cut-off approach (Smebye et al., 2017). For example, Struhs et al. (2020) and Hamedani et al. (2019) evaluated the environmental impacts of biochar production from forest residues and manure via the pyrolysis process, using functional units based on the mass of feedstock and the mass of product, respectively. Only one study, conducted by Oldfield et al. (2018), has compared biochar with other waste management methods. This study compared biochar, compost, and a biochar-compost blend in terms of acidification, eutrophication, and global warming potential impact categories. The findings revealed that biochar, compost, and the biochar-compost blend all resulted in lower environmental impacts compared to mineral fertilizers from a systems perspective. The biochar-compost blend improved both nutrient availability and carbon sequestration. Additionally, it produced yields comparable to those of mineral fertilizers, making it more likely to be accepted by farmers while also reducing environmental impacts. Struhs et al. (2020) further explored the market opportunity and sustainability benefits of converting manure to biochar on-site using a portable refinery unit. Techno-economic and environmental impact assessments were conducted on a real case study in Twin Falls, Idaho, USA. The study found that optimizing on-site operations and manure moisture content can reduce biochar production costs and lower the carbon footprint of manure management. Processing cattle manure near collection sites helps address key sustainability challenges and supports biochar industry growth.

In addition to biochar and compost, different studies have investigated the potential use of insect frass as an organic fertilizer (Nugroho et al., 2023; Dzepe et al., 2022). However, only a few studies have specifically focused on the sustainability and environmental consequences of using insect frass as a biofertilizer. These studies are limited to understanding the impact of post-composting of frass (Song et al., 2021) or to developing a conceptual framework that includes the use of frass(Paris et al., 2024). Several studies have examined the environmental impact of producing and utilizing larval biomass derived from waste bioconversion, which, along with frass, is one of the key products obtained through this technology (Smetana et al., 2019). Nevertheless, significant knowledge gaps remain regarding the use of insect frass and its associated environmental benefits.

While many studies explore the use of digestate, most have compared anaerobic digestion with incineration (Matsuda et al., 2012; Evangelisti et al., 2014), or landfilling (Evangelisti et al., 2014), with a research focus on climate change. In these studies, anaerobic digestion was evaluated as a method for managing waste, therefore, a functional unit based on the “feedstock” was used. However, some studies have also used a functional unit based on “energy output”, as reported by Mezzullo et al. (2013). In all these studies, anaerobic digestion was identified as the most favourable treatment option. In a study by Styles et al. (2018), an LCA was applied to compare the conventional management of 1 m^3 of liquid digestate from food waste with the production and use of digestate biofertilizer (DBF) extracted from LD, considering its efficacy in improving soil fertility and structure (SFS). The avoidance of CH_4, N_2O, and NH_3 emissions from LD handling, combined with improved SFS through the more efficient use of nutrients in the versatile DBF product, could lead to environmental savings in sulphur dioxide, phosphate, carbon dioxide equivalent, and energy consumption. Another study by Temizel-Sekeryan et al. (2021) assessed the potential environmental impacts of the struvite recovery process from the liquid portion of anaerobically digested dairy cow manure in Wisconsin, USA, using LCA for both bench-scale and farm-scale scenarios. The struvite precipitation process, which involves additional chemical inputs and energy use, was assessed to understand its upstream impacts. The results showed up to a 78 % reduction in eutrophication potential when P and N were recovered as struvite and used instead of conventional fertilizers. However, significant differences in most environmental impact categories were observed when the process was scaled up to the farm level.

The literature review on compost, biofertilizers, and biostimulants, including biochar, insect frass, vermicomposting, anaerobic digestion, and fish hydrolysate, highlights the diverse environmental impacts and benefits associated with their application. However, it also underscores the variability in results due to differences in LCA methodological approaches and the lack of standardized studies for certain biofertilizers and biostimulants. For example, while insect frass shows promise as a biofertilizer, comprehensive environmental studies specifically examining its sustainability and impacts are lacking. Similarly, the environmental impact of fish hydrolysate and compost tea as a biostimulant remains largely unexplored, highlighting the need for further research to fully assess its potential benefits and implications.

In cases where LCA studies are available, the results are highly dependent on factors such as system boundaries, allocation methods, functional units used, and the specific impact categories assessed.

Despite the acceptance of LCA as a tool for evaluating environmental performance, there is a lack of clear guidance on its application to assess environmental impacts of biofertilizer production systems. A review study by Egas et al. (2023) examined the extent to which LCA standards and guidelines are properly implemented, based on an analysis of 48 documents (8 standards and guidelines, 40 studies). Most studies considered biofertilizer as the main product, but applying standards was challenging. Common issues included unclear definitions of study objectives and inadequate justification for methodological choices, such as the selection of functional units, allocation criteria, biogenic carbon management, and assumptions regarding feedstock end-of-life. Therefore, selecting the appropriate methodological approach is essential for harmonization and facilitating meaningful comparisons across studies. As highlighted, studies have employed different functional units, allocation methods, and impact assessment approaches.

Overall, while significant progress has been made in understanding the environmental impacts of various compost types, biofertilizers, and biostimulants, several gaps still exist.

2. Methods

To assess the environmental impacts of composts, biofertilizers, and biostimulants, a LCA was conducted following ISO 14040 standards and Product Environmental Footprint (PEF) Guidelines (EC, 2021). As the most widely used method for environmental impact assessment, LCA ensures consistency and scientific credibility (ISO 14040, 2006).

2.1. Goal and scope definition

This study applies the LCA approach to evaluate and compare the environmental impacts of eight products using real production data from Ukraine, Denmark, and Sweden. A nutrient-based functional unit was used to enable a consistent and meaningful comparison, offering a comprehensive perspective on their sustainability and environmental performance. Therefore, the objective is to generate insights that support and inform sustainable agricultural practices.

The technologies used in these case studies to produce composts, biofertilizers, and biostimulants are not new. However, black soldier fly composting to produce insect frass is a relatively new and innovative method. Comparing the environmental impacts of these technologies offers a critical evaluation of newer methods with traditional ones.

The study assesses the environmental impacts from feedstock collection to the production site, including the manufacturing of the finished product. The products under analysis include:

- The low biology compost (low fungal: bacterial ratio) and high biology compost (High Fungal: bacterial ratio compost extract) produced in Denmark.
- Insect frass and digestate produced in Sweden.
- Vermicompost, compost tea, biochar, and fish hydrolysate produced in Ukraine.

2.1.1. Functional unit definition

Defining the functional unit for biofertilizer products is challenging due to their multiple functions (Novafert, 2024). This highlights the need to develop a common functional unit for all biofertilizers that accurately reflects their final function. Previous studies have commonly used functional units related to the mass of the feedstock, with some using the mass of the product. The choice of functional unit in this context depends on the system's purpose: if the system aims to process organic waste from a disposal perspective, the functional unit is based on the input feedstock mass. Conversely, if the focus is on waste valorization, the functional unit is based on the mass of the product (Serafini et al., 2023).

Using 1 kg of fertilizer product for agricultural application as the reference flow are suggested in (Novafert, 2024). However, since biofertilizers vary in their physical and chemical properties and have diverse applications, using emissions per kilogram of fertilizer product is inappropriate if the fertilizers do not contain the essential nutrients in the same proportions. Using one kg as the functional unit is limited if the goal is to compare different fertilizer products. Therefore, PEF recommends defining the functional unit based on nutrient content and application parameters, specifying the reference flow, considering the time frame, and aligning units with industry standards.

In the present study, a functional unit based on nutrient content was used to compare compost, biofertilizer, and biostimulant products. Since the specific nutrient for which the products will be used is not defined, the three most critical nutrients for plants, nitrogen (N), phosphorus (P), and potassium (K), have been considered as functional units for all the compost, biofertilizer, and biostimulant products. Thus, the study was carefully conducted using three functional units: One tonne of N, one tonne of P, and one tonne of K.

The selection of these functional units was based on the need for a comparable metric that accounts for the varying nutrient compositions of biofertilizers, composts, and biostimulants. The products evaluated in this study contain different contents of potassium, P, and K, using a mass-based unit (such as kg of product) would not allow for a fair comparison. Instead, a nutrient-based functional unit ensures that the environmental impacts of each product are assessed based on the actual amount of plant-available nutrients they provide rather than just their total mass. Additionally, applying nutrients to crops is considered the primary driver of the production of these products, which further supports the selection of the mentioned functional units.

2.1.2. System boundaries

The system boundary in this study is cradle to gate, meaning the impacts are calculated from raw material extraction to the production of biofertilizers, up to the farm gate. The system boundaries for each compost, biofertilizer, and biostimulant are presented in Figs. 1, 2, and 3, respectively. All composts, biofertilizers, and biostimulants are assumed to substitute a certain amount of NPK (Nitrogen, Phosphorus, Potassium) fertilizers. The used NPK fertilizers are urea, triple superphosphate, and potassium chloride, respectively. The exact quantities avoided are explained in Section 2.1.3.2. The production methodologies and details for all products are provided in Section 3.2.

2.1.3. Avoided burdens

System expansion was used to account for the environmental benefits associated with co-product production and the substitution of conventional mineral fertilizers with bio-based fertilizers.

This method guarantees that the generated co-products with the production of biofertilizers are not treated as waste but as valuable by-products which displace the need for conventional alternatives.

Furthermore, the avoided use of mineral fertilizers was quantified by calculating the Nitrogen, Phosphorus, and Potassium Mineral Fertilizer Equivalents (NMFE, PMFE, KMFE). These values indicate how much of each nutrient in the products corresponds to an equivalent quantity in conventional mineral fertilizers.

2.1.3.1. Avoided burdens from co-products. Biochar, insect frass, and anaerobic digestion are systems that produce not only biofertilizers but also co-products. These co-products include bio-oil and syngas from biochar process, larvae biomass from the insect frass process, and biomethane from anaerobic digestion.

- Biochar Process: bio-oil and syngas can replace thermal and electricity energy sources.
- Insect Frass Process: Larvae biomass can serve as a protein-rich feed ingredient, reducing reliance on conventional animal feed sources.
- Anaerobic Digestion: Biomethane can substitute natural gas, reducing dependence on fossil fuels.

According to ISO 14040, allocation should be avoided whenever possible in systems with multi-functional processes (ISO 14040, 2006). Thus, to account adequately for the co-products in these systems, the system expansion approach was used. More details are provided in the inventory data.

2.1.3.2. Avoided burdens from mineral fertilizers. To estimate the avoided use of N, P, and K mineral fertilizers, a literature review was conducted. This review aimed to determine NMFE, PMFE, and KMFE for composts, biofertilizers, and biostimulants. The goal was to assess their potential as substitutes for conventional NPK fertilizers. NMFE, PMFE, and KMFE represent the equivalent percentage of N, P, and K provided by each product compared to mineral fertilizers. These percentages were used to calculate the amount of N (from urea), P (from triple superphosphate), and K (from potassium chloride) that would be avoided.

Table S1 in Supplementary Material 1 presents the nutrient content and corresponding mineral fertilizer equivalents (MFE) for each

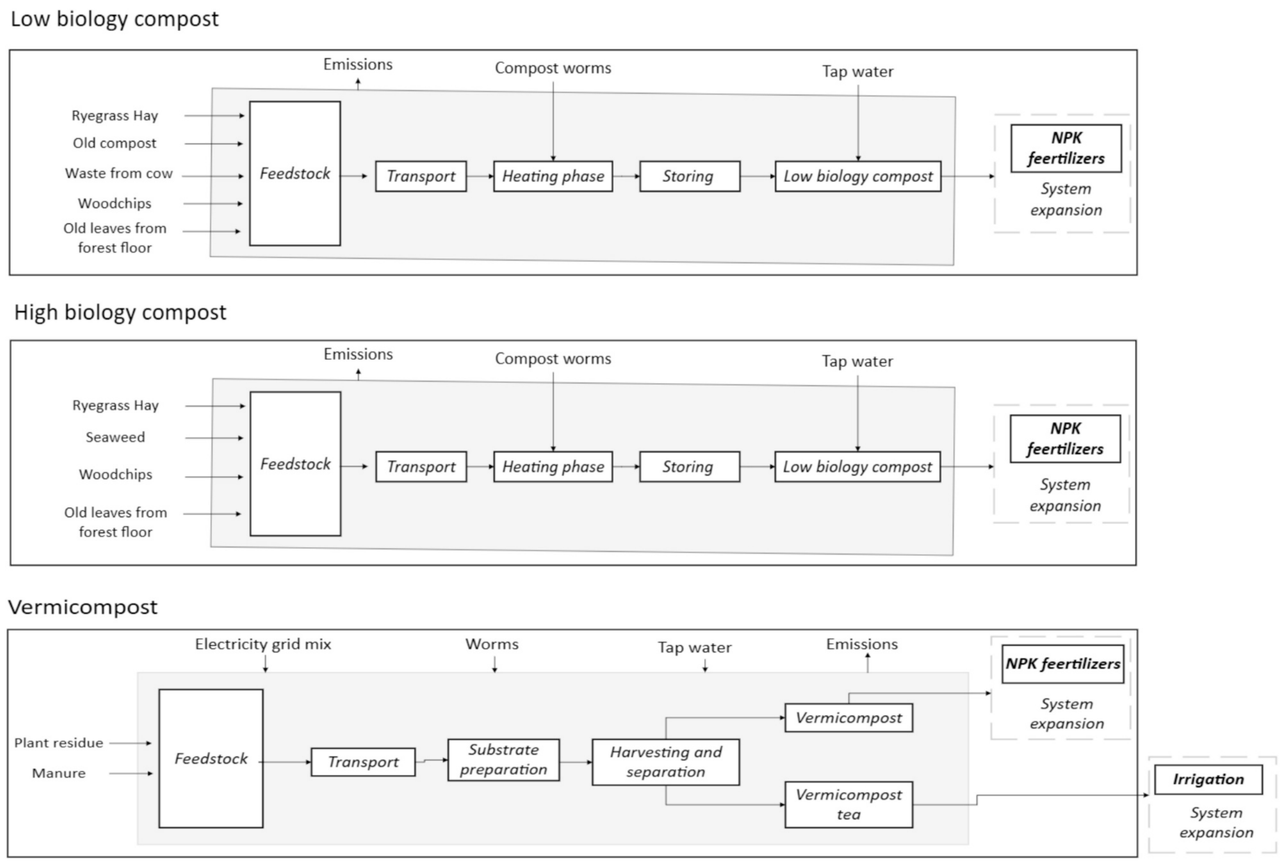


Fig. 1. System boundaries for composts.

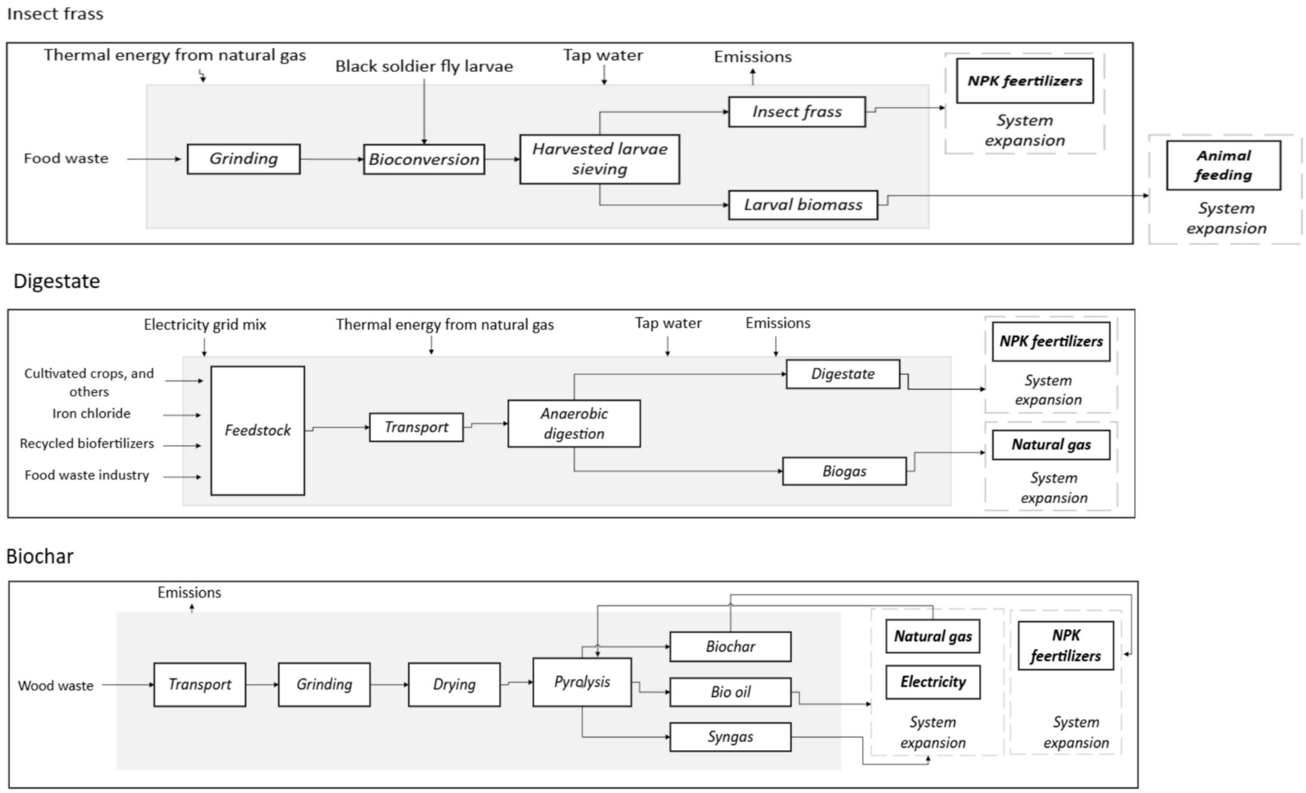
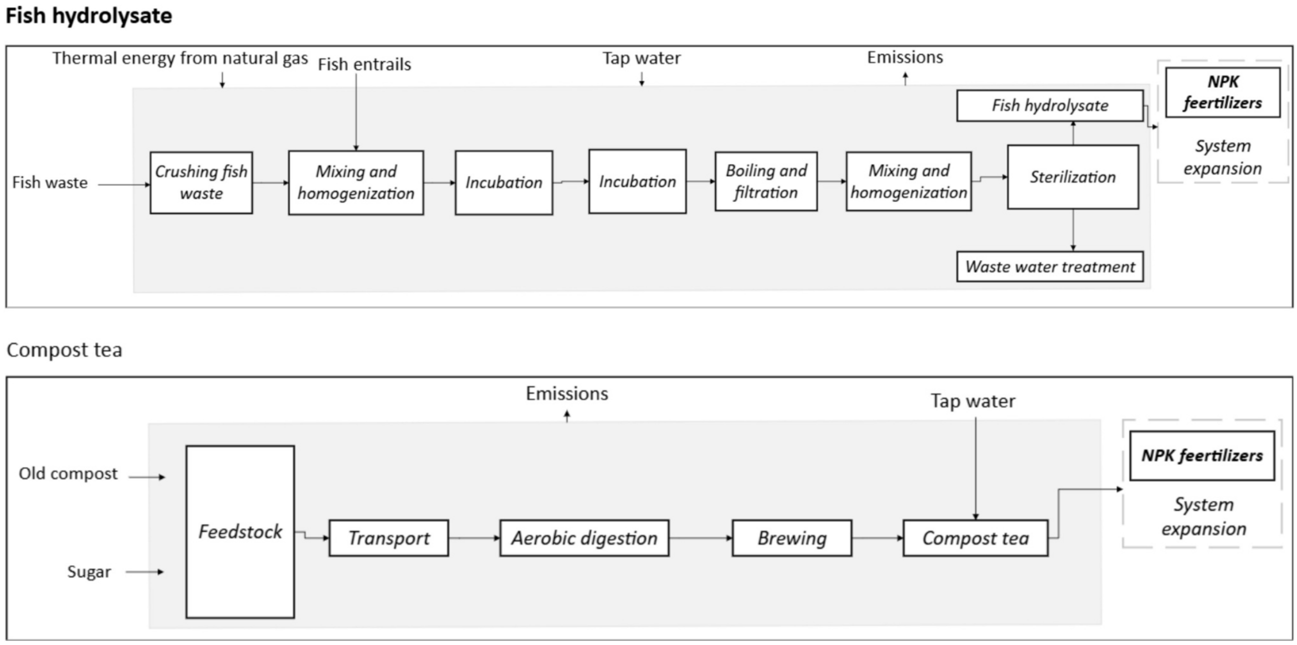


Fig. 2. System boundaries for biofertilizers.


Fish hydrolysate

Compost tea

Fig. 3. System boundaries for biostimulants.

product, along with detailed descriptions and methodologies used to estimate NMFE, PMFE, and KMFE.

2.1.4. *Life cycle impact assessment: impact categories and method selection*

According to the PEF Guidelines (EC, 2021), the environmental evaluation of biofertilizers must include at least three relevant impact categories. Relevance is defined as those categories that together contribute at least 80 % of the total environmental impact, excluding toxicity-related categories.

Therefore, in this study, three impact categories contribute at least 80 % to the total environmental impact were considered and analyzed in detail. These categories are climate change, acidification, and land use. Additionally, freshwater eutrophication and water use were also examined extensively. However, results for all the impact categories of the selected method are presented (Supplementary Information 2, Tables S2, S3 and S4). Those impact categories are:

- Acidification potential (AP, mole of H^+ eq),
- Climate change total (CC, kg CO_2 eq),
- Freshwater ecotoxicity (Ecotox-water, CTUe),
- Freshwater eutrophication (Eu-water, kg P eq),
- Marine eutrophication (Eu-marine, kg N eq),
- Terrestrial eutrophication (Eu-T, mole of N eq),
- Human toxicity-cancer (HT-cancer, CTUh),
- Human toxicity-non_cancer (HT- non_cancer, CTUh),
- Ionizing radiation-human health (IR, kBq U235 eq),
- Land use (LU, Pt),
- Ozone depletion (OD, kg CFC − 11 eq),
- Particulate matter (PM, disease incidences),
- Photochemical ozone formation (POF, kg NMVOC eq),
- Resource use-fossils (RU-fossils, MJ),
- Resource use-mineral and metals (RU-mineral, kg Sb eq), and
- Water use (water, m^3 world equivalent).

The Environmental Footprint 3.1 method, recommended by the European Commission (European Commission, 2017) was selected to evaluate all the chosen impact categories.

LCA for experts' software (version 10.8.0.14) was used for the computation of all the inventories and impact categories calculations.

2.2. *Life cycle inventory data*

The inventory data was provided by the NUBiP, the Department of Plant and Environmental Sciences at the UCPH, the SLU, the Research and Production Centre «FOREL» in Ukraine and the Gasum Jordberga biogasanläggning plant in Sweden. Missing emissions and avoided mineral fertilizer were calculated using literature data, and the inventory was completed using the LCA for expert's database.

The inventory data is provided per 1 kg of the finished product. The nutrient mass in 1 kg of product is determined based on the nutrient content (%) of each product. Finally, 1 t of N, 1 t of P, and 1 t of K are chosen as the functional units.

2.2.1. *Low biology compost*

Low biology compost is characterized by a lower fungi content and contains more bacteria, protozoa, and nematodes than the “high fungal compost”. The materials used to produce this compost are 40 % late cut hay of low feeding value, 10 % waste from cow trough and grass silage waste, 35 % rough cut wood chips, 10 % old leaves from the forest floor, and 5 % old compost.

The specified materials mentioned above were combined to create a pile weighing approximately 600 kg, which was then turned manually. Turning intervals were determined based on heat and time: 55 °C for 3 days and 66 °C for 2 days, with a total of three turns. Following the heating phase, the compost was stored in a Johnson Sue type cylinder with ventilation holes and covered with a nylon mesh to ensure proper air circulation. The compost was maintained at 60–70 % moisture for two years. When the temperature below 40 °C, a handful of compost worms were added. This process resulted in compost with a uniform color and texture from top to bottom. The finished compost has an NPK ratio of 7.89 %–1.97 %–3.29 %.

This process consumes only water and does not involve energy consumption. The corresponding amounts of feedstocks, water, finished low-biology compost, nutrients, and emissions are detailed in Table 1.

To estimate the emissions, several publications were reviewed to identify studies employing the same technology (windrow), feedstock types (garden waste, yard waste, woody materials), and aeration method (turned) as used in this composting method.

CO_2, CH_4, and N_2O emissions were estimated based on data obtained from published literature sources.

Table 1

Inventory data for composts (per one kg of compost).

Material	Low biology compost	High biology compost	Vermicompost
Inputs (dry basis in kg)			
Ryegrass Hay	0.30×10^1	0.16×10^1	–
Waste from cow trough, Grass silage waste	0.03×10^1	–	–
Woodchips	0.18×10^1	0.28×10^1	–
Old Leaves from the forest floor	0.06×10^1	0.14×10^1	–
Old Compost	0.02×10^1	–	–
Seaweed - algæres, washed up on shore	–	0.01×10^1	–
Post-consumer food waste	–	–	–
Plant residues (straw)	–	–	0.08×10^1
Manure	–	–	0.05×10^1
Worms	–	–	0.04×10^1
Water	1.62×10^1	1.76×10^1	2.24×10^1
Electricity (MJ)	–	–	7.30×10^{-2}
Avoided nitrogen (N) fertilizer	3.10×10^{-2}	2.00×10^{-2}	1.10×10^{-2}
Avoided phosphate (P) fertilizer	6.00×10^{-3}	6.00×10^{-3}	1.30×10^{-2}
Avoided potassium (K) fertilizer	3.20×10^{-2}	3.60×10^{-2}	2.00×10^{-2}
Transport for collecting feedstocks (km)	0.10×10^1	0.10×10^1	0.10×10^1
Outputs	–	–	–
Product	0.10×10^1	0.10×10^1	0.10×10^1
Vermicompost tea to irrigation	–	–	0.99×10^1
Nitrogen (N) content	8.00×10^{-2}	4.00×10^{-2}	2.00×10^{-2}
Phosphate (P) content	2.00×10^{-2}	2.10×10^{-2}	4.00×10^{-2}
Potassium (K) content	3.00×10^{-2}	3.50×10^{-2}	2.00×10^{-2}
Emissions to air	–	–	–
CO_2	0.11×10^1 [a]	0.11×10^1 [a]	0.01×10^1 [d]
CH_4	3.00×10^{-2} [b]	3.00×10^{-2} [b]	1.00×10^{-2} [d]
N_2O	1.00×10^{-4} [b]	1.00×10^{-4} [b]	5.60×10^{-2} [d,e]
NH_3	5.00×10^{-4} [c]	7.00×10^{-4} [c]	Was not observed

[a] (Andersen et al., 2010).

[b] (Zhu-Barker et al., 2017).

[c] (Nordahl et al., 2023) (Nguyen and Phong, 2012).

[d] (Yasmin et al., 2022).

[e] mg.

2.2.2. *High biology compost*

High biology compost is classified as compost containing a high fungal-to-bacterial biological activity ratio (high fungal: bacterial ratio compost extract), in contrast to low biology compost. The materials used for composting include 50 % finely chopped woodchips from garden cuttings, 20 % hay, 20 % old leaves from the forest floor, and 10 % seaweed (Ålegræs, Denmark), washed up on the shore.

The preparation process involved combining the specified materials and placing them in a Johnson Sue bioreactor, maintaining a moisture level of 60–70 %. After a few days, the temperature increased to 40 °C and remained at that level for one week, after which worms were added. The compost was kept at 60–70 % moisture for two years. The inventory data is presented in Table 1.

Emissions data were estimated based on low biology compost emissions. The NPK ratio in the finished compost is 4.22 %–2.15 %–3.58 %.

2.2.3. *Vermicompost*

Vermicompost was produced using plant residue (16 % Moisture Content), manure (80 % Moisture Content), and living worms as the main feedstocks. The conditions for vermicomposting include a temperature of 22 ± 2 °C, a pH range of 6.5 to 7.5, and a substrate moisture content maintained between 70 % and 80 %. The process takes 75–90 days from substrate preparation to harvest, with moisture levels kept within the70–80 % range. The resulting product, vermicompost, has a moisture content ranging from 45 % to 55 % (average 50 %) and an NPK ratio of 2.31 %–4.49 %–1.92 %. It can be used as an organic fertilizer. The inventory data is provided in Table 1. Vermicomposting also generates a by-product, vermicompost tea, obtained by removing excess moisture. However, it was excluded from this study due to the absence of a comparable irrigation process in the LCA for expert's database. Emissions were estimated based on data provided by Yasmin et al. (2022).

2.2.4. *Insect frass*

The main feedstock for the insect frass production was post-consumer food waste collected from Swedish restaurants and processed in a lab-scale facility in Uppsala, Sweden. The production of insect frass lies within the concept of using this insect larvae (in the case of this study, black soldier fly larvae) as a tool for the bioconversion of varied waste streams, which in turn enables the production of a protein and fat-rich larval biomass that can be used for animal feeding, and frass suitable for use in agriculture. Larval biomass was excluded in this study due to the lack of data in the LCA for experts database.

The bioconversion process was performed inside a climate-controlled room set at 25 ± 2 °C with 30 ± 10 % humidity. Young larvae (approximately 5 days old, 1.43 ± 0.1 mg individual weight) were obtained from a colony at the Swedish University of Agricultural Sciences (Uppsala, Sweden) and placed in plastic boxes containing 10 kg of pre-ground food waste, processed using a fruit gender. Approximately 12,000 larvae were introduced into each box (60 × 40 × 12 cm) and monitored periodically. After 11 days, larvae were harvested from the frass by sieving (mesh size 2–5 mm). Each treatment unit produced an average of 1.9 ± 0.2 kg of larvae and 2.3 ± 0.3 kg of frass. The obtained frass had an NPK ratio of 4.2 %–0.5 %–2.4 %, being rich in organic matter (82.8 ± 1.1 $\%_{DM}$) and other nutrients.

In this process, transport to collect feedstock from the restaurant was not included, as it was considered unnecessary according to the research facility. The inventory data is given in Table 2.

2.2.5. *Digestate*

Digestate is a biofertilizer obtained through the anaerobic digestion process from a Gasum Jordberga biogasanläggning biogas plant in Sweden. The main feedstocks for this system include cultivated crops, grain waste, vegetable by-products, recycled biofertilizer, iron chloride, and food waste. This process produces LD with a moisture content of approximately 92 % and an NPK ratio of 0.5 %–0.08 %–0.3 %, as well as biogas primarily composed of methane. Energy and resource usage in the anaerobic digestion process vary across stages: biogas upgrading to biomethane (purifying the gas from CO_2 and other impurities to obtain a methane concentration of 98 %) is the most electricity-intensive stage, while the anaerobic digestion itself requires the most heat. Water usage is distributed across different stages, with significant consumption during the pretreatment and digestion phase.

The produced biomethane was modelled by displacing natural gas. Only emissions from anaerobic digestion process were considered in this study, and these emissions were estimated based on data from Khoo et al. (2010). Emissions from the biogas upgrading stage were not considered, as the waste gas is assumed to be directed to a Combined Heat and Power (CHP) system where heat and electricity are generated (IEA Bioenergy, 2013). The inventory data is provided in Table 2.

2.2.6. *Biochar*

Wood waste, primarily consisting of pine, juniper, and fir residues, was used to produce biochar. These materials were ground to a size smaller than 30 mm and then dried to a minimal moisture content. The dried raw material was then loaded into the reactor chamber of the installation, where it underwent pyrolysis at an operating temperature of about 500 °C for up to 10 h. During this process, gases and liquids generated were removed from the chamber through corresponding pipelines, leaving biochar as the main product, with a moisture content of less than 1 %. The biochar produced typically weighs approximately

Table 2
Inventory data for biofertilizers (per one kg of biofertilizer).

Material	Insect frass	Digestate[a]	Biochar
Inputs (dry basis in kg)			
Post-consumer food waste	0.31×10^{1}	–	–
Residual products from food industry	–	0.014×10^{1}	–
Cultivated crops, grain waste, vegetable by-products	–	9.80×10^{-2}	–
Recycled biofertilizers	–	0.07×10^{1}	–
Iron Chloride dry	–	2.00×10^{-3}	–
Residual products from food industry	–	0.01×10^{1}	–
Wood waste	–	–	0.10×10^{1}
Heat (MJ)	0.33×10^{1}	0.09×10^{1}	0.45×10^{1}
Water	0.19×10^{1}	0.02×10^{1}	–
Electricity (MJ)	–	0.07×10^{1}	–
Avoided nitrogen (N) fertilizer	3.00×10^{-2}	5.00×10^{-3}	5.00×10^{-4}
Avoided phosphate (P) fertilizer	1.00×10^{-3}	8.00×10^{-4}	6.00×10^{-5}
Avoided potassium (K) fertilizer	2.00×10^{-2}	3.00×10^{-3}	5.00×10^{-3}
Transport for collecting feedstocks (km)	–	0.2×10^{1}	1.0×10^{1}
Outputs			
Insect frass	0.1×10^{1}	–	–
Larval biomass (40 % crude protein, 20 % crude fat)	0.08×10^{1}	–	–
Digestate	–	0.1×10^{1}	–
Biomethane	–	1.00×10^{-2}	–
Biochar	–	–	0.1×10^{1}
Syngas	–	–	3.00×10^{-3}
Bio-oil	–	–	0.3×10^{1}
Nitrogen (N) content	4.20×10^{-2}	5.00×10^{-3}	2.00×10^{-3}
Phosphate (P) content	5.00×10^{-3}	8.00×10^{-4}	2.00×10^{-4}
Potassium (K) content	2.40×10^{-2}	3.00×10^{-3}	5.00×10^{-3}
Heat recovery from syngas (MJ)	–	–	0.58×10^{1}
Electricity recovery from syngas (MJ)	–	–	0.45×10^{1}
Heat recovery from bio-oil (MJ)	–	–	3.5×10^{1}
Electricity recovery from bio-oil (MJ)	–		2.7×10^{1}
Emissions to air			
Process			
CO_2	0.05×10^{1} [c]	5.00×10^{-3} [d]	0.08×10^{1} [b]
N_2O	2.00×10^{-6} [c]	7.00×10^{-5} [d]	2.00×10^{-3} [b]
CH_4	3.70×10^{-6} [c]	1.00×10^{-5} [d]	–
Syngas combustion			
CO_2	–	–	0.13×10^{1}
CO	–	–	1.00×10^{-3}
NO_x	–	–	1.00×10^{-3}
SO_2	–	–	5.00×10^{-4}
Dust	–	–	2.00×10^{-4}
Bio-oil combustion[e]	–		
CO_2	–	–	0.51×10^{1}
CO	–	–	1.00×10^{-3}
HCl	–	–	1.00×10^{-4}
CH_4	–	–	2.00×10^{-4}
NO_x	–	–	1.00×10^{-2}
Particulates[f]	–	–	4.00×10^{-4}
SO_x	–	–	8.00×10^{-3}
VOC	–	–	5.63×10^{-5}

[a] Wet basis.
[b] Emissions communicated by the research centre.
[c] Pang et al., 2020)
[d] (Khoo et al., 2010).
[e] (Yu et al., 2020).
[f] (Steele et al., 2012).

30–40 % of the initial mass of the raw materials, depending on the specific type of wood waste used. The biochar has an NPK ratio of 0.2 %–0.02 %–0.5 %. Emissions data from the production of biochar were provided by the biochar centre. The inventory data is given in Table 2.

Syngas (a mixture of CH_4, H_2 and CO) and bio-oil are generated as co-products during the pyrolysis process. The heating value of syngas is 4.15 MJ/m^3 and the heating value of boil-oil is 25.9 MJ/kg.

CHP generation was used to recover heat and electricity from both co-products. Electrical and heat efficiencies of 35 % and 45 %, respectively, were considered (Roibás-Rozas et al., 2020). Part of the produced heat (4.5 MJ) was used to meet the internal heat requirements of the pyrolysis process, while the rest was directed to a similar product in the market, specifically thermal energy produced from natural gas. The electricity generated was sent to an electricity grid mix. Emissions from CHP were sourced from Yu et al. (2020) for syngas combustion and from Steele et al. (2012) for bio-oil combustion.

2.2.7. *Fish hydrolysate*

Fish hydrolysate biostimulant is produced from fish waste, including guts, bones, cartilage, and scales, where water constitutes 50 % of the fish mass. The process begins by crushing fish bones and heads, which are then mixed with homogenized fish entrails at a 1:1 ratio. This mixture undergoes incubation in a water bath at 37 °C for 24 h, followed by additional incubation with distilled water at the same temperature. After 12 h of incubation, the hydrolysate was boiled for 1 h, filtered, and then sterilized using the tyndallization method. The inventory data can be found in Table 3.

The final product is an organic liquid biostimulant with an NPK ratio of 0.988 %–0.135 %–0.13 %, providing essential nutrients for plant growth. Waste generated during the process was directed to a wastewater treatment facility. Emissions data were provided by the Forel Research Centre from Ukraine.

2.2.8. *Compost tea*

The production of compost tea involves mixing wet compost (30 %) with dry sugar and water under aerobic conditions at 20 °C and a pH range of 6.5–7.0. This mixture is brewed for 48 h, resulting in a liquid compost tea with a moisture content exceeding 90 %. Emissions data were estimated similarly to those for low-biology compost. The inventory data is given in Table 3. The NPK ratio of the finished compost tea is 0.005 %–0.01 %–0.012 %.

3. Results

The results of the sixteen impact categories are given in Tables S2, S3, and S4 (Supplementary Information 2). The study revealed significant variability in environmental performance among the analyzed products. Climate change, acidification potential, water-use, land use, and freshwater eutrophication impact categories are analyzed in depth in the subsequent sections.

The environmental impacts per one tonne of nitrogen (Table S2 in Supplementary Information 2) revealed that compost tea had high

Table 3
Inventory data for biostimulants (per one kg of biostimulants).

Material	Compost tea	Fish hydrolysate
Inputs (wet basis in kg)		
Compost	2.00×10^{-1}	–
Sugar (for Fermentation)	4.00×10^{-3}	–
Guts, bones, cartilage, scales	–	0.10×10^{1}
Water	8.10×10^{-1}	7.50×10^{-1}
Electricity MJ	5.00×10^{-3}	0.11×10^{1}
Avoided nitrogen (N) fertilizer	5.00×10^{-6}	2.00×10^{-3}
Avoided phosphate (P) fertilizer	3.00×10^{-5}	4.00×10^{-4}
Avoided potassium (K) fertilizer	1.00×10^{-4}	1.00×10^{-3}
Transport for collecting feedstocks (km)	0.5×10^{1}	0.15×10^{1}
Outputs	–	–
Product	0.1×10^{1}	0.1×10^{1}
Waste water	–	3.10×10^{-2}
Nitrogen (N) content	5.00×10^{-5}	1.00×10^{-3}
Phosphate (P) content	1.00×10^{-4}	1.00×10^{-3}
Potassium (K) content	1.00×10^{-4}	1.00×10^{-3}
Emissions to air	–	–
CO_2	2.30×10^{-2} [a]	1.70×10^{-5} [d]
CH_4	5.00×10^{-4} [b]	–
N_2O	2.00×10^{-6} [b]	–
NH_3	9.00×10^{-6} [c]	–
H_2	–	3.00×10^{-8} [d]
N_2	–	3.00×10^{-4} [d]

[a] (Andersen et al., 2010)

[b] (Zhu-Barker et al., 2017).

[c] (Nordahl et al., 2023) (Nguyen and Phong, 2012).

[d] Emissions communicated by the Research and Production Centre «FOREL».

impacts across several categories, including climate change, freshwater ecotoxicity, ionizing radiation, and water use, indicating a significant environmental burden. Vermicompost and insect frass consistently demonstrated lower impacts in human toxicity, freshwater ecotoxicity, and ozone depletion impact categories, highlighting their potential as more sustainable options. Biochar exhibited mixed performance, it has high impacts in some categories, such as marine eutrophication, but relatively low values in others, such as ionizing radiation. Digestate performed well in several categories, with moderate to low impacts in most impact categories.

Similarly, the environmental impacts per 1 t P and 1 t K reveal variability among the products (Tables S3 and S4-Supplementary information 2), with vermicompost and insect frass emerging as the most sustainable options, while compost tea and fish hydrolysate required detailed consideration due to their higher impacts. Interestingly, digestate showed moderate performance overall, while biochar delivered varied results, with high impacts in climate change but producing lower effects in acidification, freshwater ecotoxicity, and other categories.

3.1. *Climate change*

Results for climate change are presented in Fig. 4. Regarding N as a reference (one tonne N), digestate (80 % NMFE) is the most environmentally favourable option, followed by fish hydrolysate (64 % NMFE), with a 21 % increase in climate change (in comparison to digestate), and then insect frass (80 % NMFE), with a 22 % increase in climate change (in comparison to digestate). The primary contributor to the impacts of digestate is the heat from natural gas, whereas for fish hydrolysate and insect frass, the impacts arising from electricity use and process emissions, respectively.

Although digestate is not rich in N (0.005 kg N/kg), it shows the lowest climate change impact due to minimal emissions from the process; considering only the emissions from anaerobic digestion and excluding emissions from biogas upgrading to biomethane. The environmental benefit from biogas recovery accounted for 42 % (of the total environmental impact), and the benefit from avoiding inorganic fertilizers was 12 %. Even without considering the credit from biogas, digestate remained a better option.

Fish hydrolysate contains 0.0098 kg N/kg, which is lower than the nitrogen content of insect frass (0.042 kg N/kg), yet it yielded similar climate change results due to the low emissions reported by the research centre. The main contributor to the impacts of fish hydrolysate was the usage of electricity. The environmental benefit from avoiding inorganic fertilizers was 7 % for fish hydrolysate and 9 % for insect frass.

Compost tea and biochar delivered the highest climate change impact, primarily due to emissions. In the case of biochar, transport also contributed significantly to its overall carbon footprint.

For biochar, the emissions are associated with the combustion of syngas and bio-oil. Despite obtaining savings of 3.46×10^{6} kg CO_2eq from heat and electricity recovery, and 8.47×10^{3} kg CO_2eq from avoiding inorganic fertilizers, biochar is not considered the “perfect” and environmentally friendly option. Additionally, its impacts are linked to the low N content of both products, with compost tea containing 0.00005 kg N/kg (NMFE of 10 %) and biochar containing 0.002 kg N/kg (NMFE of 27 %).

Similarly, the influence of climate change caused by the other products was attributed to the emissions of the process. The climate

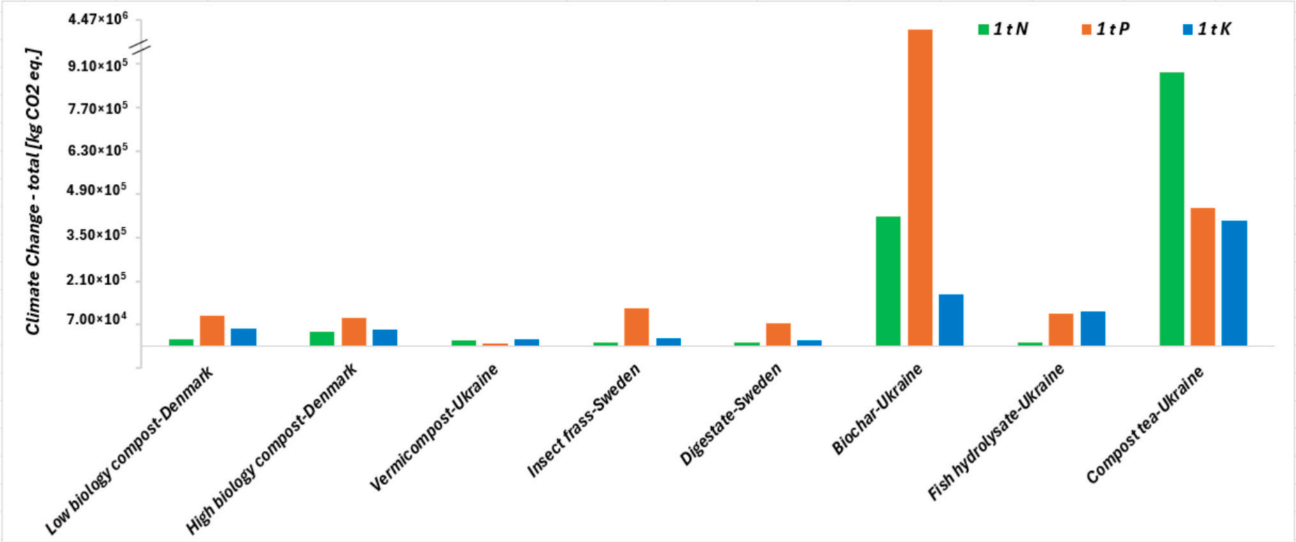


Fig. 4. Results for climate change impact (one tonne N, one tonne P, one tonne K)

change impact for high-biology compost was approximately double that of low-biology compost, as the latter contained more N (0.07 kg N/kg vs. 0.04 kg N/kg).

For one tonne P as a functional unit, and assuming a 30 % Phosphorus Mineral Fertilizer Equivalent (PMFE) for all products except digestate, which has a 50 % PMFE, vermicompost emerges as the best option due to its high P content (0.044 kg P/kg). On the other hand, biochar performed poorly because of its low P content (0.0002 kg P/kg) and higher emissions from the combustion of syngas and bio-oil, even when considering energy savings and avoiding inorganic fertilizers. Compost tea also performed poorly, with a phosphorus content of only 0.0001 kg P per kg of compost.

For the other products, even with higher intrinsic P content, the overall environmental impacts can be significant due to emissions from the respective technologies.

For one tonne K as a functional unit, and assuming a 100 % Potassium Mineral Fertilizer Equivalent (KMFE) for all products, digestate was assessed to be the most environmentally favourable, followed by vermicompost and insect frass. This assessment was attributed to the lower emissions associated with anaerobic digestion compared to other processes. Digestate delivered low impact even without considering the benefits of biogas recovery and avoiding inorganic fertilizers.

3.2. *Acidification*

Results for acidification are presented in Fig. 5. When considering one tonne N as the functional unit, biochar emerged as the most favourable option. This was primarily attributed to substantial savings from heat and electricity recovery (4×10^4 Mole of H^+ eq), and additional savings from avoiding inorganic fertilizers (1.82 Mole of H^+ eq).

Following biochar, vermicompost, digestate, and insect frass also gave significant benefits. For digestate, the saving from biomethane recovery was 13.36 mol of H^+ eq. The observed variations in the impacts among the products are attributed to the emissions associated with each process, even in those with higher N content, such as high-biology compost and low-biology compost, which contain 0.04 kg and 0.07 kg of N, respectively. Compost tea had the highest impact due to its low N content (0.00005 kg) and higher emissions.

This trend was also observed when considering both P and K as references, highlighting the overall efficiency of biochar and digestate in mitigating acidification.

3.3. *Water use*

Results for water use are presented in Fig. 6. For one tonne N, the impacts were mainly due to water consumption and the differences in N content across the products. The same was observed for P and K as references. However, when P is used as a reference, with a PMFE of 30 %, it gave the most positive impact on water use compared to N and K.

Biochar was identified as the most environmentally positive process since it was characterized by negative burdens. Heat and electricity credits contributed entirely (100 %) to the total environmental benefit. The primary factor affecting water use for biochar (206 m^3 world eq) was diesel consumption for feedstock collection from a distance of 10 km. Insect frass was the second most environmentally friendly process, followed by digestate. Biomethane recovery from anaerobic digestion contributed only 2 % to the environmental benefit.

Compost tea gave the highest impact on water consumption, with 99.3 % of this impact attributed to the water used in its preparation process, N is the nutrient with the highest impact on water use, primarily due to the low N content in compost tea and an NMFE of 10 %.

3.4. *Freshwater Eutrophication*

Results for freshwater eutrophication are presented in Fig. 7. Biochar showed a high reduction in freshwater eutrophication, especially for 1 t P followed by insect frass. Meanwhile, low biology compost, vermicompost, fish hydrolysate, high biology compost, and digestate present minimal impact. On the other hand, compost tea showed the highest eutrophication impact, particularly for 1 t N, followed by 1 t P and 1 t K, suggesting a significant contribution to nutrient runoff and water pollution. This makes compost tea the least favourable option, mainly due to its low nutrient content. Although biochar is not particularly rich in nutrients, it has negative eutrophication values due to the savings from avoiding mineral fertilizers and the recovery of heat and electricity.

3.5. *Land use*

Results for land use are presented in Fig. 8. Compost tea, digestate, and fish hydrolysate require significantly more land compared to the other products (to obtain 1 t N, 1 t P, and 1 t K). For compost tea, obtaining one tonne of N has the highest impact on land use, primarily due to its low N content and an NMFE of 10 %.

For digestate, the greatest land use impact is associated with obtaining one tonne of P, attributed to its relatively low P content. In the case of fish hydrolysate, obtaining one tonne of P or K resulted in similarly high land use impacts, both exceeding that of nitrogen.

On the other hand, biochar, insect frass, and both high and low biology composts are the most land-efficient options, showing negative

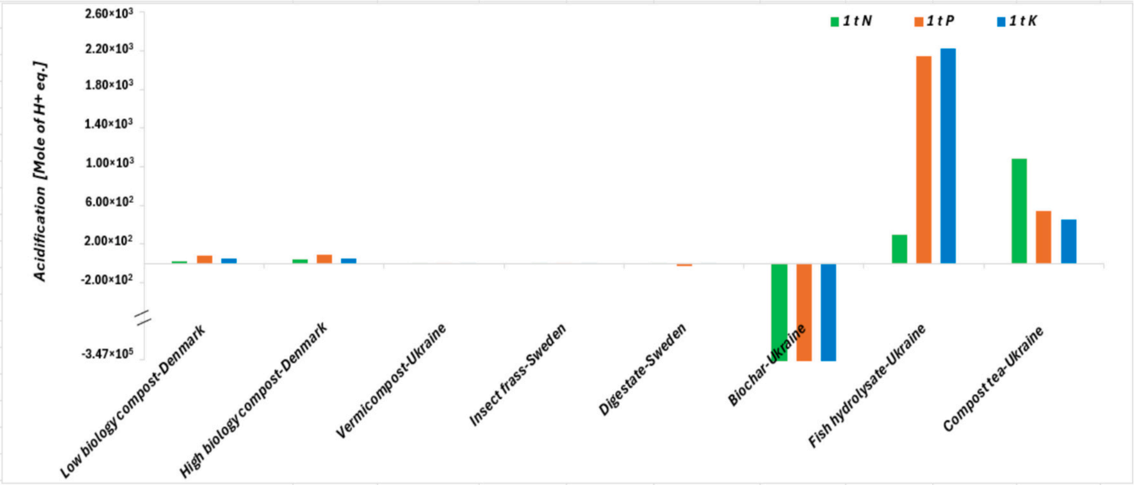


Fig. 5. Results for acidification impact (one tonne N, one tonne P, one tonne K).

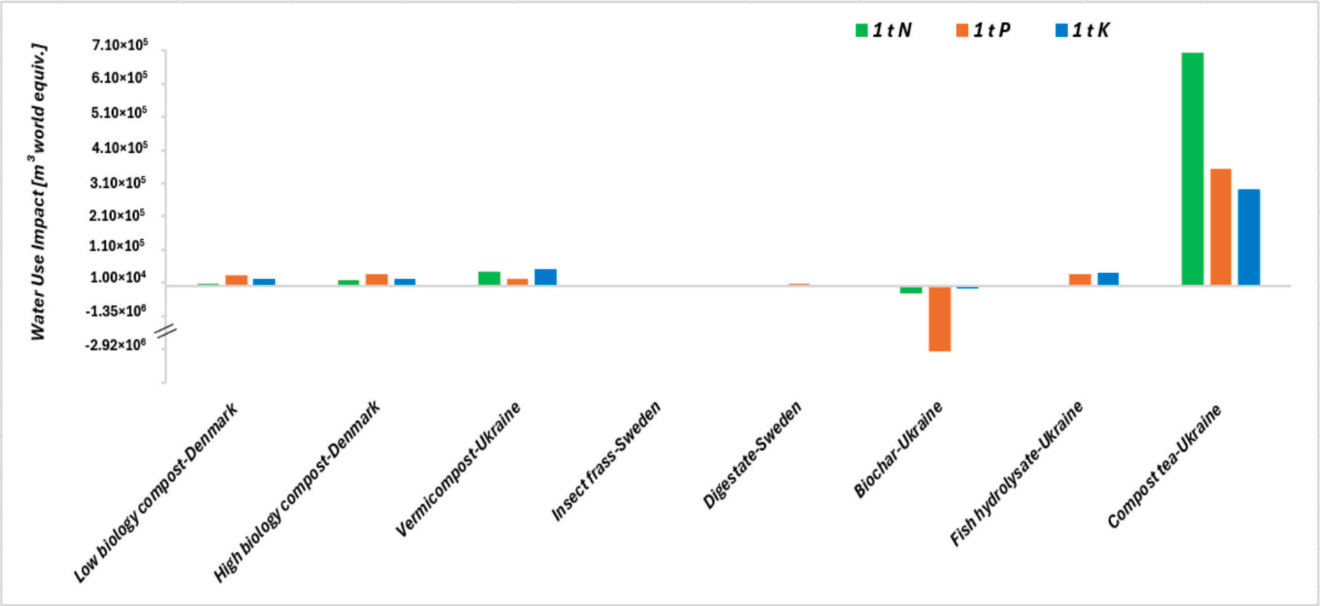


Fig. 6. Results for water use (one tonne N, one tonne P, one tonne K).

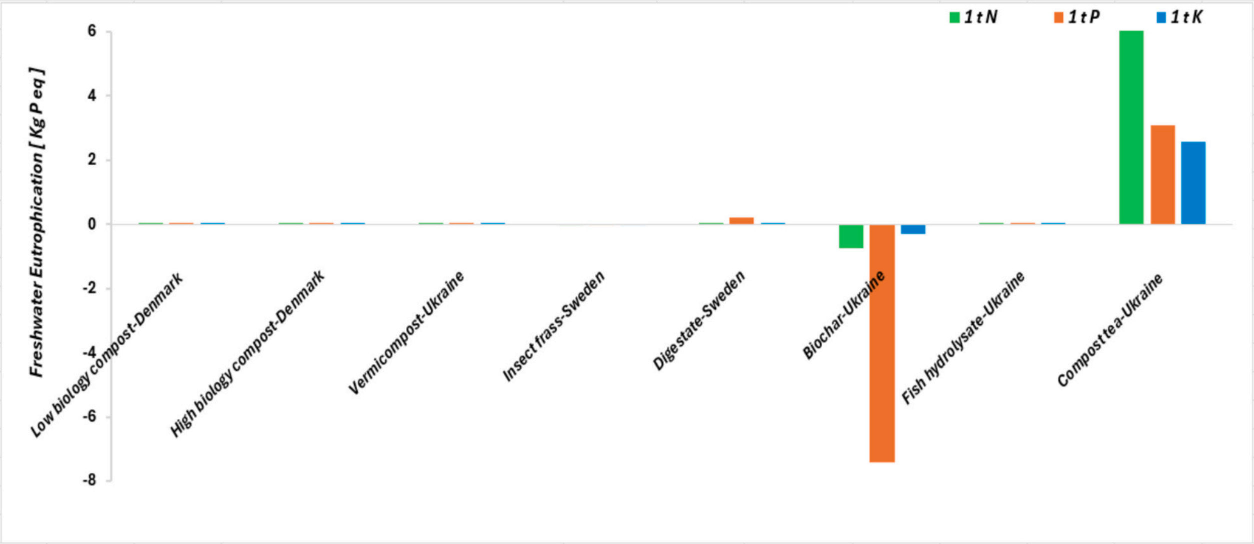


Fig. 7. Results for freshwater eutrophication (one tonne N, one tonne P, one tonne K).

impacts.

These negative values are attributed to benefits gained from avoiding mineral fertilizers and recovering heat and electricity, which contribute positively to the overall land use category.

3.6. Sensitivity analysis

The present study involved estimating NMFE and PMFE values. To evaluate the uncertainty associated with these estimations and assess how variations in these values could affect the results, a sensitivity analysis was conducted.

Sensitivity analysis is a crucial tool for evaluating the robustness of results and their sensitivity to specific variables in LCA. This technique is essential for determining how changes in one or more assumptions can influence the results of a decision or model (Wei et al., 2015).

A scenario analysis was performed to compare different NMFE values and an alternative PMFE value, different from 30 %. KMFE was fixed at 100 % for all products, as no uncertainty was associated with KMFE.

In detail, the following scenarios are examined:

- Scenario analysis (phosphate mineral fertilizer equivalent and potassium mineral fertilizer equivalent constants):

In this analysis, different NMFE values were evaluated, while PMFE and KMFE values were kept constant, as described in the base case scenario (Table 4).

➢ Scenario 1:

For low biology compost, high biology compost, vermicompost, and compost tea:

According to Martínez-Blanco et al. (2013), the NMFE of compost ranges from 20 % to 60 %. This range was used to conduct a sensitivity analysis for these products. The same range was also evaluated for

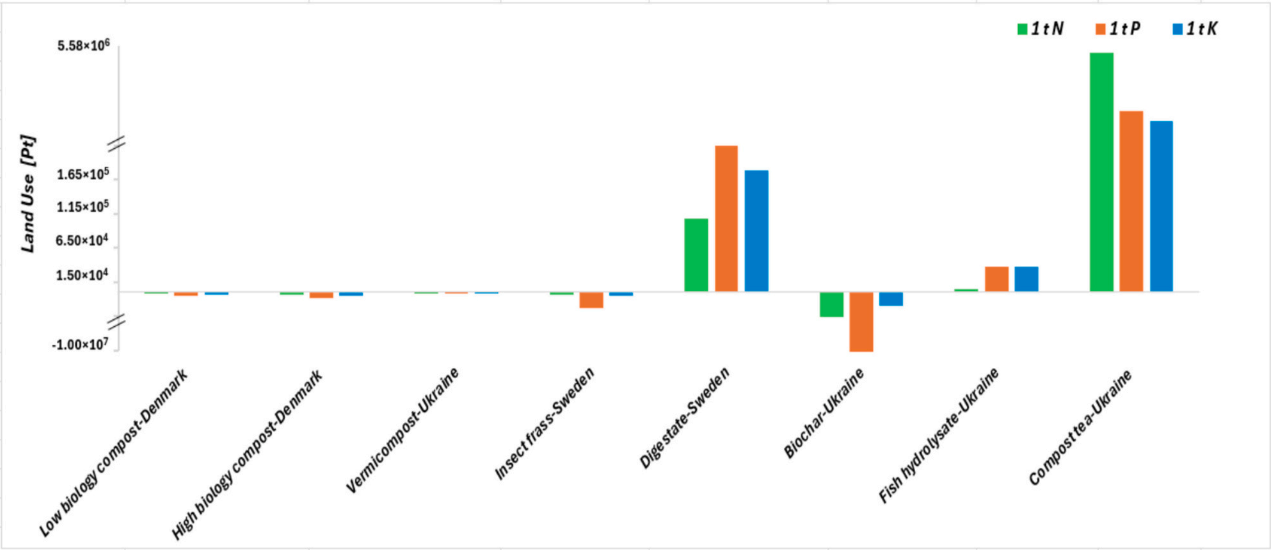


Fig. 8. Results for land use (one tonne N, one tonne P, one tonne K)

Table 4
The scenarios used in the sensitivity analysis (PMFE and PMFE constants).

Compost/biofertilizer/biostimulant	Base case scenario			Scenario 1			Scenario 2		
	NMFE	PMFE	KMFE	NMFE	PMFE	KMFE	NMFE	PMFE	KMFE
Low biology compost	40	30	100	20	30	100	60	30	100
High biology compost	60	30	100	20	30	100	–	–	100
Insect frass	80	30	100	90	30	100	–	–	100
Digestate	80	50	100	90	50	100	–	–	100
Vermicompost	50	30	100	20	30	100	60	30	100
Biochar	27	30	100	20	30	100	–	–	100
Compost tea	10	30	100	20	30	100	60	30	100

NMFE: Nitrogen mineral fertilizer equivalent (%); PMFE: Phosphate mineral fertilizer equivalent (%); KMFE: Potassium mineral fertilizer equivalent (%).

compost tea, even though it is not considered a substitute for inorganic fertilizers. In this scenario, the NMFE values of these products were adjusted to the minimum reported value of 20 %.

For biochar: Studies have found that the NMFE can range from 20 % to 27 % (Ning et al., 2022)(Li et al., 2023). In the base scenario, a value of 27 % was considered. In this scenario, the lower value of the range (20 %) was evaluated.

For insect frass and digestate: Studies indicate that the NMFE could reach 100 % (see Supplementary Information 1). However, the base case scenario was conducted using a moderate value of 80 %. In this scenario, a higher NMFE of 90 % was evaluated for both products, assuming that the remaining 10 % of N would not be available to plants and would be lost as emissions.

For fish hydrolysate: No adjustments were made due to the lack of studies.

➢ Scenario 2:

In this scenario, the maximum NMFE value of 60 %, as reported by Martínez-Blanco et al. (2013), was evaluated for low biology compost, vermicompost, and compost tea. A second scenario was used for these products since their NMFE values could range between 20 % and 60 %, while the NMFE values for the other products were kept constant, as in the base case scenario.

- Scenario analysis (nitrogen mineral fertilizer equivalent and potassium mineral fertilizer equivalent constants):

In this analysis, different values of PMFE were evaluated, while NMFE and KMFE values were kept constant as described in the base case scenario (Table 5).

➢ Scenario 1 (higher PMFE assumption):

For high biology compost, low biology compost, insect frass, vermicompost, biochar, fish hydrolysate, and compost tea: A PMFE value of 50 % was used instead of 30 % (in the base case scenario) as reported by Santolin et al. (2024). Santolin et al. (2024) estimated a PMFE value of 50 % for a variety of organic fertilizers, including microbial, animal-based, and plant-based sources.

For digestate: A value of 100 % was considered in this scenario, reflecting the effectiveness of P in digestate, as previously mentioned in Supplementary Information 1. Lower PMFE values for digestate were

Table 5
The scenarios used in the sensitivity analysis (NMFE and PMFE constants).

Compost/biofertilizer/biostimulant	Base case scenario			Scenario 1		
	NMFE	PMFE	KMFE	NMFE	PMFE	KMFE
Low biology compost	40	30	100	40	50	100
High biology compost	60	30	100	60	50	100
Insect frass	80	30	100	80	50	100
Digestate	80	50	100	80	100	100
Vermicompost	50	30	100	50	50	100
Biochar	27	30	100	27	50	100
Fish hydrolysate	64	30	100	64	50	100
Compost tea	10	30	100	10	50	100

NMFE: Nitrogen mineral fertilizer equivalent (%); PMFE: Phosphate mineral fertilizer equivalent (%); KMFE: Potassium mineral fertilizer equivalent (%).

not evaluated due to the lack of precise values in the literature.

Results for obtaining one tonne of N are presented in Table 6. The sensitivity analysis, conducted by varying NMFE values while keeping PMFE and KMFE constant, revealed no significant changes in the results for climate change, water use, and acidification results. The changes were mainly observed for land use and freshwater eutrophication. Specifically, for high biology compost, low biology compost, insect frass, and vermicompost (see Table 6).

For high biology compost, reducing NMFE from 60 % (base case scenario) to 20 % in Scenario 1 resulted in a 57 % increase in land use and a 58 % increase in freshwater eutrophication, respectively. Low biology compost followed a similar pattern: decreasing NMFE to 20 % in Scenario 1 led to a 45 % increase in land use and an 89 % increase in freshwater eutrophication. Vermicompost likewise showed changes, with land use increasing by 56 % and freshwater eutrophication by 14 % when NMFE was reduced to 20 % in Scenario 1, compared to the base scenario (NMFE: 50 %). Insect frass showed environmental benefits when NMFE is increased. Raising NMFE from 80 % to 90 % in Scenario 1 results in an 11 % decrease in land use and a 14 % reduction in freshwater eutrophication. Similarly, further increasing NMFE in Scenario 2 led to additional decreases in both indicators. However, no changes were observed for compost tea in Scenario 2.

High biology compost, low biology compost, insect frass, and vermicompost are rich in N compared to the other products. Consequently, when NMFE decreases or increases, it directly influences environmental impacts, leading to a corresponding rise or reduction in land use and freshwater eutrophication.

Consequently, the higher the N content in composts, biostimulants, and biofertilizers, the more N (in the form of urea) can be avoided, resulting in lower impacts on land use and freshwater eutrophication. Similar results were observed when considering one tonne P and one tonne K as functional units.

Results for obtaining one tonne of N are presented in Table 7. Regarding the sensitivity analysis for PMFE, with NMFE and KMFE kept constant, no significant changes were observed in climate change, water use, or land use results when the PMFE value was increased from 30 % to 50 % for all products, and from 50 % to 100 % for digestate (Table 5). Nevertheless, freshwater eutrophication was influenced, specifically for high biology compost, low biology compost, and vermicompost, where a decrease in impact was observed. This reduction is attributed to the high P content in these products in comparison to the others. Consequently, the higher the P content, the more triple superphosphate is avoided, leading to a lower impact. Additionally, a significant improvement in acidification and land use impact was observed for vermicompost, with a benefit of 63 % and 24 %, respectively.

Overall, the sensitivity analysis on NMFE and PMFE indicates that changes primarily affect land use, acidification (for vermicompost), and freshwater eutrophication, while the impacts on climate change, water use, and acidification (for the other products) remain relatively stable. Similar results were observed when considering one tonne P and one tonne K as functional units.

4. Discussion

The LCA results highlight significant variability in the environmental performance of the analyzed biofertilizers, biostimulants, and composts, emphasizing the importance of carefully selecting sustainable options. The differences in results among the products can be attributed to the emissions produced during their manufacturing processes and the nutrient composition of each product.

From both environmental and agronomic perspectives, it is important to interpret these impacts in relation to the nutrient content, and how well they align with soil limitations and crop nutritional needs. For example, crops such as strawberries demand high nitrogen during vegetative growth and increased potassium during fruiting stages (Yara United States, 2024). In this context, digestate, with its N and K content, low emissions, and biogas recovery, can be a suitable option, particularly for mitigating climate change (results for one tonne of N and K: 1.20×10^4 kg CO_2 and 2×10^4 kg CO_2 eq, respectively). Its application should be promoted to specific crop growth stages to maximize nutrient use efficiency.

Vermicompost showed minimal impacts for phosphorus provision, due to its higher P content. It is therefore recommended for phosphorus-deficient soils or phosphorus-demanding crops such as legumes during early development stages (Julia et al., 2018). Similarly, biochar shows the most favourable performance across multiple environmental impacts, including acidification, water use, and eutrophication, due to its energy recovery benefits. It is also among the most land-efficient products, along with insect frass and compost, making it a strong option for broader use. However, optimizing biochar production technologies is essential to further reduce emissions and enhance its sustainability.

Compost tea consistently shows the highest environmental impact, due to its low nutrient content. Agronomically, it may be better suited as a soil conditioner rather than a nutrient source.

Ultimately, aligning fertilizer choices with both environmental performance and crop-specific nutrient requirements, considering soil limitations and growth stages, can enhance agronomic efficiency and reduce environmental burdens.

Table 6

Sensitivity analysis results for one tonne of nitrogen as the functional unit (PMFE and PMFE constants).

Composts/biofertilizer/biostimulant scenarios	Climate change [CO_2 eq.]	Acidification [SO_2 eq.]	Water use [m^3 world eq.]	Land use [Pt]	Eutrophication freshwater [kg P eq.]
High biology compost, base case	46,515	43.16	17,947	-2370	2.04×10^{-3}
High biology compost, scenario1	**+1 %**	**+3 %**	**0 %**	**+57 %**	**+58%**
Low biology compost, base case	24,802	19.38	8822	-1484	6.72×10^{-4}
Low biology compost, scenario 1	**+1 %**	**+3 %**	**0 %**	**+45%**	**+89 %**
Low biology compost, scenario 2	**−1.2 %**	**−3.1 %**	**0 %**	**−45 %**	**−89 %**
Insect frass, base case	14,675	−1.259	200.1	−2827	-2.13×10^{-3}
Insect frass, scenario 1	**−1 %**	**−2 %**	**−0.1 %**	**−11 %**	**−14 %**
Digestate, base case	12,007	−4.024	1399	107,511	3.52×10^{-2}
Digestate, scenario 1	**−1.2 %**	**−7 %**	**−1.5 %**	**−0.1 %**	**−0.1 %**
Vermicompost, base case	19,187	−7.319	43,696	−1796	6.57×10^{-3}
Vermicompost, scenario 1	**+2 %**	**+13 %**	**0 %**	**+56 %**	**+14 %**
Vermicompost, scenario 2	**−0.8 %**	**−4 %**	**0 %**	**−19 %**	**−4.5 %**
Biochar, base case	446,758	−34,725	−292,401	−1,000,239	-7.42×10^{-1}
Biochar, scenario 1	**0 %**	**0 %**	**0 %**	**0 %**	**+0.1 %**
Compost tea, base case	871,947	1077	704,153	5,580,529	6.170
Compost tea, scenario 1	**0 %**	**−0.1 %**	**0 %**	**0 %**	**0 %**
Compost tea, scenario 2	**0 %**	**−0.2 %**	**0 %**	**0 %**	**0 %**

0% → No change between the base case scenario and scenario 1 or 2. **Negative values** → Environmental impact is reduced compared to the base case scenario. **Positive values** → Environmental impact is increased compared to the base case scenario.

Table 7

Sensitivity analysis results for one tonne of nitrogen as the functional unit (nitrogen mineral fertilizer equivalent and potassium mineral fertilizer equivalent constants).

Compost/biofertilizer/biostimulant scenarios	Climate change [CO_2 eq.]	Acidification [SO_2 eq.]	Water use [m^3 world eq.]	Land use [Pt]	Eutrophication freshwater [kg P eq.]
High biology compost, base case	46,515	43.16	17,947	−2370	2.040×10^{-3}
High biology compost, scenario1	**0 %**	**0 %**	**0 %**	**0 %**	**−29 %**
Low biology compost, base case	24,802	19.38	8822	−1484	6.720×10^{-4}
Low biology compost, scenario 1	**−0.2 %**	**−3 %**	**0 %**	**−3 %**	**−42 %**
Insect frass, base case	14,675	−1.259	200.1	−2827	-2.130×10^{-3}
Insect frass, scenario 1	**0 %**	**0 %**	**0 %**	**0 %**	**−6.4 %**
Digestate, base case	12,007	−4.024	1399	107,511	3.520×10^{-2}
Digestate, scenario 1	**−0.7 %**	**−7 %**	**−2 %**	**−0.1 %**	**−1.6 %**
Vermicompost, base case	19,187	−7.319	43,696	−1796	6.570×10^{-3}
Vermicompost, scenario 1	**−2 %**	**−63 %**	**0 %**	**−24 %**	**−33 %**
Biochar, base case	446,758	−34,725	−292,401	−1,000,239	-7.420×10^{-1}
Biochar, scenario 1	**0 %**	**0 %**	**0 %**	**0 %**	**0 %**
Fish hydrolysate, base case	14,532	291.8	5141	5025	5.565×10^{-3}
Fish hydrolysate, scenario 1	**−0.2 %**	**−0.1 %**	**0 %**	**−0.6 %**	**−3 %**
Compost tea, base case	871,947	1077	704,153	5,580,529	6.170
Compost tea, scenario 1	**0 %**	**−0.1 %**	**0 %**	**0 %**	**0 %**

0% → No change between the base case scenario and scenario 1 or 2. **Negative values** → Environmental impact is reduced compared to the base case scenario. **Positive values** → Environmental impact is increased compared to the base case scenario.

The sensitivity analysis conducted in this study on the estimated NMFE and PMFE values revealed that fluctuations in NMFE and PMFE primarily influence land use, freshwater eutrophication, and acidification. This suggests that these environmental impacts are more sensitive to changes in nutrient equivalence assumptions.

On the other hand, impact categories such as climate change, water use, and acidification for the other products remain relatively stable, indicating that these parameters have a limited influence on overall environmental performance. Similar trends were observed when using functional units based on P (one tonne P) and K (one tonne K).

Recent scientific studies supported the findings on the environmental impacts and nutrient efficiencies of various biofertilizers and biostimulants. Biostimulant's effectiveness for climate change mitigation is corroborated by a study, which found that biostimulant application reduced CO_2eq emissions in crops (Hamedani et al., 2020). Vermicompost's superior phosphorus content is confirmed by a study, showing that vermicompost treatment resulted in the highest released P compared to other humic substances (Hejazi Mehrizi et al., 2015). The effectiveness of vermicompost for P provision is further supported by a study showing that cow dung vermicompost had the highest total phosphorus content (12.70 mg/g) (Pramanik et al., 2007).

However, the environmental impacts of the products assessed in this study cannot be directly compared with those from previous research. Each study uses different functional units and system boundaries, as previously mentioned in the literature review, which may restrict comparisons between studies.

The results of this study are based on different assumptions, particularly in the estimation of emissions and the inventory data. These factors may vary when the production processes are scaled up, which may affect the results. Additionally, the system boundaries in this study focus solely on feedstock acquisition to the production site, excluding other critical life cycle stages, such as land application. Such limitations can impact the environmental performance of the assessed products. Moreover, the generalizability of the findings may be constrained by geographical variations, as the evaluated products were produced in different countries, where factors such as electricity sources, energy mix, and technological efficiencies differ. Differences in agricultural practices, raw material availability, and waste management systems can further influence the environmental performance of these products.

Based on these results, transitioning toward the use of organic fertilizers requires a deep understanding of their environmental performance. Future research should focus on integrating field-scale assessments, long-term agronomic performance data to complement LCA findings, and the need for region-specific LCAs to ensure more accurate and applicable conclusions.

5. Conclusions

Transitioning to a circular economy in Europe offers the potential to enhance resilience by reducing the need for primary resources and energy.

This study includes the life stages from raw material acquisition to the production of bio-based fertilizers. The findings highlight the diverse environmental impacts of composts, biofertilizers, and biostimulants across different nutrient categories. Digestate emerges as a favourable option for mitigating climate change impacts associated with N and K inputs, while vermicompost demonstrates effectiveness in enhancing phosphate availability. Biochar, while having a high climate change impact due to emissions, performs well in reducing acidification, water use, and land use due to heat and electricity recovery. Compost tea is the least efficient across all assessed impacts.

To assess the uncertainty in nitrogen mineral fertilizer equivalent and phosphate mineral fertilizer equivalent estimations and their impact on the results, a sensitivity analysis was conducted. This involved scenario analysis to compare different nitrogen mineral fertilizer equivalent and phosphate mineral fertilizer equivalent values, while the potassium mineral fertilizer equivalent was maintained at 100 % for all products due to the absence of associated uncertainty. The sensitivity analysis revealed that variations in N mineral fertilizer equivalent and phosphate mineral fertilizer equivalent primarily influence land use, freshwater eutrophication, and acidification for certain products, while the impacts on climate change, water use, and acidification remain relatively stable. Similar trends were observed when using functional units of one tonne of phosphorus and one tonne of K.

In practice, optimizing the use of these products can support circular agricultural practices by reducing reliance on mineral fertilizers and improving nutrient utilization efficiency. This approach not only minimizes environmental impacts, such as GHG emissions and water pollution, but also promotes sustainable agricultural systems. Moving forward, further research and collaboration between stakeholders are essential to refine the environmental performance of composts, biofertilizers and biostimulants, contributing to resilient and environmentally responsible food production systems.

Land application was excluded from the environmental assessment. Further research is needed to compare the impacts of using these organic fertilizers on land. Moreover, ongoing research is essential to address uncertainties in data quality and assumptions inherent in life cycle assessment studies. Comprehensive assessments are needed to understand the long-term and ecosystem-wide effects of these products on soil health, water quality, and biodiversity. An economic analysis of biofertilizer production costs versus traditional fertilizers would provide a broader perspective on sustainability and should be considered in future research. Additionally, involving stakeholders, such as farmers, policymakers, and industry leaders will be pivotal in identifying adoption challenges, evaluating policy implications, and advocating for sustainable agricultural practices that effectively incorporate composts, biofertilizers, and biostimulants. By closing these research gaps, understanding can be advanced, and informed decision-making to promote sustainable agriculture practices globally can be facilitated.

To enhance the practical adoption of these findings, policymakers should consider promoting and encouraging the use of bio-based fertilizers through subsidies, regulatory frameworks, and certification schemes that promote their environmental benefits. Farmers and agricultural practitioners can optimize nutrient management strategies by integrating digestate and vermicompost to enhance soil fertility while minimizing climate change. Additionally, industry stakeholders should invest in further technological innovations to improve biochar production efficiency, reducing its climate impact while maintaining its benefits in acidification, freshwater eutrophication, and land use reduction. Collaboration among researchers, policymakers, and industry leaders will be essential to develop best practices, ensuring that bio-based fertilizers play an important role in sustainable and climate-resilient agriculture.

CRediT authorship contribution statement

Ibtissam Bouhzam: Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation. **Sahar Azarkamand:** Supervision, Software, Data curation, Writing – review & editing. **Rita Puig:** Supervision, Investigation, Writing – review & editing. **Alba Bala:** Supervision, Writing – review & editing. **Pere Fullana-i-Palmer:** Supervision, Conceptualization. **Ilija Sazdovski:** Investigation, Writing – review & editing. **Bohdan Mazurenko:** Investigation, Data curation. **Saad Mir:** Investigation, Data curation. **Md. Nasir Hossain Sani:** Investigation, Data curation. **Ivã Guidini Lopes:** Investigation, Data curation, Writing – review & editing. **Tetiana Maievska:** Data curation. **Nataliia Raksha:** Data curation. **Olexiy Savchuk:** Data curation. **Bhim Bahadur Ghaley:** Data curation, Writing – review & editing. **Jean Wan Hong Yong:** Data curation, Funding acquisition, Writing – review & editing. **Oksana Tonkha:** Project administration, Funding acquisition, Data curation, Conceptualization. **IBTISSAM BOUHZAM:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

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

Acknowledgments

This study was conducted as part of the ECOTWINS (Research Capacity Building and Upskilling and Upgrading the Research Team in NUBiP (Ukraine) on Agroecological Intensification for Crop Production) project. ECOTWINS has received funding from the Horizon 2020 Framework Programme (HORIZON) under the grant agreement No 101079308. The authors are also grateful for the funding of the Spanish Ministry of Science, Innovation and Universities through the KAIROS-BIOCIR project (PID2019-104925RB-C32).

Ibtissam Bouhzam also appreciates the support (2021FI SDUR 00130) from the Secretariat for Universities and Research of the Ministry of Business and Knowledge of the Government of Catalonia and the European Social Fund.

The authors are responsible for the choice and presentation of information contained in this paper as well as for the opinions expressed therein, which are not necessarily those of UNESCO and do not commit this Organization.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2025.04.012.

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