Journal of Cleaner Production 573 (2026) 148949

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Biobased fertilisers from fishery side-streams: an environmentally friendly alternative to mineral fertilisers?

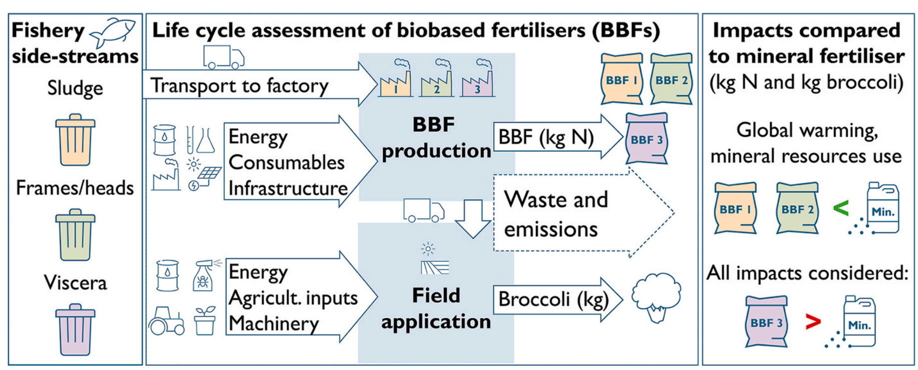
Jan Landert [a,b,*], Nicolas Wittmann [a], Jean-François Fabre [b], Claire Vialle [b], Caroline Sablayrolles [b], Diogo A. Teixeira [c], Helena I. Monteiro [c], Bruna Moura [c], Carlos Bald [d], Bruno Iñarra [d], Laura de Baan [a]

[a] Research Institute of Organic Agriculture FiBL, Frick, Switzerland
[b] Univ Toulouse, Toulouse INP, INRAE, LCA (Laboratoire de Chimie Agro-industrielle), Toulouse, France
[c] Low Carbon & Resource Efficiency, R&Di, Instituto de Soldadura e Qualidade, Grijó, Portugal
[d] AZTI, Food Research, Basque Research and Technology Alliance (BRTA), Derio, Bizkaia, Spain

HIGHLIGHTS

- Life cycle assessment of three biobased fertilisers and their application performed.
- Replacing mineral with biobased fertilisers can provide environmental benefits.
- Two biobased fertilisers reduce global warming potential and resource use.
- One biobased fertiliser shows overall high environmental impacts.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Life cycle assessment
Biobased fertilisers
Organic fertilisers
Bioeconomy
Biorefinery

ABSTRACT

The replacement of mineral fertilisers by biobased fertilisers (BBFs) produced from organic waste streams is promoted by the European Union to reduce political dependencies and nutrient excess. Life cycle assessment (LCA) studies have so far been mainly conducted on BBFs produced from municipal biowaste, sewage sludge and animal manures, primarily considering their production phase. This LCA study compares for the first time environmental impacts of three BBFs produced from fishery side-streams against those of mineral fertilisers assessing both BBF production (per kg N) and application (per kg broccoli), assuming burden-free side-streams. Compared to mineral fertilisers, two BBFs (one from fish sludge, the other from fish frames and heads) had a 3-62% (per kg N) and 11% (per kg broccoli) lower global warming potential and a 1-12% (per kg N) and 7-13% (per kg broccoli) lower mineral resources use. However, the third BBF from fish viscera showed overall higher impacts than the mineral fertiliser highlighting the importance of optimising the production of BBFs and their agronomic performance. Levers for optimisation include establishing the BBF production close to the location of the side-stream, implementing energy-efficient drying technologies and appropriate BBF application techniques.

* Corresponding author. Research Institute of Organic Agriculture FiBL, Frick, Switzerland.
E-mail address: jan.landert@fibl.org (J. Landert).

https://doi.org/10.1016/j.jclepro.2026.148949
Received 23 March 2026; Received in revised form 31 May 2026; Accepted 9 July 2026
Available online 16 July 2026

Methodological challenges such as modelling field emissions of BBFs and lacking harmonization of LCA methodology for the assessment of BBFs are discussed. By considering both production and application of BBFs, this study shows that BBFs from fishery side-streams can provide environmental benefits when used as a substitute for mineral fertilisers and identifies optimisation potential along the life cycle.

1. Introduction

Commercial fertilisers have been shown to contribute substantially to crop yields and thus to satisfying the needs of a growing world population (Stewart et al., 2005). However, the production and application of mineral fertilisers is connected to several sustainability issues. For example, the Haber–Bosch process to manufacture nitrogen fertilisers requires a high energy input (Chojnacka et al., 2020). So far, production relies mostly on natural gas thus contributing to global warming. Furthermore, nitrogen fertiliser prices can fluctuate substantially (e.g. increase by 300% in 2021) with variations in natural gas prices (Chojnacka et al., 2024) posing an economic risk for farmers. On the other hand, phosphorus fertilisers are produced from a finite source of phosphate rock (Hernandez-Mora et al., 2024). The widespread application of nitrogen and phosphorus fertilisers strongly contributes to transgressing planetary boundaries (te Wierik et al., 2025). Fertiliser-related emissions lead to eutrophication, global warming, air pollution as well as acidification of terrestrial and aquatic habitat (de Vries, 2021; Richardson et al., 2023; Shukla et al., 2019; Ti et al., 2019).

To reduce the dependence on non-renewable resources in agriculture and mitigate the nutrient excess within Europe, nutrient recovery from organic waste streams is increasingly seen as an alternative to mineral fertiliser production. The European Updated Bioeconomy Strategy (European Commission, 2018) identified nutrient recycling as one of the levers for future proofing of the European food and farming systems. The European Union therefore aims to stimulate markets for recovered nutrients (European Commission, 2022), boost research in this field (European Commission, 2018) and regulate (Regulation (EU) 2019/1009, 2019) market access of biobased fertilisers (BBFs; Cucina et al., 2021). However, also BBFs require energy and material inputs during production and cause emissions of greenhouse gases and pollutants when being applied on the field. To understand the environmental performance of BBFs, life cycle assessment (LCA) is a typically applied methodology.

In the past, LCA studies on organic waste analysed ways to reduce environmental impacts of waste management (e.g. composting vs. incineration or landfilling) or of energy production, considering nutrient recovery as a secondary function of biorefineries (Egas et al., 2023; Lam et al., 2020). In recent years, LCA studies on BBF production from important organic waste streams, such as municipal biowaste, sewage sludge and animal manures, have been conducted (Egas et al., 2023; Tanzer et al., 2021). For other relevant organic waste streams, studies are scarce. For example, to our knowledge, no LCA studies have been conducted so far on side-streams from the fish industry. In addition, LCA studies on BBFs often do not consider the main function of fertilisers, i.e. crop production, but only compare environmental impacts related to the production, but not the application of the BBFs (Egas et al., 2023).

Globally, discards from large-scale fisheries and on-shore fish processing side-streams (from both large-scale capture fisheries and aquaculture) amounted to a total of 11.7 million tons of non-edible loss in 2021 (excluding aquaculture production loss and valorised side-streams; WEF, 2024). In the EU, the non-edible discards were around 1.2 million tons for the same year (WEF, 2024). The side-streams from aquaculture and capture fisheries (hereinafter defined as fishery) shows high nutrient contents and fertilisers produced from them showed a similar or better agronomic performance compared to mineral fertilisers (Zhang et al., 2023).

These potential advantages of nutrient recovery from fishery side-streams can be leveraged by novel processing approaches that go beyond the traditional processing technologies such as composting by fractionating side-streams and concentrating nutrients. This study therefore aims to address the question whether the resulting BBFs from such valorisation can be an environmentally friendly alternative to mineral fertilisers. In a first step, the environmental impacts of producing three novel BBFs from aquaculture side-streams are assessed as an example for novel processing pathways that valorise the untapped potential of fishery side-streams. In a second step, data from an agronomic field trial are integrated into an agricultural LCA model to analyse and compare the environmental performance of broccoli grown with BBFs or with mineral fertilisers.

2. Materials and methods

Goal and Scope. The goal of the study was to compare the environmental impacts of three BBFs produced in Norway (industrial scale), France and Spain (both pilot scale) from fishery side-streams with those of mineral fertiliser. The LCA was conducted in two steps and included both the production of fertilisers (1st step of LCA) and their application (2nd step of LCA) during one growing season. Impacts from upstream fishery (incl. Fish processing) were excluded, assuming their outputs as burden-free because of their low economic value (cut-off approach). The life cycle inventory (LCI) of the production of BBFs covered the pre-processing of raw material, its transport to the factory, the production infrastructure (buildings and main materials for machinery), energy input, consumables and waste generated (see Fig. 1). The application of BBFs (broccoli cultivation in Estonia, 2023) included the transport of BBFs to the farm, necessary inputs for crop management (e.g. sowing, soil management, fertilisation, crop protection, and harvesting), the related machinery and field emissions of ammonia (NH_3), nitrous oxide (N_2O), nitrate (NO_3^-), nitrogen oxides (NO_x), and phosphorus. For other inputs than fertilisers, no specific transport was considered in the foreground data.

Functional unit. To be able to compare against mineral fertilisers, 1 kg of total nitrogen (TN) was chosen as a functional unit for the first step of the LCA covering the production. For the second step of the LCA, the functional unit was 1 kg of broccoli fresh weight (hereafter referred to as 1 kg of broccoli). In addition, impacts per were calculated per ha (see supplementary materials). While the first step enables a technology-focused comparison, the second step integrates crop yield effects and field emissions to compare the overall environmental performance of fertilisers.

Overview of fertilisers. The three BBFs assessed in the study (BBF Pellets, Solid BBF, Liquid BBF) are produced from different materials (see Fig. 2): fish sludge (in case of the BBF Pellets), fish frames and heads (Solid BBF), and fish viscera (Liquid BBF), all derived from aquaculture side-streams. They represent different types of fertilisers (see Table 1) and production processes (see Fig. 2).

The BBF Pellets have a high dry matter content (DMC) of 94.4% and are biobased only. They were produced at industrial level (technology readiness level 9) without co-products by first drying fish sludge (disk dryer) and then mixing, grinding, and pelleting it (Fig. 2). The Solid BBF also has a high DMC of 98.1% and is biobased only. It was produced at pilot scale by first freezing and grinding fish frames and heads before extruding and drying them. Fish oil resulted as a co-product. The Liquid BBF has a low DMC of 34.5% and is an organo-mineral fertiliser (enriched with conventional mineral fertiliser). It was produced in a pilot plant, by first grinding fish viscera and separating the oil, followed by an acid autolysis of 12 days, membrane filtration and then mixing it with mineral 0-40-40 NPK fertiliser. Fish oil and solids resulted as co-products.

As a reference for the comparison of environmental impacts of BBF production and application, mineral fertiliser in the form of ammonium nitrate (AN) was selected. AN, alongside its formulated form, calcium ammonium nitrate (CAN) and urea, constitutes the predominant mineral nitrogen fertiliser types in Europe, representing 18%, 23%, and 37% of the N supplied in 2023, respectively (IFA, 2026). The LCI data for the mineral reference fertilisers originated from the ecoinvent activities and are further detailed in the supplementary materials, Table S1. In the field trial, AN was the source of N in the mineral fertiliser treatment (MFT, see Table 3).

Inventory of BBF production. The inventory was created based on specific primary data collected from the BBF producers, as well as ecoinvent version 3.9.1 (Wernet et al., 2016; system model allocation, cut-off by classification) for background data. Economic allocation was applied to the co-products of the Liquid and Solid BBF (fish oil and solids; see supplementary materials, Table S2, for used prices). In case of the Liquid BBF and Solid BBF, the foreground data of the current pilot production was upscaled to a potential future industrial scale using the conceptual framework of van der Hulst et al. (2020). In a semi-structured exchange with the chemical engineers of the pilot production, (A) process changes, (B) size scaling effects and (C) potential ways of minimizing waste and processing input were explored. The resulting processes changes are displayed in Fig. 2. They included the omission of the mechanical pre-processing (freezing and grinding) in case of the Solid BBF, the introduction of an industrial decanter centrifuge for oil separation in case of the Liquid BBF (instead of passive oil separation) and four 16′000 L silos for the autolysis for the new batch system that replaced the pilot-scale multipurpose bioreactor. The capacity of the remaining machinery was generally increased. The resulting BBF production inputs are summarised in Table 2. Detailed inventories can be found on Zenodo (see Data availability). Inventories were compiled using SimaPro 9.6.0.1 software.

Inventory of BBF application. The environmental impacts of BBF application were assessed for broccoli production, based on data from a field trial with the three BBFs conducted in Jõgeva (Estonia) on Endogleyic Luvisol soil (Zhang et al., 2025). Estonia has a humid continental climate. The trial was conducted during one growing season in three replicates per treatment (for more information on the field trial see Zhang et al., 2025). The inventory for the application of BBFs was compiled and modelled using the FarmLCA tool (Moakes et al., 2026). The tool allows for the creation of an inventory for crop and/or livestock production using background data from ecoinvent (Wernet et al., 2016; version 3.9.1) and includes models for field emissions. The calculation of N_2O emissions to air was based on IPCC methodology (IPCC, 2019). For the BBFs, the emission factor for "other N inputs in wet climates" was used, for mineral N fertiliser, the emission factor for "Synthetic fertiliser inputs in wet climates". Ammonia (NH_3) and nitrogen oxides (NO_x) emissions to air were calculated following the EMEP/EEA guidelines (EMEP/EEA, 2023; NH3 at Tier 1, NOx at Tier 1). Nitrate (NO_3^-) leaching to water was estimated using the SQCB method (Faist Emmenegger et al., 2009) assuming one third of the crop area drained into surface waters and two third of water emissions transported to groundwater. Phosphorous exports in solid and dissolved form were modelled based on Prasuhn (2006; general model) and Oberholzer et al. (2006; erosion quantification). For the modelling of phosphate leaching, all BBFs were categorized as solid organic fertilisers according to the IPCC threshold of >15% DMC (Gavrilova et al., 2019). The resulting fertilising-related field emissions are displayed in Table 3.

The FarmLCA tool was parametrized with environmental impacts calculated in step 1 per produced kg of BBF and agronomic data from the field trial. The amounts of fertiliser in the field experiment corresponded to 120 kg TN-equivalents per ha applied for both BBFs and mineral fertiliser. The application rate was thus 1939 kg/ha for the BBF Pellets, 1575 kg/ha for Solid BBF, 2260 kg/ha for Liquid BBF, and 775 kg/ha of mineral fertilisers (see Table 3). The MFT received 95 kg N/ha from N34.5 and 25 kg N/ha from an N-P_2O_5-K_2O + S fertiliser. The broccoli output in the FarmLCA tool was parametrized with the actual yields from the field experiment (assuming 10% residues of total above-ground biomass). The yield-related uncertainty derived from the standard deviation of the three field trial replicates (see Table 3) was accounted for in calculation of the overall environmental impacts per kg of broccoli. For the emission modelling, data on chemical properties of BBFs measured by Zhang et al. (2025; dry matter content and nutrient composition) was used. Tillage, weed management, crop protection, and yield-scaled harvesting was the same for all fertilisers with the data taken from the field trial and complemented with the ecoinvent inventory for global broccoli production (without CO_2 emissions from land transformation).

Impact assessment (LCIA). Five midpoint indicators covering the most relevant environmental impacts of BBF production and application were calculated with the ImpactWorld+ 2.0 method (Bulle et al., 2019): Climate change, short term (GWP 100; kg CO_2 eq; referred to as global warming in the following), terrestrial acidification (kg SO_2 eq), marine eutrophication (kg N N-lim eq), freshwater eutrophication (kg PO_4 P-lim eq), mineral resources use (kg deprived). The environmental impacts of BBF production were calculated in Brightway 2.5 open-source software (Mutel, 2017; packages bw2calc 2.0.1, bw2data 4.4.2 and bw2io 0.9.6) using the inventories compiled in SimaPro, the impacts of BBF application were calculated with FarmLCA 4.1.3.2 (Moakes et al., 2026).

Sensitivity analysis. To understand how uncertainties of the inventory influence results, several sensitivity analysis scenarios were explored. Since BBFs are still a niche market but aim to replace mineral fertilisers in Europe in the future, the uncertainties related to future BBF production were covered by scenarios (1) increasing the transport distance from the source of BBFs to the factory by 150 km, (2) increasing the share to 50% of renewable electricity or heat (used for steam

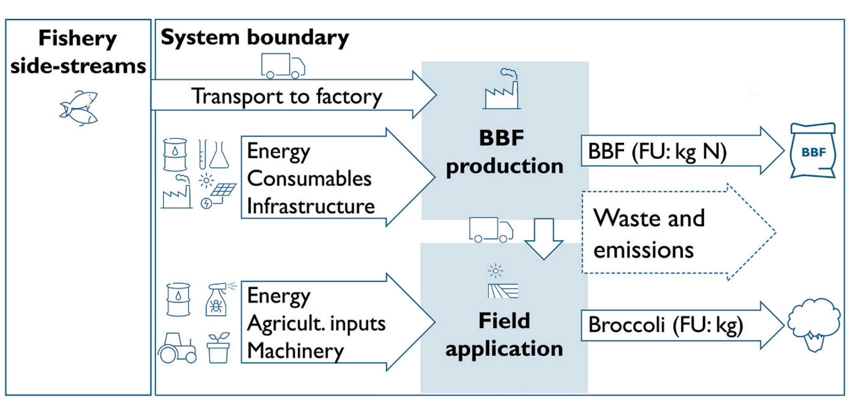


Fig. 1. LCA system boundary (FU = functional unit).

generation) for BBF production (if current renewable energy mixes in a country are below 50%), (3) increasing fish oil price by 50% (allocation), and (4) reducing the use of multi-storey office buildings by 50%. Uncertainties related to the future BBF market were assessed by (5) increasing the transport distance to the farm from 10 km to 500 km. Finally, uncertainties related to the modelling of field emissions of BBFs were explored by (6) using the lower range instead of the average of the IPCC emission factor for N_2O (IPCC, 2019) and (7) selecting a different source for the NH_3 emission factor for BBFs (van der Zee T. et al., 2021), which assumes for "other organic fertilisers applied to soils" 46% of the total ammoniacal nitrogen content (TAN = NH_3-N + NH_4^+-N) volatilised as NH_3-N after application (in contrast to the default NH_3 emission factor of 0.08 kg NH_3 per kg of total N applied). For better readability, the environmental impacts of the scenarios were normalised to the default impacts without any of the scenarios applied (referred to as baseline).

3. Results

The environmental impacts of the **production of BBFs** per kg of N were lower, similar, or higher compared to mineral fertiliser (ammonium nitrate; see Fig. 3). The Liquid BBF showed higher impacts for all environmental impacts (up to 26-fold in the case of freshwater eutrophication). While also the Solid BBF showed higher impacts for freshwater eutrophication and terrestrial acidification (78% and 30% higher, respectively), it exhibited slightly lower impacts for global warming (3% lower) and mineral resources use (1% lower). For marine eutrophication, its impact was 81% lower compared to mineral fertiliser. The BBF Pellets performed best with lower overall impacts than mineral fertiliser ranging from 91% lower impacts (marine eutrophication) to 12% lower impacts (mineral resources use).

.

Table 1
BBF characteristics as determined by Zhang et al. (2025).

Property	Unit	BBF Pellets	Solid BBF	Liquid BBF
Abbrev. in Zhang et al. (2025)		FSP	PF	NPKA
Country of production		Norway	France	Spain
Form		solid, pelleted	solid	liquid
Dry matter content	% fresh weight	94.4 ± 0.2	98.1 ± 0.2	34.5 ± 0.2
Organic matter content	% dry weight	82.5 ± 0.4	83.8 ± 0.7	78.8 ± 0.2
Total nitrogen (TN) content	% fresh weight	6.2 ± 0.1	7.6 ± 0.7	5.3 ± 0.1
Phosphorus (P) content	% fresh weight	2.7 ± 0.5	3.1 ± 0.1	1.6 ± 0.1
Potassium (K) content	% fresh weight	1.5 ± 0.2	0.6 ± 0.01	2.2 ± 0.2
C/N ratio	-	6.35:1	6.11:1	2.67:1
NH_{4+}	g/kg fresh weight	0.62 ± 0.06	0.34 ± 0.02	2.56 ± 0.01

Compared to the reference treatment with mineral fertiliser, the environmental impacts of producing 1 kg of broccoli were mostly similar or higher for the three BBF treatments (Fig. 4). Similar to the impacts of BBF production, broccoli produced with Liquid BBF exhibited the highest impacts for global warming and mineral resources use (66% and 37% higher than the MFT, respectively). For freshwater and marine eutrophication, impacts of Liquid BBF were 19% and 46% higher than those of the MFT. Except for marine eutrophication, the treatment with Liquid BBF also showed the highest impacts per ha exceeding those of the MFT by 2% (freshwater eutrophication) to 43% (global warming; see supplementary materials). The yield-derived uncertainty of the

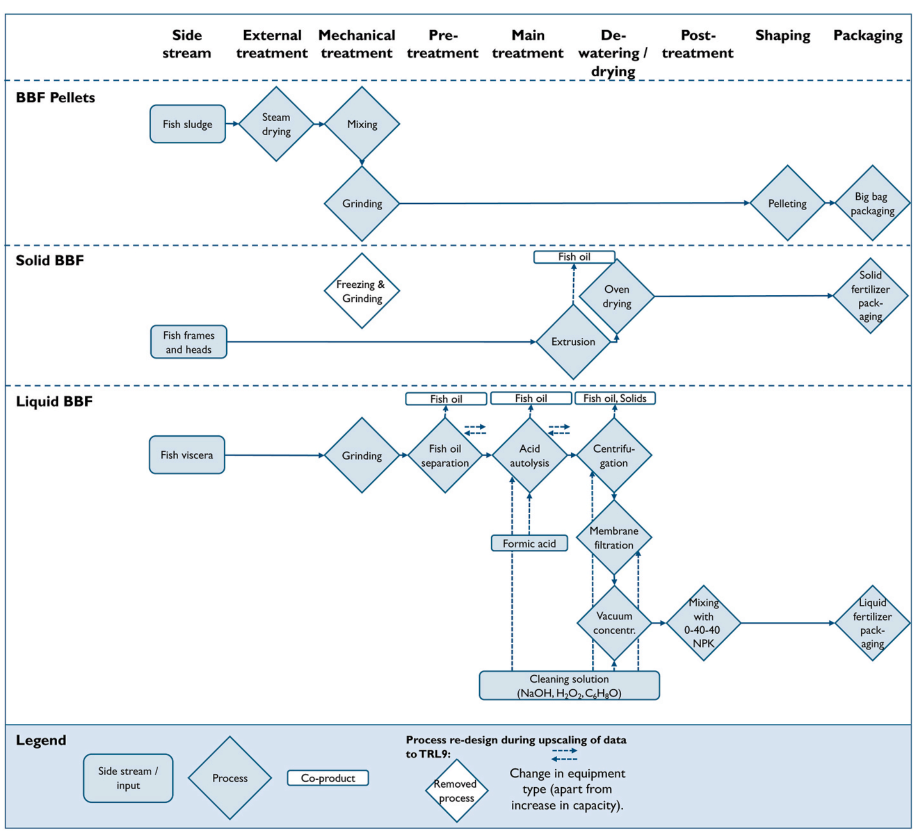


Fig. 2. Process diagrams for the three assessed BBF. For the sake of readability, transport, electricity, and water inputs as well as infrastructure (machinery, buildings) have been omitted in the figure. External treatment = treatment outside of the investigated facilities (assessment without installations).

Table 2
Production inputs per kg of BBFs based on primary data.

	Input	Location	Unit	BBF Pellets	Solid BBF	Liquid BBF
Side-streams (fresh weight)	Fish sludge (raw)	NO	kg	5.83 E+01		
	Fish frames and heads	FR	kg		5.00 E+00	
	Fish viscera	ES	kg			8.36 E+00
Chemicals, packaging, and other inputs	Citric acid	GLO	kg			1.83E-03
	Dolomite	RER	kg			2.20E-02
	Formic acid	RoW	kg			7.49E-03
	Hydrogen peroxide, w/o water, in 50% solution	RER	kg			1.55E-03
	Monoammonium phosphate	RER	kg			6.14E-02
	Packaging: Per kg of liquid fertiliser	GLO	p			1.00 E+00
	Packaging: Per kg of solid fertiliser	GLO	p		1.00 E+00	
	Packaging: Polyethylene for big bags	GLO	kg	1.67E-03		
	Potassium chloride	RER	kg			5.33E-02
	Sodium hydroxide, w/o water, in 50% solution	GLO	kg			2.94E-02
	Tap water	Europe w/o CH	kg			2.93 E+00
Electricity and heat	Electricity	ES	kWh			1.26E-01
	Electricity	FR	kWh		3.50 E+00	
	Electricity	NO	kWh	6.93E-01		
	Electricity	RER	kWh			2.22E-03
	Steam, in chemical industry	RER	kg			2.37 E+00
Machinery materials and buildings	Building, hall	GLO	m^2	1.14E-06	3.53E-07	3.74E-07
	Building, multi-storey	RER	m^3	1.71E-05	5.29E-06	5.61E-06
	Polyethylene	GLO	kg		5.06E-05	
	Steel, low-alloyed	GLO	kg	4.17E-04	2.03E-04	6.94E-03
	Synthetic rubber	GLO	kg	4.29E-06		
Transport of machinery and side streams	Transport, freight train	RER	tkm	1.95E-05	1.21E-05	3.83E-03
	Transport, freight, aircraft, short haul	GLO	tkm	1.62E-05	1.00E-05	2.69E-04
	Transport, freight, inland waterways, barge	RER	tkm			1.75E-03
	Transport, freight, lorry with refrig. machine, cooling	GLO	tkm		5.88E-02	4.49E-01
	Transport, freight, lorry, unspecified	RER	tkm	5.00E-01	2.05E-04	1.92E-02

Table 3
Fertilising-related inventory for BBF application including inputs, field emissions, and outputs (yields). Inputs and yields are based on Zhang et al. (2025). MFT: mineral fertiliser treatment.

			BBF Pellets	Solid BBF	Liquid BBF	MFT
Inputs	Amount of fertiliser applied	kg/ha	1939	1575	2260	275 (N34.5) + 500 (N-P_2O_5-K_2O + S)
	N	kg/ha	120	120	120	120
	P	kg/ha	53	48	36	22
	K	kg/ha	28	9	51	124.5
Emissions	Ammonia (air)	kg/ha	9.6	9.6	9.6	3.9
	Nitrous oxide (air)	kg/ha	3.1	3.2	3.2	4.9
	Nitrogen oxides (air)	kg/ha	4.8	4.8	4.8	4.8
	Nitrate (water, unspec.)	kg/ha	62.6	49.4	44.1	34.7
	Nitrate (groundwater)	kg/ha	146.2	115.3	102.9	81.0
	Phosphate (river)	kg/ha	0.9	0.8	0.8	0.6
Outputs	Total above-ground biomass fresh-matter broccoli yield	t/ha	56.7 ± 7.3	65.8 ± 2.7	68.2 ± 4.6	79.4 ± 8.2

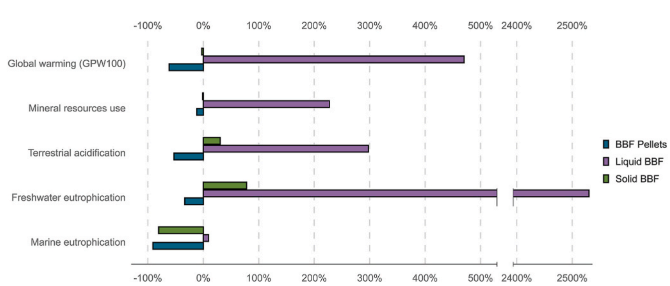


Fig. 3. Impacts of BBF production (per kg N) relative to the production of mineral N fertiliser (ammonium nitrate). Bars to the left indicate lower impacts of BBFs than mineral fertiliser, bars to the right indicate higher impacts.

environmental impacts of the treatments with Solid BBF and the BBF Pellets was mostly within a similar range (except for eutrophication). For global warming and mineral resources use, the impacts of Solid BBF and BBF Pellets were 7-13% lower compared to the MFT, per ha even 26-37% lower. For the other three categories, impacts of Solid BBF and BBF Pellets were 20-132% higher than the MFT. Accordingly, for terrestrial acidification, freshwater and marine eutrophication, the MFT showed the lowest impacts. These ranking changes when considering per ha impacts were the treatment with BBF Pellets has 1% lower impacts in case of terrestrial acidification and the one with Solid BBF 1% lower impacts for freshwater eutrophication.

The production of fertilisers showed varying contributions to the overall impacts of 1 kg of broccoli, depending on the BBFs and the impact category (Fig. 5). For the Liquid BBF, the fertiliser production constituted up to 58% and 54% of impacts for global warming and mineral resources use, respectively. The BBF production showed a limited contribution to terrestrial acidification (4-26%) while being more relevant for the MFT (44%). For freshwater and marine eutrophication, BBF production showed only minor contributions.

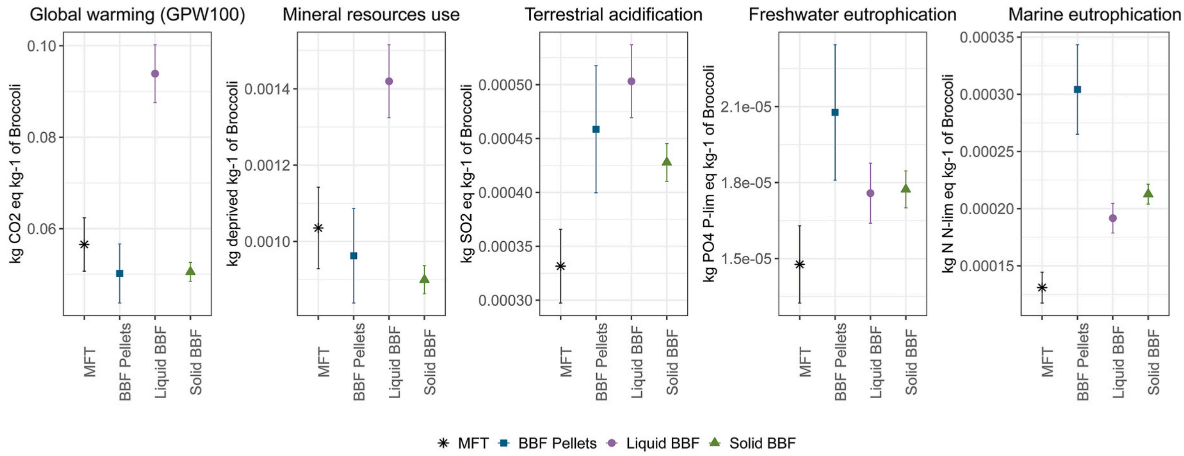


Fig. 4. Environmental impacts of producing 1 kg broccoli with different fertilisers. Standard deviation shown as uncertainty ranges, based on yields from three replicates in the field trial.

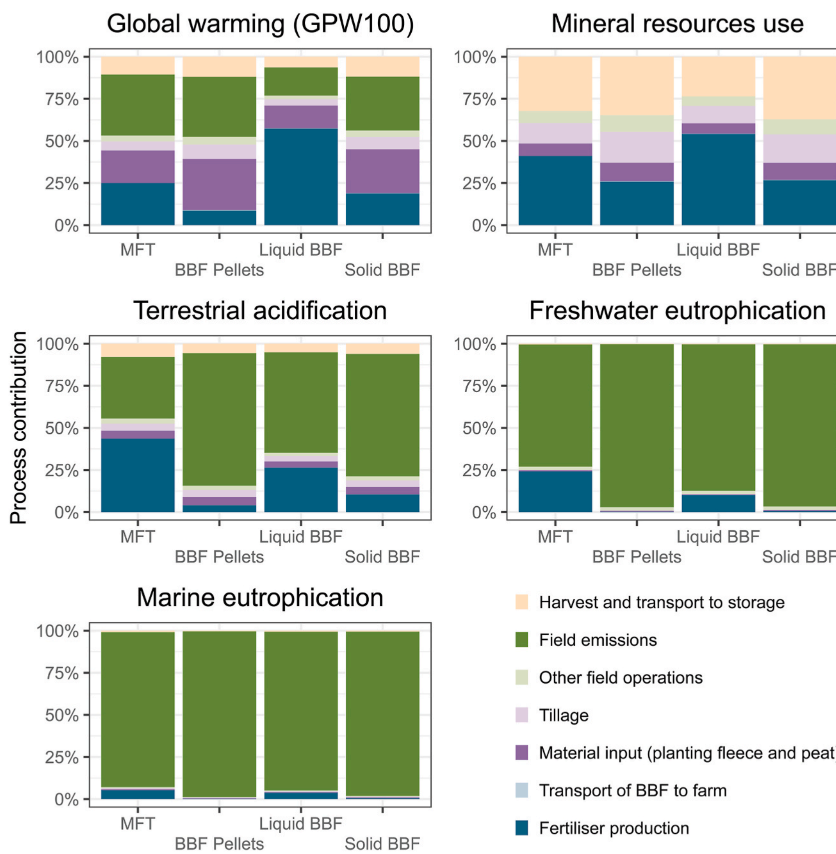


Fig. 5. Process contributions of producing 1 kg of broccoli for the three assessed BBFs and the Mineral fertiliser treatment.

Terrestrial acidification, freshwater and marine eutrophication were dominated by field emissions during fertiliser application. For marine and freshwater eutrophication, field emissions constituted between 92-98% and 73-97% of impacts, for terrestrial acidification 37-79%. Other agricultural processes showed a relevant contribution to global warming and mineral resources use, such as material input (peat and planting fleece for broccoli; 6-30%), machinery use for tillage (4-18%) and harvesting and transport to the storage (6-37%).

The relevant contribution from field emissions to global warming was mirrored in the conducted sensitivity analysis for the environmental impacts of producing 1 kg of broccoli: using the lower boundary of the uncertainty range instead of the average for the N_2O emission factor provided by IPCC (2019; 0.001 kg N2O–N (kg N) −1) resulted in up to an 11% lower impact for global warming (see Fig. 6). Global warming was also sensitive to changes in processes upstream of the application of BBF: among all these scenarios, a share of at least 50% of renewable energy in production showed the highest effect, reducing the impact by 13% for the Liquid BBF treatment and 4% for Solid BBF. As the BBF Pellets from Norway are already produced with more than 50% renewables, no effect was observed for them. Also changes in transport proved to be relevant: the transport of raw materials to the BBF factory by 150 km resulted in up to 6% higher impacts in case of global warming. A similar range of sensitivity could be observed when increasing the transport of BBFs to the farm from 20 km to 500 km (increases by up to 6%). Global warming

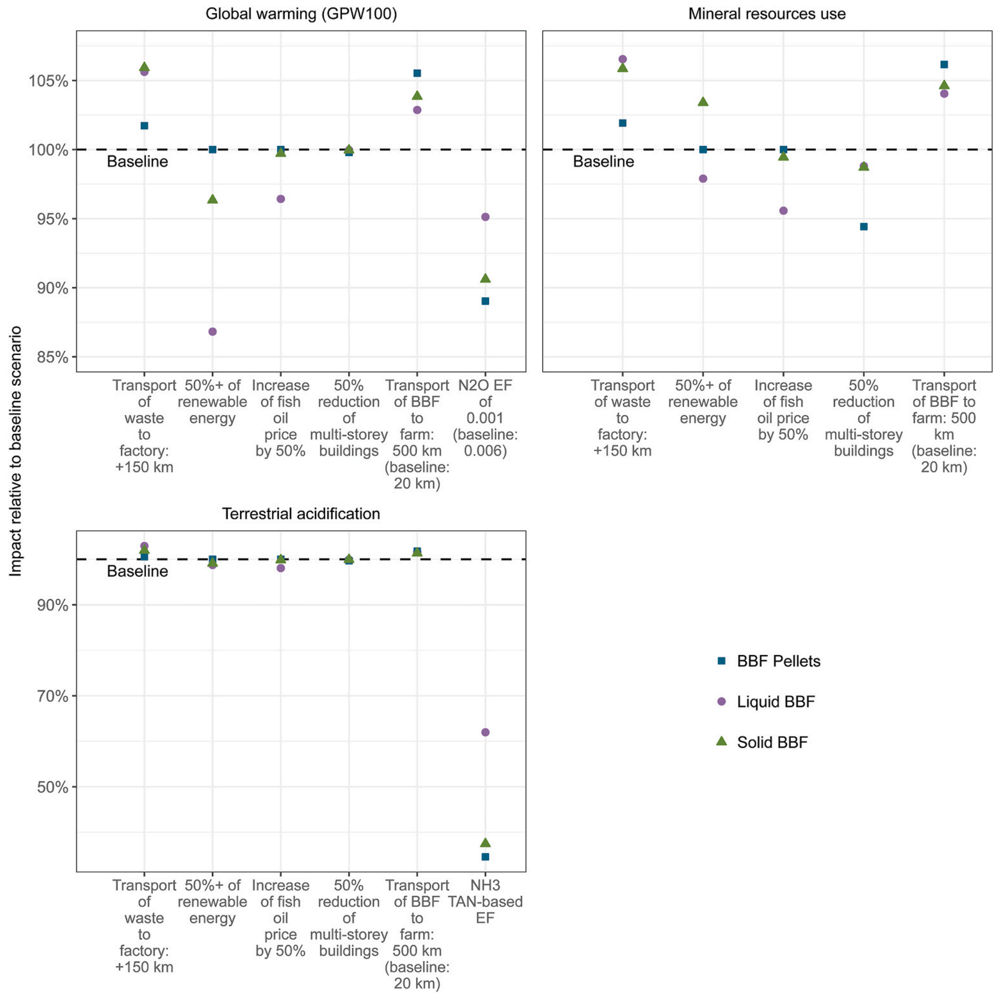


Fig. 6. Sensitivity analysis for the environmental impacts of producing 1 kg of broccoli with BBF. Effects are normalised to the corresponding baseline (default) scenario (dashed line). EF = Emission factor.

showed limited sensitivity regarding the increase in fish oil price used in the economic allocation of multi-output processes and buildings or the reduction of assumed multi-storey office buildings by 50%.

The additional distance of 150 km for the transport of raw materials proved also to be relevant for mineral resources use (up to 7% increase in impacts) with the increased BBF transport having a similar effect range. In contrast to global warming, the reduction of assumed multi-storey office buildings by 50% also affected mineral resources (6% reduction in impact in case of the BBF Pellets). The increase in fish oil price used in the economic allocation of multi-output processes and buildings by 50% mainly affected the Liquid BBF with a reduction of up to 4%. The share of at least 50% of renewable energy increased the impacts in case of the Solid BBF treatment by 3% and reduced them in case of the fertilisation with Liquid BBF by 2%.

The highest effect showed the choice of NH_3 emission factor on terrestrial acidification: the TAN-based emission factor for NH_3 (van der Zee T. et al., 2021) instead of the EMEP/EEA Tier 1 NH_3-EF reduced impacts up to 65%. Changes in transport of raw material led to a slight increase in terrestrial acidification (up to 3%; 2% in case of increased transport distance for BBF). The share of at least 50% of renewable energy during production showed a low sensitivity (maximum decrease of 1% of impacts).

4. Discussion

This study shows that BBFs from fishery side-streams can present an environmentally friendly alternative to mineral fertilisers. The production of 1 kg N from BBF Pellets showed lower impacts than ammonium nitrate for all impact categories, while the Solid BBF had similar or lower impacts for three impact categories (global warming, mineral resources use and marine eutrophication). Additionally, the impacts of producing 1 kg of broccoli with the Solid BBF and BBF Pellets were lower than the MFT for global warming and mineral resources use. The Liquid BBF, in contrary, showed consistently higher impacts than mineral fertilisers both during BBF production and application. This demonstrates that the environmental benefits of BBFs can vary strongly as a function of their production impacts and agronomic performance.

4.1. *Comparability of results*

Since agronomic performance and field emissions of BBFs are impacted by the nutrient needs of the crop grown and the pedo-climatic conditions such as soil moisture, temperature, soil organic carbon (SOC) content and pH (Müller et al., 2024; Wester-Larsen et al., 2022), other studies are needed to contextualise the results of this study. Three previous, similar studies that compare environmental impacts of production and application of BBFs derived from other organic wastes to those of mineral fertilisers also identified lower impacts for crops fertilised with BBFs for global warming and mineral resources use (or similar indicators): Cortés et al. (2020) assessed the application of composted viticulture waste (2.4% N, 1.6% P, 3% K) to tomato, maize and strawberry. Herrera et al. (2022) studied mix of digestate (0.8% N, 0.3% P, 0.07% K) and digestate-derived ammonium sulphate (7.4% N) applied to maize (3.7:1 mixing ratio of total nitrogen applied). Jasiński et al. (2026) investigated the application of two BBFs on leek and cauliflower in Flanders representing different blends of compost, biochar and insect frass from the processing of fruit and vegetable waste (1.0-2.4% N, 0.3-0.5% P and 0.7-1.4% K; all shares provided related to wet weight). For marine eutrophication, our study found higher impacts for all BBFs compared to the MFT while in the other studies, impacts of BBFs were similar or lower than the MFT (Herrera et al., 2022; Jasiński et al., 2026). Concerning freshwater eutrophication, the comparably higher impacts for the BBF treatments in this study were both mirrored (Herrera et al., 2022; Jasiński et al., 2026) and contrasted (Cortés et al., 2020) in the other studies. Likewise, the higher acidification impacts for the BBF treatments are in line (Jasiński et al., 2026) or not (Cortés et al., 2020; Herrera et al., 2022) with the other studies' findings. Yet the results from the mentioned studies are not fully comparable to the current study due to different BBFs, organic waste streams (viticulture waste, mix of food processing side-streams, domestic biowaste and sewage sludge), treatment methods (e.g. anaerobic digestion), and reference fertilisers, but also different methodologies (functional units and tested crops, system boundaries, field emission quantification, LCIA methods). This shows the need for more studies on organic BBFs from fishery side-streams under different agronomic conditions with a unified LCA approach (as also proposed by e.g. Vikki et al., 2025).

4.2. Influence of BBF characteristics

The properties of the BBFs investigated (see Table 1) potentially affect environmental impacts of their production and application. The DMC provides an indication on the extent of the concentration process needed during the production. Paradoxically, the Liquid BBF with the lowest DMC showed the highest impacts during production, highlighting the relevance of energy efficiency and sources of the concentration process as discussed in section 4.5.

For broccoli cultivation, environmental impacts per kg depend on the agronomic performance as manifested in the difference in per ha and per kg impacts. For example, for freshwater eutrophication, Liquid BBF had lower impacts than BBF Pellets per kg broccoli, although per ha impacts of Liquid BBF were higher. This different ranking was due to the higher yields of broccoli fertilised with Liquid BBF compared to BBF Pellets. According to Zhang et al. (2025), yields strongly depend on the mineralisation of the BBFs. They argue that the low C/N ratio of the Liquid BBF could have promoted mineralisation and hence crop nutrient availability, resulting in higher yields. Broccoli treated with BBF Pellets showed low yields, which Zhang et al. (2025) explained by the low mineralisation due to the pelleted form that releases nutrients too slowly.

The nutrient release dynamics not only affect yields but also the emission behaviour. However, the generic nitrogen emission models used in this study do only partially account for this by differentiating organic and mineral fertilisation in the case of N_2O and NH_3 emissions (see next section). For phosphorous field emissions leading to freshwater eutrophication, the P content of BBFs is relevant. Yet, despite its low P content (1.6% of fresh weight), the Liquid BBF still showed the highest freshwater eutrophication impacts per ha since they were dominated by its high production-related emissions and background emissions from soil.

4.3. Need for improved emission modelling

The sensitivity analysis exposed methodological challenges and uncertainties when assessing BBFs' environmental impacts. Applying the NH_3 emission factor (NH_3-EF) from the Dutch national emission inventory (van der Zee T. et al., 2021) for "other organic fertilisers applied to soils (including compost)" for BBF-related NH_3 field emissions would have reversed the ranking for terrestrial acidification: all three BBF treatment would have lower impacts than the MFT. The emission factor is related to the TAN applied in the BBF treatments (46% of TAN). The Tier 1 NH_3-EF that was used in the baseline instead relates to total nitrogen applied (0.08 kg NH3/kg N applied; EMEP/EEA, 2023). This is a simplification, since NH_3 emissions are, among other factors such as pH, mainly dependent on the TAN content in organic fertilisers (Wester-Larsen et al., 2022). Given the low TAN content of the BBFs in this study (0.3-2.6 g/kg BBF; 0.4 – 4.8% of total nitrogen), it is likely that NH_3 emissions and therefore impacts for terrestrial acidification might have been overestimated with the used Tier 1 approach. This tendency could have even been more pronounced by adopting default IPCC volatilisation (NH_3 + NO_x) rates for organic fertilisers of 21% per kg N applied (IPCC, 2019). These considerable uncertainties demonstrate the limitations of the standard emission models used in LCA and the need for these to better account for the different types of BBFs (e.g. in pelleted form) by calibrating and validating with field studies on organic BBF application. This is also true for the generic N_2O-EF that covers a wide range of different organic substrates (IPCC, 2019), which exposes further uncertainty as shown in the sensitivity analysis. Similarly, the NO_3^- leaching model only accounts indirectly for the type of fertiliser treatment by the resulting yield (Faist Emmenegger et al., 2009). Although more data intense, mechanistic models could be an alternative to better account for differences in fertiliser characteristics when modelling nitrogen emissions (Andrade et al., 2021). Yet, fertiliser characteristics are subject to seasonal changes in feedstock composition across production batches, which introduces further uncertainty in the emission modelling. These variations thus hamper the calculation of standardised environmental footprints, even more so if the functional unit is related to a variable nutrient composition.

4.4. Other environmental impacts

Not all relevant impacts of BBF application could be quantified in this study such as the impacts of heavy metals and pathogens. The related legal limits are defined EU Fertilising Products Regulation (EU) 2019/1009 (Regulation (EU) 2019/1009, 2019) along with minimum nutrient concentrations and marketing requirements (Aborisade et al., 2026). Zhang et al. (2025) report compliance with legal limits for the three BBFs analysed in this study with regard to heavy metals and pathogens. Also, the reported potential of BBFs to improve physico-chemical and biological properties of the soil (Aborisade et al., 2026) could not be covered in this study. For example, BBF application could have a positive impact on soil quality by adding organic carbon to soils (He et al., 2022). For the BBFs in this study, Zhang et al. (2025) showed an increase in soil organic matter in their field experiment but with no significant difference between the BBFs and (unfertilised) control treatments. For other soils, the effect might also be limited: Steffens and Bünemann (2025) were able to demonstrate based on a data set from 60 field trials that BBFs generally increased soil organic carbon with an above-average effect for carbon rich BBFs exhibiting a C/N ratio higher than 10. The BBFs in this study with a C/N ratio between 2.67 (Liquid BBF) and 6.35 (BBF Pellets; see Table 1) might therefore generally show a limited contribution to soil organic carbon. However, to rule out significant differences in soil organic carbon stocks between BBF application and the MFT, a long-term field trial would be required to capture the slow rate of passive carbon pool change (Steffens and Bünemann, 2025). Also not covered in this study is the related mineralisation of organic matter from BBF fertilisation beyond the crop growing period, thus the supply of plant-available nutrient into the next growing season. To cover this effect, the LCA would need to be based on a multi-season field trial as proposed e.g. by Jasiński et al. (2026). While this would mean, among others, a change in functional unit accounting for the production of two products from two growing seasons, the effect on the overall ranking of fertiliser treatments is uncertain: Müller et al. (2024) for example could not detect significant residual effects of fertilisation in the second year of their field trials with 18 BBFs.

4.5. Optimisation potential of future BBF production and transport

Regardless of current limitations of LCA studies on BBF application, the high contribution of BBF production to overall impacts per kg broccoli for global warming and mineral resources use (Fig. 5) demonstrate the importance of directly reducing upstream impacts of BBFs, especially in the case of Liquid BBF. Here, the high contribution of BBF production to overall impacts per kg of broccoli is largely caused by the energy intense vacuum concentration process. This process involves a single-effect concentrator (3000 L capacity) removing 2.4 kg of water per kg of Liquid BBF by using 0.9 kg of steam per kg of water evaporated. Also, the mixing with 0-40-40 NPK, the transport of raw materials to the BBF factory and the packaging contribute to high production impacts (also see Fig. 2 for the process diagram). This aligns with Jasiński et al. (2026) who found a high contribution of production-related impacts on the normalised and weighted LCIA score for both leek and cauliflower cultivation. They also identified an energy-intense drying process and transport as upstream hotspots. The importance of the drying process during the valorisation of fishery side-streams is also confirmed by the studies of Petrova et al. (2018) and Gaviria Gaviria et al. (2021). Consequently, the production-related impacts of BBFs from fishery side-streams need to be optimised as much as possible. Regarding the thermal processes for concentration and drying, this includes switching to a renewable energy source (Guerra-Gorostegi et al., 2021) and/or using more efficient drying technologies, most importantly with heat recovery (Moejes et al., 2018). An initial de-watering process can additionally reduce energy consumption, followed by a thermal drying process that is appropriate to the material's properties (Perazzini et al., 2016). Also, emerging technologies such as biodrying or electro-dewatering, could be promising options. However, these technologies would have to be evaluated individually, as the efficiency of biodrying depends on the final desired moisture content and there is a risk of greenhouse emissions during the process (Guerra-Gorostegi et al., 2021) while electro-dewatering and other novel technologies still need to mature technologically (Lv et al., 2021; Perazzini et al., 2016). To reduce the transportation impacts, the fertiliser production should be located as close to the side-stream as possible. This will not only reduce environmental impacts but also create co-benefits by reducing odour emissions and sanitary issues during transport (Chojnacka et al., 2020).

4.6. Optimisation potential of BBF application

Optimisation potential was also identified for the BBF application. For terrestrial acidification, the BBF Pellets treatment exhibited lower impacts per ha of broccoli cultivation than the MFT (see supplementary materials, Fig. S1), while impacts were higher than the MFT per kg of broccoli. A higher agronomic performance would allow to apply less BBFs to achieve the same yield which in turn would reduce production impacts and field emissions per kg of product (Jasiński et al., 2026; Rashid et al., 2025). A higher agronomic performance may be achieved by optimising chemo-physical properties of the BBFs during the production. However, the application method may be equally important: Müller et al. (2024) found in field trials with total 18 BBFs that soil incorporation tended to increase their agronomic efficiency. Therefore, considering the application method in the design of agronomic trials to evaluate new BBFs may also help to increase their potential environmental given that also other effects, e.g. on NH_3 and N_2O emissions, are considered. When BBF application rates are derived based on their N-content to substitute mineral N fertiliser as for this study (N equivalence), comparably high amounts of P can be applied as a result (64%-141% higher than the MFT in this study; see Table 3). While this can compensate for the generally lower availability of P in organic BBF (Hernandez-Mora et al., 2024), the potential for P overfertilisation stemming from excessive P inputs must be carefully considered (Hanserud et al., 2018; Herrera et al., 2022; Jasiński et al., 2026; Rashid et al., 2025). This is particularly an issue on the 72% European cropland soils for which Recena et al. (2022) modelled an excess of available P.

Considering P overfertilisation also demonstrates the need for generally applying good practice in fertilisation such as optimising its timing and rate (Johnston and Bruulsema, 2014). However, to further reduce environmental impacts of broccoli production, other measures beyond fertilising, e.g. substituting plastic mulch films or avoiding peat soils for seedling production, will also need to be implemented.

4.7. Burden-free assumption

Like the majority of LCA studies on valorisation of organic waste streams to biobased fertilisers, this study assumes no environmental burdens for the side-streams used to produce the BBFs (Egas et al., 2023; Tanzer et al., 2021). However, this assumption needs to be reviewed if the market value of side-streams increases, e.g. due to increased demand caused by the promotion of valorisation of organic waste streams by the European Union. This could ultimately lead to higher modelled impacts for BBFs, thereby affecting their comparison with mineral fertilisers. Therefore, Vikki et al. (2025) recommend that an eventual Environmental Footprint Product Category Rule for BBFs should strictly distinguish between material with economic value (allocation of upstream impacts) and without (burden-free). Future circular economy policies should therefore aim to minimize both impacts of BBF production and of organic waste streams.

4.8. Limitations of the study and outlook

In addition to the uncertainty regarding the allocation of upstream impacts, other limitations apply. Upscaling the foreground data from the current pilot production introduced additional uncertainty, which could only be partially addressed by the sensitivity analysis. This could have led to an overestimation of impacts for Liquid and Solid BBF at industrial production, as the upscaling generally covered smaller changes (see Fig. 2). Another limitation concerns the functional unit of 1 kg N that was selected which is also reflected in the N-equivalent field trials: while this common functional unit (Egas et al., 2023) reflects the main function of the BBFs considered (source of N) and makes results from the impacts from the production of BBF relatable to the overall impacts of producing 1 kg of broccoli, it does not account for the provision of other nutrients such as P and K. Furthermore, the study focuses on a single field trial with one crop (broccoli) and specific pedoclimatic conditions. Therefore, more crops and growing conditions should be considered in future studies, also broadening the knowledge regarding potential residual effects of BBFs across multiple seasons. In addition, emission measurements should be conducted in parallel to enable the validation of finer-grained emission models (both mechanistic models and Tier 2 emission factors) that better account for different chemo-physical characteristics of BBFs.

5. Conclusion

This LCA study assessed selected environmental impacts of production and application of three BBFs from fishery side-streams in comparison to those of mineral fertilisers. To do so, life cycle inventories of novel processing pathways for BBFs were integrated with field trial data and modelled field emissions into a comprehensive life cycle assessment. The results showed for global warming and mineral resources use that the BBFs can have environmental benefits when applied instead of mineral fertilisers reducing impacts per kg of broccoli by 7-13%. However, the environmental performance between the BBFs varied, influenced by their production impacts and agronomic performance. Regardless of the identified uncertainties, the results demonstrate the importance of optimising production and application. This includes, among others, a production location close to the side-stream, the use of energy-efficient drying technologies and appropriate application techniques. Apart from the environmental impacts investigated in this study, the investigated BBFs may only have a limited effect on soil organic carbon increase. To assess environmental implications of BBF adoption on a larger scale, this study has identified the need for improved emission modelling and aligned LCA methodologies that allow for better integration of results from different studies.

Data availability

Life cycle inventories have been made available on Zenodo: https://doi.org/10.5281/zenodo.19133450

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT to improve the language of selected sentences and paragraphs of the manuscript or to shorten them. After using this tool/service, the author (s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

Funding sources

This work has benefited from a state grant managed by the Agence Nationale de la Recherche under the Investissements d'Avenir Programme with the reference ANR-18-EURE-0021. It received funding from the EU Horizon 2020 research program as well as the Swiss State Secretariat for Education, Research and Innovation (SERI) under the following projects: SEA2LAND (grant agreement No. 101000402) and ReLeaf (grant agreement No. 101156998; project co-financed by the Circular Bio-Based Europe Joint Undertaking (CBE-JU) and its members, by UKRI [grant agreement No. 10127468] and SERI [grant No. 24.00216, 101156998]).

CRediT authorship contribution statement

Jan Landert: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nicolas Wittmann:** Formal analysis, Methodology, Validation, Writing – review & editing. **Jean-François Fabre:** Data curation, Funding acquisition, Investigation, Methodology, Resources, Validation, Writing – review & editing. **Claire Vialle:** Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – review & editing. **Caroline Sablayrolles:** Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – review & editing. **Diogo A. Teixeira:** Data curation, Investigation, Methodology, Validation, Writing – review & editing. **Helena I. Monteiro:** Funding acquisition, Investigation, Methodology, Validation, Writing – review & editing. **Bruna Moura:** Data curation, Investigation, Methodology, Validation, Writing – review & editing. **Carlos Bald:** Funding acquisition, Methodology, Resources, Validation, Writing – review & editing. **Bruno Iñarra:** Funding acquisition, Methodology, Resources, Validation, Writing – review & editing. **Laura de Baan:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Supervision, Validation, Writing – review & editing.

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.

Acknowledgements

We would like to thank Corinne Andreola, Marie Soone, Tommy C. Olsen, Laure Candy, Clement Chastrette, Christine Raynaud, Monica Gutierrez, Haizea Domínguez, Joaquin Romero, Iñaki Aramburu, Jingsi Zhang, Çağrı Akyol, Liina Edesi, Tiina Talve, Marta Aranguren and Sarah Symanczik for providing data, and Saioa Ramos for reviewing inventory data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.148949.

Data availability

Research Link Provided.

References

Aborisade, M.A., Long, H., Rong, H., Kumar, A., Cui, B., Oladeji, O.A., Okimiji, O.P., Oba, B.T., Guo, D., 2026. Bio-based fertilizers from waste: nutrient recovery, soil health, and circular economy impacts. Toxics 14, 90. https://doi.org/10.3390/toxics14010090.

Andrade, E.P., Bonmati, A., Esteller, L.J., Montemayor, E., Vallejo, A.A., 2021. Performance and environmental accounting of nutrient cycling models to estimate nitrogen emissions in agriculture and their sensitivity in life cycle assessment. Int. J. Life Cycle Assess. 26, 371–387. https://doi.org/10.1007/s11367-021-01867-4.

Bulle, C., Margni, M., Patouillard, L., Boulay, A.-M., Bourgault, G., De Bruille, V., Cao, V., Hauschild, M., Henderson, A., Humbert, S., Kashef-Haghighi, S., Kounina, A., Laurent, A., Levasseur, A., Liard, G., Rosenbaum, R.K., Roy, P.-O., Shaked, S., Fantke, P., Jolliet, O., 2019. IMPACT World+: a globally regionalized life cycle impact assessment method. Int. J. Life Cycle Assess. 24, 1653–1674. https://doi.org/10.1007/s11367-019-01583-0.

Chojnacka, K., Mikula, K., Skrzypczak, D., Izydorczyk, G., Gorazda, K., Kulczycka, J., Kominko, H., Moustakas, K., Witek-Krowiak, A., 2024. Practical aspects of biowastes conversion to fertilizers. Biomass Convers. Biorefinery 14, 1515–1533. https://doi.org/10.1007/s13399-022-02477-2.

Chojnacka, K., Moustakas, K., Witek-Krowiak, A., 2020. Bio-based fertilizers: a practical approach towards circular economy. Bioresour. Technol. 295, 122223. https://doi.org/10.1016/j.biortech.2019.122223.

Cortés, A., Oliveira, L.F.S., Ferrari, V., Taffarel, S.R., Feijoo, G., Moreira, M.T., 2020. Environmental assessment of viticulture waste valorisation through composting as a biofertilisation strategy for cereal and fruit crops. Environ. Pollut. 264, 114794. https://doi.org/10.1016/J.ENVPOL.2020.114794.

Cucina, M., De Nisi, P., Sordi, S., Adani, F., 2021. Sewage sludge as N-Fertilizers for crop production enabling the circular bioeconomy in agriculture: a challenge for the new EU regulation 1009/2019. Sustainability 13, 13165. https://doi.org/10.3390/su132313165.

de Vries, W., 2021. Impacts of nitrogen emissions on ecosystems and human health: a mini review. Curr. Opin. Environ. Sci. Health 21, 100249. https://doi.org/10.1016/j.coesh.2021.100249.

Egas, D., Azarkamand, S., Casals, C., Ponsá, S., Llenas, L., Colón, J., 2023. Life cycle assessment of bio-based fertilizers production systems: where are we and where should we be heading? Int. J. Life Cycle Assess. 28, 626–650. https://doi.org/10.1007/s11367-023-02168-8.

EMEP/EEA, 2023. EMEP/EEA air pollutant emission inventory guidebook 2023. Technical Guidance to Prepare National Emission Inventories.

European Commission, 2018. A Sustainable Bioeconomy for Europe: Strengthening the Connection Between Economy. society and the environment.

European Commission, 2022. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - a New Circular Economy Action Plan for a Cleaner and More Competitive Europe.

Faist Emmenegger, M., Zah, R., Reinhard, J., 2009. Sustainability Quick Check for Biofuels (SQCB): a web-based tool for streamlined biofuels' LCA. Enviro 1, 317–323.

Gaviria Gaviria, Y.S., Camaño Echavarría, J.A., Zapata Montoya, J.E., 2021. Evaluation of the environmental impact of dry chemical silage obtained from the viscera of red tilapia (Oreochromis spp.) using ecological footprint methodology. Heliyon 7, e07337. https://doi.org/10.1016/j.heliyon.2021.e07337.

Gavrilova, O., Leip, A., Dong, H., Douglas MacDonald, J., Alfredo Gomez Bravo, C., Amon, B., Barahona Rosales, R., del Prado, A., Aparecida de Lima, M., Oyhantçabal, W., John van der Weerden, T., Widiawati, Y., Bannink, A., Beauchemin, K., Clark, H., 2019. Chapter 10 emissions from livestock and manure management. In: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Guerra-Gorostegi, N., González, D., Puyuelo, B., Ovejero, J., Colón, J., Gabriel, D., Sánchez, A., Ponsá, S., 2021. Biomass fuel production from cellulosic sludge through biodrying: aeration strategies, quality of end-products, gaseous emissions and techno-economic assessment. Waste Manag. 126, 487–496. https://doi.org/10.1016/J.WASMAN.2021.03.036.

Hanserud, O.S., Cherubini, F., Øgaard, A.F., Müller, D.B., Brattebø, H., 2018. Choice of mineral fertilizer substitution principle strongly influences LCA environmental

benefits of nutrient cycling in the agri-food system. Sci. Total Environ. 615, 219–227. https://doi.org/10.1016/j.scitotenv.2017.09.215.
He, H., Peng, M., Lu, W., Hou, Z., Li, J., 2022. Commercial organic fertilizer substitution increases wheat yield by improving soil quality. Sci. Total Environ. 851, 158132. https://doi.org/10.1016/j.scitotenv.2022.158132.
Hernandez-Mora, A., Duboc, O., Lombi, E., Bünemann, E.K., Ylivainio, K., Symanczik, S., Delgado, A., Abu Zahra, N., Nikama, J., Zuin, L., Doolette, C.L., Eigner, H., Santner, J., 2024. Fertilization efficiency of thirty marketed and experimental recycled phosphorus fertilizers. J. Clean. Prod. 467, 142957. https://doi.org/10.1016/j.jclepro.2024.142957.
Herrera, A., D'Imporzano, G., Zilio, M., Pigoli, A., Rizzi, B., Meers, E., Schouman, O., Schepis, M., Barone, F., Giordano, A., Adani, F., 2022. Environmental performance in the production and use of recovered fertilizers from organic wastes treated by anaerobic digestion vs synthetic mineral fertilizers. ACS Sustain. Chem. Eng. 10, 986–997. https://doi.org/10.1021/acssuschemeng.1c07028.
IFA, 2026. Global Fertilizer database | IFASTAT Data query [WWW Document]. IFAStat. URL. https://ifastat.org/fertilizer-data-query. (Accessed 18 May 2026).
IPCC, 2019. Guidelines for National Greenhouse Gas Inventories.
Jasiński, D., De Keyser, E., Mondini, C., Amery, F., Baran, J., Ronchin, E., Cisilino, F., Angeloni, A., Kuiper, D., Visser, R., Deman, N., Adame, A.A., Martínez-Gaitán, C.C., Ramos, R., Dobrović, L., 2026. The environmental sustainability of bio-based fertilisers produced via integrated nutrient recycling technologies. Biomass Bioenergy 207, 108705. https://doi.org/10.1016/j.biombioe.2025.108705.
Johnston, A.M., Bruulsema, T.W., 2014. 4R nutrient stewardship for improved nutrient use efficiency. Procedia Engineering, SYMPHOS 2013 - 2nd International Symposium on Innovation and Technology in the Phosphate Industry 83, 365–370. https://doi.org/10.1016/j.proeng.2014.09.029.
Lam, K.L., Zlatanović, L., van der Hoek, J.P., 2020. Life cycle assessment of nutrient recycling from wastewater: a critical review. Water Res. 173, 115519. https://doi.org/10.1016/j.watres.2020.115519.
Lv, H., Xiong, Q., Liu, D., Wu, X., 2021. Coupling electro-dewatering and low-temperature air-drying for efficient dewatering of sludge. Sci. Rep. 11 (1 11), 1–10. https://doi.org/10.1038/s41598-021-98477-9, 2021.
Müller, B., Wester-Larsen, L., Jensen, L.S., Salo, T., Garrido, R.R., Arkoun, M., D'Oria, A., Lewandowski, I., Müller, T., Bauerle, A., 2024. Agronomic performance of novel, nitrogen-rich biobased fertilizers across European field trial sites. Field Crops Res. 316, 109486. https://doi.org/10.1016/J.FCR.2024.109486.
Moakes, S., Oggiano, P., Landert, J., Pfeifer, C., de Baan, L., 2026. FarmLCA: a novel approach to assess agroecological innovations in Life Cycle Assessment. Agric. Syst. 232, 104560. https://doi.org/10.1016/j.agsy.2025.104560.
Moejes, S.N., Visser, Q., Bitter, J.H., van Boxtel, A.J.B., 2018. Closed-loop spray drying solutions for energy efficient powder production. Innov. Food Sci. Emerg. Technol. 47, 24–37. https://doi.org/10.1016/J.IFSET.2018.01.005.
Mutel, C., 2017. Brightway: an open source framework for Life Cycle Assessment. J. Open Source Softw. 2, 236. https://doi.org/10.21105/joss.00236.
Oberholzer, H.R., Weisskopf, P., Gaillard, G., Weiss, F., Freiermuth, R., 2006. Methode Zur Beurteilung Der Wirkungen Landwirtschaftlicher Bewirtschaftung Auf Die Bodenqualität in Ökobilanzen – SALCA-SQ. Agroscope FAL Reckenholz, Zurich.
Perazzini, H., Freire, Flavio Bentes, Freire, Fábio Bentes, Freire, J.T., 2016. Thermal treatment of solid wastes using drying technologies: a review. Dry. Technol. 34, 39–52. https://doi.org/10.1080/07373937.2014.995803.
Petrova, I., Tolstorebrov, I., Eikevik, T.M., 2018. Production of fish protein hydrolysates step by step: technological aspects, equipment used, major energy costs and methods of their minimizing. Int. Aquat. Res. 10, 223–241. https://doi.org/10.1007/S40071-018-0207-4/FIGURES/10.
Prasuhn, V., 2006. Erfassung Der PO4-Austräge Für Die Ökobilanzierung - SALCA-Phosphor. Agroscope Reckenholz, Zurich.
Rashid, M.A., Wester-Larsen, L., Agostini, L., Jensen, L.S., 2025. Modelling agronomic and environmental effects of bio-based nitrogen fertilisers in Europe. Nutrient Cycl. Agroecosyst. 132, 11. https://doi.org/10.1007/s10705-025-10463-z.
Recena, R., García-López, A.M., Quintero, J.M., Skyttä, A., Ylivainio, K., Santner, J., Buenemann, E., Delgado, A., 2022. Assessing the phosphorus demand in European agricultural soils based on the Olsen method. J. Clean. Prod. 379, 134749. https://doi.org/10.1016/J.JCLEPRO.2022.134749.
Regulation (EU) 2019/1009, 2019. 2019/1009 of the European Parliament and of the Council of 5 June 2019 Laying down Rules on the Making Available on the Market of EU Fertilising Products and Amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and Repealing Regulation (EC) No 2003/2003.
Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., Rockström, J., 2023. Earth beyond six of nine planetary boundaries. Sci. Adv. 9. https://doi.org/10.1126/sciadv.adh2458.
Shukla, P.R., Skeg, J., Buendia, E.C., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D., Zhai, P., Slade, R., Connors, S., Van Diemen, S., 2019. Climate Change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management. Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.
Steffens, M., Bünemann, E.K., 2025. Quality of bio-based fertilizers is decisive for improving soil quality in Europe—A meta-analysis. Soil Use Manage. 41, e70012. https://doi.org/10.1111/sum.70012.
Stewart, W.M., Dibb, D.W., Johnston, A.E., Smyth, T.J., 2005. The contribution of commercial fertilizer nutrients to food production. Agron. J. 97, 1–6. https://doi.org/10.2134/agronj2005.0001.
Tanzer, J., Hermann, R., Hermann, L., 2021. LEX4BIO D6.1: Review and Assessment of Published Life Cycle Assessment Studies on Bio-based Fertilisers.
te Wierik, S., DeClerck, F., Beusen, A., Gerten, D., Maggi, F., Norberg, A., Noone, K., Schulte-Uebbing, L., Springmann, M., Tang, F.H.M., de Vries, W., van Vuuren, D., Vermeulen, S., Rockström, J., 2025. Identifying the safe operating space for food systems. Nat. Food 6, 1153–1163. https://doi.org/10.1038/s43016-025-01252-6.
Ti, C., Xia, L., Chang, S.X., Yan, X., 2019. Potential for mitigating global agricultural ammonia emission: a meta-analysis. Environ. Pollut. 245, 141–148. https://doi.org/10.1016/j.envpol.2018.10.124.
van der Hulst, M.K., Huijbregts, M.A.J., van Loon, N., Theelen, M., Kootstra, L., Bergesen, J.D., Hauck, M., 2020. A systematic approach to assess the environmental impact of emerging technologies: a case study for the GHG footprint of CIGS solar photovoltaic laminate. J. Ind. Ecol. 24, 1234–1249. https://doi.org/10.1111/JIEC.13027.
van der Zee, T., Bannink, A., van Bruggen, C., Groenestein, K., Huijsman, J., van der Kolk, J., Lagerwerf, L., Luesink, H., Velthof, G., Von, J., 2021. Methodology for estimating emissions from agriculture in the Netherlands. https://doi.org/10.21945/RIVM-2021-0008.
Vikki, K., Korkalo, P., Abdulkareem, M., Senán-Salinas, J., Heusala, H., 2025. Harmonizing and aligning life cycle assessments of bio-based fertilizers towards environmental footprint methods. Int. J. Environ. Sci. Technol. 23, 152. https://doi.org/10.1007/s13762-025-06827-1.
WEF, 2024. Investigating Global Aquatic Food Loss and Waste (Whitepaper). World Economic Forum, Geneva.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.
Wester-Larsen, L., Müller-Stöver, D.S., Salo, T., Jensen, L.S., 2022. Potential ammonia volatilization from 39 different novel biobased fertilizers on the European market – a laboratory study using 5 European soils. J. Environ. Manag. 323, 116249. https://doi.org/10.1016/J.JENVMAN.2022.116249.
Zhang, J., Akyol, Ç., Meers, E., 2023. Nutrient recovery and recycling from fishery waste and by-products. J. Environ. Manag. 348. https://doi.org/10.1016/J.JENVMAN.2023.119266.
Zhang, J., Edesi, L., Talve, T., Akyol, Ç., Koll, B., Roman, I., Toom, M., Aranguren, M., Virgel Mentxaka, S., Kuu, A., De Neve, S., Meers, E., 2025. Recycling fishery waste into biobased fertilizers: agronomic performance and soil health impacts. Soil Tillage Res. 253, 106686. https://doi.org/10.1016/j.still.2025.106686.