

D7.2. Environmental impacts evaluation



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Abstract

The production of mineral fertilisers causes several sustainability issues: while the manufacturing of nitrogen fertilisers requires high energy input, phosphorus fertilisers depend on the extraction of phosphate rock from finite deposits. In this study, we assessed the environmental impacts of five Biobased fertilisers (BBF) produced from different waste streams of the fish industry in pilot facilities. In a first step, impacts of BBFs production were analysed, including potential efficiency gains for a future industrial production. In a second step, environmental impacts of crop production were assessed for four BBFs with a high agronomic performance in two pot (ryegrass and wheat) and two field trials (twice broccoli). The environmental hotspots of BBFs production as well as BBF application regarding Global warming, Mineral resources use, Terrestrial acidification as well as Freshwater and Marine eutrophication were identified. Environmental hotspots included the transport of side-streams (both, fresh and dried) to the BBF factory, the concentration process (removing water with different procedures), the packaging, as well as field emissions during application. Field emissions dominated the eutrophication impact categories while the production of BBFs had a strong impact on Global warming and Mineral resources use. The comparison with mineral fertilisers was strongly dependent on the agronomic performance on the BBFs and resulted in both similar, lower and higher impacts for BBFs in comparison with mineral fertilisers, depending on the agronomic conditions and environmental impact. This underlines the need to consequently optimize the BBF production and agronomic performance to reduce environmental impacts. The study identified key uncertainties such as modelling future industrial-scale BBF production, determining the relative agronomic performance of BBFs based on a few pot and field trials and the lack of BBFs-specific emission factors for determining field emissions. This stresses the need for more specific and standardized methods to assess the environmental impacts of BBFs.

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Glossary

AMGA: Annotated Model Grant Agreement

AMFE: Agronomic Mineral Fertiliser Equivalent

AZTI: Food Research, Basque Research and Technology Alliance, Derio (ES)

BARNA: Barna SA, Mundaka (ES)

BBF: Bio-based fertiliser

CATAR: Centre d'Application et de Traitement des Agro-Ressources, Toulouse (FR)

D: Deliverable

DM: Dry matter

dt: deciton (100 kg)

FarmLCA: LCA tool for agricultural production

FERTINAGRO: Fertinagro Biotech SL, Teruel (ES)

FU: Functional unit

Field emissions: Emissions to air, water and soil related to agricultural production.

FIBL: Research Institute of Organic Agriculture, Frick (CH)

GRONN: Grønn Gjødning AS, Rakkestad (NO)

GHG: greenhouse gas

GWP: global warming potential

INPT: Institut national polytechnique de Toulouse (FR)

ISQ: Instituto de Soldadura Equalidade, Porto (PT)

LCA: Life cycle assessment

LCI: Life cycle inventory

LCIA: Life cycle impact assessment

METK: Centre of Estonian Rural Research and Knowledge, Jõgeva (EE)

NEIKER: Instituto Vasco de Investigación y Desarrollo Agrario SA, Arkaute (ES)

NUTRI: Nutriloop OU, Tallinn (EE)

UNIVPM: Università Politecnica delle Marche, Ancona (IT)

1 Introduction

1.1 Background

The production of mineral fertilisers causes several sustainability issues: while the manufacturing of nitrogen fertilisers requires high energy input, phosphorus fertilisers depend on the extraction of phosphate rock from finite deposits (Zhang et al., 2023). In a circular economy, fertiliser production should thus be shifted towards the valorisation of so far unused biowaste streams from various sources (Chojnacka et al., 2020; Zhang et al., 2023). An increasingly important waste stream originates from fish processing and aquaculture production.

1.2 Aim of this study

In this study, we analyse the environmental impacts of the production and application of bio-based fertilisers (BBFs) produced from fish processing and aquaculture waste.

This is done in two steps: a cradle-to-factory gate assessment aims at identifying processes that have a high contribution to environmental impacts of **production**. This analysis mainly aims to optimize the production processes and is documented in more detail in section 2.2. It also covers a comparison to mineral fertiliser production.

The inventories of the aforementioned assessment will be then used in a cradle-to-farm gate assessment to cover the production **and use phase** of the BBF. Based on agronomic performance data, this assessment compares the BBFs to mineral fertilisers, the main aim of this second assessment. More details on the approach are documented in section 2.3.

1.3 Overview on case studies and analysed BBFs

In the Sea2Land project, seven case studies were established. The environmental performance of the **production of BBFs** was assessed for those case studies producing BBFs at pilot or industrial scale that qualified as "organic fertilisers" without further need for improvements in composition (five BBF). For assessing the environmental impacts of the **BBF application**, fertilisers with low fertilising effect in pot trials (less than 60% agronomic mineral fertiliser equivalent) were excluded, because it is unlikely that they will be marketed without further improvements (four BBFs remaining).

An overview of the different case studies, the used side-streams, the process types and the resulting bio-based fertiliser products and co-product (such as biostimulants, soil amendments) as well as the selection of BBFs for this LCA study is given in Table 1.

Table 1. Overview of case studies, used side-streams, process types and resulting products (products marked in bold were classified as bio-based fertiliser (BBF) by (Zhang & Akyol, 2023). (Co-)products in bold were selected for an in-depth analysis in this deliverable, for those marked with asterisk (), no LCA was conducted (but they were still considered in the economic allocation). AA: amino acids*

Industry type	Case study	Side-stream	Process types	Products (Main product, co-products)	LCA	
					Production	Application
Fish industry	Baltic Sea, Estonia (T3.1)	Fish waste, food waste, leaves, ash	Bokashi fermentation, vermicomposting, granulation	Granules (1), Vermicompost (2), Liquid biostimulant (3)	X	X
	Cantabrian Sea, Spain (T3.2)	Fish viscera	Oil separation, Acid autolysis, centrifugation, membrane filtration	NPK solution with AA (1), Fish oil* (2), Solids* (3)	X	X
	Adriatic Sea, Italy (T3.3)	Crustacean, shells molluscs	Wet separation, protein hydrolysis, pyrolysis, composting, chemical extraction	Hydrolysates (1), compost-biochar composite (2), CaCO ₃ * (3)	X	
Aqua-culture	North Sea, Norway (T4.1)	Fish sludge, blood and bone meal	Hygienisation, mixing, pelleting	Pelleted fish sludge (1), pelleted organic fertiliser (2)	X	X
	Atlantic Sea, France (T4.2)	Fish waste	TMC (twin-screw extrusion), centrifugation, hydrolysis,	Solid BBF (1), biostimulant (2), fish oil (3)	X	X

2 Methods

2.1 Overall framework

2.1.1 Two step assessment

In this study, the BBF's were analysed from cradle-to-farm gate. As outlined in section 1.2, the analysis was performed in two steps (Figure 1). In a first step, an LCA was conducted for the BBF production, from cradle-to-factory gate. In a second step, a cradle-to-farm-gate analysis was conducted, using the FarmLCA model (Meier & Moakes, 2019; Schader et al., 2014) to assess impacts of fertiliser utilisation.

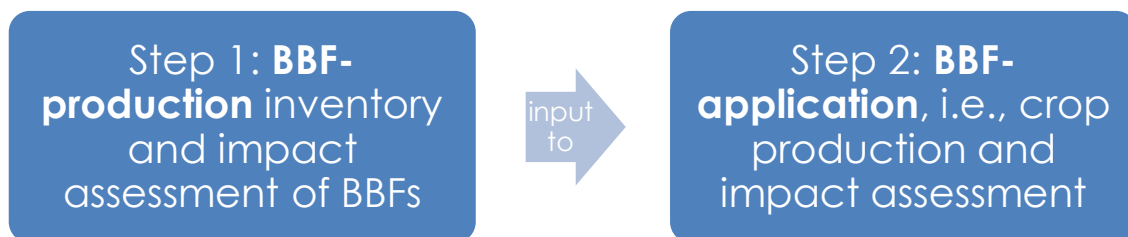


Figure 1: Two step approach of LCA in Sea2Land

2.1.2 Pilot scale and upscaling to industrial scale

In most Sea2Land case studies, BBF production is currently at pilot scale, and not yet at industrial production. To get a more realistic comparison with existing fertilisers, an upscaling to industrial scale (TRL 9) was performed.

Following process was followed for the upscaling (according to principles defined in van der Hulst et al. (2020):

A) Process changes

- Is the source of electricity still realistic in an industrial scenario (e.g. roof top- solar energy in pilot plant)?
- Is the source of side-stream still realistic in an industrial scenario, or has the side-stream to be sourced from a more distant place?
- Will the product's nutrient content / availability most likely change again?
- Is the mass ratio between co-products changing (→ e.g. effect on allocation)?

B) Size scaling

- How much does the yearly production volume change?

- Is there a need for larger machinery, larger buildings etc.?
- How does scaling affect yield, environmental burdens (e.g. electricity consumption, direct emissions etc.)?

If efficiency gains were expected, the inventory was adapted. For linear scaling, inventories did not have to be adapted

C) Minimizing waste / processing inputs

- Can inputs, waste-stream etc. be recycled? Are there synergies with other production processes?

Not included in the industrial scenarios were factors which are very difficult to quantify. Therefore, **external factors** (such as changes in future regulations or other conditions, e.g. market formation dynamics of side-streams) and **industrial learning** (optimisation after TRL 9) were not considered in the inventories of upscaled BBF production.

Data:

Since primary data was (in most cases) not available for the industrial production, estimates and assumptions were made by the case study partners. In addition, data collected in the techno-economic assessment (Task 7.1, Romero et al., 2023a) was used, where useful, and data on alternative use of side-streams was derived from Bald et al. (2021) for case studies 3.1-3.3. Estimates and assumptions were also derived from similar industrial processes (van der Hulst et al., 2020). Linear scaling (no efficiency gains etc.) and same processes / parameters (e.g. transport distances) were assumed, where no certain information was available that a process would change.

2.1.3 Harmonisation process across case studies

To harmonise LCA studies performed on BBF production (step 1) by different institutions for different case studies, a project internal guideline was established. In this guideline, a harmonised approach on goal and scope, data collection, inventory creation and impact assessment were defined. This harmonised approach should allow cross-case study comparisons of BBFs production. An internal review process of inventories was conducted, to find discrepancies in approaches and potential errors across case studies. Common assumptions are presented in section 2.2 and in the Appendix 10.1.1.

For step 2, work was conducted by one partner and no harmonisation was needed.

2.2 Step 1: LCA of fertiliser production

2.2.1 Goal and scope

Goal: The aim of the LCA on fertiliser production was (1) to identify hotspots of environmental impacts and optimisation potential for each of the most promising BBFs at pilot scale, (2) to understand how environmental impacts could change with an upscales industrial production and (3) to compare impacts of BBFs produced at industrial scale to conventional mineral and tradable ready-to-use organic fertiliser.

Scope: To analyse the environmental impacts of BBFs production, a cradle-to-factory gate attributional LCA was conducted. All upstream processes, inputs and outputs involved in BBF production were included. Among others, this includes:

- manufacturing of inputs and related processes, including packaging
- transportation of inputs to the facility
- manufacturing of capital goods, such as machinery (Frischknecht et al., 2007)
- buildings
- direct emissions of processes (e.g. NH_3 , N_2O , CH_4 , CO_2).
- co-products and waste

As a default, the production of the organic input material for BBFs (e.g. fish sludge) was considered as "waste" with no environmental impacts associated to it ("burden-free"). Environmental impacts were only considered from the point where "organic waste" is processed, cooled, dried or transported to produce BBF. Alternative uses (e.g. fishmeal production) that would justify a consequential approach accounting for impacts of substitution were not considered for the sake of transparency and comparability between the BBF¹.

Functional unit: Because most BBFs contain different macronutrients (N, P, K) with various concentrations, two functional units were chosen for the comparison with other fertilisers: 1 kg N in fertiliser (for all fertilisers) and 1 kg BBF (for each BBF with a different content of macronutrients)

Allocation: Economic allocation was chosen as a default to allocate impacts of several co-products resulting from one process.

¹ To our knowledge, this was only the case in the Atlantic Sea case study.

2.2.2 Inventory / data collection

Primary data on pilot scale production as well as expected changes for industrial scale were collected from case studies via a harmonised questionnaire for all case studies. Individual clarification meetings were held to obtain the necessary data.

For background processes and processes with lacking primary data at pilot scale, common assumptions were taken. An overview on assumptions regarding transport of machinery to BBF facility and recycling rates of material is given in Table 2. Common inventories from the ecoinvent database were selected for buildings, some machinery and reference fertilisers (see chapters 2.2.5 and 10). For direct emissions, standard values were assumed, if no data was available from case studies (Table 3), and sensitivity analyses were performed.

Table 2. Common assumptions across case studies for transport of machinery and recycling rates after end-of-life for different types of material.

	Unit	Value	Source / comment
Transport machinery to factory gate			
rail	km	787.5 ²	(Borken-Kleefeld, 2012)
road	km	46.3 ³	(Borken-Kleefeld, 2012)
domestic air	km	38.4 ⁴	(Borken-Kleefeld, 2012)
Recycling rates of material			
Plastic (polyethylene)	%	32.5	(Economist, 2016)
Steel / cast iron	%	90.0	(EuRIC, 2020)
Electronics	%	42.5	(euronews, 2022)
Glass fibre	%	0	(European Commission, 2018; Rytka, 2023)
Bricks (e.g sand-lime brick)	%	50.0	(European Commission, 2018)

² 822 km average transport distance x 95.8 % mode share.

³ 1218 km average transport distance x 3.8 % mode share.

⁴ 1239 km average transport distance x 3.1 % mode share.

Table 3: Common assumptions on direct emissions

	Value	Unit	Source	Comment
Composting				
CH ₄	4 (0.03 - 8)	kg emitted / t waste composted	On a wet weight basis (60% moisture content)	On a wet weight basis (60% moisture content)
N ₂ O	0.24 (0.06 – 0.6)	kg emitted / t waste composted	(IPCC, 2006)	On a wet weight basis (60% moisture content)
VOC	0.205 – 7.3 (average 3.7525)	kg emitted / t waste composted	(Cadena et al., 2009)	Aerobic composting (tunnel vs confined windrow)
NH ₃	2 – 3.9 (average 2.95)	kg emitted / t waste composted	(Cadena et al., 2009)	Aerobic composting (tunnel vs confined windrow)
CO ₂	Not relevant (biogenic source)		(Cadena et al., 2009)	Based on reference to Rabl et al. 2007
CH ₄	0.8 (0 - 8)	kg emitted / t waste composted	(IPCC, 2006)	On a wet weight basis (60% moisture content)
N ₂ O	Assumed negligible	kg emitted / t waste composted	(IPCC, 2006)	
Vermicomposting				
CH ₄	0.015 (0.00029 - 7.6)	kg emitted / t waste composted	Studies listed in review by Yasmin et al. (2022) (values extracted from original studies), see this document	Diverse waste types and studies
N ₂ O	0.019 (0.000034 - 0.64)	Kg emitted / t waste composted	Studies listed in review by Yasmin et al. (2022) (values extracted from original studies), see this document	Diverse waste types and studies
CO ₂	Not relevant (biogenic source)		(Cadena et al., 2009)	Based on reference to Rabl et al. 2007

2.2.3 Impact assessment

The method Impact World+ version 2.0 was selected for the impact assessment. Following midpoint impact categories were chosen for the analysis and comparison of BBFs, because they cover the most relevant environmental impacts related to bio-based fertiliser production:

- Climate change, short term (GWP 100) [kg CO₂ eq] (referred to as Global warming in the following)
- Terrestrial acidification [kg SO₂ eq]
- Marine Eutrophication [kg N N-lim eq]
- Freshwater Eutrophication [kg PO₄ P-lim eq]
- Mineral resources use [kg deprived]

2.2.4 Sensitivity analysis

For highly uncertain parameters, sensitivity analyses were performed. For the cross comparison of BBFs with mineral N fertiliser, environmental impacts of different mineral N fertiliser were compared. Additional sensitivity analyses were performed per case study (see description in chapter 3).

2.2.5 Comparison of BBF at industrial scale with other fertilisers

For a comparison of environmental impacts per kg N contained in the BBFs across all case studies, mineral nitrogen fertiliser and pelleted poultry manure were selected as typical alternative mineral or organic ready-to-use, processed and tradable solid fertiliser with high N content (see Table 4).

For a comparison of environmental impacts per kg BBF, a hypothetical mineral fertiliser containing the same amounts of macronutrient (N, P, K) was used as a comparison. Since macronutrient contents differ between case studies, a so called “NPK-equivalent fertiliser” was constructed for each case study separately. For example, a BBF containing 4% N, 3% N₂O and 2% K₂O was compared as follows:

- BBFs from Sea2Land:
 - o 1 kg BBF (corresponding to 0.04 kg N / kg BBF, 0.03 kg P / kg BBF and 0.02 kg K / kg BBF)
- NPK equivalent fertiliser (based on processes shown in Table 4, with a conversion factor from P to P₂O₅ of 2.291 and from K to K₂O of 1.205):
 - o 0.04 kg mineral nitrogen + 0.06873 kg P₂O₅ from mineral phosphorus + 0.024102 kg K₂O mineral potassium

For nitrogen, several fertiliser inventories exist in ecoinvent, with strongly variable environmental impacts (see Appendix, 10.1.4). Fertiliser consumption statistics were therefore used to reflect the most commonly used solid N-fertilisers in Europe (liquid fertilisers were excluded). Consumption data of Ammonium Nitrate (AN), Calcium

Ammonium Nitrate (CAN) and urea in West and Central Europe for the years 2010-21 was obtained from IFA (2023). Data on East Europe as well as Calcium Nitrate (CN) was not available separately and was therefore not considered. The average consumption was calculated as the sum of West and Central Europe, averaged over the years 2010-21 and market shares of each fertiliser were calculated as the percentage of the average total consumption (see Appendix, Section 10.1.4). The average consumption was calculated as the sum of West and Central Europe, averaged over the years 2010-21 and market shares of each fertiliser were calculated as the percentage of the average total consumption (see Appendix, section 10.1.4).

For phosphorus, triple superphosphate was selected based on European Commission (2019) as the only fertiliser containing only phosphorus. For potassium, potassium chloride (or muriate of potash, MOP) was selected as the only relevant mineral fertiliser containing no other nutrients (European Commission, 2019).

Table 4. Overview on fertiliser used to compare to BBFs content in N, P₂O₅ and K₂O. Share of nutrients were determined based on market share of single nutrient fertiliser according to IFA (2023)

Fertiliser type	Nutrient	Inputs	Amount of product (kg)	Share of input in final product
Mineral	Nitrogen (per kg N)	Urea production {RER} (46 % N)	1.07	49%
		Calcium ammonium nitrate production {RER} (27 % N)	0.963	26%
		Ammonium nitrate production {RER} (33.5 % N)	0.746	25%
		Packaging	2.78	-
	Phosphorus (per kg P ₂ O ₅)	Triple superphosphate production {RER} (46 % P ₂ O ₅)	2.17	100%
		Packaging	2.17	-
	Potassium (per kg K ₂ O)	Potassium chloride production {RER} (60 % K ₂ O)	1.67	100%
		Packaging	1.67	-
Organic	Poultry manure (per kg N)	Poultry manure, pelleted, dried {RER} (4.6 % N, 3.3 % P ₂ O ₅ , 2.5 % K ₂ O, 85 % organic matter)	21.74	100%
		Packaging	21.74	-

2.3 Step 2: LCA of fertiliser use

2.3.1 Goal and scope

Goal: The aim of the LCA on fertiliser use was to compare impacts of BBFs produced at industrial scale to conventional mineral fertiliser, including field emissions after application of fertilisers and potential differences in crop management and yields.

Scope: To analyse the environmental impacts of BBFs use, a cradle-to-farm gate attributional LCA was conducted. All upstream processes, inputs and outputs involved in BBF production calculated in step 1 were included, as well as the field emissions, tractor use during fertiliser application, transport of fertilisers to farm, effects on yields, and general crop management (sowing, soil management, fertilisation, crop protection, harvesting, etc.)

To estimate effects on yields, data from pot and field trials conducted within the Sea2Land project were available for wheat (pot trials on N-fertilisation), rye grass (pot trials on P- and K-fertilisation) and broccoli (field trials on N-fertilisation). The environmental impacts of using different BBFs were modelled for these three crops. Impacts were compared to impacts of crops grown with mineral fertilisers (reference) and in case of field trials additionally to crops grown without any fertilisation.

The functional units were 1 kg of wheat grains (fresh matter), 1 kg of harvested rye grass (dry matter) or 1 kg of broccoli (heads, stalks and leaves as fresh matter) as well as 1 ha of the respective fields (to analyse yield effects).

Allocation: Economic allocation was chosen as a default to allocate impacts of several co-products resulting from one process.

2.3.2 FarmLCA model

For the agricultural phase, the model "FarmLCA" (Meier & Moakes, 2019; Moakes et al., 2024; Schader et al., 2014) was used. It consists of a farm system model coupled with an LCA. The model enables to capture all farm activities until the farm gate and to model at varying degree of detail, depending on the available data. Field emissions (to air) of nitrous oxide (N_2O) are calculated with IPCC (2019) disaggregated emission factors, ammonia (NH_3) and nitric oxide (NO_x) field emissions are calculated utilising EMEP/EEA (2019) (NH_3 at Tier 2, NO_x at Tier 1) and nitrate (NO_3) losses (to water) is estimated using the SQCB method (Faist Emmenegger et al., 2009)⁵. Here, we assumed that 30% of nitrate emissions are reaching surface waters via drainage, the rest was assumed to be transferred to groundwater bodies. Phosphate losses are calculated with SALCA-Phosphorus (Oberholzer et al., 2006; Prasuhn, 2006) by classifying all BBFs as solid organic fertilisers (>15% DM according to IPCC; Gavrilova et al., 2019).

To cover background processes, the ecoinvent 3.9.1 LCI database (Wernet et al., 2016) is used, which is incorporated as the model's inventory database. This approach allows for inputs and outputs that are specific to a farm or region.

2.3.3 Description of pot and field trials

Wheat

The pot trial experiment for wheat was set up in a randomized block design by the project partner METK (Estonia; Edesi & Talve, 2024), with four replicates for each treatment. The plants were grown for 8 weeks in a greenhouse/ growth room under controlled

⁵ It is assumed that one-third of the crop area has been drained.

conditions, with a 10/ 14-hour light/ dark regime of 13.000 LUX and a temperature of 16-18 °C. The soil had a neutral pH and a low amount of nutrients and was collected from the top 0 - 20cm of a permanent grassland site in June 2022. Mineral fertiliser and BBFs were applied one day before sowing. For all pots with nutrient solution, each chemical element with demineralized water was added, except for nitrogen. BBFs were added at a rate of 0.3 g N per pot and were ground to 1 mm. The soil and BBFs were thoroughly mixed and all pots were watered to half of the field capacity. The spring wheat variety *Hiie* was selected and sown at a rate of 20 seeds per pot, with a sowing depth of 1.5 cm from the soil surface. The seeds were untreated and originated from a certified seed production. After the germination of the seeds, the plants were thinned to 15 plants in each pot. Watering with demineralized water was carried out at least twice a week and the pots were randomly rearranged in the greenhouse after each watering due to small differences in light levels.

Ryegrass

The pot trial experiment for rye grass was set up in a randomized block design by the project partner FiBL (Switzerland; Symanczik, 2024), with four replicates for each treatment. The plants were grown for 14 weeks in a climate chamber under controlled conditions, with 14-hour light regime of 28000 LUX, a temperature of 21 - 23 °C and a relative humidity of 60 - 80%. The soil had a pH of 6.7 and was a substrate consisting of a commercial potting substrate and sand (1:1 ratio). The BBFs were ground at 1mm and homogeneously mixed into the experimental substrate. The ryegrass variety *Gemini* was selected and homogeneously distributed at a rate of 0.5 g per pot on the surface of each pot, followed by a coverage of 5 g vermiculite and sprayed with demineralized water. The pots were watered from the bottom with a fertiliser solution to provide them with a total of 450 mg nitrogen, 60 mg magnesium, 410 mg calcium and 80 mg sulphur per kg substrate assuming nutrient concentrations high enough not to be limiting plant growth. Then, BBF were added in amounts equalling to 50 mg P/kg substrate to test P availability (including a mineral and unfertilised control).

Broccoli Estonia and Spain

Two field trial experiments for Broccoli were conducted in Estonia and Spain. Additional field trials were performed within the Sea2Land project, comparing the BBFs to other organic fertilisers. However, these fertilisers were not analysed here because no detailed inventory of these reference fertilisers was available.

Estonia

The field trial experiment for broccoli started on the 5th of June 2023 with the transplanting of seedlings. The trials had 1026 seedlings and contained 3 planting rows with a length of 8 m for each row. The planting distance between the seedlings was 45 cm between the single plants and 45 cm between each row. The total area of the experimental plot was 11.2 m². Each treatment has three replicates. The soil had a pH below 7 and a clay portion of 13.4%, silt portion of 70% and sand portion of 16.6%. Prior to the planting of the seedlings, the experimental field was ploughed and the seedbed prepared once with a rotary harrow. The BBFs and mineral fertiliser were tilled into the soil with a hand rake prior to the planting of the seedlings. Weeds were manually removed twice. A horticultural fleece was used to protect the plants against insect damage. The broccoli field trial was harvested on the 4th of August 2023. The Broccoli weight (dt FM⁶) was measured for heads (> 8 cm), as well as for heads, stalks and leaves (< 8 cm >).

Spain

The field trial experiment for broccoli started on the 19th of March 2024 with the transplanting of seedlings. The trials had 1026 seedlings and contained 3 planting rows with a length of 8 m for each row. The planting distance between the seedlings was 45 cm between the single plants and 45 cm between each row. The total area of the experimental plot was 11.2 m². Each treatment had three replicates. The soil had a pH of 6, a clay portion of 15.9% and a sand portion of 27.4%. Prior to the planting of the seedlings, the experimental field was ploughed and the seedbed prepared once with a rotary harrow. The BBFs and mineral fertiliser were tilled into the soil with a hand rake prior to the planting of the seedlings. Weeds were manually removed twice. A horticultural fleece was used to protect the plants against insect damage. The broccoli field trial was harvested on the 28th of May 2024. The Broccoli weight (dt FM) was measured for heads (> 8 cm), as well as for heads, stalks and leaves (< 8 cm >).

In this trial, the expected biostimulating effect of the BBF 3.2 Cantabrian Sea was tested instead of a direct fertilizing effect. The BBF was applied at a low dose of 1.5 kg BBF/ha together with a reduced amount of ammonium nitrate.

2.3.4 Inventory for wheat and rye grass

To compare the **environmental impacts** of using BBFs or mineral fertiliser to grow wheat or ryegrass, data on relative yield effects and fertilisation was extrapolated from the pot experiments. Data on crop management was based on standard inventories from

⁶ dt = deciton (100 kg)

ecoinvent of intensive Swiss lowland production⁷, and adapted where needed as outlined below. The region specific pedo-climatic conditions for wheat and ryegrass were used to match the conditions of the standard inventories⁸ and the fertilizer requirements used. They are shown in Table 5.

Table 5: Region specific pedo-climatic conditions used for modelling of pot trials for wheat and ryegrass.

Parameter	Switzerland (lowlands)
Elevation, m a.s.l.	400
mean annual precipitation, mm/a	900*
mean annual temperature, °C	9*
soil type: sand portion, %	48%+
soil type: clay portion, %	20%+
soil pH	6.2+

* estimated based on Federal Office of Meteorology and Climatology MeteoSwiss (2024)

+ derived from Agroscope & Federal Office for the Environment (FOEN) (2023)

For the **mineral fertiliser reference**, the fertilisation and yields in the standard inventories were adapted to correspond to the most recent Swiss fertilising recommendations of these crops, so called "GRUD" (Richner & Sinaj, 2017). Additionally, it was assumed that only mineral fertiliser is applied (in contrast to the ecoinvent inventories, where manure or slurry is also included). For the mineral fertiliser, the same assumptions were used as in step 1. To increase the relevance of assessment, an average market mix of 49% urea, 26% calcium ammonium nitrate and 25% ammonium nitrate was taken as N fertiliser assuming similar agronomic performance compared to the N fertiliser used in the pot experiments. For K, potassium chloride was assumed and for P, triple superphosphate was assumed in the FarmLCA model.

For the crops fertilised with **BBFs**, the same two standard inventories from ecoinvent of intensive Swiss lowland production were used as for the mineral fertiliser reference, but adapted where needed. For wheat, the amount of BBFs required to obtain a total N-

⁷ Ryegrass ecoinvent inventory: Grass, Swiss integrated production {CH} | grass production, Swiss integrated production, intensive | Cut-off, U

Wheat ecoinvent inventory: Wheat grain, Swiss integrated production {CH} | wheat production, Swiss integrated production, intensive | Cut-off, U

⁸ This includes the simplified assumption that the relative agronomic performance of BBF does not change in different pedo-climatic conditions.

content according to the GRUD recommendations was calculated. As the necessary amount of BBFs did not yet provide K according to GRUD, the missing amounts were provided as mineral fertiliser (see Table 8).

For rye grass, the required amount of each BBF to fulfil the P-fertiliser requirements was calculated. As the necessary applied amount of N and K was not meeting the GRUD recommendations, the difference in N and K was added as mineral fertiliser in the inventories (see Table 9). All other **data on crop management** was directly taken from ecoinvent and only adapted, where a clear relationship between yields or fertilisation was present (e.g. tractor use for fertilisation and harvest). Activities such as tillage, seeding, pest management or irrigation were assumed the same independent of the fertilisation regime.

Yield effects were calculated based on the results of the pot experiments conducted within the Sea2Land project. For N, pot experiments were conducted with spring wheat in two batches (results see Table 6). For P, pot experiments were conducted with rye grass (results see Table 7). These experiments encompassed a positive control (C+) with sufficient mineral N, P and K fertilisers and a negative control (C-) where no mineral N, but sufficient P and K were supplied (wheat) or no mineral P, but sufficient N and K were supplied (rye grass). A description of the experiments can be found in section 2.3.3. Since yields per hectare cannot be directly extrapolated from pot experiments, the difference in yields were determined by calculating the agronomic mineral fertiliser equivalent (AMFE) separately for each pot experiment:

$$\text{AMFE \%} = (\text{BM}_{\text{BBF}} - \text{BM}_{\text{C-}}) / (\text{BM}_{\text{C+}} - \text{BM}_{\text{C-}}) \times 100$$

BM: biomass of shoot:

Wheat: dry matter of shoot at end of pot experiment [g per pot]

Rye grass: cumulative shoot dry weight (sum of three cuts) [g per pot]

C-: control, where one macro nutrient (N or P) is not applied.

C+: control, fully fertilised with N-P-K mineral fertiliser.

BBF: bio-based fertiliser applied to obtain same amount of N (wheat) or P (rye grass) as in C+.

An AMFE of 100% expresses that the BBF showed the same yield as mineral fertilisers. An AMFE smaller than 100% means the BBF resulted in lower yield and a value higher than 100% corresponds to a BBF with higher crop yield compared to mineral fertilisers.

*Table 6: Agronomic mineral fertiliser equivalent (AMFE) calculated based on the wheat pot experiments with nitrogen (N). The experiment was conducted in two batches, with different controls. Data represent averages of 4 replicates (pots). *Fertiliser with AMFE below 60% are marked with an asterisk and were not analysed as N fertiliser in the LCA of fertiliser application.*

Batch	Case Study (fertiliser)	Wheat, shoot dry weight [g pot ⁻¹], average	Agronomic MFE (%), average
1	C- (no N fertiliser)	3.37	0
	C+ (NPK mineral fert.)	9.34	100
	3.1 Baltic Sea (BP)	3.94	9.5*
	3.3 Adriatic Sea (UNI1)	5.30	32.3*
	4.1 North Sea (FSP)	8.65	88.5
	4.2 Atlantic Sea (CAT1)	6.97	60.4
2	C- (no N fertiliser)	1.85	0
	C+ (NPK mineral fert.)	6.10	100
	3.2 Cantabrian Sea (FER3)	5.74	91.5

Table 7: Agronomic mineral fertiliser equivalent (AMFE) calculated based on the rye grass pot experiments with phosphorus (P). Data represent averages of 4 replicates consisting of pooled biomass from 3 pots. Fertiliser with AMFE slightly lower than 60% are marked with an asterisk and included in the LCA. Cumulative shoot dry weight was calculated as the sum of three cuts of rye grass. n.t. not tested due to low P-content in BBF.

Case Study (fertiliser)	Rye grass, cumulative shoot dry weight [g pot ⁻¹], average	Agronomic MFE (%) average
C- (no P fertiliser)	17.0	0
C+ (NPK mineral fert.)	25.8	100
3.1 Baltic Sea (BP)	25.2	93.2
3.2 Cantabrian Sea (FER3)	25.4	95.1
3.3 Adriatic Sea (UNI1)	n.t.	n.t.
4.1 North Sea (FSP)	22.0	57.3*
4.2 Atlantic Sea (CAT1)	27.0	113.6

Table 8: Overview on assumptions on fertilisation with BBFs and mineral fertiliser in winter **wheat** (intensive, Switzerland). Yield expressed in fresh matter (FM).

	Applied as BBF (kg/ha)				Applied as mineral fertiliser (kg/ha) (numbers rounded)			Yield (dt FM / ha)	Number of passes to spread mineral fertiliser with broadcaster ⁹
	BBF	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O		
Mineral Fertiliser¹⁰	-	-	-	-	140	63	81	60.0	4
3.2 Cantabrian Sea (FER3)	2637	140	96	71	-	-	10	54.9	1
4.1 North Sea (FSP)	2262	140	142	40	-	-	41	53.1	1
4.2 Atlantic Sea (CAT1)	1837	140	130	14	-	-	67	36.2	1

⁹ ecoinvent inventory: "Fertilising, by broadcaster {GLO} | market for | Cut-off, U". The machinery used for spreading the BBFs follows the method applied in the ecoinvent wheat inventory (see above) for loading and spreading solid organic fertiliser: The amount of BBFs applied is multiplied with the ecoinvent inventory "Solid manure loading and spreading, by hydraulic loader and spreader {GLO} | market for | Cut-off, U (working load 5t)." (Richner & Sinaj, 2017)

¹⁰ All values based on GRUD (Richner & Sinaj, 2017).

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Table 9: Overview on assumptions on fertilisation with BBFs and mineral fertiliser in **rye grass** (intensive, 5-6 cuts, >500 m a.s.l, Switzerland.) Yield expressed in dry matter, total of 5 cuts, with a dry matter content of 85%.

	Applied as BBF (kg/ha)				Applied as mineral fertiliser (kg/ha) (numbers rounded)			Yield (dt DM / ha)	Number of passes to spread mineral fertiliser with broadcaster ¹¹
	BBF	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O		
Mineral Fertiliser¹²	-	-	-	-	157	107	345	130.0	5
3.1 Baltic Sea (BP)	4469	118	107	103	39	-	242	121.1	1
3.2 Cantabrian Sea (FER3)	2931	156	107	79	1	-	266	123.7	1
4.1 North Sea (FSP)	1703	105	107	30	51	-	315	74.4	1.3
4.2 Atlantic Sea (CAT1)	1512	115	107	11	41	-	334	147.6	1.3

¹¹ ecoinvent inventory: "Fertilising, by broadcaster {GLO} | market for | Cut-off, U". The machinery used for spreading the BBFs follows the method applied in the ecoinvent wheat inventory (see above) for loading and spreading solid organic fertiliser: The amount of BBFs applied is multiplied with the ecoinvent inventory "Solid manure loading and spreading, by hydraulic loader and spreader {GLO} | market for | Cut-off, U (working load 5t)."

¹² All values based on GRUD (Richner & Sinaj, 2017).

2.3.5 Inventory for broccoli

To compare the **environmental impacts** of using BBFs or mineral fertilisers to grow broccoli, data on crop management and yield effects were extrapolated from the two field experiments in Estonia and Spain. For missing data, the parameters defined in the ecoinvent data base for global broccoli production were used. For both the mineral fertiliser control as well as the BBF treatments, the ecoinvent inventory was adapted for yields, fertilisation, related machinery, other external materials and emissions. For broccoli, the data of the field trials with the actual pedo-climatic conditions, fertilisation and measured yields were available. The region specific pedo-climatic conditions of the broccoli field trials for Estonia and Spain are shown in Table 10 (Aranguren & Pinto, 2024; Edesi, 2024).

Table 10: Region specific pedo-climatic conditions used for modelling of the broccoli field trials in Estonia and Spain.

Parameter	Estonia	Spain
Elevation, m a.s.l.	67	50
mean annual precipitation, mm/a	670	1200
mean annual temperature, °C	3.6	13.5
soil type: sand portion, %	16.6%	27.42
soil type: clay portion, %	13.4%	15.93
soil pH	<7	<7 (6)

The amount of mineral fertilisers and BBFs were taken from the actual field trials (Table 11). Moreover, the actual yields for the Broccoli heads (> 8 cm) and the whole Broccoli biomass, including heads, stalks and leaves (< 8 cm >) were directly taken from the field trials and thus the AMFE was only calculated for the purpose of selecting BBF with relatively high agronomic performance for the assessment (Table 12). The mineral fertiliser control treatment in the experiment, which consisted of ammonium nitrate was compared with a mineral fertiliser average market mix, which contained urea, ammonium nitrate and calcium ammonium nitrate (see 2.2.5). The field was ploughed and the seedbed prepared once with a rotary harrow before seeding. Afterwards, the BBFs were incorporated at the same time than the planting of the seedlings, thus no extra field pass was needed for the BBF application. The mineral fertilisers were surface-applied before the planting of the seedlings and mixed into the soil during the planting process of the seedlings. Weeds were sprayed once with a herbicide in a conventional broccoli

production process and an average horticultural fleece with a weight of 17 g / m² and a lifetime of 5 years was used to protect the crops from any insect damage. For the broccoli harvest, a standard tractor, equipped with a 10 m wide conveyor belt on the broccoli field as well as a tractor with a trailer that transports the broccoli from the field to the farm was included. The transportation volume was calculated based on the amount of harvested broccoli (kg FM ha⁻¹). All crop management activities which are not related to yields, fertilisation, related machinery, other external materials and emissions were not changed between the scenarios.

Table 11: Fertilisation of broccoli in field trials, conducted in the year 2023 in Estonia (E) and Spain (S).

Fertiliser	Total amount	Applied as BBF (kg/ha)			Applied as mineral fertiliser (kg/ha)			No. passes with broadcaster
		N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	
Unfertilized control	0	0	0	0	0	0	0	0
Mineral fertilizer control	0	0	0	0	120	22(E), 40(S)	124.5 (E), 150 (S)	1
4.1 North, FSP	1939	120	122	34	0	0	0	0
4.2 Atlantic, CAT1	1575	120	111	12	0	0	0	0
3.2 Cantabrian, FER3 ¹³	2260 (E), 1.5 (S)	120 (E) 8.E-02 (S)	82 (E) 5E-02 (S)	61 (E) 4E-02 (S)	0 (E) 84 (S)	0 (E) 0 (S)	0 (E) 0 (S)	0 (E) 1 (S)

¹³ In Spain, the BBF 3.2 Cantabrian, FER3 was applied as biostimulant (1.5 kg/ha assuming 1 kg / l density), together with ammonium nitrate.

Table 12: Average broccoli fresh matter yields (heads, stalks and leaves < 8 cm >; heads) in field trials, conducted in the year 2023 in Estonia and 2024 in Spain. Fertilisers with agronomic MFE below 60% (with regard to heads, stalks and leaves < 8 cm >) are marked with an asterisk and were excluded from the LCA of fertiliser use in the case of broccoli. n.t. = not tested.

Fertiliser	Yields (t FM/ ha)			
	(heads [all sizes], stalks and leaves)		(heads)	
	Estonia	Spain	Estonia (> 8 cm)	Spain (> 8 cm)
Unfertilized control	46.8±3.8	9.6±1.3	8.9	0.3 ¹⁴
Mineral fertilizer control	79.4±8.2	37.3±8.0	14.1	1.9
3.1 Baltic, BP*	50.9±4.9	n.t.	8.0	n.t.
3.2 Cantabrian, FER3 ¹⁵	68.2±4.6	40.6±8.0	14.7	1.9
3.3 Adriatic Sea, UNI1	n.t.	n.t.	n.t.	n.t.
4.1 North, FSP	56.7±7.3	25.0±3.7	9.8	0.5
4.2 Atlantic, CAT1	65.8±2.7	24.2±1.1	11.9	0.2

2.3.6 Impact assessment

The same impact assessment was applied as in step 1 (see 2.2.3).

2.3.7 Sensitivity analysis

2.3.7.1 Pot and field trials: Different NH₃ emission factors

For NH₃ emissions of the BBF, the emission factor from EMEP/EEA air pollutant emission inventory guidebook 2023 (Nicholas Hutchings et al., 2023) for “Other organic wastes” (0.08 kg NH₃ / kg N applied) was used in the baseline. For the sensitivity analysis, this emission factor for the BBFs was replaced with the emission factor from the Dutch national emission inventory (van der Zee T. et al., 2021) for “other organic fertilisers applied to soils (including compost)” (46% of TAN applied). It corresponds to the emission factor of solid

¹⁴ All sizes of heads considered.

¹⁵ In Spain, the BBF 3.2 Cantabrian, FER3 was applied as biostimulant (1.5 kg/ha assuming 1 kg / l density), together with ammonium nitrate.

manure application and incorporation in two passes which is also used for sewage sludge in the same inventory.

2.3.7.2 Pot and field trials: Different N₂O emission factors

For N₂O, the emission factor from IPCC (IPCC, 2019) for "Other N inputs" in wet climates is used in the baseline for the BBFs (0.006). For "Synthetic fertiliser inputs" in wet climates, the same source was used (0.016). For the sensitivity analysis, these emission factors were subsequently replaced by the lower boundary of the provided uncertainty range (0.013 for the mineral fertilisers, 0.001 for the BBF) and by its upper boundary (0.019 for the mineral fertilisers, 0.011 for the BBF).

2.3.7.3 Field trials: Only markable broccoli yield

For the sensitivity analysis, the only markable yield for of the heads (> 8 cm) was taken and was compared with the yield of the whole biomass from broccoli for the heads, stalks and leaves (< 8 cm >) of the broccoli from Spain and Estonia.

2.3.7.4 Field trials: Mineral nitrogen fertiliser composition according to market shares.

For broccoli, ammonium nitrate fertiliser was used in both field experiments, Estonia and Spain. For the sensitivity analysis, a mix of mineral nitrogen fertiliser of the market share was used to reflect the environmental impacts of the mineral nitrogen fertiliser, that are commonly used in conventional broccoli production. The market share mix of nitrogen fertilisers in broccoli production consisted of 25% ammonium nitrate, 26% calcium ammonium nitrate and 49% urea.

2.3.7.5 Pot and field trials: Transportation of BBFs to farm gate

For wheat, ryegrass and broccoli, a sensitivity analysis for the transportation of the BBFs from the factory to the farm gate was conducted. A transportation distance of 500 km was assumed (default 20 km).

3 Case study inventories of BBFs production

A general description of the case studies can be found in report D7.1 (Romero et al., 2023b). Below, a short description on the case studies (process descriptions based on Romero et al., 2023b) and on the compiled data for the most important production parameters can be found.

3.1 Baltic Sea (T3.1)

3.1.1 Pilot production: process description

The Baltic Sea pilot produces granulated bokashi ferment ("granules") as a BBF, a foliar spray (as biostimulant/foliar fertiliser) and vermicompost (as soil amendment). The raw materials come from different food waste side streams such as fish processing by-products (salmon scraps: mainly heads, bones, collars, cheeks, spines and bellies), food waste from restaurants, catering and groceries, mixed with tree leaves and ash.

The production process consists of the following principal stages (see Figure 2):

1. Side stream collection, manual removal of any non-organic impurities.
2. Fish and other food waste crushing and directing to bokashi fermentation unit for two weeks of fermentation.
3. Separation of the liquid, gravitational free flow with sieves.
4. Mixing tree leaves with ferment and directing part of the mixed mass to a vermicomposting unit.
5. Adding ash to the rest of the mass, mixing it and directing to the granulation unit.
6. Granulation followed by drying of the granules, at 40 °C, in order to maintain microbiology.
7. Packing
 - a. granules (BBF) in a jute bag,
 - b. liquid foliar fertiliser (co-product) in a plastic barrel,
 - c. vermicompost (co-product) in a plastic bag.

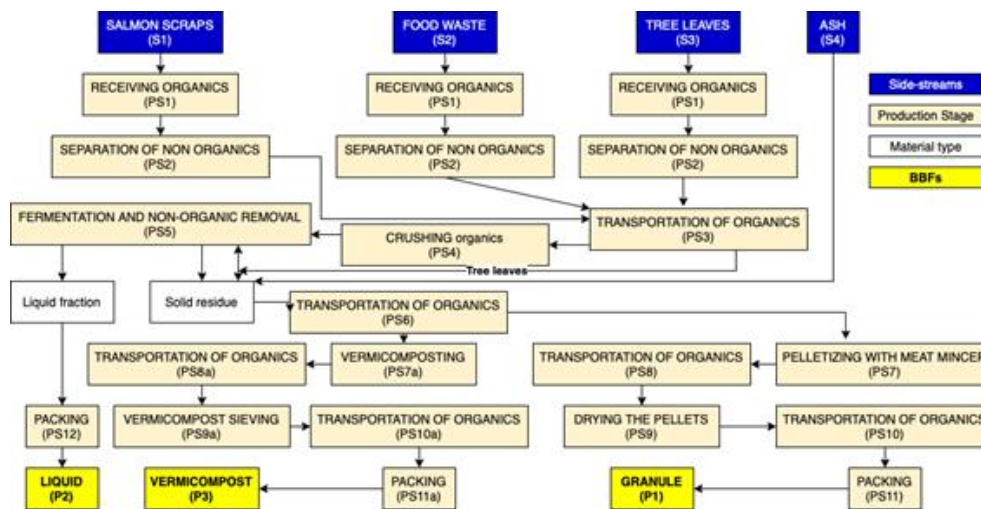


Figure 2: Process diagram of the Baltic Sea case study

Table 13 summarises the stages involved in the production of the (co-)products and highlights main changes during the assumed upscaled production.

Table 13: Overview on processes in BBF production in the Baltic-Sea case study (T3.1).

Nr	Production stage	Process needed for which BBF			Expected changes in process in an upscaled production
		Granules (BBF1)	Vermi-compost (Co-product)	Foliar fertiliser (Co-Product)	
3.1.1	Transport of organic material to factory	x	x	x	
3.1.2	Preparation of organic material (sorting, crushing)	x	x	x	
3.1.3	Fermentation and separation of liquid/solid fraction	x	x	x	Less bokashi bran needed
3.1.4	Vermicomposting of solid fraction		x		
3.1.5	Granulation of solid fraction	x			Grid energy instead of generator powered machinery
3.1.6	Drying of granules (PV powered)	x			
3.1.7	Packaging	x	x	x	
	General				Higher production capacity in same buildings, but additional office spaces

The characteristics such as price and composition of the produced BBFs are summarized in Table 14.

Table 14. Overview on BBF and co-products characteristics in the Baltic-Sea case study (T3.1). Based on data from (Zhang & Akyol, 2023) including the standard deviation for the measurements.

Property	Unit	Granules (BBF)	Vermi-compost (Co-product)	Foliar fertiliser (Co-product)
Price	Euro / kg	3.00	3.00	10.00
Dry matter content	% FW	90.65 ± 0.17	45.54 ± 0.28	2.56 ± 0.01
Organic matter content	% DW	61.85 ± 1.28	33.17 ± 0.76	71.46 ± 0.16
TN-fresh matter content	% FW	2.63 ± 0.09	0.89 ± 0.06	0.12 ± 0.00
P- fresh matter content	g/kg FW	10.45 ± 3.80	2.65 ± 0.05	0.70 ± 0.02
K- fresh matter content	g/kg FW	19.09 ± 1.68	9.68 ± 0.53	1.32 ± 0.01

3.1.2 Life cycle inventory of BBFs production

For the LCA, the granules, as the most promising BBF, were selected and most important assumptions on the inventory are displayed below. Because the solid ferment can be used either to produce granules or vermicompost, the alternative use as vermicompost was excluded here, and only an allocation between the liquid and solid fraction was performed.

Pilot scale

The complete life cycle inventories are available on Zenodo (Landert et al., 2024). In Table 16 a summary of in- and outputs and assumptions per production stage is provided.

Industrial scale

A doubled production was assumed for industrial scale (Romero et al., 2023a). 20% less bokashi bran was assumed with an increased production volume (reuse of bran). Machinery is assumed to be used more efficiently and the mixer/grinder is assumed to be powered by grid-energy instead of a generator at pilot scale. For buildings, additional office spaces were assumed at industrial scale (same share as for other chemicals in ecoinvent).

Table 15. Production volumes of granules at pilot and industrial scale

Property	Unit	Granules (BBF1)	
		Pilot	Industrial
Yearly production volume	ton / year	48.89*	97.78

* Input: 77.6 t organic material used in fermenter; 90% solid fraction; 30% water evaporated after drying
 $= 77.6 \text{ t} * 0.9 * (1-0.3) = 48.89 \text{ t}$

Table 16. Overview of in- and outputs of different production stages for the granules (BBF1). Changes in industrial scenario in square brackets. Please refer to the Life Cycle Inventories uploaded on Zenodo for detailed mass flows. EOL: End of Life

Nr	Production stage	Outputs / Intermediates	Ingredients	Process inputs	Machinery / Building	Waste / emissions
3.1.1	Transport of organic material to factory	Organic material at factory gate	Fish waste, food waste, leaves, ash	Transport, lorry, uncooled		-
3.1.2	Preparation of organic material (sorting, crushing)	Sorted organic material	Intermediate from 3.1.1	Organic material, manual sorting		Separated waste
3.1.3	Fermentation and separation of liquid/solid fraction	Liquid (10%) and solid (90%) ferment	Intermediate from 3.1.2	Bokashi bran	Bulk container, barrel lifter, hammer mill, transport conveyor	EOL of equipment
3.1.5	Granulation of solid fraction		Intermediate from 3.1.3	Energy, ash, leaves	Meat mincer/granulator, screw conveyer	EOL of machinery
3.1.6	Drying of granules		Intermediate from 3.1.5	Energy	Sun-powered drum-dryer, PV cell, battery, screw conveyer	EOL of machinery and battery (0% recycling)
3.1.7	Packaging		Intermediate from 3.1.6	Jute bags		EOL of packaging, 90% recycling assumed
-	General	-	-	-	Factory building [office buildings]	EOL of building

3.1.3 Major uncertainties and sensitivity analysis

For the industrial scale, some uncertainties exist on how production of granules would change. In a sensitivity analysis, following aspects were analysed:

- 1) Baseline scenario
- 2) Drying of granules: In the baseline scenario, drying is performed as in the pilot scale with a sun-powered drum-dryer. As a sensitivity analysis, an alternative energy source was assumed. The drying process was approximated with drying and pelleting chicken manure (based on ecoinvent) with changed energy source (Estonian electricity grid mix).
- 3) Packaging
 - a. Plastic bags instead of jute bags assumed
 - b. Jute bags: 0% recycling instead of 90% recycling assumed.
- 4) Direct emissions for bokashi fermentation: nearly no gaseous emissions are typically assumed to take place during bokashi fermentation. However, the literature about direct emissions of bokashi fermentation is scarce. A study by Hitman et al. (2013) showed that bokashi had almost 27 times lower GHG emissions (in kg CO₂ equivalents / kg final product) compared to "normal" compost. In a sensitivity analysis, we therefore assumed a rather high estimate of 10% of average for composting emissions from IPCC.
- 5) Longer transport of side-streams: all transported over 100 km (instead of 20-30 km at pilot scale)
- 6) Allocation: price of liquid vs. granules changes
 - a. doubled
 - b. halved
- 7) Production volume at industrial scale: 4x more than pilot (instead of 2x more)

3.2 Cantabrian Sea (T3.2)

3.2.1 Pilot production: process description

The goal of the Cantabrian Sea pilot is to produce five biofertilisers from fish waste originated by the aquaculture and canning industries.

The BBFs produced within the Cantabrian Sea are a collaboration between AZTI, FERTINAGRO and NEIKER that can be divided based on its initial processing steps and side stream, the Table 17 summarizes the value chain of each BBF.

Table 17. Value-chains of all BBFs produced within the Cantabrian Sea case study.

Side stream	AZTI Process	NEIKER Process	FERTINAGRO Process	BBF
Fish Viscera	Enzymatic Hydrolysis	-	Mixing with lignosulfonate and FERTINAGRO raw material	BBF 1
		-	-	BBF 2
	Acid Autolysis (Silage)	-	Mixing with NPK fertiliser	BBF 3
		-	Mixing with lignosulfonate	BBF 4
Cooking Brine	Enzymatic Hydrolysis	Microalgae Production	Mixing with organic matter	BBF 5

Each BBF has a slightly different production process. The assessment covers BBF3 - NPK solution with amino acids as it is the most complete in terms of data availability and qualified as organic fertiliser according to D6.1 (Zhang & Akyol, 2023).

For this bio-based fertiliser, a concentrated source of free amino acids, obtained from fish protein autolyzed, is mixed with an inorganic fertiliser. The process to obtain the concentrated source of free amino acids consists of the following steps (Figure 3).

Initially, the size of the fish viscera is reduced via a grinding process to assist in the oil separation step and increase the efficiency of the autolysis that follows said separation. After the autolysis process, heat is applied to the solution to stop the autolysis, the solids are then removed via a centrifugation process and the liquid fraction is concentrated in a membrane ultrafiltration plant similar to a reverse osmosis plant and followed by a vacuum concentration. Finally, the concentrate is mixed with an (0-40-40) NPK mineral fertiliser at a 92/8 ratio of autolysate/mineral fertiliser.

During the BBF production, fish oil and solids are separated from the main stream and listed as co-products. At the moment, no market value exists for the solids produced and therefore no impact was allocated to this co-product, nonetheless the benefits of commercializing the solids produced will be accounted for in the sensitivity analysis in section 4.3.4.

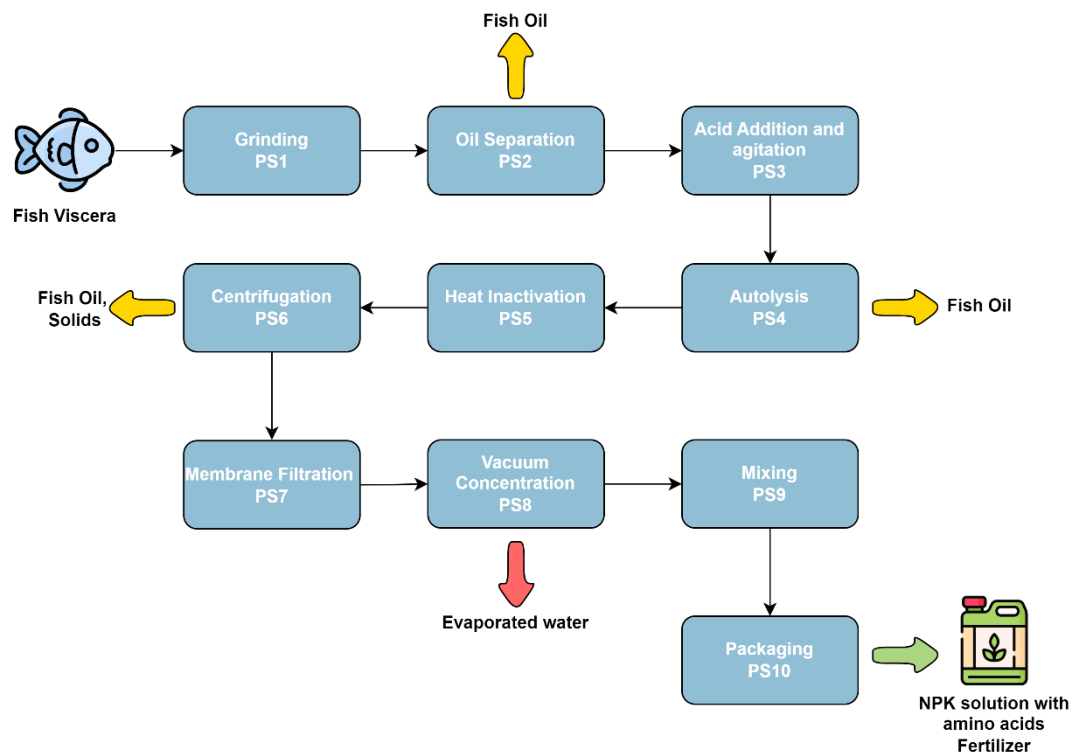


Figure 3: Pilot plant scheme of Cantabrian Sea case study. PS: process steps; green arrow: final product; yellow arrow: co-products; red arrow: waste.

Table 18 summarises the stages involved in the production of the product and highlights the main changes during the assumed upscaled production.

Table 18. Overview on processes in BBF3 production in the Cantabrian Sea case study (T3.2).

Nr	Production stage	Process needed for NPK solution with amino acids	Expected changes in process in an upscaled production ¹⁶
3.2.1	Grinding	X	Increase machinery capacity
3.2.2	Oil Separation	X	From gravitational separation to powered decanter
3.2.3	Acid Addition and Agitation	X	Machinery change, from a multipurpose reactor to a 16000L capacity silo with agitation and heating
3.2.4	Acid Autolysis	X	
3.2.5	Heat Inactivation	X	
3.2.6	Centrifugation	X	Increase machinery capacity
3.2.7	Membrane Filtration	X	Increase machinery capacity
3.2.8	Vacuum Concentration	X	Increase machinery capacity
3.2.9	Fertiliser mixing	X	No changes, step already provided in industrial scale
3.2.10	Packaging	X	-

For the upscaling of the processes, the main changes were a higher production capacity, where the fish waste is expected to be received in 16-ton batches twice a week (instead of 100 kg at the pilot scale). In such a scenario, a continuous process is not feasible but a batch system needs to be established along all processing steps. Therefore, most machinery was assumed to be changed and adapted to allow a more efficient processing line (see more details in section 3.2.2). These changes enabled a similar production time but with the decrease in foreground energy consumption per kg of BBFs produced, the main step (autolysis, from step 3.2.3 to 3.5.2) was changed in order to have a constant rotation of 4 16000L capacity silos as to not compromise the rest of the steps and allow the processing of the received viscera immediately.

¹⁶ In addition to the generic assumed upscaling effects, such as higher machinery use outlined in section 2.1.2.

Table 19. Overview on BBF3 and co-products characteristics in the Cantabrian Sea case study (T3.2).

Property	Unit	NPK solution with amino acids (BBF3)
Price	Euro/kg	1.91
Co-product: Fish Oil	Euro/kg	1.49
Co-product: Solids	Euro/kg	0.2
Dry matter content	% FW	34.46 ± 0.16
Organic matter content	% DW	78.78 ± 0.17
TN-fresh matter content	% FW	5.31 ± 0.10
P- fresh matter content	g/kg FW	15.93 ± 1.11
K- fresh matter content	g/kg FW	22.38 ± 1.89

The P and K content of the final fertiliser are not identical possibly due to already existing potassium in the amino acids' solution produced by AZTI.

3.2.2 Life cycle inventory of BBFs production

This and the following section provide an overview of the life cycle inventory creation and related main assumptions.

Pilot scale

In Table 20, a summary can be found of in- and outputs and assumptions per production stage of the NPK solution with amino acids (BBF3). For the (0-40-40) NPK solution, an ecoinvent database process for mineral fertiliser production was adapted to reach the needed concentrations of phosphorus and potassium content in the mixture.

Table 20. Overview of in- and outputs of different production stages for the NPK solution with amino acids. Changes in industrial scenario in square brackets. Please refer to the Life Cycle Inventories uploaded on Zenodo for detailed mass flows. EOL: End of Life; CIP: Clean-in-place.

Nr	Production stage	Outputs / Intermediates	Ingredients	Process inputs	Machinery / Building	Waste / emissions
3.2.1	Grinding	Shredded fish viscera	Trout viscera	Electricity	Shredder	EOL of machinery
3.2.2	Oil Separation	Shredded fish viscera Fish oil	Intermediate from 3.2.1	--	Conic container [2 phase decanter]	EOL of machinery
3.2.3	Acid Addition and Agitation	Acidulated fish viscera	Intermediate from 3.2.2	Electricity Formic acid Washing solution	Agitator. Container with reinforced stainless-steel grid [Silo]	EOL of machinery Wastewater
3.2.4	Acid Autolysis	Autolysed fish protein Fish oil	Intermediate from 3.2.3	Washing solution	Container with reinforced stainless-steel grid [Silo]	EOL of machinery Wastewater
3.2.5	Heat Inactivation	Free amino acids dispersion	Intermediate from 3.2.4	Electricity Heat	Agitator. Container with reinforced stainless-steel grid [Silo]	EOL of machinery
3.2.6	Centrifugation	Free amino acids dispersion Fish oil Solids	Intermediate from 3.2.5	Electricity Washing solution	Centrifuge [3 phase decanter]	EOL of machinery Wastewater
3.2.7	Membrane Filtration	Free amino acids solution	Intermediate from 3.2.6	Electricity Washing solution	Membrane filtration plant	EOL of machinery Wastewater (CIP solutions)
3.2.8	Vacuum Concentration	Concentrated free amino acids solution	Intermediate from 3.2.7	Electricity Washing solution	Vacuum concentrator	EOL of machinery Water evaporated
3.2.9	Fertiliser mixing	NPK solution with amino acids	Intermediate from 3.2.8 (0-40-40) NPK solution	Electricity	Mixer	EOL of machinery
3.2.10	Packaging	Packed NPK solution with amino acids	Intermediate from 3.2.9	Electricity	Packaging machine	EOL of machinery Packaging waste
-	General	-	-	-	Factory building [Office]	EOL building

Industrial scale

The production is projected to increase by a factor of 6.8 under industrial conditions (see Table 21).

Table 21. Production volumes of BBFs3 at pilot and industrial scale

Property	Unit	NPK solution with amino acids (BBF3)	
		Pilot	Industrial
Yearly production volume	ton/year	3.57	220.00

For the upscaled process, 16 tons of viscera were assumed to be delivered twice a week. This requires that the material be processed as soon as it reaches the facility.

Concerning the building changes from pilot to industrial scale, alongside the dedicated space for the machinery, it was also considered the office space needed to support the facilities. In the Cantabrian Sea the multi-storage solution was considered as a market activity taking into consideration the connections of supplier and consumer.

For the majority of the process, only an increase in the machinery capacity was considered. For the autolysis, new 16000 L silos with incorporated agitation and heating systems were assumed. As the process takes 12 days to be completed, 4 silos need to be in constant rotation to be able to process the incoming raw material as soon as it reaches the facilities.

Table 22. Machinery used for industrial scale.

Equipment	Production stage	Parameters	
		Capacity	Consumption
Grinder	3.2.1	16 ton/h	46 kWh
2 phase decanter	3.2.2	20 m ³ /h	28 kWh
Silo (agitation and heating systems)	3.2.1, 3.2.3, 3.2.4, 3.2.5	16000 L	30 kWh
3 phase decanter	3.2.6	4 ton/h	22 kWh
Filtration plant	3.2.7	3.5 ton/h	45 kWh
Vacuum concentrator	3.2.8	3 ton/h	1.5 tons/h (steam) 12 kWh

3.2.3 Major uncertainties and sensitivity analysis

The main uncertainties in the inventory were the energy consumption of machinery (either electricity or heat) and the market value of the final product and the process co-products. For both aspects, sensitivity analyses were performed.

For the energy consumption, the installed power of the equipment was used. This approximation is, in most cases, an overestimation of the real consumption and will translate into a higher environmental impact. In a sensitivity analysis, an estimation of the actual energy consumption was considered where the machinery was working only at 65% of the maximum installed power (section 4.3.4). Furthermore, and because Spain aims to increase the share of renewables in their energy mix, an additional future scenario on the energy-mix, aligned with Spain's goals for the year 2030, was calculated (MITERD, 2020).

Concerning the market value of products and co-products, two scenarios were modelled for the sensitivity analysis: one where the co-products have an increase in their market value of 20%, and the other where the final product had an increase of 20% market value (and prices of co-products remained stable).

In addition, the influence of the transportation distance between facilities (aquaculture to BBF formulation) was analysed (transport distance was decreased by 90%) as this step also had a considerable contribution to the environmental impacts.

Finally, a reduced use of cleaning solution by 50% was analysed as this consumable also represented a high contribution for the overall impacts following the composition presented in Table 23.

Table 23. Cleaning water reduction.

Material	Original composition	Composition used for sensitivity analysis
	kg/ kg of viscera	
Water	0.568	0.284
Sodium Hydroxide	0.0076	0.0038
Hydrogen peroxide	0.0004	0.0002
Citric Acid	0.0095	0.00475

3.3 Adriatic Sea (T3.3)

3.3.1 Pilot production: process description

The Adriatic Sea pilot produces bio-based fertilisers starting from mollusc and fish by-products. A liming agent is obtained from the mollusc shells which are previously separated from organic leftovers through a mechanical process (Table 24). Enzymatic hydrolysis of fish and mollusc waste yields in protein hydrolysates. The remaining insoluble fraction is further treated by pyrolysis and composting to produce a soil amendment (compost-biochar composite) acting also as a carbon sink.

The main feedstocks of the Adriatic biorefinery consist of not-marketable (e.g. undersized, damaged) molluscs and fish wastes, such as viscera, heads, bones, and whatever results from fish cleaning (bleeding, gutting, beheading, filleting, skinning and trimming) before selling.

The production process can be summarized in four main steps (Figure 4):

1. pre-treatments, consisting of the mechanical separation of harder (shell) and lighter (meat) fractions of mollusc waste and mincing of fish waste;
2. enzymatic hydrolysis of the organic fraction;
3. treatment of not hydrolysed solid residue through pyrolysis and composting;

First of all, fish waste needs to be minced and homogenized, while mollusc meat needs to be mechanically separated from the shell. Mollusc shells are then dried and milled to be used as an alternative CaCO_3 source in liming agents (to increase soil pH). The latter is not included in the LCA directly but used for economic allocation of the environmental impacts across the three co-products. Proteins of mollusc meat and fish waste are hydrolysed by commercial protease enzymes (Alcalase Pure 4.0L). Not hydrolysed fractions are further composted to obtain a soil amendment (as a co-substrate to tree-pruning wastes). Biochar is added during composting to reduce environmental drawbacks (GHGs, odours) and improve compost quality (minimisation of nutrient losses, higher stability, porosity, etc.). Biochar is obtained by pyrolyzing part of the solid residue from hydrolysis.

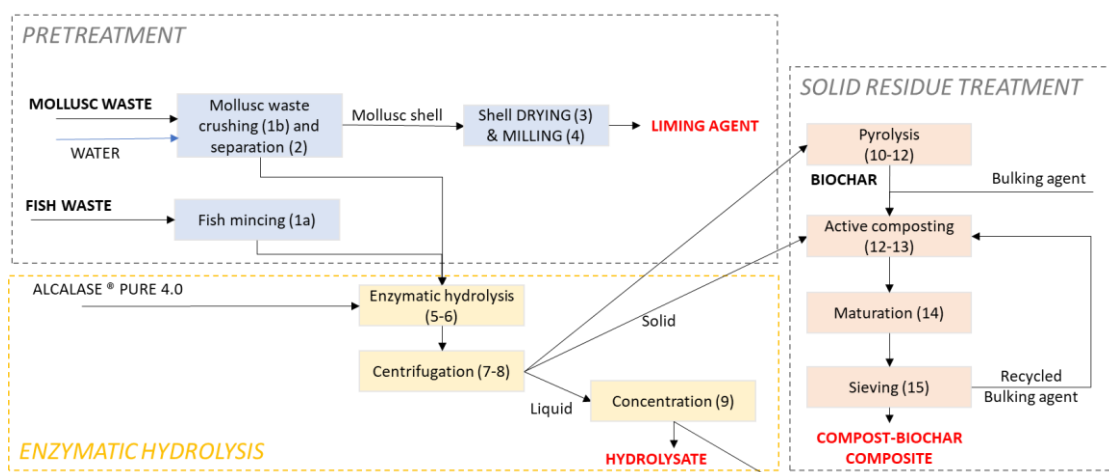


Figure 4: Process scheme of the biorefinery of the Adriatic Sea pilot. Red: resulting product (hydrolysate) and co-products

Table 24 summarises the stages involved in the production of the product and highlights main changes during the assumed upscaled production.

Table 24: Overview on processes in BBF production in the Adriatic-Sea case study (T3.3).

Nr	Production stage	Process needed for which BBF			Expected changes in process in an upscaled production ¹⁷
		Hydrolysates (BBF1)	Compost-Biochar Composite (BBF2)	Liming agent (Co-product) ¹⁸	
3.3.1	Crushing of mollusk waste	x	x	x	Higher throughput (less time needed / kg).
3.3.2	Separation of mollusk shell and meat	x	x	x	Higher throughput (less time needed / kg).
3.3.3	Mincing of fish wastes	x	x		Higher throughput (less time needed / kg).
3.3.4	Enzymatic hydrolysis	x	x		-
3.3.5	Centrifugation	x	x		Higher throughput (less time needed / kg).
3.3.6	Concentration	x			Change in technology (to spray drying) and energy source (to natural gas). Need to evaporate more water because of changed side-stream mixing ratio.
3.3.7	Pyrolysis		x		Reuse / burning of syngas.
3.3.8	Composting		x		-
3.3.9	Packaging	x	x		-

¹⁷ In addition to the generic assumed upscaling effects, such as higher machinery use outlined in section 2.1.2.

¹⁸ The co-product was not modelled but only used in the study to allocate the environmental impacts economically across all three co-products.

Table 25. Overview on BBF and co-products characteristics in the Adriatic-Sea case study (T3.3). Based on data from (Zhang & Akyol, 2023) including the standard deviation for the measurements.

Property	Unit	Hydrolysates (BBF1)	Compost-biochar composite (BBF2)	CaCO ₃ (Liming agent) ¹⁹
Price	Euro / kg	2	0.11	0.03
Dry matter content	% FW	42.12 ± 1.71	94.59 ± 0.07	99.66 ± 0.04
Organic matter content	% DW	82.46 ± 0.21	77.32 ± 0.14	2.14 ± 0.19
TN-fresh matter content	% FW	4.82 ± 0.17	3.72 ± 0.08	0.18 ± 0.03
P- fresh matter content	g/kg FW	3.25 ± 0.09	7.09 ± 0.96	0.15 ± 0.02
K- fresh matter content	g/kg FW	6.08 ± 0.11	10.93 ± 1.42	0.09 ± 0.01

3.3.2 Life cycle inventory of BBFs production

This and the following section focus on the most promising BBF of the case study, the hydrolysates (BBF1), and provides an overview of the life cycle inventory creation (incl. the link to the complete inventory including all co-products) and related main assumption.

Pilot scale

The complete life cycle inventories of all co-products are available on Zenodo (Landert et al., 2024). In Table 26, a summary can be found of in- and outputs and assumptions per production stage of the hydrolysates (BBF1).

¹⁹ The co-product was not modelled but only used in the study to allocate the environmental impacts economically across all three co-products.

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Table 26. Overview of in- and outputs of different production stages for the hydrolysates (BBF1). Changes in industrial scenario in square brackets. Please refer to the Life Cycle Inventories uploaded on Zenodo for detailed mass flows. (EOL = End of Life)

Nr	Production stage	Outputs / Intermediates	Ingredients	Process inputs	Machinery / Building	Waste / emissions
3.3.1	Crushing of mollusk waste	Crushed mollusc waste	Mollusk waste (side-stream)	Electricity, Water	Sewage pump	EOL of machinery.
3.3.2	Separation of mollusk shell and meat	Mollusk Meat and Shell	Intermediate from 3.3.1	Electricity	Hydrocyclone	EOL of machinery
3.3.3	Mincing of fish wastes	Minced fish waste	Fish waste (side-stream)	Electricity	Mincer	EOL of machinery
3.3.4	Enzymatic hydrolysis	Hydrolysate	Intermediates from 3.3.2 (meat) and 3.3.3.	Electricity, Enzymes (Alcalase Pure 4.0)	Stirred tank	EOL of machinery
3.3.5	Centrifugation	Liquid and solid fraction of hydrolysate	Intermediate from 3.3.4	Electricity	Centrifuge	EOL of machinery
3.3.6	Concentration	Concentrated hydrolysate	Intermediate from 3.3.5 (liquid fraction).	Electricity [Natural Gas]	Distiller [Spray drier]	EOL of machinery
3.3.9	Packaging	Hydrolysates (BBF 1)	Intermediate from 3.3.6	Packaging material.	-	Packaging waste.
-	General	-	-	-	Factory building, [Biofilter]	EOL of machinery and building

Industrial scale

The production is projected to increase by a factor of 15 under industrial conditions (see Table 27).

Table 27. Production volumes of BBFs1 at pilot and industrial scale

Property	Unit	Hydrolysates (BBF1)	
		Pilot	Industrial
Yearly production volume	ton / year	1.690	19.743

For upscaling, the duration to process a certain amount of input was estimated to be shorter (higher throughput). From this estimate, an efficiency factor was calculated for each production stage x:

$$\text{Efficiency factor}_{\text{Mechanical production stage } x} = \frac{\frac{m_{\text{daily processed batch amount, pilot}}}{t_{\text{time needed to process batch, pilot}}}}{\frac{m_{\text{daily processed batch amount, industrial}}}{t_{\text{time needed to process batch, industrial}}}}$$

The calculated efficiency factors range from 5% to 26% depending on the production stage. They influence the use time of the machinery (less machinery material input). However, as a simplification, energy use is assumed to be constant per kg of output.

For the LCA at industrial scale, a change in technology with regard to the concentration process was assumed: Instead of a distiller, spray drying and a change in the corresponding energy supply (electricity to natural gas) was considered. By doing so, the same amount of machinery material input was assumed.

In addition, more mollusc waste (compared to fish waste) was assumed to be added in the industrial scenario (7:1 instead of 5:1 mixing ratio) because of available side-streams at the fish industry. That means that more process water for the mechanical separation is needed and in turn that more water needs to be evaporated in the concentration step.

Finally, a biofilter of the upscaled inventory is assumed to be installed to avoid odour emissions from the production plant.

3.3.3 Major uncertainties and sensitivity analysis

The inventory contains data of varying degree of uncertainties. Especially the **prices** (and therefore the economic allocation) of BBFs varies depending on their marketed function. In the given inventory, the function of the selected BBF is assumed to be an organic fertiliser (to enable the comparison with other fertilisers on the market). If the concentrated hydrolysate was marketed as biostimulant, the price could be three times higher. The sensitivity of the results to this difference in price is shown in section 4.4.4.

Because of lack of data, no cleaning water was considered. Also, in line with the ecoinvent database²⁰, the growth substrate for the commercial enzyme used during the hydrolysis was assumed to be potato starch. The selected process exhibits a relatively high environmental footprint compared to other enzyme production processes from literature (Nielsen et al., 2007) with potato starch being the most relevant contributor. Therefore, in section 4.4.4, a sensitivity analysis with different kind of starch was conducted. This was done by substituting potato starch 1:1 with maize and wheat starch (the latter approximated with wheat flour of 63% starch content; Ackar et al., 2009).

When upscaling, the relatively short transport distances from the pilot plant (average of 35 km) was assumed the same for industrial scale. Therefore, in section 4.4.4, a sensitivity analysis covering a 100 km distance is shown.

Also related to upscaling, a rather rough assumption needed to be taken with regard to more efficient use of machinery during physical-mechanical treatments (mincing, separation of meat and shell, concentration and centrifugation). As mentioned in section 3.3.2, the efficiency gains were estimated between 5% - 26% of the original pilot operation time / kg of BBFs. In section 4.4.4, a sensitivity analysis was conducted assuming 3-fold lower efficiencies, namely between 15% - 78% of pilot operation time / kg of BBFs.

3.4 North Sea (T4.1)

3.4.1 Industrial production: process description

Fish sludge comes from filtering wastewater at fish farms on shore, either as an effluent treatment or from recirculation systems. In most fish farms the sludge contains 99% water and is thickened, pressed and dried. Dried fish sludge holds 5% water and has been in the market for 20 years. Grønn Gjødelse currently produce hybrid fertilisers from fish sludge at industrial scale, which is used in conventional agriculture. No pilot scale was assessed for this case study, since an initial trial with Bokashi treatment showed no added value to the pelleted sludge and therefore the pilot was not further developed.

Due to its good fertiliser quality, the main product decided to pursue in the North Sea case study is pelleted pure fish sludge. Dried fish sludge is a fluffy coarse powder easy to be compressed into pellets, due to a small fraction of fish oil originating from the fish feed. Figure 5 shows the general process diagram used in the North Sea case study. The previous drying (at another site), transport to factory and initial hygienisation is not displayed in the graph, but is considered in the LCA. Drying of sludge was included in the

²⁰ Process "Enzymes {GLO} | market for enzymes | Cut-off, U".

LCA, because it is a requirement for producing BBF, but not required for the aquaculture (but generally done to dispose/reuse sludge). The sludge is dried at the aquaculture site and thus not transported before drying.

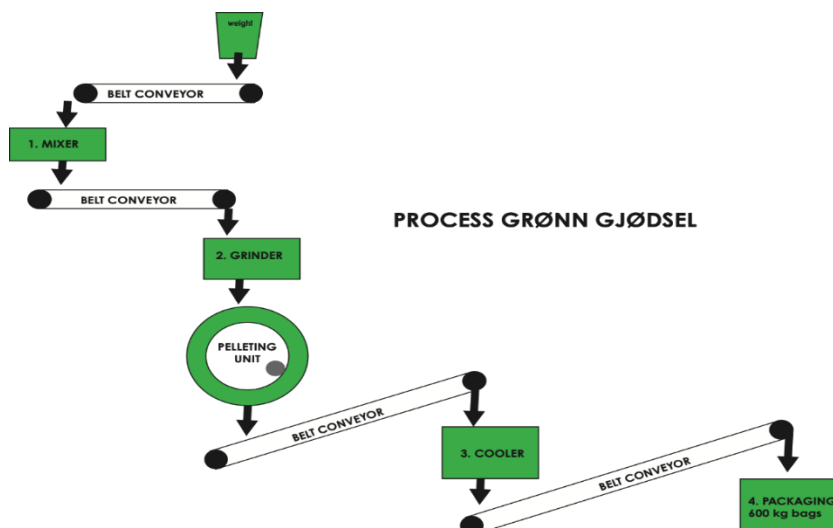


Figure 5: Process diagram of the North Sea case study (excluding previous drying and hygienisation).

Another product is pelleted organic fertiliser, containing of different organic ingredients (fish sludge, blood meal, bone meal), as well as inorganic ingredients. LCA results of this BBF are not displayed here, but were communicated to the case study for potential optimisation of the processes. Table 28 and Table 29 give an overview on the processes involved in BBF production in the North Sea case study and on the characteristics of the two BBFs.

Table 28. Overview on processes in BBF production in the North Sea case study (T4.1).

Nr	Production stage	Process needed for which BBF		Expected changes in process in an upscaled production
		Pelleted fish sludge (BBF1)	Pelleted organic fertiliser (BBF2)	
4.1.0	Initial drying (other site)	x	x	Already industrial production
4.1.1	Transport of organic material to factory	x	x	-
4.1.2	Hygienisation	x	x	-
4.1.3	Mixing	x	x	-
4.1.4	Pelleting	x	x	-
4.1.5	Cooling	x	x	-
4.1.6	Packaging	x	x	-

Table 29. Overview on BBF characteristics in the North-Sea case study (T4.1). Based on data from (Zhang & Akyol, 2023) including the standard deviation for the measurements.

Property	Unit	Pelleted fish sludge (BBF1)	Pelleted organic fertiliser (BBF2)
Price	Euro / kg	0.40	
Dry matter content	% FW	94.4 ± 0.23	94.5 ± 0.11
Organic matter content	% DW	82.5 ± 0.39	71.1 ± 0.72
TN-fresh matter content	% FW	6.19 ± 0.07	9.77 ± 0.22
P- fresh matter content	g/kg FW	27.42 ± 4.51	20.23 ± 1.70
K- fresh matter content	g/kg FW	14.62 ± 2.04	56.01 ± 0.74

3.4.2 Life cycle inventory of BBFs production

The current production volume is already at industrial scale (7000 t/year) for Pelleted fish sludge (BBF1). An overview of in-and outputs during the different production stages is given in Table 30.

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Table 30. Overview of in- and outputs of different production stages for the Pelleted fish sludge (BBF1) at industrial scale. Please refer to the Life Cycle Inventories uploaded on Zenodo for detailed mass flows. EOL = End of Life

Nr	Production stage	Outputs / Intermediates	Ingredients	Process inputs	Machinery / Building	Waste / emissions
4.1.0	Initial drying (other site)	Dried fish sludge	Wet fish sludge	Energy	Approximated with sewage sludge drying	Waste water
4.1.2	Hygienisation	Hygienised fish sludge	Intermediate from 4.1.0	Plastic cover	-	EOL plastic cover
4.1.3	Mixing	Mixed fish sludge	Intermediate from 4.1.2	Energy	Mixer	EOL of machinery
4.1.4	Pelleting	Pelleted fish sludge	Intermediate from 4.1.3	Energy	Pelleting	EOL of machinery
4.1.5	Cooling	Cooled pellets	Intermediate from 4.1.4	Energy	Cooler	EOL of machinery
4.1.6	Packaging	Packaged pellets	Intermediate from 4.1.5	Packaging material	Packaging unit	EOL of packaging
-	General	-			Factory building	EOL of building



3.4.3 Major uncertainties and sensitivity analysis

The process of drying of fish sludge (from 1% dry matter to 95%) is highly uncertain, because it is taking place outside of the scope of the case study (i.e. dried fish sludge is bought by the BBF production facility). Since no primary data was available on this process, it was approximated with the energy requirements for drying sewage sludge in a two-step procedure:

- Step 1: mechanical dewatering from 1% to 30% dry matter, requiring 2.7kWh/t water removed (Vetter & Burger, 2006).
- Step 2: high temperature thermal drying, requiring 3087 MJ/t water removed (50% natural gas; 50% other than natural gas) (Vetter & Burger, 2006).

Data on energy requirements were taken from an ecoinvent dataset from Switzerland (based on Vetter & Burger, 2006) and energy sources were adapted to Norway. As a sensitivity analysis, five options were analysed: 1) baseline, 2) sludge dried to 90% dry matter instead of 95% (because this can vary), 3) replacing the high temperature drying process with a low temperature drying process, which requires 1692 MJ / t water removed (pers. communication Grønn), 4) replacing the heat sources in step 2 with sources with lower footprints (50% natural gas from power co-generation and 50% heat from municipal waste incineration), 5) drying not considered at all (i.e. assuming a different system boundary).

To test the impact of transport distance of fish sludge on the environmental performance, a different source of dried sludge with half the transport distance (250 km instead of 500 km) was assumed in a sensitivity analysis. It was assumed, that the sludge is dried at the aquaculture site and not transported before drying.

3.5 Atlantic Sea (T4.2)

3.5.1 Pilot production: process description

The Atlantic Sea pilot produces bio-based fertilisers based on the fish side-streams coming from a French aquaculture company. Frames and heads are collected and provided to the BBF pilot free of charge. They are otherwise sold at a very low price to a company transforming it for animal feeding. Viscera often contains stones, which need to be removed to avoid damaging the extruder and thus only frames and heads are processed to BBF²¹. At the end, fish oil and both a solid and a liquid BBF are obtained. The

²¹ Only frames and heads are provided by the aquaculture company.

solid fertiliser (BBF1) showed to have the most promising properties and was therefore selected here for showing the LCA results.

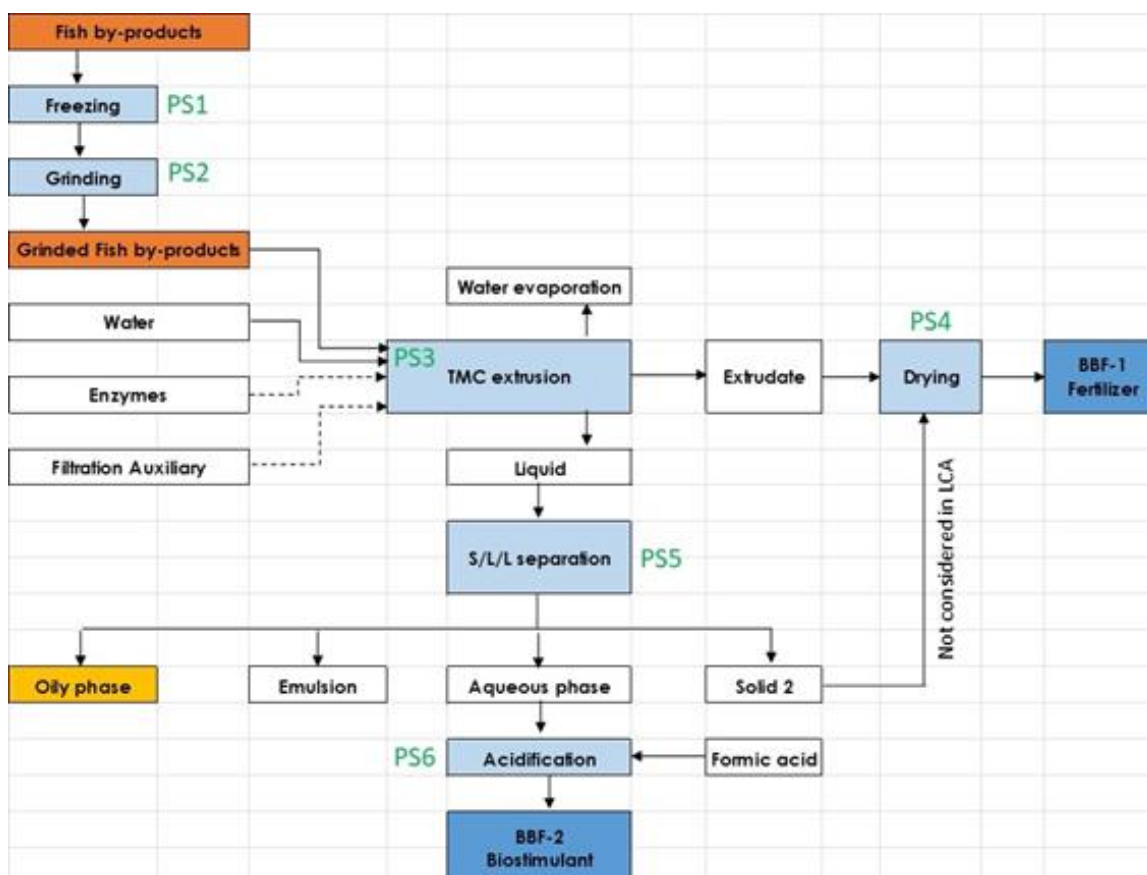


Figure 6: Process diagram of the Atlantic case study. Dark blue: BBF, light blue: processing steps; white boxes: inputs or outputs from processes. Yellow: final co-product.

The process, schematically represented in Figure 6, can be divided in six processing stages (PS). Once collected, the wastes are frozen (PS1) to both avoid degradation with time and facilitate the grinding (PS2). The grinded fish waste is then entering the twin-screw extruder (PS3), where it is extruded with the addition of water²². The liquid parts are removed and a mostly solid extrudate is obtained at the end of the conveying screw. The solid extrudate is dried in an oven (PS4), to prevent quality alteration, which finally results in BBF1 (protein fraction). The mostly liquid (filtrate) part is centrifuged, resulting in four separate phases with different densities (PS5). At the bottom, a solid phase is collected. This could be merged with the solid part before PS4, but this was not considered in the LCA. On the top of the centrifuged solution, an oily phase is collected

²²In some experiments, enzymes were used to try hydrolyzing the liquid phase in the extruder. Nevertheless, the use of enzyme (protease) only resulted in a weak hydrolysis. While the BBFs produced with the enzyme were tested in the pot trials, it was decided to produce BBF for field tests without enzymes.

and can be valorised as a fish oil (co-product). In the middle, a thin emulsion phase of oil and water, as well as an aqueous phase are remaining. The aqueous phase is then acidified by adding formic acid, to obtain amino-acids and peptides which can be used as biostimulant (BBF2).

An overview of the processing steps and how they are expected to change at industrial scale is given in Table 31. The composition in organic matter, nitrogen, phosphorus and potassium was determined in the WP6 (Table 32). The agronomic tests in pot trials favoured the Solid BBF compared to the liquid one.

Table 31. Overview on processes in BBF production in the Atlantic-Sea case study (T4.2).

Nr	Production stage	Process needed for which BBF			Expected changes in process in an upscaled production ^{23,24}
		Solid BBF (BBF1)	Liquid BBF (BBF2)	Fish oil ²⁵	
3.5.1	Freezing	x	x	x	process not needed
3.5.2	Grinding	x	x	x	process not needed
3.5.3	Extruding	x	x	x	Higher throughput (less time needed / kg).
3.5.4	Drying	x			-
3.5.5	Centrifuging	x	x	X	Lower percentage of emulsion phase, higher throughput (less time needed / kg).
3.5.6	Acidifying		x		Higher throughput (less time needed / kg).
3.5.7	Packaging	x	x	x	-

²³ In addition to the generic assumed upscaling effects, such as higher machinery use outlined in section 2.1.2.

²⁴ At high scale, the machineries would have higher capacities with increased flow rates so a shorter time is modelled to produce 1kg of output.

²⁵ Fish oil, even not considered in fertilisation, is a valorisable co-product to which environmental impacts can be allocated.

Table 32. Overview on BBF and co-products characteristics in the Atlantic Ocean case study (T4.2). Based on data from (Zhang & Akyol, 2023).

Property	Unit	Solid BBF (BBF1)	Liquid BBF (BBF2)	Fish Oil
Price	Euro / kg	1.5	1	2
Dry matter content	% FW	98.06 ± 0.24	11.14 ± 0.33	>99.5.
Organic matter content	% DW	83.82 ± 0.74	93.48 ± 0.46	100
TN-fresh matter content	% FW	7.62 ± 0.72	1.48 ± 0.03	N.D.*
P- fresh matter content	g/kg FW	30.89 ± 0.71	0.76 ± 0.03	N.D.
K- fresh matter content	g/kg FW	6.15 ± 0.11	2.04 ± 0.11	N.D.

*N.D.: Not determined

3.5.2 Life cycle inventory of BBFs production

This and the following section focus on the most promising BBF of the case study, the solid extruded fraction, and provides an overview of the life cycle inventory creation (incl. the link to the complete inventory) and related main assumption.

Pilot scale

The complete life cycle inventories are available on Zenodo (Landert et al., 2024). In Table 34 you find a summary of in- and outputs and assumptions per production stage.

Industrial scale

Table 33. Production volumes of BBFs1 at pilot and industrial scale in the Atlantic Sea case study

Property	Unit	Solid BBF (BBF1)	
		Pilot	Industrial
Yearly production volume	ton / year	1.378	753

For upscaling, the higher throughput (Table 32) was estimated based on the available fish side-streams from local aquaculture. In addition, a change in technology with regard to the extrusion process was assumed: with a daily treatment of the wastes and the use of a large-scale extruder, the freezing and grinding phase will no longer be required. Transportation distances are assumed to be lower. The distance from aquaculture to BBF production was estimated to 347 km at pilot scale. It would rather be 40 km at an industrial scale.

Table 34 Overview of in- and outputs of different production stages for the Solid BBF (BBF1). Changes in industrial scenario in square brackets. Please refer to the Life Cycle Inventories uploaded on Zenodo for detailed mass flows. EOL = End of Life

Nr	Production stage	Outputs / Intermediates	Ingredients	Process inputs	Machinery / Building	Waste emissions /
3.5.1	Freezing [removed]	Frozen wastes [removed]	Fish wastes [removed]	Electricity [removed]	Freezer [removed]	EOL of machinery [removed]
3.5.2	Grinding [removed]	Minced fish wastes [removed]	Frozen wastes [removed]	Electricity [removed]	Mincer [removed]	EOL of machinery [removed]
3.5.3	Extruding	Solid output, Liquid filtrate	Outputs from 3.5.2 [fish waste with lower transport distance]	Electricity, Water	Twin-screw extruder	EOL of machinery
3.5.4	Drying	Dried solid output (BBF1)	Intermediate from 3.5.3 (solid fraction)	Electricity	Oven	EOL of machinery

3.5.3 Major uncertainties and sensitivity analysis

The inventory contains data of varying degrees of uncertainties. Especially the **prices** (and therefore the economic allocation) of the different outputs varies depending on their marketed function. In the given inventory, the function of the selected BBF is assumed to be the one of an organic fertiliser (to enable the comparison with other fertilisers on the market) with a price of 1.5 €/kg. The process also generates a liquid fraction that could be used as a biostimulant with a lower price (1 €/kg) and fish oil with a higher price (2 €/kg). In a sensitivity analysis, the price of BBFs1 was changed to 1 and 2 €, with constant prices for oil and biostimulant (BBF2).

Because of lack of data, the weight and **composition of the machineries** were estimated in the inventory. In a sensitivity analysis, the share of electronic materials relative to the other assumed components (steel and plastic) was changed from 0.1% to 2%.

In the industrial production, the BBF production facility was assumed to be in proximity of the aquaculture company and a `strongly reduced **transport** distance was assumed (40 km instead of 347 km). In a sensitivity analysis, a higher transport distance of 100 km was assessed. In addition, different sizes of buildings were tested: A surface of 200 m² and another one of 400 m² were tested.

Even if the addition of **enzymes** for the purpose of a hydrolysis have been shown to not strongly improve the quality of the BBF, an additional sensitivity analysis evaluated the environmental performance if they are used in during the extrusion phase.

4 Results and discussion: Impact assessment of BBFs production

In this section, the environmental impacts of the BBFs from the different case studies are compared against each other based on their N-content. Then, for each case study, main contributing processes are identified, the difference in impacts between pilot and industrial scenario analysed and the effect of major uncertainties in data assessed in a sensitivity analysis. Finally, results of each case study are briefly discussed.

4.1 Cross-comparison with other fertilisers based on N-content

BBF showed generally similar or higher impacts per kg of N than mineral nitrogen fertiliser and higher impacts than poultry manure (Figure 7; see section 2.2.5 for more details on the inventories). These differences were especially pronounced for Freshwater eutrophication where the granules (BBF T3.1 Baltic Sea), for example, exhibited a 223 times higher impact compared to mineral reference fertiliser and 371 times higher than poultry manure. The NPK solution (BBF T3.2 Cantabrian Sea) and the hydrolysates (BBF T3.3 Adriatic Sea) also showed considerably higher Freshwater eutrophication impacts.

The latter two BBFs also showed generally higher impacts compared to the two reference fertilisers in all other impact categories: the NPK solution exceeded the mineral nitrogen fertiliser impacts by a factor 1.5 (Marine Eutrophication) to factor 6.7 (Global warming). The hydrolysates ranged between double (Marine Eutrophication) and 8-fold (Terrestrial acidification) of the impacts of the mineral nitrogen fertiliser. This picture was even more pronounced in the case of poultry manure (exception Terrestrial acidification). In general, poultry manure had lower impacts in all impact categories compared to the BBFs investigated in the project. This was also mostly true for the mineral nitrogen fertiliser with the exception of Marine eutrophication where the granules, the Pelleted fish sludge (T4.1 North Sea) and the Solid BBF (T4.2 Atlantic Sea) exhibited lower impacts (27% - 35% of the impacts of the mineral nitrogen fertiliser reference).

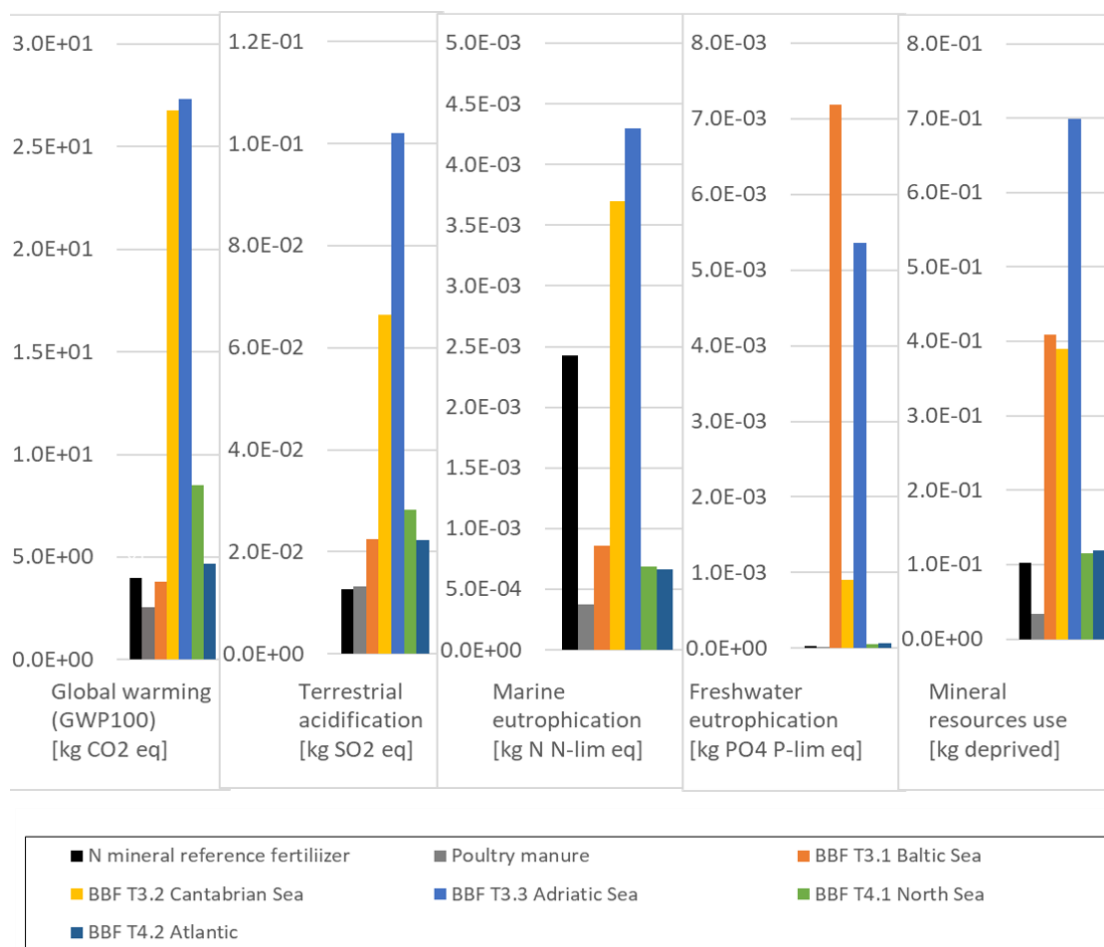


Figure 7: Comparison per kg of N from all selected fertilisers in the study (at industrial stage) against 1 kg of N from composite mineral N fertiliser and poultry manure.

4.1.1 Sensitivity analysis of cross-comparison

The mineral nitrogen fertiliser used as a reference for the comparison with BBFs consisted of a market average of 46% Urea-N, 26% CAN-N and 25% AN-N (see section 2.2.5). Data from ecoinvent showed that the production of an N-fertiliser with 100% urea had generally lower environmental impacts than the market average N-fertiliser (11% lower for Freshwater eutrophication and up to 36% for Terrestrial acidification). A CAN/AN fertiliser without Urea (51% CAN-N, 49% AN-N) showed generally higher impacts than the market average, from 11% (Freshwater eutrophication) to 34% (Terrestrial acidification). Ammonia and nitrogen oxides (NO_x) emissions from nitric acid production (needed to manufacture AN and CAN) led to increased Acidification and Marine eutrophication.

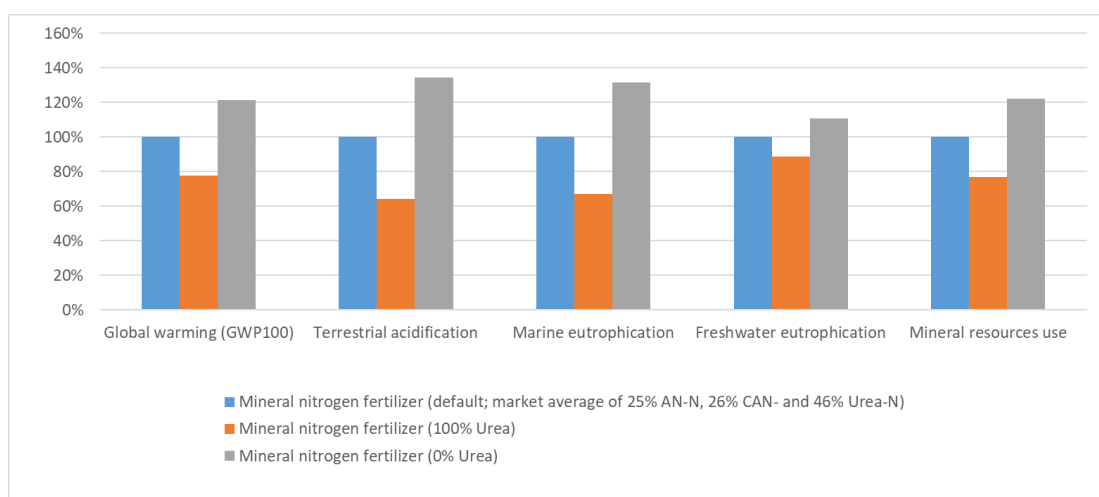


Figure 8: Sensitivity analysis of the reference N mineral fertiliser, with different shares of urea

4.1.2 Discussion of cross-comparison results

Three BBFs showed much higher impacts than mineral N reference fertiliser regarding Freshwater Eutrophication. This was mainly due to agricultural inputs with high Freshwater eutrophication potential, such as jute bags for packaging granules (T3.1), potato starch used for the enzyme production (T3.3 hydrolysates) and corn glucose to produce citric acid as cleaning agent (T3.2 NPK solution). For NPK solution (T3.2), additional impacts were caused by the P fertiliser that was added to the BBF. For poultry manure, agricultural inputs (e.g. feed production) were not accounted for, since it was modelled as burden-free waste.

The above comparison was performed per kg N fertiliser produced. In contrast to the mineral N fertiliser, all analysed BBFs contain relevant amounts of P and K. Comparing BBFs and mineral fertiliser based on their full NPK content thus changes the picture, especially for Freshwater Eutrophication (see following sections on comparison with NPK equivalent fertilisers). This is mainly due to the impacts related to mineral P fertiliser (i.e. triple super phosphate production).

The observed high difference in impacts between the poultry manure reference fertiliser and the BBFs demonstrates the potential to drastically reduce impacts for bio-based fertilisers by e.g. reducing transport of raw materials and degree of processing (also see following sections). Because poultry manure is also rich in P and K, a comparison based on P or K would probably not change this conclusion.

4.2 Baltic Sea: Bokashi granules (T3.1)

4.2.1 Process contributions

For the environmental impacts of granules production at pilot scale, the most important processes were packaging (7-94%), fermentation (6-40%) and buildings (0-66%). Smaller contributions showed tree leaves (0-10%), drying granules (0-16%), mixing and grinding (0-4%) and screw conveyers (0-1%, Figure 9).

For Global warming, the process with the highest contribution was fermented organic waste, mainly due to the production of bokashi bran and the transport of fish and food waste. For Terrestrial acidification, Marine and Freshwater eutrophication packaging dominated impacts and for Mineral resources use buildings dominated impacts.

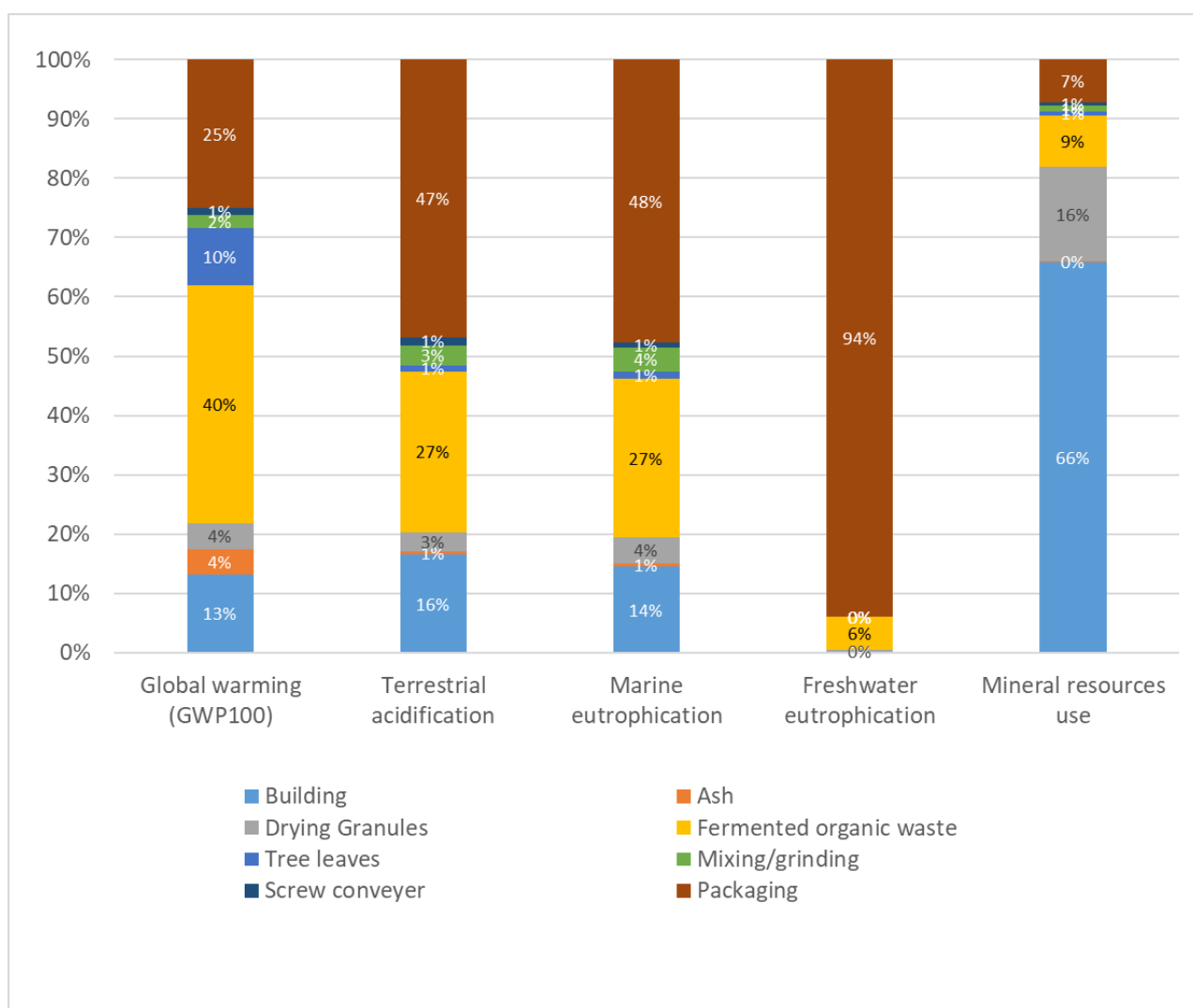


Figure 9: Process contribution at pilot scale for granules (Baltic case study, T3.1).

4.2.2 Upscaling to industrial scale

Modelled at industrial scale, the production of granules showed similar impacts than at pilot scale for Marine and Freshwater eutrophication, but higher impacts for the other impact categories (+7 to +118%) (Table 35). The impact of buildings was nearly doubled, although a twofold production volume in the same production hall was assumed. The increase in impacts was caused by including the use of office spaces (to be in line with the assumptions for mineral fertiliser), which have much higher impacts than a simple production hall. For Mineral resources use, where buildings made up 66% of the impacts at pilot scale, impacts therefore were increased by 118% at industrial scale. For Freshwater eutrophication, where packaging (jute bag) made up the largest share of the impacts, impact did not change much because the same packaging was assumed for industrial scale. The reduced use of bokashi bran at industrial scale lead to reduced impacts of fermented organic waste (-10 to -30%), but due to an increase impact of buildings, this was in most impact categories not visible in the final impact of the BBF.

Table 35. Impacts at industrial scale compared to pilot scale per kg BBF (granules, Baltic case study, T3.1).

Impact category	Unit	Pilot scale	Industrial scale	Relative change
Global warming (GWP100)	kg CO ₂ eq	9.37E-02	9.99E-02	+7%
Terrestrial acidification	kg SO ₂ eq	4.41E-04	5.93E-04	+34%
Marine eutrophication	kg N N-lim eq	2.29E-05	2.26E-05	-1%
Freshwater eutrophication	kg PO ₄ P-lim eq	1.91E-04	1.89E-04	-1%
Mineral resources use	kg deprived	4.97E-03	1.08E-02	+118%

4.2.3 Comparison with NPK equivalent fertiliser

Compared to NPK equivalent mineral fertiliser, the environmental impact of granules was 41-76% lower in three impact categories, and 59-149% higher in two impact categories (Figure 10). For Freshwater eutrophication, impacts were mainly higher due to the jute packaging, and for Mineral resources use, the rather long production process (14 days of fermentation) lead to an increased resource use of buildings compared to mineral fertiliser.

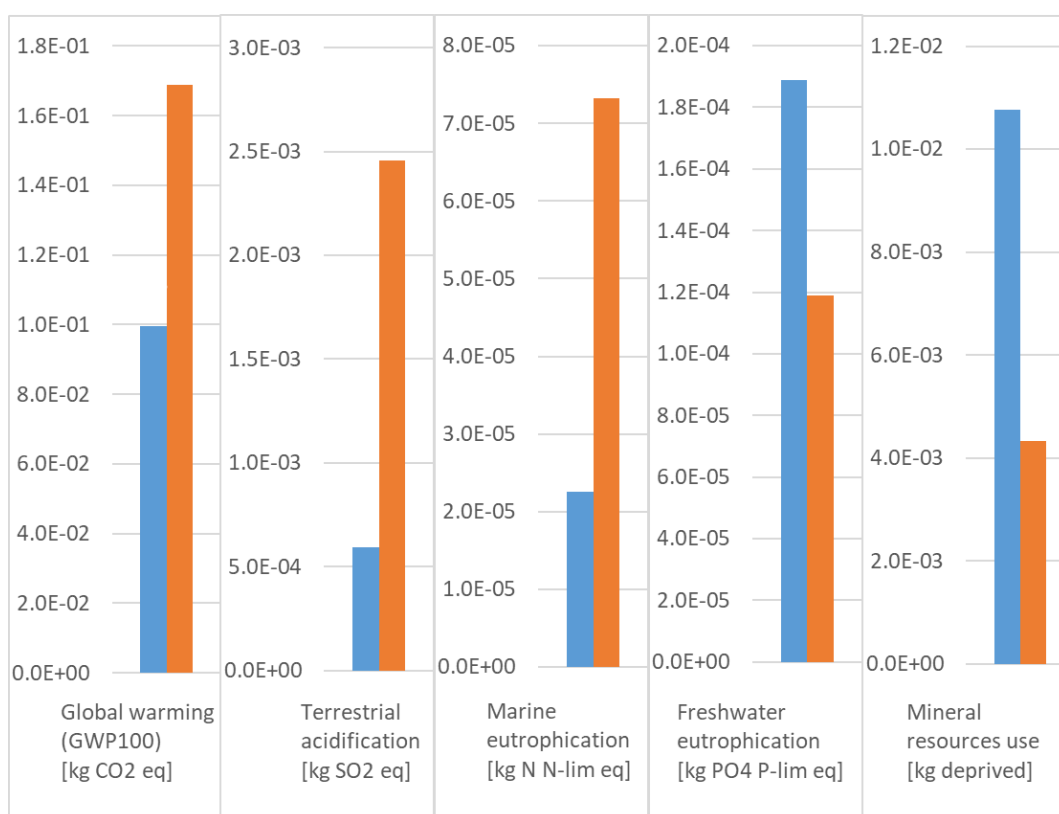


Figure 10: Comparison of environmental impacts of 1 kg BBF (granules) at industrial scale (blue) against an NPK equivalent fertiliser (orange).

4.2.4 Sensitivity analysis

Of the uncertain parameters of industrial granule production, the most sensitive ones were energy source for drying of granules, choice of packaging material and potential direct emissions during bokashi fermentation (Figure 11). Transport distances of side-streams, price assumptions on liquid fertiliser and granules as well as lower recycling rates of jute bag packaging had only a minor impact on results.

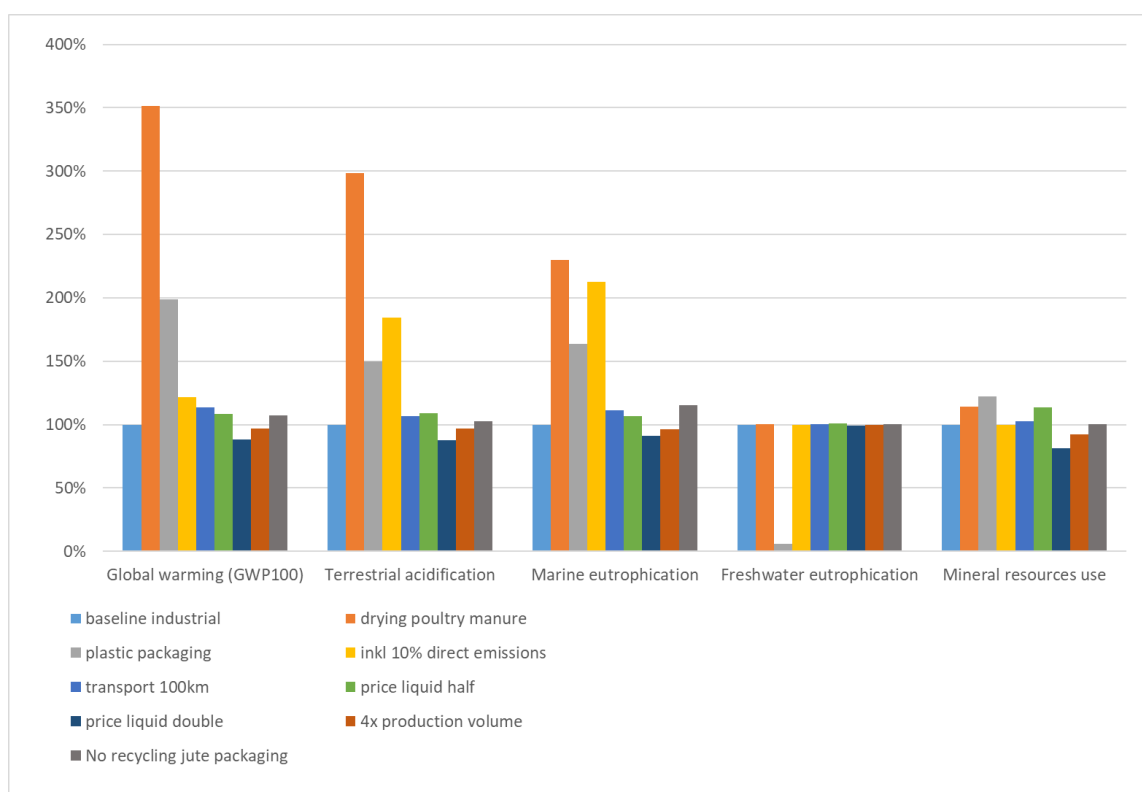


Figure 11: Sensitivity analysis for industrial scale production of granules (Baltic Sea case study). Baseline scenario, drying approximated with poultry manure instead of sun-powered, plastic instead of jute packaging, assumed direct emission (10% of IPCC average for composting), transport of side-streams over 100km (instead of 20-30 km), doubled price of granules (allocation), half price of granules (allocation), industrial production volume 4x pilot (instead of 2x), no recycling of jute bags (packaging) assumed.

4.2.5 Discussion of case-study results

The granules showed lower environmental impacts compared to NPK equivalent fertiliser, except for Freshwater eutrophication and Mineral resources use. However, results showed to be highly sensitive on the assumptions taken for the upscaling. This study therefore provides valuable insights on aspects to be considered for planning an industrial scale production. A minimal use of bokashi bran, an efficient use of buildings and offices, avoiding direct emissions during fermentation, selecting renewable energy sources and optimizing packaging are important aspects to consider for optimizing a future industrial scale production.

Since the energy supply in Estonia is mainly based on domestically produced oil shale, it has the highest carbon intensity among the 32-member countries of the international energy agency (IEA, 2023). Therefore, using renewable energy sources is crucial for a reduced carbon footprint for production facilities in Estonia. In the pilot facility, a sun-powered dryer was used as well as a generator to run machinery. For industrial scale, using little grid-energy and producing own electricity and heat (e.g. sun or wind-powered) would be important to keep GHG at low levels. If the process of drying would

be similar to drying poultry manure, environmental impacts drastically increase for all considered impact categories except Freshwater eutrophication.

Choosing jute or plastic packaging showed clear trade-offs: while jute performed better than plastic for most impact categories, it showed very high impact regarding Freshwater eutrophication from the agricultural production of the jute fibres. At industrial scale, the packaging material should be reconsidered and a potential re-use system of jute bags evaluated.

Potential direct emissions of greenhouse gases during fermentation should be avoided. Although bokashi fermentation is expected to produce no or only very low greenhouse gas emissions (especially non-CO₂), little scientific evidence was found for this claim in literature. A study by Hitman et al. (2013) found that after 6 weeks of composting road side cutting material, 60.2% of the starting material had “disappeared” (i.e. emitted in some form), only 3.2% material was lost for bokashi fermentation. Including a rather high estimate of direct emissions (10% of composting), in the sensitivity analysis considerably increased impacts for Global warming, Terrestrial acidification and Marine eutrophication. If possible, measurement of gaseous emissions during bokashi fermentation should be performed in future and the fermentation process optimized to avoid any emissions.

Buildings showed a relevant environmental impact, especially when the use of offices was included, which have a much higher impact than just a simple production hall. Compared to chemical processes, the biological process of fermentation might use more time and thus more space of a building hall. For office use, the same assumptions were used as for chemicals, which showed to be a relevant contributor to Global warming and resource use. This generally shows the importance of the building sector on environmental impacts of societies in Europe.

4.3 Cantabrian Sea: NPK solution (T3.2)

4.3.1 Process contributions

An important step that contributes strongly to the environmental impacts of the pilot production of NPK solution with amino acids in the Cantabrian Sea case study is the vacuum concentration (Figure 12). The high amount of electricity used for the process is the main reason for such a high contribution to the environmental impacts.

The heat inactivation and the viscera transport in refrigerated trucks also have a significant contribution to the overall environmental impact. The first also results from

energy consumption and the latter is highly dependent on the travelling distance, in this case, it was considered a 240 km distance between the waste origin and the pilot plant.

Regarding the acid autolysis, it comprises acid addition and the 12 days of autolysis, it has a more significant contribution on the Freshwater and Marine eutrophication due to the washing solution and its disposal as wastewater.

The mixing of amino acids solution with the 0-40-40 fertiliser, the membrane filtration and the packaging of the final product also contribute considerably to the environmental impacts, mainly due to the foreground energy consumed.

Finally, both the oil separation and the grinding processes have a low contribution to the overall process environmental impacts as they are not subjected to frequent cleaning nor have a high energy consumption.

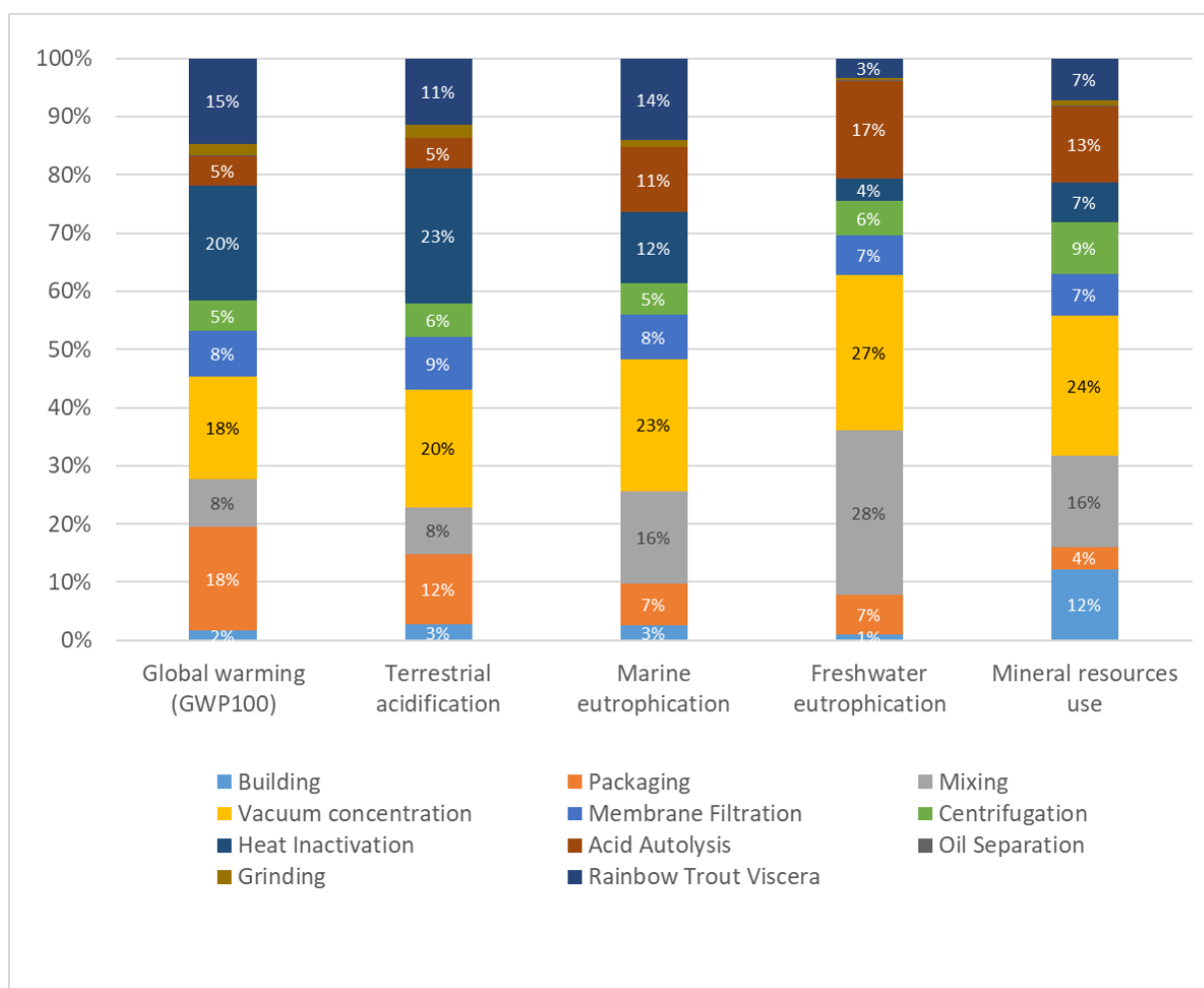


Figure 12: Process contribution at pilot scale for NPK solution with amino acids (Cantabrian Sea case study, T3.2)

4.3.2 Upscaling to industrial scale

The upscaling process resulted in a general reduction of environmental impacts (Table 36). All impact categories decreased considerably, between 5% (Global Warming) and 61% (Mineral resources use). The impact of buildings decreased in the upscaling. For Mineral resources, the dominant processes in the upscaled scenario was the fertiliser mixing step (40%). 76% of the average impacts of the mixing step come from the addition of the 8% (0-40-40) fertiliser in the mixture, in this category.

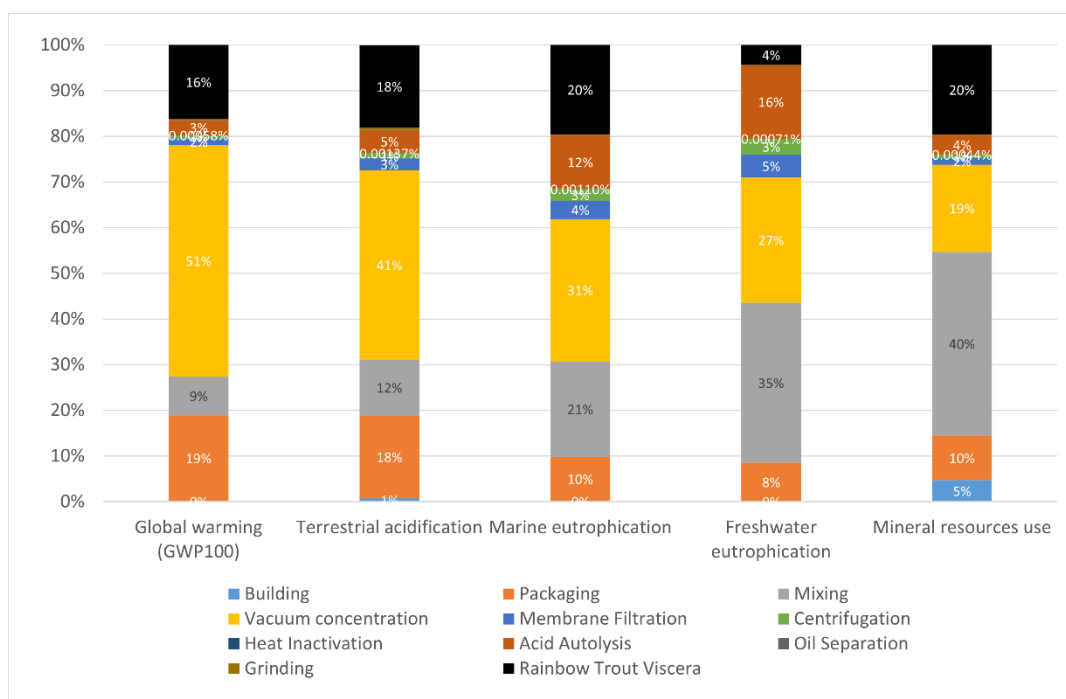


Figure 13: Process contribution at industrial scale for NPK solution with amino acids (Cantabrian Sea case study, T3.2)

Table 36. Impacts at industrial scale compared to pilot scale per kg BBF (NPK solution with amino acids, Cantabrian Sea case study, T3.2).

Impact category	Unit	Pilot scale	Industrial scale	Relative change
Global warming (GWP100)	kg CO ₂ eq	1.49	1.42	-5%
Terrestrial acidification	kg SO ₂ eq	5.31×10 ⁻⁰³	3.52×10 ⁻⁰³	-34%
Marine eutrophication	kg N N-lim eq	2.60×10 ⁻⁰⁴	1.96×10 ⁻⁰⁴	-25%
Freshwater eutrophication	kg PO ₄ P-lim eq	5.94×10 ⁻⁰⁵	4.79×10 ⁻⁰⁵	-19%
Mineral resources use	kg deprived	5.30×10 ⁻⁰²	2.07×10 ⁻⁰²	-61%

When upscaling the processes, most of the steps had a reduction in the environmental impacts, the only exceptions were the biomass transportation step and the last steps of the fertiliser formulation and packaging impacts. These results are aligned with the assumption used for the industrial scale, where the formulation steps were not changed as the process was already modelled with industrial scale data.

4.3.3 Comparison with NPK equivalent fertiliser

When comparing the BBF upscaled to industrial scale against NPK equivalent fertiliser with the same macronutrient content, the BBF exhibited higher environmental impacts for Global warming (482% of NPK equivalent fertilizer), for Mineral resources use (248%), followed by Marine eutrophication (162%). Only for the impact categories Terrestrial Acidification (91%) and Freshwater eutrophication (26%), the BBF exhibited a lower impact.

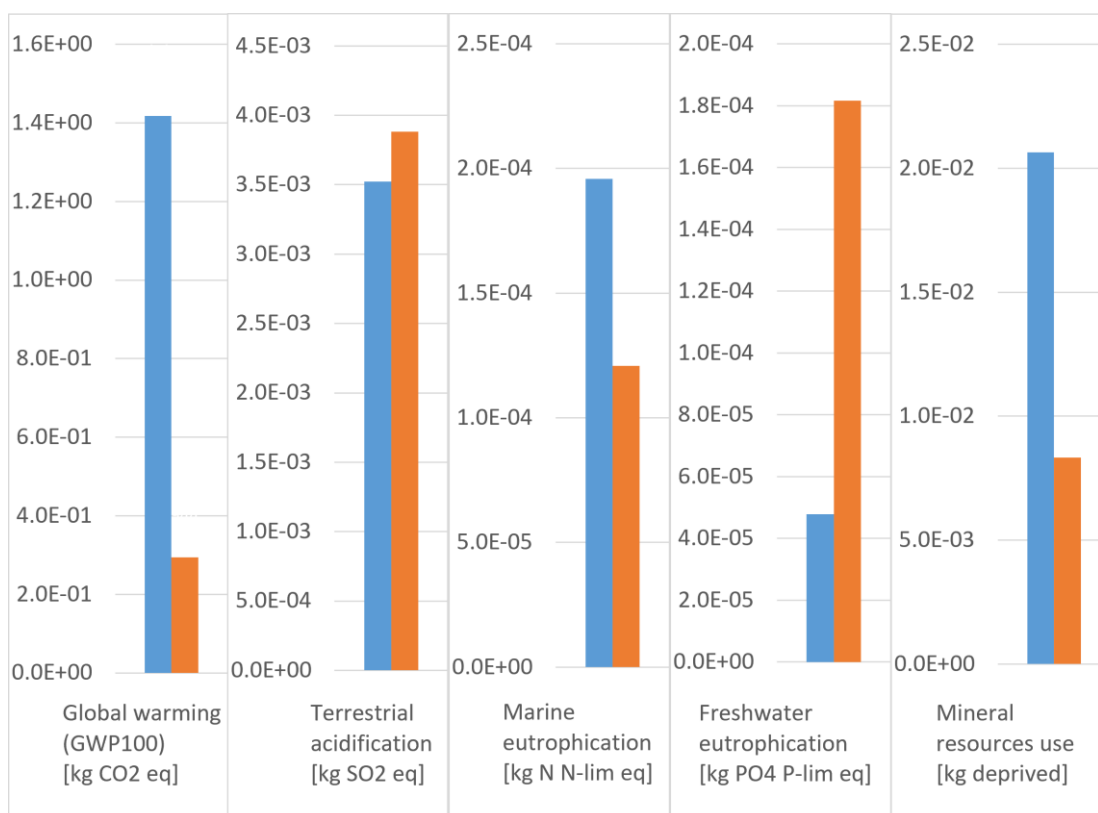


Figure 14: Comparison of environmental impacts of 1 kg BBF (NPK solution with amino acids) at industrial stage (blue) against an NPK equivalent fertiliser (orange).

4.3.4 Sensitivity analysis

As mentioned in the section 3.2.3, several parameters were altered to have a better view of the main environmental impact key variables.

Firstly, a very straightforward conclusion was taken from the changes in the market value of both products and co-products. With the increase of the BBF market value, more impacts would be associated with the final product. On the other hand, a possible approach to reduce said impacts would be not only to increase the market value but also to commercialize all the co-products generated during the process. This approach does not reduce the total environmental impacts of the system and should not be used to promote a lower impact on the final product.

Spain foresees to have around 53% of renewable electricity injected in their power supply until the year 2030 (MITERD, 2020). With this goal in mind, the impacts would be reduced by up to 0.4% (see Figure 15). The reduction of the equipment's installed power to 65% yields similar results. Hence, changes to the energy consumption and electricity mix alone will not have a significant influence on the final impacts.

The scenario with the reduction of the distance between the industrial facility and waste stream production proved that when the travelling distance is reduced to 10% of the original distance, from 240 km to 24 km, a reduction of up to 18% of impacts (Marine eutrophication) is possible.

One last scenario, also the scenario with higher benefits, is the reduction of the amount of cleaning solution used per kg of viscera. When only 50% of the cleaning solution is used, there is an improvement in the environmental performance especially for the Freshwater and Marine eutrophication with a 22% and 15% reduction for these impact categories respectively.

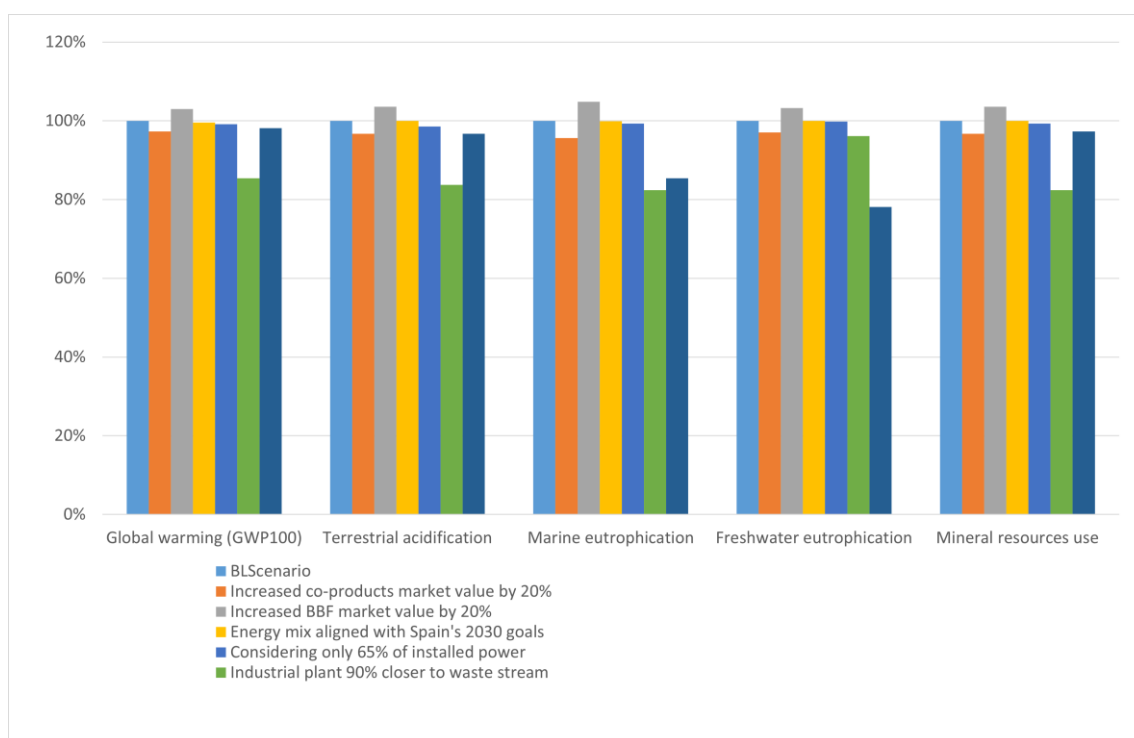


Figure 15: Sensitivity analysis for industrial scale production of NPK solution with amino acids (Cantabrian Sea case study).

4.3.5 Discussion of case-study results

The NPK Fertiliser proves to be a less promising solution in terms of environmental performance when compared to the mineral fertiliser equivalent and even when the foreground energy consumption was reduced to 0 kW the BBF had higher impacts. For

the industrial scale, impacts could have been even higher if the actual heating in addition to the agitation during the heating inactivation would have been considered (lack of data). In contrast, for the pilot scale, the duration of the same process was estimated rather conservatively with 8 hours and could have led to an overestimation of impacts even without not considering the heating energy.

In order to improve the BBF environmental performance, several parameters need to be adjusted being the main points to address the travelling distance between plants, the improvement in the energy consumption of the equipment and the cleaning procedure²⁶ of the industrial plant and equipment.

4.4 Adriatic Sea: Hydrolysates (T3.3)

4.4.1 Process contributions

Two factors dominated the environmental impacts of the hydrolysates in the Adriatic Sea case study: The electricity and enzymes needed for the enzymatic hydrolysis as well as the subsequent concentration step.

At pilot scale (Figure 16), the enzymatic hydrolysis made up 95% of the impact category Freshwater eutrophication. This was mainly caused by production of the potato starch assumed to be used as a substrate for the production of the enzyme. For Global warming, the concentration of the hydrolysate showed the highest contribution, followed by enzymatic hydrolysis. The concentration of the hydrolysate is energy intensive: 2.5 kWh/kg BBF of Italian electricity mix, which includes fossil sources such as coal, are required. It therefore represented a relevant contribution to Global warming (47%) but also other impacts apart from Freshwater eutrophication. Packaging contributed between 1 – 13% to the selected impact categories while the building contributed between 1 – 27 %, mainly impacting Mineral resources use.

²⁶ The 5% citric acid in the cleaning solution could be replaced 1:1 with 0.5% nitric acid but trade-offs between the different impacts would need to be evaluated carefully beforehand.

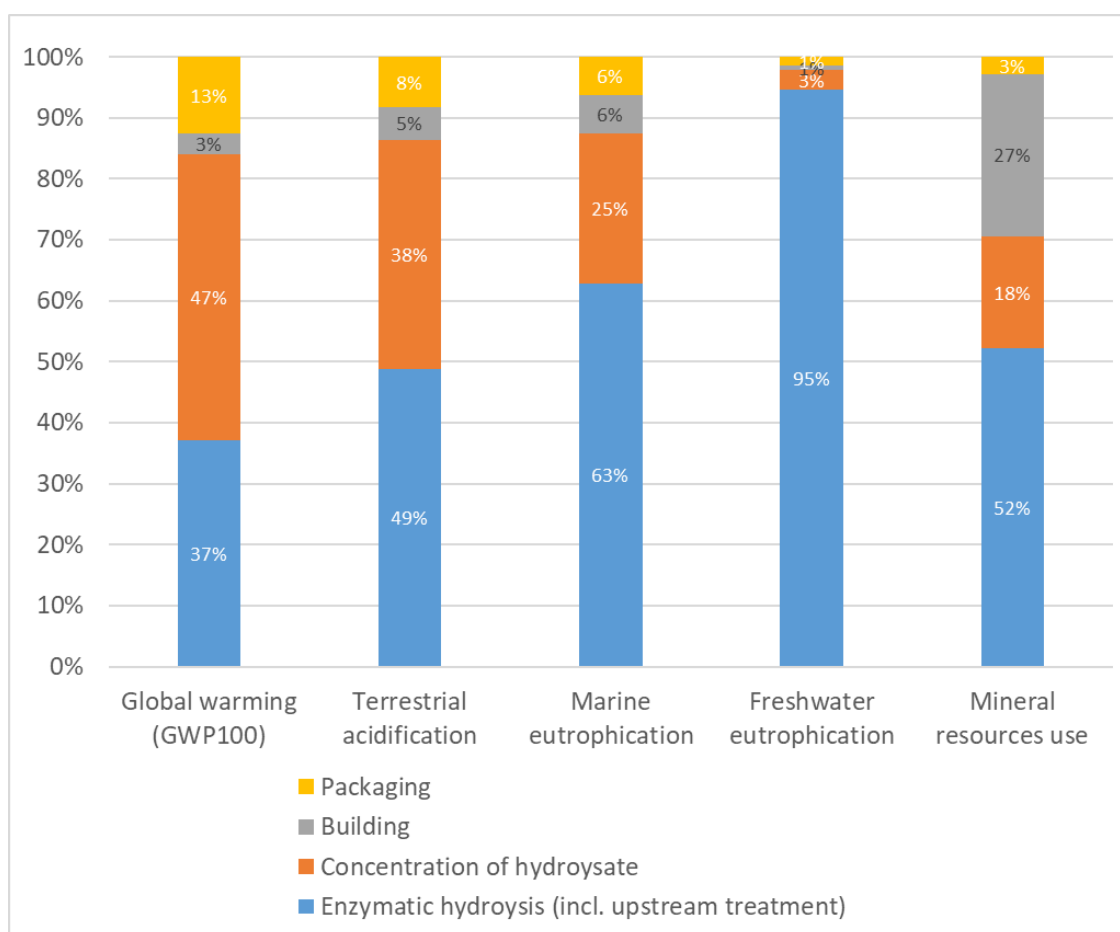


Figure 16: Process contribution at pilot scale for protein hydrolysate (Adriatic case study, T3.3).

At industrial level, the shares of contributions were mostly similar to the pilot scale. However, the contribution of the concentration step to all impact categories decreased. Although more energy was needed due to a higher water content in side-streams (altered mixing ratio, section 3.3.2), a change in energy source from electricity (incl. coal) to natural gas lead to decreased GHG emissions. For Mineral resources use, buildings (including additional use of offices etc. at industrial scale) contributed 33% of the impacts.

4.4.2 Upscaling to industrial scale

The upscaling process resulted in a general reduction of environmental impacts (Table 37). While some impact categories like Freshwater eutrophication did not substantially change (reduction around 4%), greenhouse gas emission reduced by 36% from 2 kg of CO₂eq to 1.3 kg of CO₂eq.

Table 37. Impacts at industrial scale compared to pilot scale pro kg BBF (protein hydrolysate, Adriatic case study, T3.3).

Impact category	Unit	Pilot scale	Industrial scale	Relative change
Global warming (GWP100)	kg CO ₂ eq	2.05	1.32	-38%
Terrestrial acidification	kg SO ₂ eq	0.00780	0.00492	-37%
Marine eutrophication	kg N N-lim eq	0.000301	0.000207	-31%
Freshwater eutrophication	kg PO ₄ P-lim eq	0.000272	0.000258	-5%
Mineral resources use	kg deprived	0.0711	0.0337	-53%

4.4.3 Comparison with NPK equivalent fertiliser

When comparing the hydrolysates at industrial scale against NPK equivalent fertiliser that match the macronutrient content of the BBF, the hydrolysates exhibited generally higher environmental impacts: in the case of Global warming, impacts were 6-fold higher, for Marine eutrophication, impacts of BBFs were about 30% higher compared to NPK-equivalent fertiliser.

The main source of impacts of the NPK equivalent fertiliser was the N-fertiliser. For GPW100, 90% of the impacts of NPK equivalent fertiliser was caused by its N-fertiliser components.

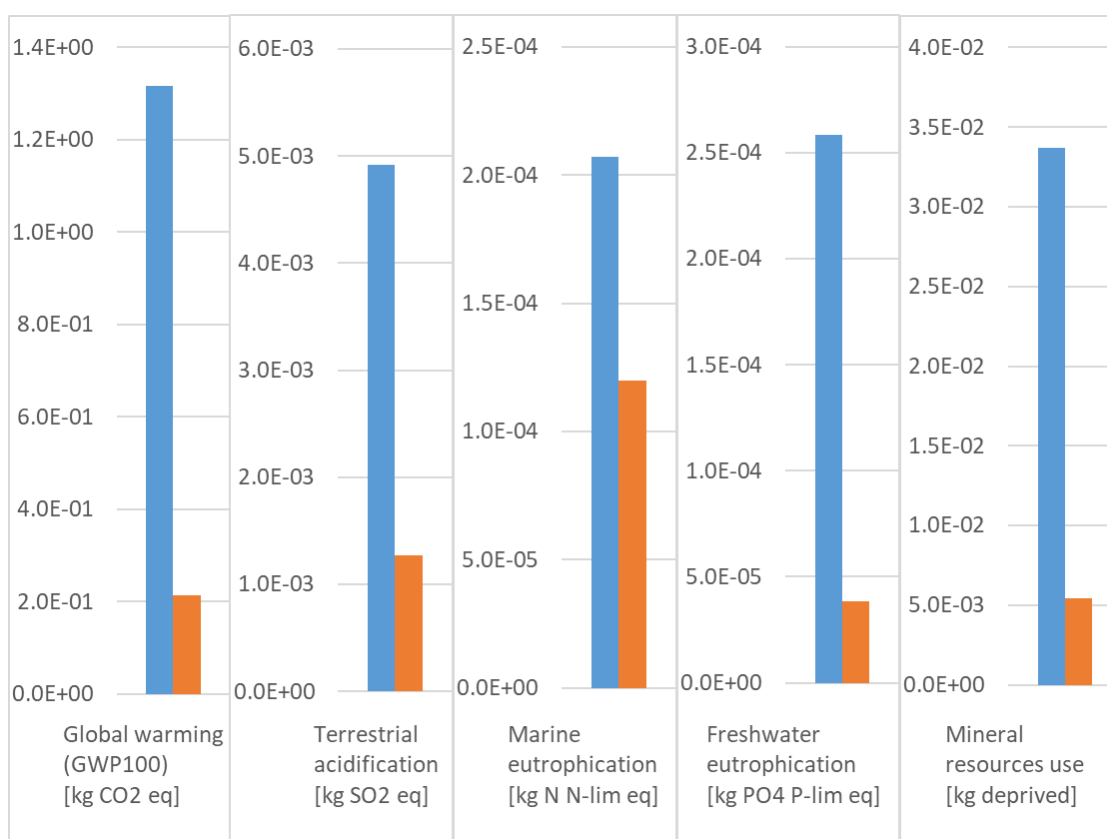


Figure 17: Comparison of environmental impacts of 1 kg BBF (hydrolysates) at industrial stage (blue) against an NPK equivalent fertiliser (orange).

4.4.4 Sensitivity analysis

As mentioned in section 3.3.3, the price of the product is depending on whether it is being marketed as organic fertiliser (2 €/kg) or biostimulant (7 €/kg). While this uncertainty affected the economic allocation, it did not have a relevant impact on the environmental impacts (Figure 18), because the other by-products (compost biochar composite and liming agent) both had much lower prices (0.11 and 0.03 €/kg).

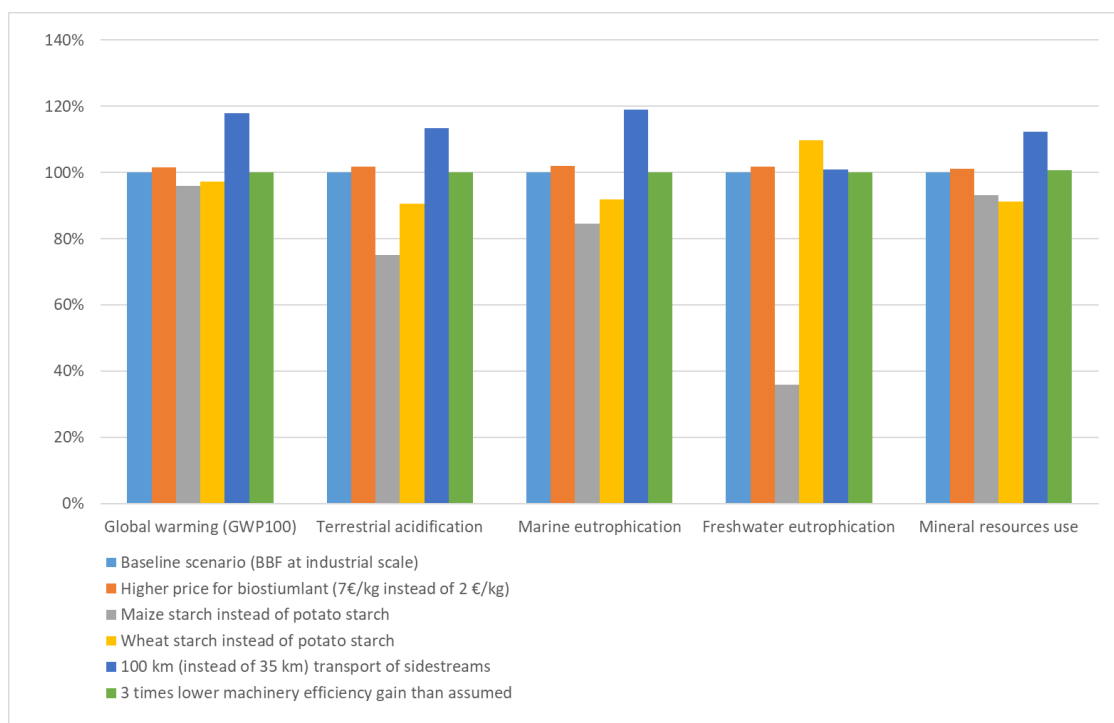


Figure 18: Sensitivity analysis for industrial scale production of protein hydrolysate (Adriatic case study). Baseline scenario, higher market prices, different growth substrate for the used enzymes, higher transport distances and lower machinery efficiency gain during upscaling.

A generally higher sensitivity of the results could be noticed with regard to the substrate used in the production of the commercial enzyme used for the enzymatic hydrolysis. The use of maize starch instead of potato starch lowered the impacts for Terrestrial acidification by 25% and for Freshwater eutrophication by 64%. For wheat starch, the reduction was, apart from Mineral resources use, less pronounced: the Terrestrial acidification was only reduced by 9% while Freshwater eutrophication even increased compared to the baseline by 10%.

When the transport distance was roughly tripled (increased from 35 to 100 km), the environmental impacts of the product increased between 1 and 19% depending on the impact category.

Results did practically not change when lower machinery use times were assumed since only material input from the machinery changed as a consequence while the energy input per kg of output remained the same (also see section 3.3.3).

4.4.5 Discussion of case-study results

The use of enzymes, the concentration process and the packaging were identified as the most important overall contributors to environmental impacts. Accordingly, in order to decrease impacts, packaging should be reduced, reused or recycled. With regard to the concentration process, heat recovery could be considered to reduce the energy demand of the spray drying or renewable energy sources such as biogas could be used. The use of enzymes should be minimized by e.g. increasing the efficiency of the enzymatic hydrolysis by using ultrasound (Qian et al., 2023).

Concerning the uncertainty of results due to assumptions needed to be taken to compile the inventory, the main factors of uncertainty seem to be the starch used in commercial enzyme production and transport in the industrial scenario. However, apart from the change with regard to the above-mentioned change in Freshwater eutrophication due to the use of maize starch, the variation between scenarios is rather moderate.

The change from the use of maize starch from ecoinvent stems due to the fact that there is approximately double the amount of P leaching and colloidal transport per kg of potato than of maize²⁷ and a higher amount of potato than maize needed to produce the starch. The higher leaching of P₂O₅ is surprising since at least under nutrient demand-based fertilisation, potatoes should be supplied with less P₂O₅ per kg fresh matter. Likewise, the double as high colloidal P transport seems unlikely since also maize -like potato cultivation- is prone to erosion. Hence, the impact on *Freshwater eutrophication* due to a switch to maize starch is expected to be smaller.

The main driver of the reduced impacts in the industrial scenario is the change from electricity to natural gas under industrial conditions which leads to a higher energy efficiency (based on the Italian grid mix). Even with no foreground energy consumption modelled, the comparably low greenhouse gas emissions of the NPK equivalent fertiliser cannot be matched: due to the addition of enzymes (43% contribution to Global), the increased amount of packaging due to higher volume/mass of fertiliser (35% contribution to Global warming) and the refrigerated transport of side-streams (14% contribution to

²⁷ Relevant, compared ecoinvent inventories: *Potato {RoW} | potato production | Cut-off, U* and *Maize grain {RoW} | maize grain production, rainfed | Cut-off, U*.

Global warming), the GWP100 still remains about 3-fold higher for the BBF compared to the NPK equivalent fertiliser.

4.5 North Sea: Pelleted Fish sludge (T4.1)

4.5.1 Process contributions

The Pelleted fish sludge produced in the North Sea case study is already at industrial scale. Figure 19 therefore shows the process contribution at industrial scale. The main contributions were drying the fish sludge before transport (30-83%), transporting the dried fish sludge to the BBF factory (13-34%) and buildings (1-41%). Packaging, machinery (manufacturing, transporting and disposal) and electricity usage of all machinery showed only minor contributions to environmental impacts (0-4%). For Global warming, Terrestrial acidification, Marine and Freshwater eutrophication drying of fish sludge dominated impacts, for mineral resources buildings, drying and transport of sludge showed the highest contributions.

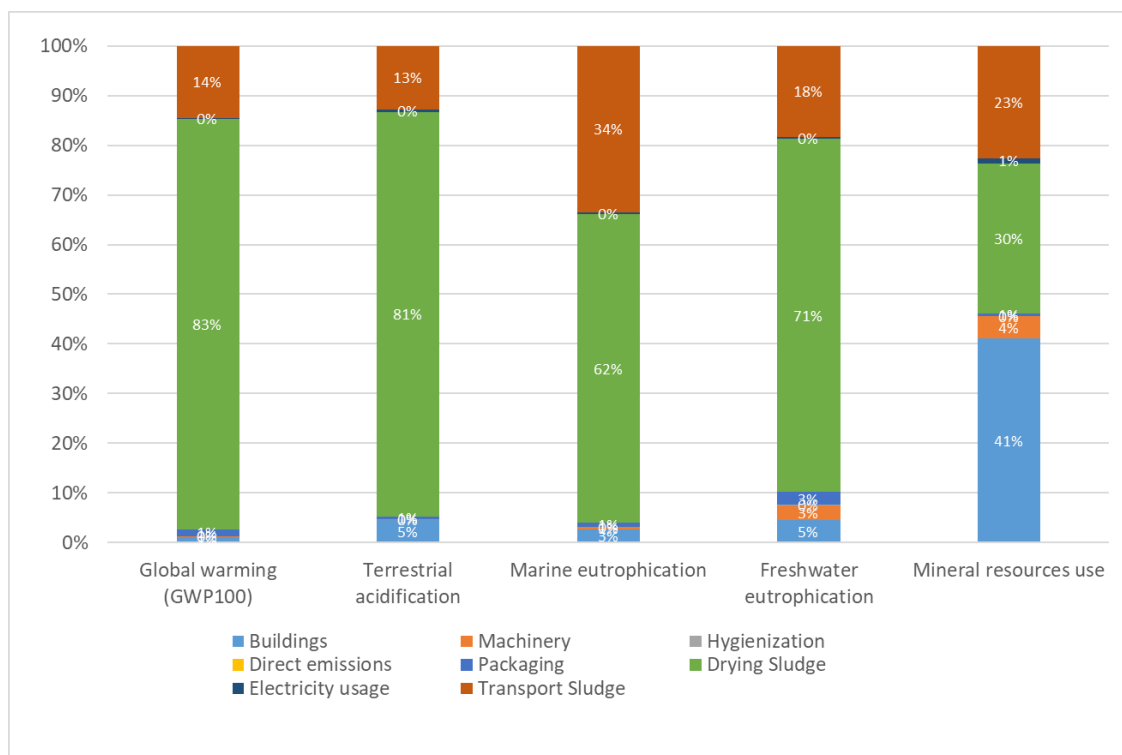


Figure 19: Process contribution at industrial scale for Pelleted fish sludge (North Sea case study, T4.1).

4.5.2 Comparison with NPK equivalent fertiliser

Compared with an NPK-equivalent fertiliser, the Pelleted fish sludge showed 19 – 99 % lower environmental impacts for the assessed impact categories, except for Global warming where impacts were 43 % higher (Figure 20).

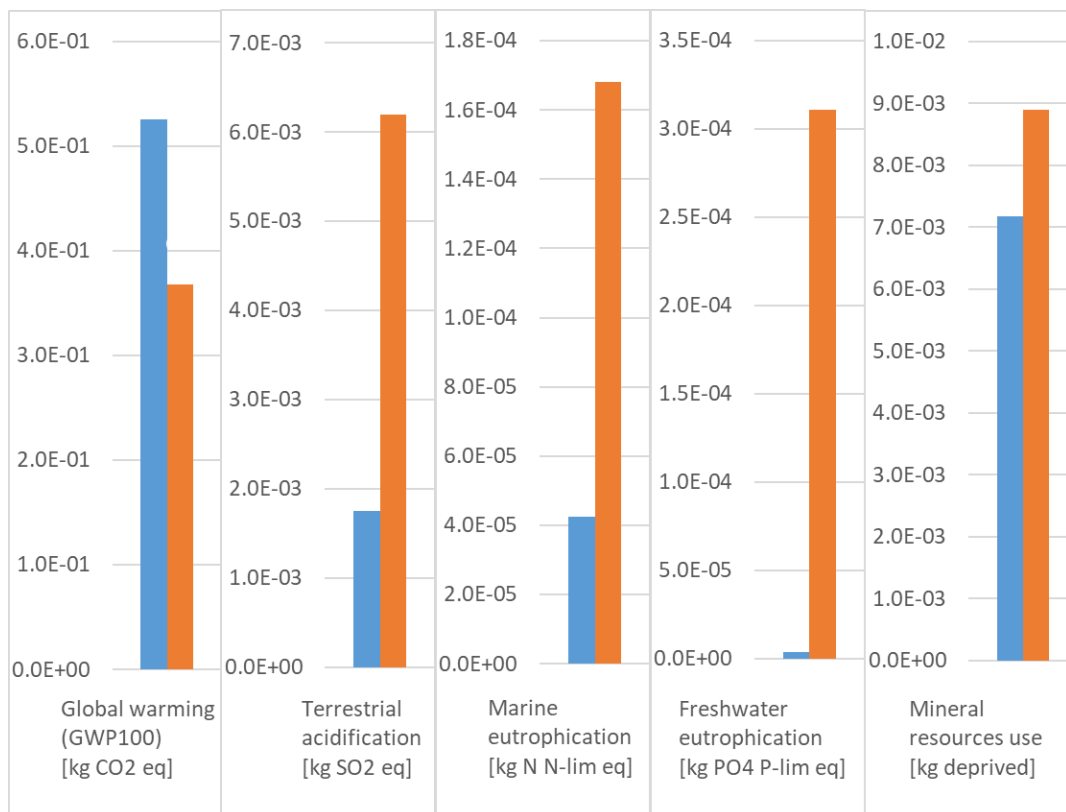


Figure 20: Comparison of environmental impacts of 1 kg BBF (Pelleted fish sludge; blue) against an NPK equivalent fertiliser (orange).

4.5.3 Sensitivity analysis

In a sensitivity analysis, different assumptions and data sources for drying of fish sludge as well as a reduced transport distance for the fish sludge were analysed (Figure 21). Reducing the degree of drying of fish sludge from 95% dry matter to 90% dry matter resulted in a 2-6% lower impact. If fish sludge was dried with a low temperature drying process (using less energy), impacts were reduced by 11 – 37%. When different heat sources were used, impacts were reduced by 21-79%. Excluding the drying completely from the analysis would result in a 30-83% lower impact. When transport distance of fish sludge would be halved (250 km instead of 500 km of non-refrigerated transport), impacts would be reduced by 6-17%.

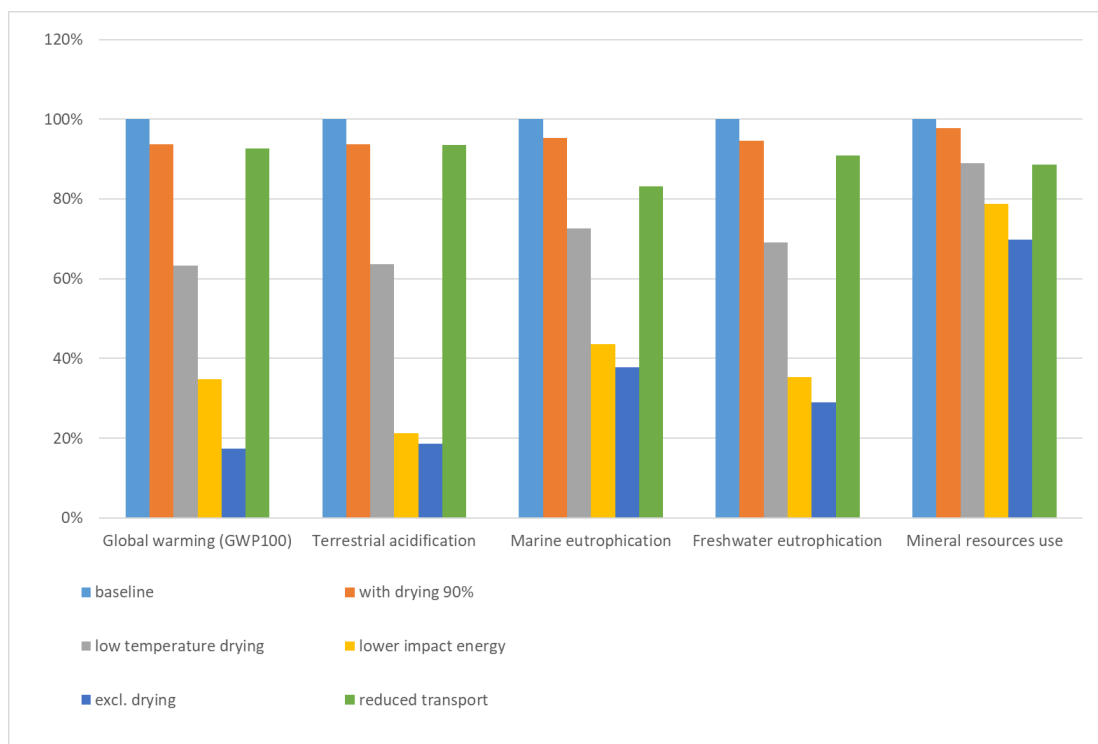


Figure 21: Sensitivity Analysis for Pelleted Fish sludge (T4.1). light blue: Baseline (drying of fish sludge approximated with energy needed for drying sewage sludge); orange: fish sludge dried up to 90% instead of 95% dry matter; grey: low temperature drying; yellow: lower impacting heat source (e.g. from municipal waste); dark blue: drying of fish sludge excluded from analysis; green: transport of fish sludge reduced from 500km to 250km.

4.5.4 Discussion of case-study results

The Pelleted fish sludge showed considerably lower environmental impacts compared to NPK equivalent fertiliser, except for Global warming. This is due to the rather high N, P and K content of the Pelleted fish sludge (see Table 29) and due to the rather low energy requirement for processing of the dried fish sludge (0.03 kWh/ kg BBF). Drying and then transporting the fish sludge to the BBF production facility showed the highest contribution to environmental impacts. Since the drying process is not part of the case study, no detailed information on the processing, energy requirements and energy sources were available and the data was approximated with energy needs per kg water removed for drying sewage sludge (Vetter & Burger, 2006). Therefore, the most relevant impacts are also the most uncertain ones.

To perform equally or better than mineral fertiliser in terms of Global warming, the energy needed for drying fish sludge before pelleting would have to be drastically reduced or a heat source with lower GHG emissions would be needed. A low-temperature drying process, for example, which is already being used by some aquaculture companies in Norway, would result in a 10% lower GWP100 compared to NPK-eq. mineral fertiliser. As

shown in Cristiano et al., (2022), recirculating aquaculture systems provide the opportunity to largely reduce the environmental impact of aquacultures compared to traditional flow-through land-based systems. In these innovative systems, the effluent is treated through mechanical and biofiltration and sterilized by ultra-violet radiation before the water it is fed back into the fish tanks. Through the filtration, the water content of the fish sludge can be reduced to 10%, and the subsequent drying can be performed with an energy-efficient infrared system.

Transport also had a significant share of environmental impacts. Sourcing fish sludge from a closer location would substantially reduce all impact categories.

4.6 Atlantic Sea: Solid BBF (T4.2)

4.6.1 Process contributions

At pilot scale, the main impacts resulted from the extrusion process, particularly for Freshwater eutrophication and Mineral resources use, as well as from the drying phase, particularly for Global warming and Terrestrial acidification (Figure 22). For extrusion, the machinery (twin screw extruder) was more important than electricity required for the operation comprising notably a heating. Steel was the main component of the extruder (weight: 3t, size close to industrial scale) and was responsible of the major impacts. For the drying phase, the machinery represented an important contribution (average 16%) even if it is lower than electricity used during this phase. Transportation of the frozen fish wastes with a truck for a long distance (347 km) represented also a significant part (up to 28%; Marine eutrophication) of the impacts, particularly for Global warming due to the emission of carbon dioxide by this vehicle.

Packaging contributed little (max 1%) to the selected environmental impacts while building's contribution was relevant for Mineral resources use (15% contribution to this impact).

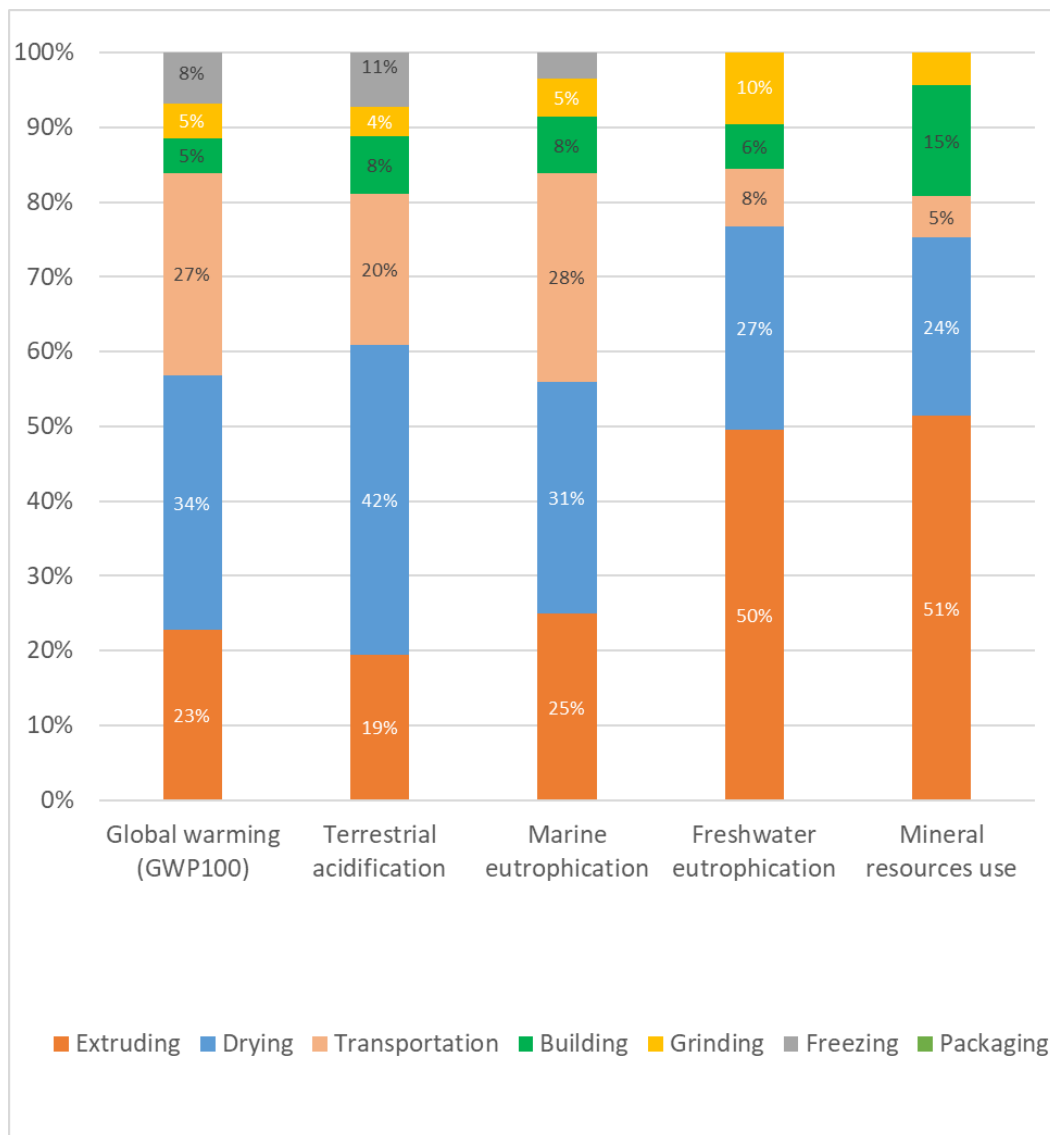


Figure 22: Process contribution at pilot scale for BBF1 (solid) of the Atlantic Sea case study (T4.2).

4.6.2 Upscaling to industrial scale

The upscaling process resulted in a general reduction of environmental impacts (Table 38). The strongest reduction in impact occurred for Mineral resources use and freshwater eutrophication, mainly due to the more efficient use of machineries (steel) with a better use of capacity (assumed weight of extruder: 5t). Regarding Mineral resources use, infrastructure (building and machineries) largely represent the highest contribution at pilot scale (83%), while it only represents 10% at industrial scale where electricity predominates. Transportation distances were also assumed to be lower and the fish waste was just refrigerated (instead of frozen, as in pilot scale). This partially explained the change in Global warming and Terrestrial acidification. The stage with the greatest

impact was extrusion on the pilot scale, whereas on an industrial scale it's the drying stage.

Table 38: Impacts at industrial scale compared to pilot scale pro kg BBF1 (Atlantic Sea, T4.2)

Impact category	Unit	Pilot scale	Industrial scale	Relative change
Global warming (GWP100)	kg CO2 eq	0.96	0.36	-63%
Terrestrial acidification	kg SO2 eq	0.0036	0.0017	-53%
Marine eutrophication	kg N N-lim eq	1.56E-4	5.05E-5	-68%
Freshwater eutrophication	kg PO4 P-lim eq	3.07E-5	4.67E-6	-85%
Mineral resources use	kg deprived	0.083	0.0090	-89%

4.6.3 Comparison with NPK equivalent fertiliser

When comparing the solid bio-based fertiliser at industrial scale against NPK equivalent fertiliser with the same macronutrient content (Figure 23), impacts were slightly lower for Global warming and Mineral resources use (11% and 16%, respectively), while the BBF showed about 75% lower impacts for Terrestrial acidification and Marine Eutrophication and over 95% lower impacts for Freshwater eutrophication than mineral fertiliser.

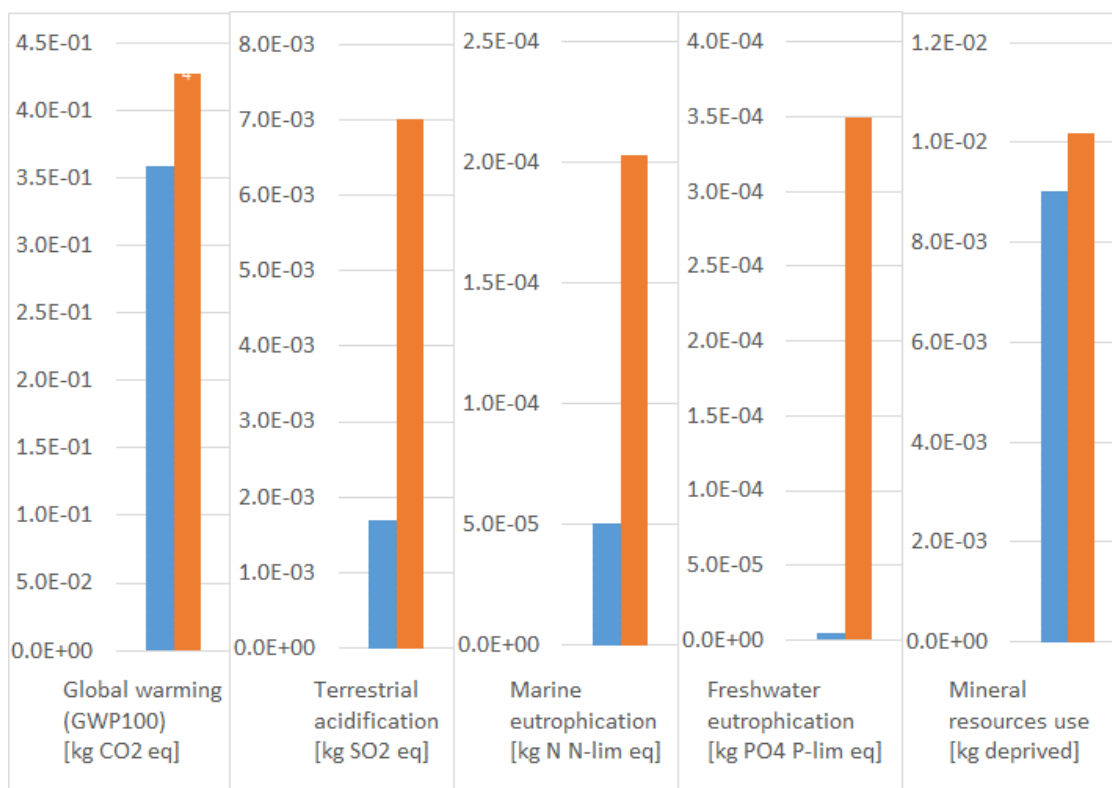


Figure 23: Comparison of environmental impacts of 1 kg of BBFs1 (blue) at industrial stage (Atlantic case study, T4.2) against an NPK equivalent mineral fertiliser (red bar).

4.6.4 Sensitivity analysis

The price of the product is depending on how it is being marketed. As the impacts are allocated according to the monetary value of the final products, lowering the price per kg of the BBF1 (1€ instead of 1.5 €), the impacts considered decreased between 5% to 8%. With a higher price (2€ instead of 1.5€), impacts increased between 4% to 6%.

The composition of material for machineries is uncertain for an industrial scale. Per kg, electronic parts show higher impacts than plastics and steel. However, when the share of electronics in machineries was increased from 0.1% to 2% this had no visible effect on the different impact categories represented here (Figure 24). If the distance from the aquaculture to the processing company would be increased (from 40 km to 100 km), the environmental impacts increased by 7 to 15%.

Also, increasing the surface of the building hall from 200 m² to 400 m² did not result in a significant increase in impacts, less than 2% for all impacts except the use of mineral resources, which increased by 10%. No change in electrical efficiency was observed for the extrusion stage when the process was scaled up, but if the electrical efficiency of the machines is doubled for the other operations (drying, centrifuging, etc.) compared with the pilot scale (half the amount of kWh required per kg of compounds processed), this could have a significant impact (around 38 % reduction across all impacts).

If enzymes are used for the extraction phase to improve the hydrolysis for the liquid phase (as it was the case for the fertiliser tested in pot trials, but not in field trials), the impacts globally increase especially for Freshwater Eutrophication (with relative impacts equalling 899%), but also for Marine eutrophication, Terrestrial acidification and for Global warming impacts. The enzyme is produced with the help of potato starch in the used standard ecoinvent process.

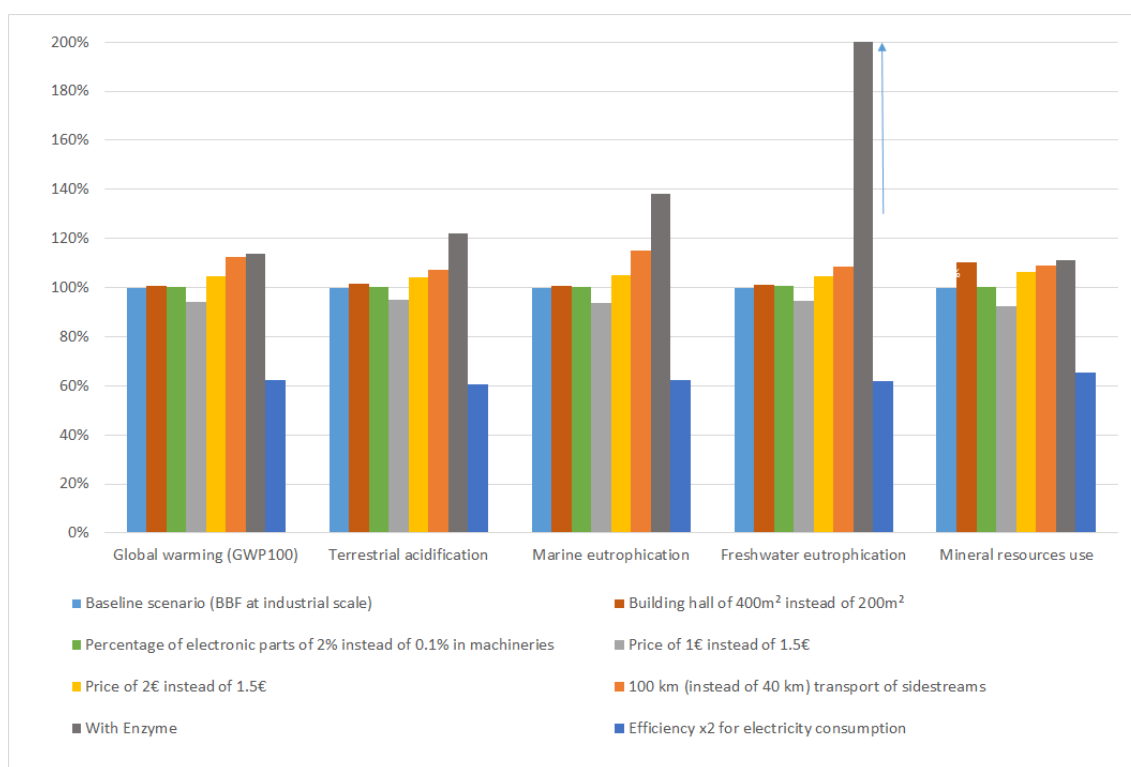


Figure 24: Sensitivity analysis for Solid BBF (T4.2) for different hypothesis based on economic, technical and logistical variations. The blue arrow signifies that the bar is visually cut at 200% (value equals 899%).

4.6.5 Discussion of case-study results

At industrial scale, impacts were mainly driven by the electricity required for extruding the fish wastes and drying them. The contribution of the infrastructure and machinery (namely the extruder) to environmental impacts were less important at an industrial scale.

The Solid BBF showed comparable or less environmental impacts than a referent NPK fertiliser on the different impact categories considered. The sensitivity analysis showed the relevant factors for optimizing production at the industrial scale: avoiding the use of enzymes substantially reduced the environmental impacts of the BBF (assuming no relevant biostimulant effect from the weak hydrolysis found in first tests).

While a short transport distance between aquaculture and BBF production facility also showed to be relevant, results were only little sensitive with regard to change in prices from 1 to 2 €. Nevertheless, since prices are uncertain, this needs to be considered when comparing to other fertilisers.

5 Results: Impact assessment of fertiliser use

5.1 Wheat (N)

5.1.1 Comparison with mineral fertiliser and hotspots

Using BBFs instead of mineral fertiliser resulted mostly in similar to higher impacts per kg of wheat (Figure 25). The **Pelleted fish sludge** (T4.1) showed the best performance of all BBFs with impacts between 92% and 117% of mineral fertiliser across the five impact categories. For the **NPK solution** (T3.2), impacts were between 101% and 175% of mineral fertiliser and for the **Solid BBF** (T4.2) between 118% and 192%. The lower wheat yields of all BBFs compared to mineral fertiliser (see Table 8) was partly responsible for the higher impacts of BBFs per kg wheat.

For Pelleted fish sludge (T4.1, 11% lower AMFE for wheat) and Solid BBF (T4.2, 40% lower AMFE for wheat), impacts per ha of wheat were lower for Global warming, Freshwater eutrophication, Mineral resources use and Terrestrial acidification (see section 10.2.1). For the NPK solution (T3.2, 8% lower AMFE for wheat), impacts per ha were, apart from lower impacts for Terrestrial acidification and similar impacts for Freshwater eutrophication, higher than mineral fertiliser.

The **production of fertiliser** (part 1 of this report) showed relevant contributions to total impacts for Mineral resources use (39-65% of overall impacts of 1kg wheat produced with the different fertilisers), Global warming (22-64%), Terrestrial acidification (13-26%), while it was less relevant for Freshwater (1-27%) and Marine eutrophication (1-3%; Figure 25). **Field emissions** (including emissions from fertiliser application as well as background emissions such as leaching from soils) made up a large share of environmental impacts for Marine (95-98% of total impacts) and Freshwater eutrophication (67-93%), Terrestrial acidification (60-71%) and Global warming (23-54%) but not for Mineral resources use (0%). **Tillage and harvesting** showed relevant contributions to overall impacts for Mineral resource (tillage: 14-24%; harvesting: 9-15%) use and Global warming (tillage: 5-11%; harvesting: 3-7%) and Terrestrial acidification (tillage: 4-5%; harvesting: 3-4%), but not for the other impact categories (0-1%). All other processes showed contributions between 0% and maximum 8% of total impacts.

For **Freshwater eutrophication**, where field emissions contributed strongly to total impacts, all BBFs showed higher impacts per kg wheat than mineral fertiliser. This can be explained by lower yields and the higher amounts of P fertilised added compared to mineral fertiliser.

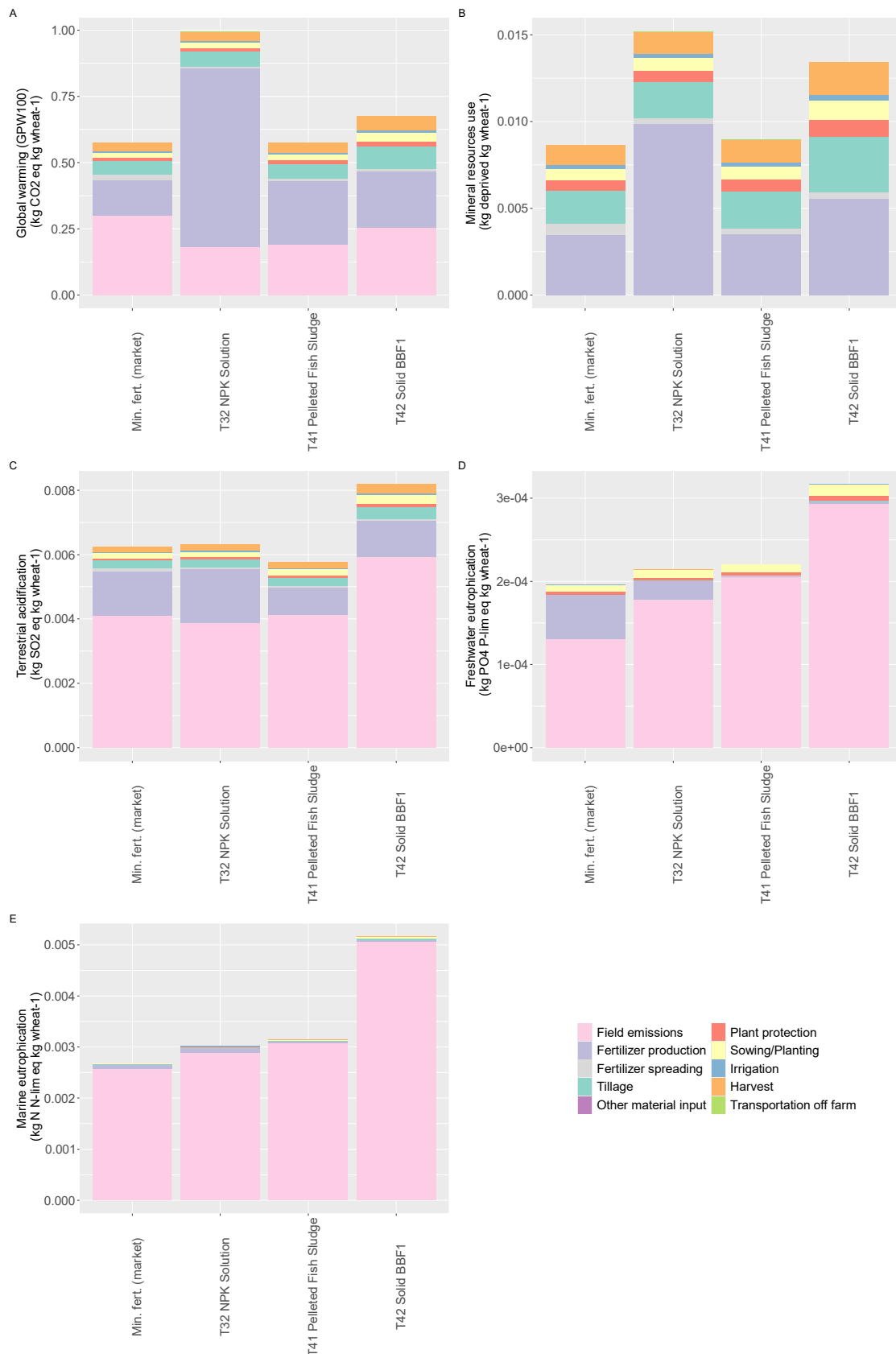


Figure 25: Environmental impacts of producing 1 kg of **wheat**, based on agronomic data from pot trials.

5.1.2 Sensitivity analysis

The sensitivity analysis (Figure 26) showed, that the impact per kg wheat were little sensitive to an additional **road transport** of BBFs to the farm (choice of emission factors for ammonia (NH_3) and nitrous oxide (N_2O) showed to be more sensitive. Calculating impacts with the **Dutch NH_3 emission factor** for organic fertilisers decreased the Terrestrial acidification of wheat fertilised with BBFs T3.2 NPK solution, T4.1 Pelleted fish sludge and T4.2 Solid BBF by 39%, 59% and 62% respectively. Assuming the Dutch emission factors for BBFs, all three BBFs show a considerably (i.e. 39-62%) lower Terrestrial acidification compared to mineral fertiliser. For Marine eutrophication, impacts slightly decreased by 2% and did not change the result for the comparison between BBFs and mineral fertiliser. If **nitrous oxide emissions** would be calculated with the lower estimate of the emission factor from IPCC, the Global warming impact (from all GHGs) would be reduced by 5-13% (including the mineral fertiliser) depending on the fertiliser. With the upper estimate, Global warming impacts would increase by 6-13% for all fertilisers. While impacts of wheat produced with BBFs were similar or higher compared to mineral fertiliser for the average (baseline) and upper estimates of the N_2O emission factors, using the lower estimates of the N_2O emission factors resulted in lower Global warming impacts of the Pelleted fish sludge (T4.1) compared to mineral fertiliser.

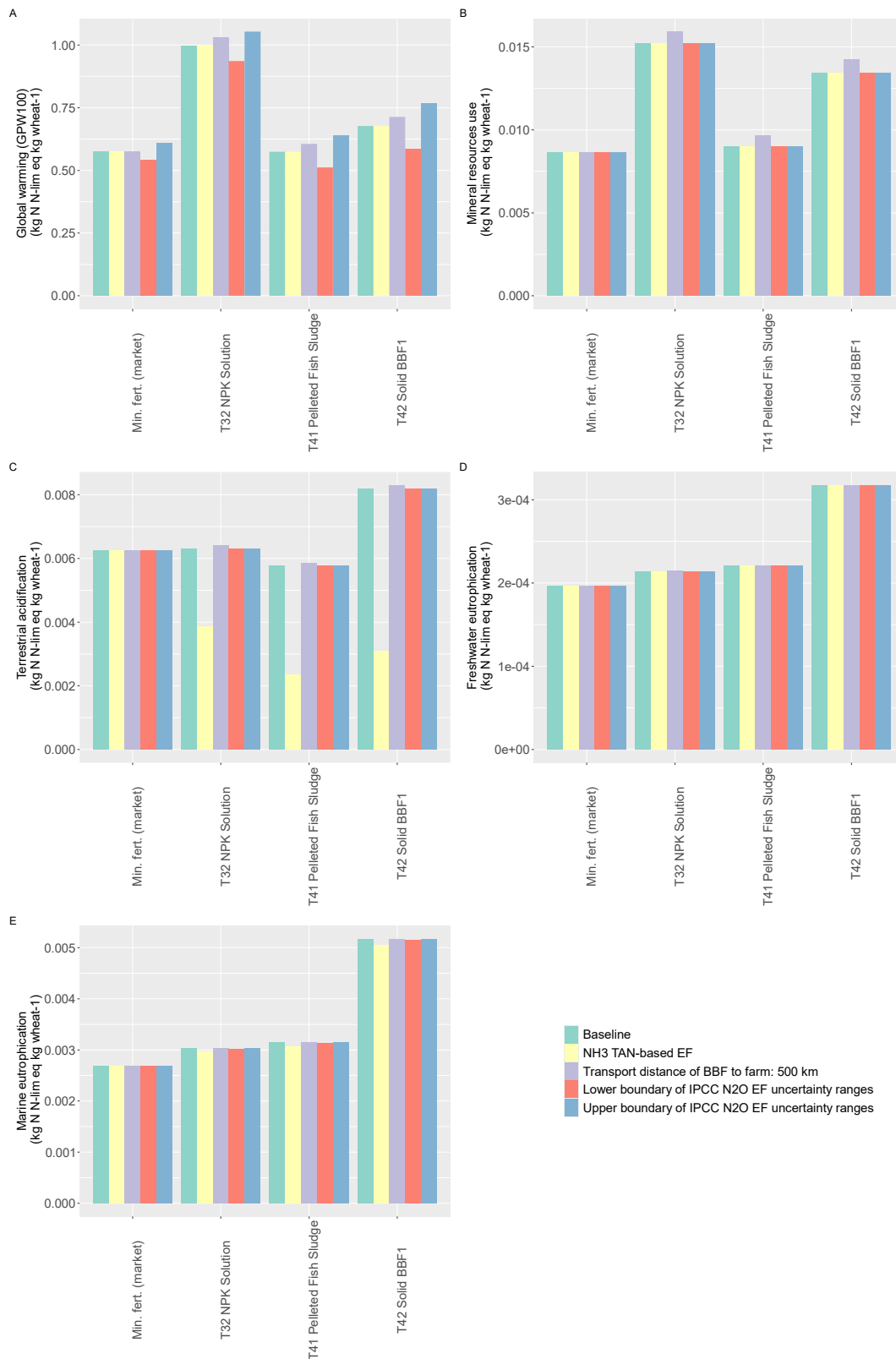


Figure 26: Sensitivity of environmental impacts of producing 1 kg of **wheat**, based on agronomic data from pot trials to changes in different parameters.

5.2 Rye grass (P)

5.2.1 Comparison with mineral fertiliser and hotspots

The environmental performance of BBFs applied on rye grass replacing mineral P-fertiliser was generally better than for wheat, where an equal amount of N fertilisation was applied (focusing on replacing mineral N-fertiliser with BBFs). The **Solid BBF** (T4.2) showed lower impacts per kg of rye grass compared to mineral fertiliser for all five impact categories, ranging between 69-88% of the impacts of mineral fertiliser (Figure 27). The **bokashi granules** (T3.1) showed lower impacts compared to mineral fertiliser for Global warming (81%) and Terrestrial acidification (80%), similar impacts for Marine eutrophication (106%), but higher impacts for Mineral resources use (128%) and Freshwater eutrophication (139%). The **NPK solution** (T3.2) showed lower impacts per kg of rye grass than mineral fertiliser for Terrestrial acidification (91%) and similar impacts for Freshwater (95%) and Marine eutrophication (105%). For Global warming and Mineral resources use, impacts were higher (152% and 134%). The **Pelleted fish sludge** (T4.1) showed higher impacts for all impact categories, ranging from 132-181% of the impacts of mineral fertiliser.

However, when considering the **environmental impacts per ha** of rye grass, **Pelleted fish sludge** (T4.1) showed lower or similar impacts compared to mineral fertiliser (75-103% of the impacts of mineral fertiliser). Here, the 43% lower yields of this BBF resulted in higher environmental impacts per kg of rye grass described above. For the **Solid BBF** (T4.2), impacts were lower or similar to mineral fertiliser per ha of rye grass (78-100%). This BBF showed 14% higher yields than mineral fertiliser, which resulted in an overall better environmental performance per kg of rye grass (see above). The other two BBFs showed only slightly lower yields than mineral fertiliser (7% lower for Bokashi granules (T3.1) and 5% lower for NPK solution (T3.2)), and the general trends of comparison to mineral fertiliser was similar with both functional units (kg and ha).

For rye grass, three processes (production of BBFs, field emissions and harvesting) were responsible for most of the environmental impacts. The **production of fertiliser** showed relevant contributions for Global warming impacts of rye grass production (25-60%), Mineral resources use (31-51%) and Terrestrial acidification (17-32%). For Freshwater eutrophication, impacts of fertiliser production were relevant for rye grass produced with mineral fertiliser, Bokashi granules (T3.1) and NPK solution (T3.2) (9-38%), but not for the other two BBFs (1%). For Marine eutrophication, the production of BBFs only contributed between 1-3% of impacts. The **field emissions** were the most relevant process for Marine eutrophication (94-97% of impacts). Field emissions also strongly contributed to

Freshwater eutrophication (60-96%) and Terrestrial acidification (54-66%) as well as Global warming (23-59%). **Harvesting** processes (incl. mowing, swathing, haying, baling, loading of bales and roughage storage for 12 months in a barn) made up 43-61% of Mineral resources use impacts, 10-14% of Terrestrial acidification and 12-21% of Global warming. All other processed contributed maximum of 6% to impacts.

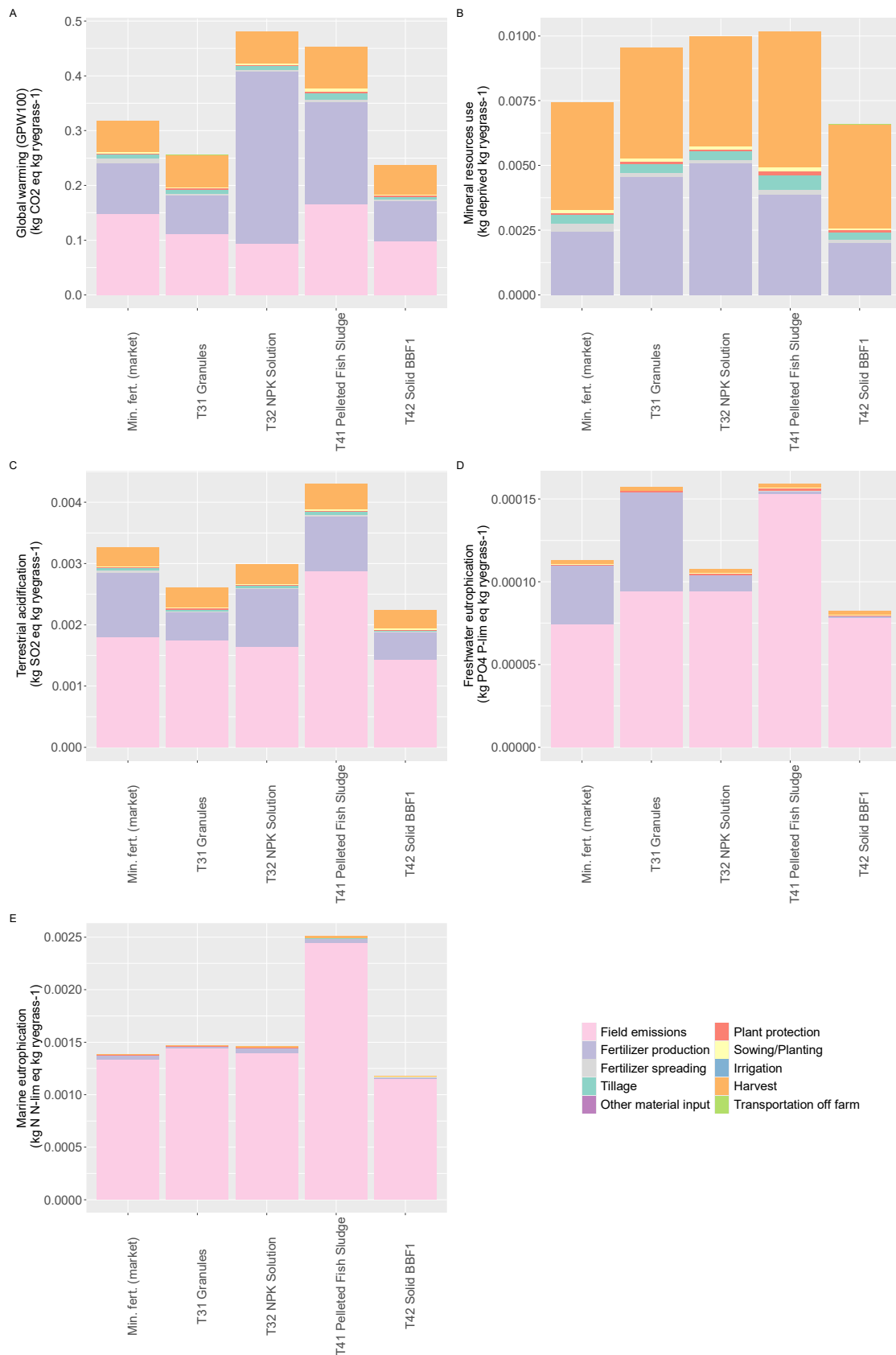


Figure 27: Environmental impacts of producing 1 kg of **rye grass**, based on agronomic data from pot trials.

5.2.2 Sensitivity analysis

Similar to wheat, the results for rye grass were little sensitive to an additional 500km **road transport** of BBFs to the farm (Figure 28). For all BBFs, impacts increased by 1-3% for Terrestrial acidification, 2-5% for Mineral resources use, and 3% for Global warming. An exception was Bokashi granules (T3.1), where Climate impacts increased by 9%, because this BBF showed lower overall Climate impacts and the contribution by an additional road transport therefore contributed to a higher share of overall impacts. Assuming **Dutch emission factors for ammonia** emissions of BBFs strongly reduced their impacts of Terrestrial acidification (35-39% lower impact compared to baseline). This resulted in considerably lower impacts of all BBFs for Terrestrial acidification compared to mineral fertiliser (15-58% lower impact compared to mineral fertiliser). The choice of **emission factors for nitrous oxide (N₂O)** did not show a very strong impact on results for Global warming, and did not affect the overall trend in the comparison of BBFs with mineral fertilisers. Using the lower boundary of the IPCC N₂O emission factors resulted in 5-9% lower impacts for BBFs compared to the baseline (average IPCC N₂O emission factor) and 5% lower results for mineral fertiliser. With the upper boundary of the IPCC N₂O emission factors, Global warming impacts increased by 5-9% for the BBFs and 5% for mineral fertiliser compared to the baseline.

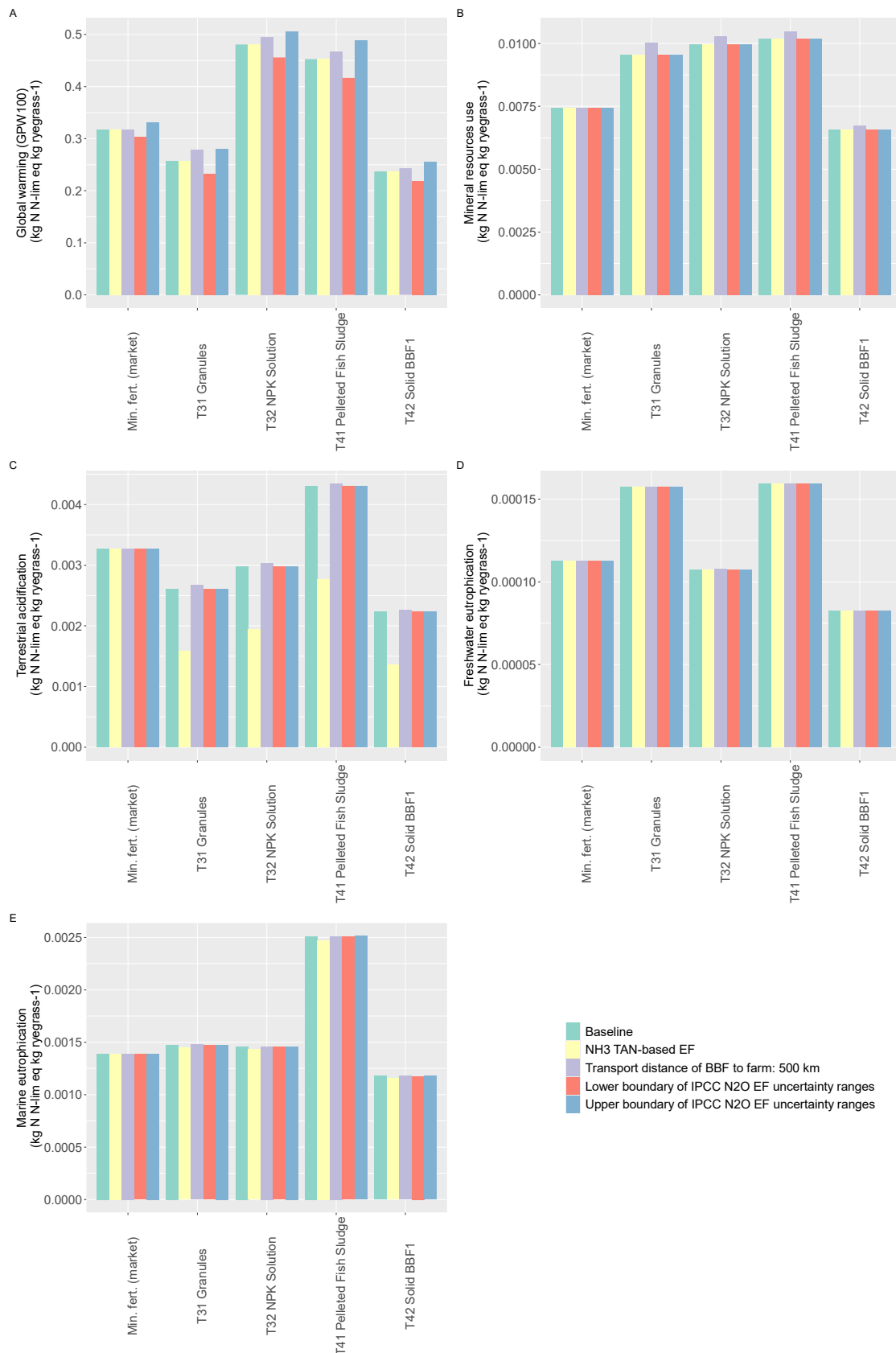


Figure 28: Sensitivity of environmental impacts of producing 1 kg of **rye grass**, based on agronomic data from pot trials to changes in different parameters

5.3 Broccoli in Estonia, season 2023 (N)

The following sections are based on the agronomic data from the Estonian broccoli field trial (season 2023).

5.3.1 Comparison with mineral fertiliser and hotspots

Apart from Global warming and Mineral resources use, substituting the mineral fertiliser from the experiment (ammonium nitrate) with BBFs resulted mostly in higher impacts per kg of broccoli (Figure 29). Among the BBF, **Solid BBF** (T4.2) showed generally the least impacts: for Global warming and Mineral resources use, it showed lower impacts compared to mineral fertiliser used in the experiment (95% and 87% of the mineral fertiliser impacts, respectively). For Terrestrial acidification, Freshwater and Marine Eutrophication, all BBFs showed higher impacts in comparison to the mineral fertiliser applied in the experiment (119–233% of the mineral fertiliser impacts). Because of low yields and high background emissions from soil, the unfertilized control also showed high impacts per kg of Broccoli for both Freshwater and Marine eutrophication. The lower yields resulting from BBF (see Table 12) could partly explain the higher impacts per kg Broccoli in Figure 29. However, for Freshwater and Marine Eutrophication, the pattern would remain the same, but less pronounced, when considering impacts per ha (see Appendix, section 10.2). Two BBFs exhibit considerably lower impacts per ha than the mineral fertiliser applied in the experiment for Global warming and Mineral Resources use (Pelleted Fish sludge: 86% and 68%, respectively; Solid BBF: 79% and 72%, respectively). Similar to the results from the pot experiments the high impacts of BBFs for Freshwater Eutrophication are caused by a 4 to 6-fold higher supply of P with the BBFs compared to fertilising rate of the mineral references (22 kg of P / ha; see Table 11).

As in the in the case of the pot trials, **production of fertiliser** showed relevant contributions to total impacts for Mineral resources use (27-54%), Global warming (14-48%), Terrestrial acidification (11-44%), while it was less relevant for Freshwater (1-24%) and Marine eutrophication (0.53-5%). The impacts per ha for the unfertilised control (see Appendix, section 10.2.3) shows that field emissions not directly relating to fertiliser input contribute the most for Freshwater and Marine eutrophication. This contrasts with Terrestrial acidification, where the unfertilised control showed no emissions. For Global warming, other material inputs such as the planting fleece showed a high contribution to the impacts (12-20%). The harvesting contributed substantially to Mineral resources use impacts (24-37%).

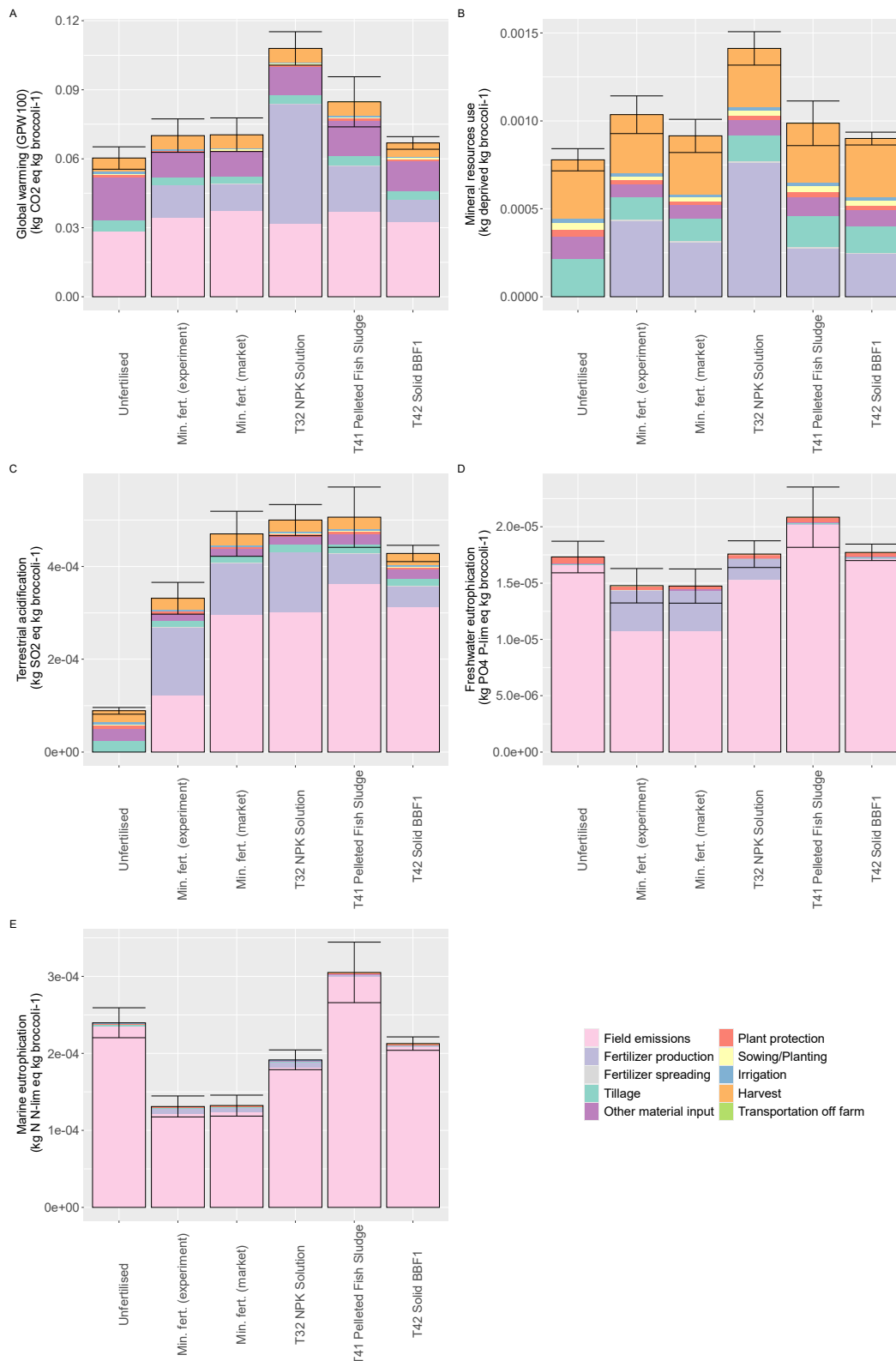


Figure 29 Environmental impacts of producing 1 kg of **broccoli**, based on agronomic data from the field trial conducted in **Estonia**. The fertiliser “Min. fert. (market)” is based on the mineral nitrogen fertiliser described in section 2.2.5. and is assumed to have the same agronomic performance than the mineral fertiliser applied in the experiment (evaluation in section 5.3.2). Error bars relate to uncertainties in yields observed in the field trials (standard error of yields).

5.3.2 Sensitivity analysis

If the BBFs are compared against the **market average mineral fertiliser** (described in section 2.2.5; assuming the same agronomic performance as the mineral fertiliser applied in the experiment), the picture only changed for Terrestrial acidification: In this case, the BBF had similar impacts than the reference fertiliser (Figure 30).

The environmental impacts per kg of broccoli increased substantially, if only **yields of heads > 8 cm** (assumed to be markable) were considered (up to 67 fold). Also, the overall pattern of differences between the fertilisers described in section 5.3.1 changed (see section 10.3) with the Pelleted fish sludge and the Solid BBF1 having comparably lower impacts.

Similar to the pot trials, the impacts per kg of broccoli were little sensitive to a **longer road transport** of BBFs to the farm (Figure 30, 500 km instead of 20 km; 0-6%). A variation of emission factors showed a mixed picture: The lower **Dutch NH₃ emission factor** for organic fertiliser reduced the impacts of BBFs with regard to Terrestrial acidification substantially (37-62% of baseline impacts). This decrease in impacts would result in lower impacts for BBFs compared to the mineral reference fertiliser of the experiment (48-93%, respectively). In contrast, the changes of impacts with regard to Global warming caused by altered **nitrous oxide emission factors** (lower and upper boundary of IPCC uncertainty range) were smaller (93-107% of the baseline for the BBF).

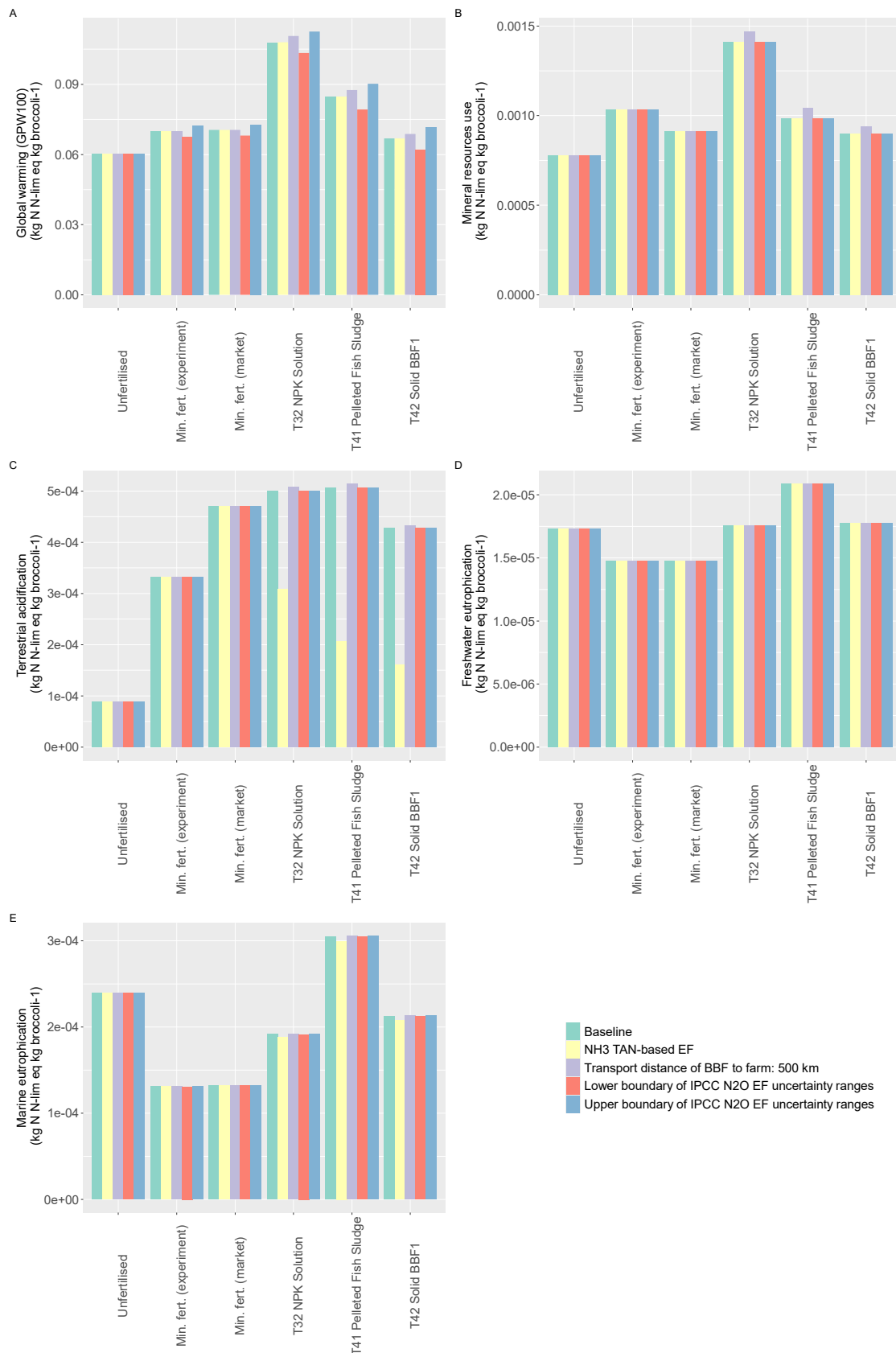


Figure 30: Sensitivity of environmental impacts of producing 1 kg of **broccoli**, based on agronomic data from the Estonian field trial to changes in different parameters.

5.4 Broccoli in Spain, season 2024 (N)

The following sections are based on the agronomic data from the second of two broccoli field trials in Spain (season 2024).

5.4.1 Comparison with mineral fertiliser and hotspots

The environmental impacts per kg of broccoli fertilized with BBFs (i.e. Pelleted Fish Sludge and Solid BBF) and mineral fertilisers were in a similar range for Global warming and Mineral resources use. The **NPK solution** (applied as biostimulant combined with mineral fertilizer) showed the lowest impact with 36-72% of the mineral fertilisers applied in the experiment. The treatment differed to the other trials with the NPK solution only being applied in a small amount combined with a reduced mineral fertilization, to test its expected biostimulant effect (Table 11). The other two BBFs showed very similar impacts ranging from 83% to 168% of the mineral fertilisers applied in the experiment. Similar to the Estonian field trial, BBFs tend to show higher impacts for Freshwater and Marine eutrophication than the reference mineral fertiliser (120%–168% of the mineral fertiliser applied in the experiment).

Like in the other trials, different yields are the main cause for the observed pattern for Freshwater and Marine eutrophication: BBF even exhibited lower (Freshwater Eutrophication) or only slightly higher (Marine Eutrophication) impacts if the fertilisers' impacts are compared per ha of Broccoli (see Appendix, section 10.2). In contrast to the Estonian field trial, the P application rate of BBFs is only 2 to 4-fold higher than the mineral P fertiliser applied (Estonia: 4 to 6-fold higher; see Table 11) leading to the lower impacts in case of Freshwater eutrophication per ha of Broccoli (impacts of BBFs ranging from 56-80% of the mineral fertiliser applied in the experiment). For Marine Eutrophication, the impacts BBFs' impacts range between 78-111% of the mineral fertiliser applied in the experiment.

As in the case of the results from other trials, the contribution of the **production of fertiliser** to environmental impacts was most relevant for Mineral resources use (26–58% of impacts), Global warming (12–25%) and Terrestrial acidification (11–60%). For Freshwater Eutrophication and Marine Eutrophication, contributions of production of BBFs to environmental impacts were low (0.45-0.17% and 0.34–1.54%, respectively) and contribution of field emission high (95-97% and 97-99%, respectively). Like in the case of the Estonian field trial, other material input (e.g. the planting fleece) showed a relevant contribution to Global warming (20–22% for the BBF) and Mineral resources use (12–13% for the BBF). The machinery use from tillage also turned out to be relevant for the latter impact category (11-22% for the BBF).

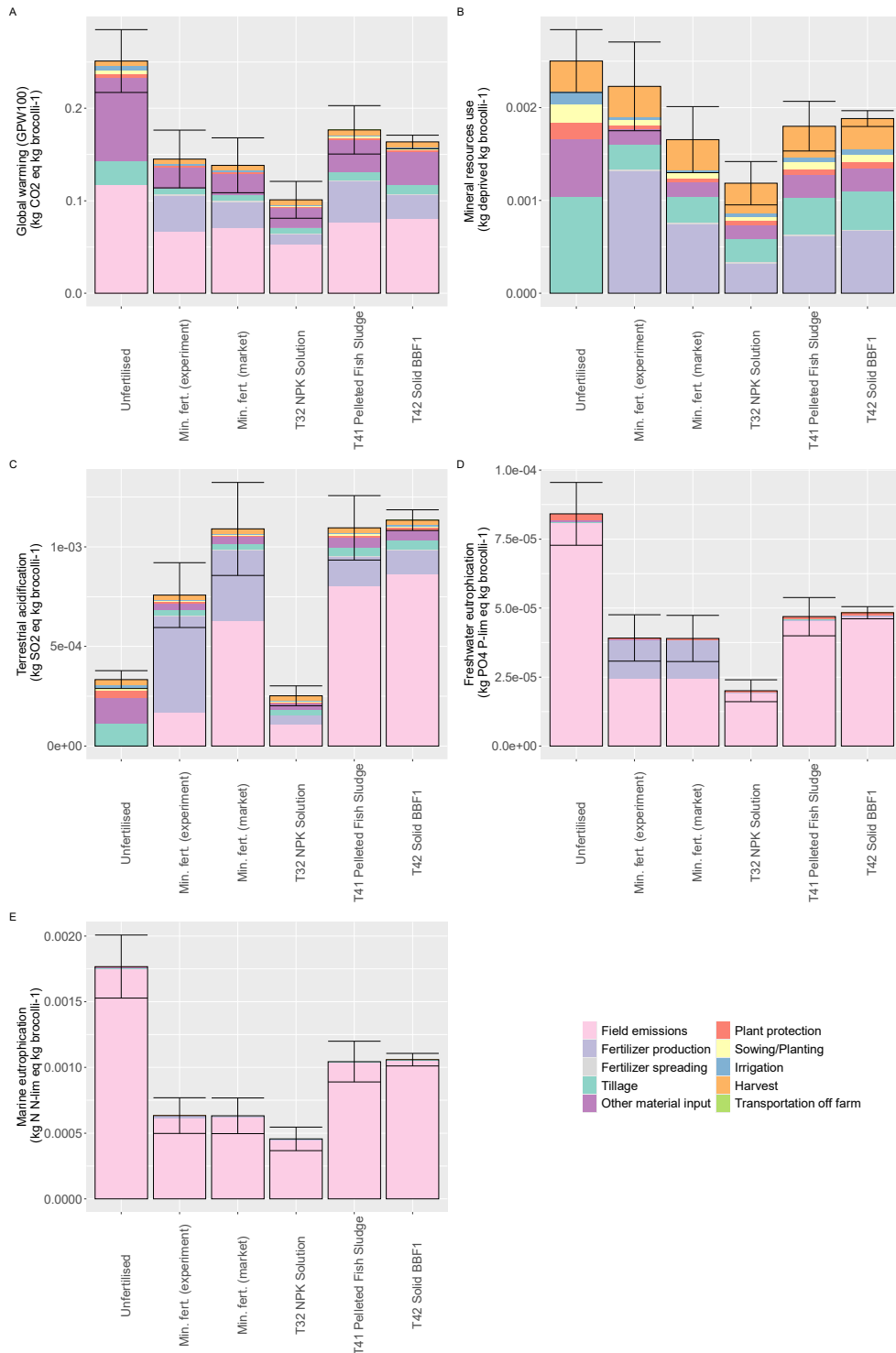


Figure 31: Environmental impacts of producing 1 kg of **broccoli**, based on agronomic data from the field trial conducted in **Spain (2024)**. The fertiliser “Min. fert. (market)” is based on the mineral nitrogen fertiliser described in section 2.2.5. and is assumed to have the same agronomic performance than the mineral fertiliser applied in the experiment (evaluation in section 5.3.2). Error bars relate to uncertainties in yields observed in the field trials (standard error of yields). T.3.2 NPK Solution was applied as biostimulants in combination with a reduced mineral N-fertilizer.

5.4.2 Sensitivity analysis

If the BBFs were compared to the **market average mineral fertiliser** instead of the mineral fertilisers applied in the experiment, results remain similar except for Mineral resources use and Terrestrial acidification, where the pelleted Fish sludge and the Solid BBF showed similar impacts than the mineral reference Figure 31.

When relating impacts to kg of **broccoli heads (all sizes)** instead of total broccoli biomass, environmental impacts increased by a factor 13-157, which is even higher than in the Estonian trial (Figure 32). This is because in the Spanish field trial only 1-5% of the total broccoli biomass consisted of heads of all sizes whereas in the Estonian field trial 16-22% of the total biomass consisted of heads (> 8 cm; see section 10.3). However, the general ranking of environmental impacts of fertiliser did not change when considering only broccoli heads or the full biomass.

The effects of **longer road transport** of BBFs to the farm (Figure 32; 500 km instead of 20 km) and altered **nitrous oxide emission factors** (lower and upper boundary of IPCC uncertainty range) were similarly small than in the case of Estonia and without any effect on the overall pattern. However, the use of the **Dutch NH₃ emission factor** for organic fertiliser would reduce the impacts of the Pelleted fish sludge and the Solid BBF with regard to Terrestrial acidification (35-39% of baseline impacts). With this change, the Solid BBF and the Pelleted Fish Sludge would perform better than the mineral fertiliser applied in the experiment.

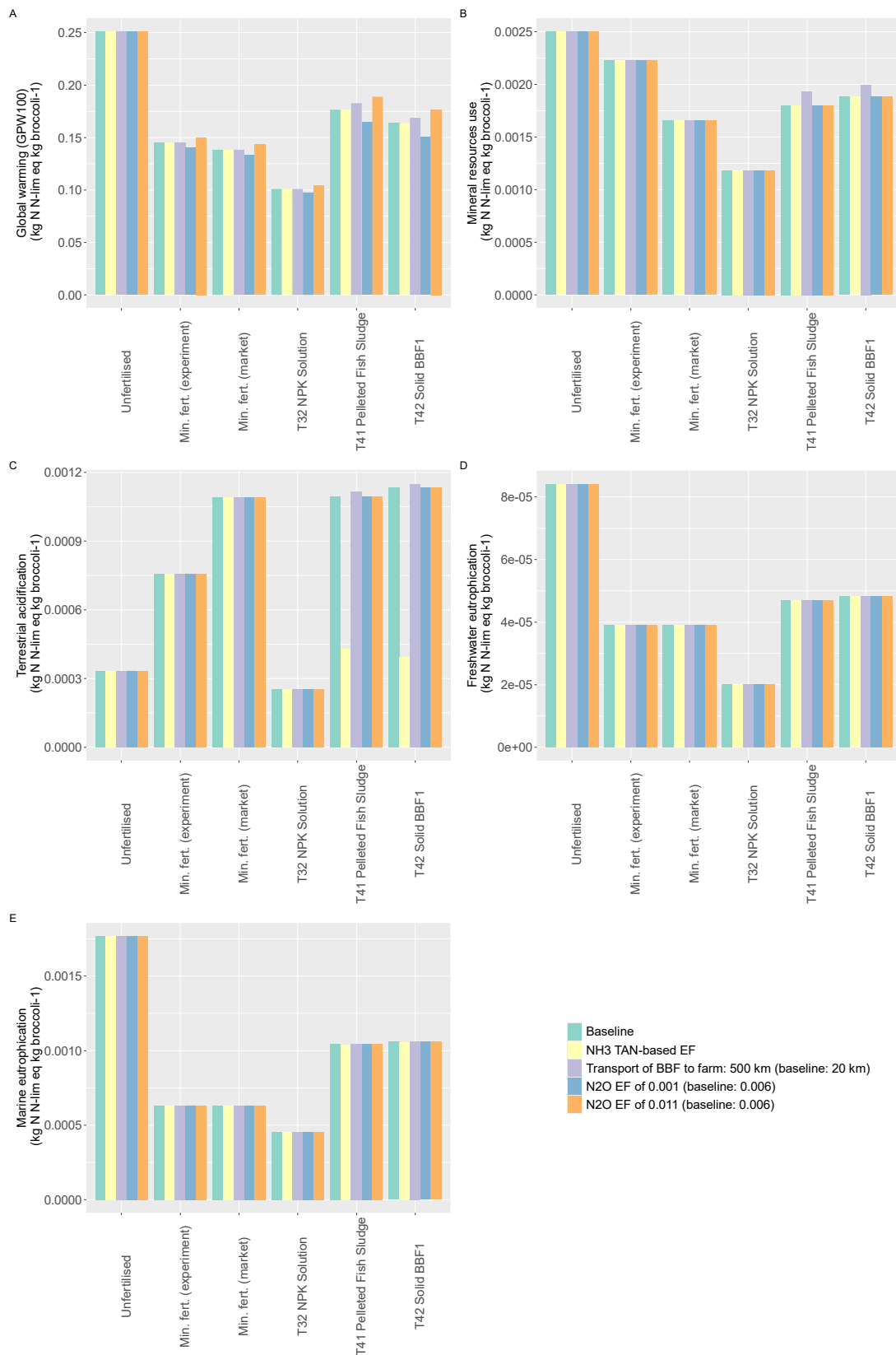


Figure 32: Sensitivity of environmental impacts of producing 1 kg of broccoli, based on agronomic data from the Spanish field trial (2024) to changes in different parameters. T.3.2 NPK Solution was applied as biostimulants in combination with a reduced mineral N-fertilizer.

6 Discussion

6.1 Fertiliser production (step 1)

The purpose of the LCA on production of BBFs is twofold: (1) to identify environmental optimisation potential of the production process of BBFs at pilot stage and (2) to compare the environmental impacts of upscaled fertiliser production to mineral fertilisers.

6.1.1 Environmental hotspots

The analysed side-streams and processes to produce BBFs from them were very diverse. Although different processes were responsible for the majority of impacts in the case studies (so called environmental hotspots), some processes were relevant for most BBFs: the transport of side-streams (both, fresh and dried), the concentration process (removing water with different procedures) and the packaging (with the exception of the Atlantic case study). In addition, buildings were relevant for Mineral resources use at pilot stage, but their impact decreased with more efficient use of facilities at industrial stage. In the following, these processes are discussed.

The **transport distances** of side-streams (refrigerated or uncooled) to BBF production facilities showed to be a sensitive parameter. In three case studies (granules in Baltic Sea, hydrolysates in Adriatic Sea (T3.3) and Solid BBF in Atlantic Sea (T4.2)) even changes in transport distances at regional scale (up to 100 km) resulted in relevant changes of environmental impacts. Locating the fertiliser production close to the side-stream source is not only important to reduce environmental impacts, but also creates co-benefits by reducing odour emissions and sanitary issues during transport (Chojnacka et al., 2020).

Processes to remove water from side-streams during different **concentration steps** showed relevant contribution to environmental impacts of BBFs. Both, membrane filtration (Cantabrian Sea case study, T3.2) as well as the various thermal drying processes (all other case studies) require large energy inputs and thus generate greenhouse gas emissions. This finding is confirmed by Petrova et al. (2018) and Gaviria Gaviria et al. (2021). Using non-fossil energy sources such as solar energy can be an option to reduce impact (Gaviria Gaviria et al. (2021)). In the Baltic Sea case study (T3.1), a sensitivity analysis showed that the environmental impact (global warming and terrestrial acidification) was four times lower with a solar drying process than with a conventional drying process. For Pelleted fish sludge in the North Sea case study (T4.1), using heat sources with comparably lower footprint than fossil fuels, e.g. heat generated from waste incineration, decreased environmental impacts up to 79% (Terrestrial acidification). Impacts could also be reduced by using more efficient drying technologies, e.g. with

heat recovery (Moejes et al., 2018) or low temperature drying, which reduced the Global warming of Pelleted fish sludge (North Sea, T4.1) by one third. 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 for de-watering, 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).

The **packaging** of fertilisers was identified as relevant contribution to environmental impacts across most of the case studies. Apart from the jute packaging in the Baltic case study (T3.1), the packaging was assumed to be plastic packaging modelled with a default process from ecoinvent. The contribution of plastic packaging to environmental impacts ranged from 0.003% (Atlantic Sea case study T4.2, Freshwater Eutrophication) to 94% (Baltic Sea case study T3.1, Freshwater Eutrophication). The comparably low contribution of packaging in the Atlantic Sea study (T4.2) can be explained by the use of the ecoinvent inventory for packaging of solid fertilisers that shows > 95% lower values for all impact categories than the packaging for liquid fertilisers in smaller 20 l-containers. Cortés et al. (2020) reported a range of impact contribution of plastic packaging with a maximum of 15% (average 7.6% across all investigated impacts) for compost from viticulture waste but also considered the transport and application of the fertiliser within their system boundaries. As the Baltic case study (T3.1) showed, the jute packaging performed better with regard to environmental impacts, except for Freshwater eutrophication caused by the agricultural production of the fibres. Since BBFs generally show lower nutrient density compared to mineral fertilisers and thus need more packaging per kg of macronutrients, the packaging of BBFs should be reduced, re-used and recycled as much as possible.

Buildings were relevant for the impact category Mineral resources use. While this impact decreases from pilot to industrial scale, it still contributed up to 86% (Granules) of the total impact in this category. Although other studies have excluded buildings from the LCA (e.g. Jeswani et al., 2015) our results suggest that depending on the impact categories considered, buildings should be included. This is in line with the recommendations of Frischknecht et al. (2007). However, the Environmental Footprint methods (EC, 2021) recommend to not to include capital goods such as buildings unless they have proven to be relevant in previous studies. Regardless of the modelling decision taken, the

environmental impact of buildings can be reduced by nearly 30% by choosing lower-impact construction materials and reducing the needed amounts (Iñarra et al., 2022) or by using the space more effectively (as seen in the industrial scenarios). Other capital goods such as machinery are often not accounted for in LCA studies (e.g. Perez-Martinez et al., 2018) because related environmental impacts are assumed to be low. In this study, production, transport and disposal of machineries was not identified as environmental hotspot. One exception was the oversized extruder in the Atlantic Sea (T4.2) pilot scale case study that weighted approximately 3 tonnes of steel. However, also its importance decreased with higher assumed industrial output.

Additional processes were relevant in several but not all case studies. The use of enzymes for enzymatic hydrolysis showed to have a particular impact on Freshwater Eutrophication in the Adriatic case study (T3.3) and in the sensitivity analysis of the Atlantic Sea case study (T4.2). The impacts mainly resulted from potato starch used as growing substrate for enzyme production. Nielsen et al. (2007) also showed the environmental relevance of substrates during enzyme production. However, the use of enzymes can also have environmental benefits such as saving energy, raw materials and chemicals in industrial process (Jegannathan & Nielsen, 2013). Additionally, using enzymes for producing free amino acids can potentially result in a biostimulating effect of the BBFs. However, the magnitude of such a biostimulating effect still needs to be quantified in agronomic trials. Hence, the substitution of enzymes-mediated processes needs careful consideration. One economically viable alternative process is acid autolysis (Domínguez et al., n.d.), which avoids both the use of enzymes and heating. Yet, it consumes formic acid and still contributed 3–16% to environmental impacts in the Cantabrian Sea case study (T3.2). Alternatively, the efficiency of the enzymatic hydrolysis could be optimized by e.g. using ultrasound (Qian et al., 2023). As shown in the Spanish field trial, combining a low dosage biostimulants with a reduced mineral fertilization could potentially lead to reduced environmental impacts.

6.1.2 Upscaling

The assumed industrial production varies between 20-7000 tonnes/year. This illustrates well the heterogeneity of the case studies, the related assumptions and the underlying variations in available amounts of side-streams from fish processing and aquaculture production. In case of the Solid BBF (T4.2), the scale factor was 546.4 which indicates the potential uncertainties related to estimating the changes such as efficiency gains under industrial production. Additionally, the upscaling was done based on availability of side-streams and does not necessarily reflect for potential market demand in the future.

Table 39: Overview of upscaling in case studies (* not upscaled since already at industrial scale)

Property	Yearly production volume		Increase in production volume at industrial scale	Resulting amounts of N, P and K in fertiliser at industrial scale		
	(ton / year)					
	Pilot	Industrial				
T3.1: Bokashi granules	48.9	97.8	2.0	2.6	102.2	186.7
T3.2: NPK solution with amino acids	3.6	222.0	62.2	11.8	353.6	496.8
T3.3: Hydrolysates	1.7	19.7	11.7	1.0	6.4	12.0
T4.1: Pelleted fish sludge	*	7000.0	*	433.3	19194.0	10234.0
T4.2: Solid BBF	1.4	753.0	546.4	57.4	2326.0	463.1

On average, the change in environmental impacts due to upscaling ranged from +18% (Bokashi granules, T3.1) to -72% (Solid BBF, T4.2; Table 40) across the impact categories. However, the variation between the individual changes of impact categories was quite large, ranging from +118% (Bokashi granules T3.1, Mineral resources use) to -89% (Solid BBF T4.2, Mineral resources use). The increased change in case of Bokashi granules is caused by a comparably small increase in output (+100%) per area from pilot to industrial scale (Table 39) that is not able to compensate for the higher impact caused by assumed additional office buildings in the industrial scenario (see section 10.1.2).

Small changes are due to processes that are assumed not to scale: for example, in the cases of the Bokashi granules and hydrolysates no change was assumed for the jute packaging or enzymes production, respectively, which both are dominating the impacts for Freshwater Eutrophication.

The overall high reduction in Mineral resources use in the industrial scale was due to a much higher assumed efficiency (output per building area), which is in line with the ecoinvent approach (see section 2.1.2).

Table 40: Relative changes in impacts due to upscaling.

	Global warming (GWP100)	Terrestrial acidification	Marine eutrophication	Freshwater eutrophication	Mineral resources use	Average per case study
T3.1: Bokashi granules	+7%	-34%	-1%	-1%	+118%	+18%
T3.2: NPK solution with amino acids	-5%	-24%	-25%	-19%	-61%	-27%
T3.3: Hydrolysates	-38%	-37%	-31%	-5%	-53%	-33%
T4.1: Pelleted fish sludge	Not upscaled (already at industrial scale)					
T4.2: Solid BBF	-63%	-53%	-68%	-85%	-89%	-72%
Average per impact category	-25%	-37%	-31%	-28%	-21%	-

The average decrease of 25% for the Global warming under industrial production contrasts with the considerably higher decrease of 83% identified by van der Hulst et al. (2020) when upscaling the production of copper indium gallium (di)selenide (CIGS) photovoltaic laminate. Even without the further optimisation of the industrial production (e.g. due to industrial learning that was not considered in this study), they still assume a reduction of 76% of GWP100. One reason for this discrepancy is the high reduction of impact due to process changes (-73%) which were either not assumed to be as fundamental in the case studies for BBFs production or for which data was lacking. For example, in case of the NPK solution with amino acids, it is likely that further energy reduction could be realized by either heating the mass with a heat exchanger previous to entering the batch reactor instead of the batch reactor itself. In addition, using triple effect vacuum evaporator with heat recovery could further decrease the energy use. Heat recovery could also further lower the impact of the spray drying in the Adriatic Sea case study. In the latter, the energy consumption per kg of input of all other processes apart from the spray drying was assumed to be the same under industrial conditions which might have also led to an overestimation of environmental impacts in industrial conditions.

Accordingly, decisions on process design (e.g. transport, drying method and choice of inputs) showed to be sensitive parameters during upscaling. The results from sensitivity analyses are therefore crucial to understand the underlying uncertainty of upscaling, as Moni et al. (2020) and Piccinno et al. (2016) also emphasise.

6.1.3 Comparison to NPK fertilisers

Comparing BBFs with mineral fertilisers with equivalent NPK content resulted in a mixed picture: the production of the BBFs from the Atlantic Sea (T4.2) and North Sea (T4.1) case studies showed generally lower environmental impacts than their mineral fertiliser references. The BBFs from Cantabrian Sea (T3.2) and Adriatic Sea case studies (T3.3) exhibited mostly higher impacts compared to their mineral reference. The granules from the Baltic Sea (T3.1) performed better in some categories and worse in others. These results contrast with the cross-case study comparison based solely on N (see section 4.1) that generally showed higher impacts for all BBFs compared to mineral N fertiliser (except for Marine Eutrophication). This demonstrates the need to consider the nutrient profile of BBFs for the comparison between BBFs and conventional fertilisers to reach a more differentiated picture.

Yet, also the results of the NPK fertiliser comparison underline the importance of considering environmental aspects when searching for alternatives to mineral fertiliser. Even though no impacts were assumed for the side-stream production (burden-free assumption), some BBFs showed similar or even higher environmental impacts compared to mineral fertilisers. One of the main underlying reasons for this result was the comparably low nutrient content in BBFs, requiring large quantities to get equal amounts of macro-nutrients. Consequently, the comparison of the BBFs against mineral fertilisers based on nutrient content could lead to wrong conclusions in case of amino-acid based fertilisers with a potential biostimulant effect that should improve the efficiency of the plant nutrient uptake. The comparison therefore needs to be extended to include the use phase by considering agronomic performance data (i.e. yields, see section 6.2). This is clearly illustrated from the results of an initial agronomic trial assessing the Cantabrian Sea (T3.2) NPK solution on Spanish broccoli (section 5.4) as biostimulants with a low dosage, allowing to reduce the mineral fertilizer impacts by up to about two-thirds.

6.1.4 General modelling approach, related assumptions and uncertainties

The main conclusions from the contribution analysis is comparably less subject to uncertainties than the aforementioned comparison with NPK fertilisers. As outlined, this is due to the upscaling assumptions but also due to the general model approach taken. In addition, uncertainties also concern the environmental impacts of the mineral reference fertilisers because they can vary considerably depending on the technology employed in the production process: Jensen et al. (2020a) point out that recent advances in mineral N fertiliser production can halve its Global warming. In addition, the impacts vary

depending on the type (and therefore production process) of the mineral fertiliser (see section 4.1.2). To enable a direct as possible comparison with the bio-based fertilisers, ecoinvent processes for the European production of mineral fertilisers were selected as a reference. However, these inventories e.g. do not account for the transport of imported raw materials (e.g. rock phosphate) to European factories (Fertilisers Europe, 2023). While this is not very sensitive for the total of impacts from the production and use phase of fertilisers, the inventories should nevertheless be revised to account for such imports in the future.

Like the majority of LCA studies on valorisation of e.g. sludge to bio-based fertilisers, this study is based on the burden-free assumption (Pradel et al., 2016; Tanzer et al., 2021). This is consistent with the used background data from ecoinvent that follows as well this cut-off logic (ecoinvent, 2023a). It is important to note that this assumption generally improves the environmental performance of the modelled BBFs compared to a scenario of a more balanced allocation between the provider of the raw materials and the users, i.e. fertiliser producers. As Pradel et al. (2016) critically note, this assumption is debatable when waste (in their review sewage sludge) is further used as a valuable resource for nutrient recovery. Yet, they also acknowledge the difficulties with determining the allocation factors between main product and waste.

Also, the avoided burdens for alternative functions (e.g. methane production in anaerobic digestion) have not been added in this attributional LCA to make the results from different case studies more uniform and comparable. However, this approach also leads to potential lower environmental impacts than there might have been in cases of alternative valorisation.

6.2 Fertiliser use (step 2)

6.2.1 Most relevant factors for reducing environmental impacts of BBFs

Some common hot spots could be identified in the LCA on wheat, ryegrass and broccoli production fertilised with different BBFs and mineral fertiliser, which are relevant starting points to optimise their environmental performance in the future.

In terms of **Global warming**, the production of fertilisers showed very relevant contributions ranging from 12-68% of the overall GHG emissions for all three crops. Thus, a reduction in GHG emissions from the production of fertilisers would have significant effects on the overall carbon footprint of the BBFs. Field emissions showed also relevant contributions (18-52%) to total GHG emissions. This includes direct and indirect emissions

such as N_2O from the application of the fertilisers as well as soil background emissions such as the decomposition of organic residues and soil organic matter. A sensitivity analysis using upper and lower boundaries of IPCC (2019) N_2O emission factors, showed that the choice of emission factors clearly influenced the overall GHG emissions for all tested crops, but in most cases did not affect the performance of BBFs compared to mineral fertilisers. Finding strategies to reduce N_2O emissions during fertiliser application would be important to reduce the Global warming impact related to fertilisers. Other processes, such as machinery use, tillage, harvest or the horticultural fleece in broccoli production contributed up to a quarter of the total GHG emissions from the three BBFs used for the three crops. The importance of fertiliser production and N_2O emissions through application for GHG emissions for crop production aligns with findings reported by Hoffman et al. (2018), which showed a share of 55% of total GHG emissions through N_2O emissions from the application of fertilisers and 45% of the overall energy consumption in conventional grain production due to synthetic nitrogen fertiliser production.

Regarding the **Mineral resources use**, the production phase of BBFs used between one- and two-thirds of the total mineral resources for all three crops. Other important processes contributing up to a quarter of Mineral resources use were machinery use for tillage (wheat and broccoli) and horticultural fleece (broccoli). For ryegrass, harvesting processes (incl. machines for mowing, swathing, haying, baling, and loading of bales) during several harvests showed much higher contributions to Mineral resources than for the other crops. Thus, beside crop-specific processes, optimising fertiliser production is relevant when aiming at reduction of Mineral resources use in crop production. For the **Freshwater- and Marine eutrophication**, the major impact came from field emissions (including leaching), having an impact of almost 100% on the Marine eutrophication and between 60% up and 97% on the Freshwater eutrophication. This finding can be confirmed by Queirós et al. (2015), reporting that the field emissions were the major impact for eutrophication. Thus, for reducing eutrophication impacts, the focus needs to be on the agricultural phase instead of the BBF production phase.

Also, for **Terrestrial acidification**, field emissions were most relevant for all three crops, making up between 43% and 76% of the impacts. Other important processes for all crops were the production phase of the BBFs, with maximum of one third contribution to overall impacts, as well crop specific processes (e.g. harvesting for rye grass with up to 14% contribution). Field emissions that are responsible for terrestrial acidification are mainly driven by NH_3 volatilisation after the application of the BBFs and the subsequent deposition into ecosystems. In the sensitivity analysis of this study, a high uncertainty of

the NH_3 emission factor was identified by using an alternative emission factor for BBFs (from a Dutch inventory instead of from EMAP). Thereby, the Terrestrial acidification decreased between one-and two-thirds for all three BBFs tested on the three crops. Here, BBF-specific emission factors would help in future, to identify fertiliser associated with lower NH_3 emissions and thus lower Terrestrial acidification potential. These emission factors should better account for the composition and accordingly for the nutrient availability in BBF. Beside the choice of fertiliser, the application technique (broadcasting vs. incorporation) and soil type determine the degree of NH_3 volatilisation. According to (Wester-Larsen et al., 2022) BBFs showed the lowest NH_3 volatilisation potential after incorporation into the soil and on clay acidic and alkaline soils compared to sandy acidic soils. More knowledge on optimal application techniques of different BBFs on different soils could contribute to reduce NH_3 emissions. For mineral fertilisers, the sensitivity analysis on broccoli using different mineral fertiliser nitrogen sources showed that the addition of urea-based fertilisers increased the Terrestrial acidification potential, because their chemical characteristics are prone to high volatilisation losses (Oliveira et al., 2023). For all five impact categories, the lower **yield** of the markable broccoli heads compared to the whole broccoli biomass increased the impacts per kg harvested broccoli significantly. This increase was even higher for Spain than for Estonia, as the yield for the Broccoli heads was smaller. Thus, reducing the amount of food waste (i.e. using parts of the plants which are often not consumed) is another important factor with yield increase to reduce environmental impacts.

For field emissions, also the unfertilised broccoli control showed high impacts for Global Warming, Freshwater and Marine eutrophication due to soil **background emissions** not related to fertilisation. For Global Warming, the N_2O emissions from nitrogen in crop residues as well as mineralised nitrogen from soil organic matter decomposition caused this effect. For the Freshwater Eutrophication, a high phosphor leaching into the surface water due to particle transport was the reason, whereas for the Marine Eutrophication, high nitrate leaching (through drainage) caused the high impacts.

6.2.2 Environmental implications when replacing mineral fertiliser with BBFs

The results of the application of fertilisers showed that BBFs can have similar, lower or even higher impacts per kg of product compared to mineral fertilisers, depending on the characteristics of the BBF, the crops and the environmental impacts considered.

Overall, **Solid BBF (T4.2)** and **Pelleted Fish sludge (T4.1)** showed the best environmental performance of the four analysed BBFs: Solid BB1 applied on ryegrass and broccoli

(Estonia), the Pelleted Fish sludge applied on wheat. The Solid BBF (T4.2) and Pelleted Fish sludge (T4.1) have the highest dry matter content (98.1 and 94.4 %DW, respectively), the highest total N (7.6 and 6.2 N %FW) and P concentration (30.9 and 27.4 g P/kg FW) of all the BBFs considered here. The third BBF applied in all trials, the **NPK solution (T3.2)**, had the highest AMFE or yields among the BBFs for wheat and broccoli (Estonia), and also if used as a biostimulant in combination with a reduced amount of mineral fertiliser on broccoli (Spain). However, it also had high production impacts (per kg of BBFs; see section 4.3.3) that was amplified by the high amounts needed for fertilising due to a low nutrient content (5.3 N % FW, 15.9 g P/kg FW) and, as the only liquid fertiliser tested here, a low dry matter content (34.5 %). The example of the NPK solution shows that impacts of production and the resulting nutrient content need to be optimized even with a good agronomic performance (based on N equivalence). However, if applied as a biostimulant, the initial results from the Spanish field trial indicate a potential to reduce mineral fertilisers, while not being a solution to replace mineral fertilisers. Further test are needed, to better understand the biostimulating effect under different conditions.

For **Bokashi Granules (T3.1)**, only data from the pot trials on ryegrass were included here, replacing mineral P fertiliser, because it is not suited as N fertiliser due to its low N content (2.6 N % FW). Impacts were lower for two impact categories (Global warming and Terrestrial acidification), and higher for two others (Mineral Resources and Freshwater Eutrophication). More agronomic tests (including field trials with relevant crops) would be needed for this BBF, to better understand its agronomic and environmental performance compared to P fertiliser. Finally, the **Hydrolisates (T3.3)** showed a too low agronomic performance for both N and P in the pot trials and were thus not included in the LCA of fertiliser application.

For all four tested BBFs, the **N:P ratio** was in the range of 2.3:1 and 3.3:1 and thus considerably lower than the optimal N:P nutrient supply ratio of 15:1 for most plants (Luo et al., 2016). If applied as replacement for an N fertiliser, the respective dosage of P is thus mostly too high and plants are over-fertilised with P. For Freshwater Eutrophication, the higher fertilisation rate of P in the case of wheat and broccoli even lead (among other factors²⁸) to higher impacts of BBFs per ha compared to the reference mineral fertiliser. This oversupply of P is potentially compensated by the lower P leaching in case of BBFs compared to mineral fertiliser (Ylivainio et al., 2023)²⁹ but cause issues on those

²⁸ Even with the same P application rate in the case of ryegrass, Freshwater eutrophication impacts are higher for BBFs per ha, since the applied P emission model by Prasuhn (2006) assumes more emissions through surface transport of P (independent of soil erosion) from organic fertilisers than from mineral fertilisers.

²⁹ The applied P emission model by Prasuhn (2006) assumes no P leaching for solid fertilisers. Based on their DM content >20%, all BBFs were considered solid.

72% European cropland soils for which Recena et al. (2022) modelled an excess of available P. In contrast to the oversupply of P, in the case of ryegrass where BBFs were used as substitute for P fertiliser, additional N had to be supplied to meet the fertiliser guidelines by Richner & Sinaj (2017). Thus, additional N fertilisers might be needed when applying those BBFs to improve their environmental performance and avoid over-fertilising for P.

For all trials, **per ha of crop**, the impact of Solid BBF (T4.2) and Pelleted Fish sludge (T4.1) relating to Global warming and Mineral resources use were lower than the reference mineral fertilisers, while the NPK solution (T3.2) showed higher impacts in the case of broccoli in Estonia, Ryegrass and Wheat. This pattern can be explained by the fact that production of BBFs contributes substantially to Global warming and Mineral resources and the differences in step 1 (chapter 4) and is thus still visible even when including the use phase of the fertilizers. For Freshwater and Marine Eutrophication (see section 6.2.1), background emissions are very relevant, which are independent of the fertiliser and also present on unfertilised crop land. The latter results in small differences of impacts between the fertilisers per ha and mostly in higher emissions caused by BBFs per kg of product compared to the reference mineral fertilisers (exception ryegrass).

The comparison of BBFs against mineral fertilisers for **Terrestrial acidification** showed a less clear picture across the different experiments that was additionally affected by generally high uncertainties. These were rooted in the assumed NH_3 emission factor for organic fertilisers (also see section 6.2.3.2) and the type of mineral fertiliser reference. While the impacts of BBFs in pot trials were lower compared to the market average mineral fertiliser, their impacts for the broccoli (Spain) field trial were all higher compared to the mineral fertiliser applied in the experiment. If the market average mineral fertiliser was taken as a reference in Spanish field instead of the mineral fertiliser applied in the experiment (assuming similar agronomic performance), the Solid BBF (Estonia), the Pelleted Fish Sludge (Spain) and the NPK solution achieved lower environmental impacts. This is due to the high NH_3 emissions of urea contained in the market average mineral fertiliser (Jensen et al., 2020a; Klimczyk et al., 2021). Thus, the environmental implications of replacing mineral fertilisers with BBFs highly depend on the types of fertilisers they can substitute.

In general, BBFs should show a high **agronomic performance** to be environmentally beneficial over mineral fertilisers (see section 6.2.1). The range of AMFEs in the wheat pot trials of the selected three BBFs (60-92% for NPK solution, Pelleted Fish Sludge and Solid BBF) was higher than the range Brod et al. (2017) identified in their study in case of barley:

Their pot trials data yielded AMFE of 53-67% for pellets and granules from fish sludge as well as 48% and 68% (two experiments) for fresh fish sludge. Their field trial data for grain yield resulted in AMFEs of 45% and 75% for two experiments with fish sludge. For ryegrass, a generally high AMFE was observed in the present study. High AMFEs for P substitution with BBFs were also identified by (Jensen et al., 2020a) in case of manure-based fertilisers and are reflected in pot trials by Hernandez-Mora et al. (2024) for 9 nine organic P BBF with high TRL with a range between 46-103% AMFE for ryegrass (median of 78%). While the same study did not find significant differences of the ryegrass AMFE to those of wheat, it found significant differences to the AMFE from the spring barley pot trials (range of 16-104%, median of 45%). This difference in AMFEs illustrates well that the environmental impacts presented in this study are only valid for certain agronomic conditions (soil, climate and crops; also see section 6.2.3.1 or e.g. Cortés et al. (2020)).

Comparing our results to other studies is difficult, because of different methods, BBFs, crops, soils and climatic conditions studied. This heterogeneity is accordingly mirrored in the range of results from different studies: For Global warming, Cortés et al. (2020) report for the replacement of mineral fertiliser by compost similar impacts in case of maize, higher impacts for tomato, and lower impacts for strawberry. Herrera et al. (2022) reported lower Global warming impacts for anaerobically digested organic waste replacing 50% of applied urea. Without the credited methane production, impacts would have been higher. For Terrestrial acidification, Cortés et al. (2020) report lower impacts for maize and tomato and similar impacts for strawberry compared to the fertilisation with mineral fertilisers. Herrera et al. (2022) report lower Terrestrial acidification, also due to the credited methane production. In contrast to this study, for Freshwater eutrophication, impacts of applying compost were overall lower for all three crops in the study of Cortés et al. (2020). This may be due to the assumed AMFE of 100% for compost (1:1 replacement of mineral fertiliser nutrients). The study of Herrera et al. (2022) showed a contrasting result: the digestate showed 16-fold higher Freshwater eutrophication impacts than urea. For Marine eutrophication, Herrera et al. (2022) modelled the same impacts for the digestate and urea production and use. Both, Herrera et al. (2022) and Cortés et al. (2020), showed lower impacts for BBFs in case of Mineral resource scarcity.

The results show that crops produced with BBFs could compete with mineral fertilisers with regard to environmental impacts, but production impacts and yields should be further optimized. In addition, alternative uses of side-streams from fisheries should be evaluated, for example biogas (energy) production with subsequent reuse of digestates as fertilisers.

6.2.3 Methodological challenges for assessing environmental impacts of BBFs and research need

6.2.3.1 Agronomic performance

In this study, **yields** had a strong impact on the environmental performance assessed per kg of crop, which is often observed in comparative agricultural LCAs. Here, differences in yields obtained with different fertiliser were derived from pot experiments conducted with two crop species (wheat and ryegrass) and field trials with broccoli in two countries (Spain and Estonia). Testing yield effects experimentally is challenging, since plant growth depends on many factors, such as crop species and variety, site (soil, climate), crop management and season specific conditions (e.g. weather, pest dynamics, etc.). The agronomic experiments conducted in the Sea2Land project showed a large variation in the performance of single BBFs. For all the BBF, yields varied across the trials showing large differences.

Although data from pot and field trials was available in this project, a series of **assumptions** had to be made to calculate an LCA of “real” crop production, introducing additional uncertainties. For the pot experiments on wheat and ryegrass, only data on above and belowground biomass was available. While for ryegrass, the full plant is used as fodder, for wheat, the grains are economically more important than the straw. A linear relationship between aboveground biomass and grain yields was therefore assumed for wheat. However, the BBFs might affect the plants strategy to allocate more or less resources to different parts of the plant, including grains. This was also seen in the pot experiments, where roots often showed increased biomass for the treatments BBFs compared to mineral fertiliser. For broccoli, data on the biomass of the full plant, on all heads and on heads larger 8 cm were recorded. For the baseline, the full biomass was considered, assuming all parts are edible. In a sensitivity analysis, only heads larger than 8 cm were considered as marketable yield. This drastically increased the overall impacts per kg of crop for all treatments, including mineral fertiliser, showing the importance of avoiding food waste. However, the relative performance of most BBFs compared to mineral fertiliser remained similar. An exception was the NPK solution (T3.2) in the Estonian trial where differences in impacts between BBFs and mineral fertiliser were smaller when only considering heads. In the Spanish trial, the heads only contributed to about 1-5% of the total biomass and yields were generally very low, but the difference between mineral fertiliser and all other treatments became even larger when only considering the heads.

Drawing general conclusions on the agronomic and environmental performance of BBFs would still require additional data on the performance of the analysed BBFs for different crops and under different growing conditions and in different crop rotations. More trials

on cash crops such as vegetables are needed, which could be potential markets for these BBFs. Additional trials on fodder crops such as ryegrass might not be needed, because a future application of BBFs might be rather unlikely, unless prices of the BBFs would decrease drastically. For vegetables, a high quality is expected by retailers and consumers, and thus not only the full biomass, but the size, colour and form of heads is decisive for farmers to be able to sell their products. This could be additional aspects considered in future studies, for example distinguishing between quality classes and prices of vegetables in functional units. In addition, more knowledge on the performance of BBFs under different production intensities would be valuable. In this study, the broccoli trials were conducted with rather low N inputs and yields, compared to for example recommendations for broccoli growers in Switzerland, where about the double amount of N is recommended and expected yields are about 70-90% higher. Additional aspects that could not be considered here were the expected long-term biostimulating effect as well as the nutrient carry-over to following crops. Jensen et al. (2020a) for example concluded that composts release nutrients slowly and have rather low yield effect in the year of application, but this increases after several years of application. In general, more knowledge on an optimal use of these BBFs, including the most suitable crops, soils, regions, production intensities as well as dosage of BBFs or combinations with other fertilisers (e.g. understanding the interplay between different nutrients and release dynamics) would be valuable to maximize agronomic performance and potentially reduce environmental impacts.

Another option to test the agronomic (and environmental) performance of BBFs are crop models. In the Lex4Bio project (Jensen et al., 2024), the Daisy soil-plant-atmosphere model was used to assess soil C and N turnover, denitrification, crop yields, N uptake and N leaching. They investigated different scenarios of BBFs replacing mineral N fertilisers: Beside a 1:1 N replacement and a substitution based on the 1st-year AMFE (as in this study), they also investigated the above-mentioned nutrient carry-over effects by taking the average of the first two scenarios. For a 1:1 N replacement, they modelled lower yields and similar N leaching. However, in this study, impacts were not reported per kg crops, but rather on a per ha basis.

6.2.3.2 Emission factors

The amount of NH_3 and N_2O is emitted after fertiliser application is uncertain, and no specific data for the studied BBFs were available. In the sensitivity analysis, the choice of N_2O and NH_3 emission factors (EF) showed an impact on the results for Global warming and Terrestrial acidification. In particular assuming other **NH_3 emission factors** for the BBFs resulted in a considerable change in the comparison between BBFs and mineral fertilisers

(see chapter 5). The EMEP/EEA Tier 1 emission factor (Nicholas Hutchings et al., 2023) that was used in the baseline for the BBFs relates to total nitrogen applied. This is a simplification since NH_3 emissions are, among other factors such as pH, mainly dependent on the total available N (TAN) content in the organic fertilisers (Wester-Larsen et al., 2022). EMEP/EEA Tier 2 emission factors for manures do account for TAN content, but no specific values for BBFs were available. This is why the Tier 1 emission factor was taken in the baseline. Using an average EMEP/EEA Tier 2 EF for solid manures of cattle, poultry, pigs and horses (61% of TAN³⁰), organic fertilisers with a TAN content lower than 13% would have lower NH_3 emissions than calculated with the Tier 1 EF. Since the TAN content of the assessed BBFs was considerably lower than 13% (0.4–5%), the NH_3 emissions of BBFs in the baseline (Tier 1 approach) were likely overestimated and as a consequence the BBF's impact on Terrestrial acidification.

Yet, uncertainties remain high with an estimated uncertainty of 100% for the Dutch emission factor (T. van der Zee et al., 2021). This illustrates the need for finer-grained standard emission factors and models for novel BBF. Optimally this would include a differentiation by of application technique, soil and BBF characteristics. Based on the latter³¹, Wester-Larsen et al. (2022) were able to explain 89% of the variation in NH_3 volatilisation of 39 different BBFs in pot experiments.

Although less pronounced, also the use of different **N₂O emission factors** in the baseline scenario and sensitivity analysis had a significant effect on Global warming from the different BBFs. However, so far, limited research has been done on estimating site- and crop-specific N₂O emission factors from agricultural production systems applying mineral- and organic fertilisers. Thus, average emission factors such as from IPCC (2019) are used. In this study, the emission factor (0.6%) for “Other N inputs in wet climates” from IPCC (2019) was used to estimate the N₂O emissions from the different BBFs, which is based on the Tier 1 method. However, as the emission factor includes “organic amendments, animal manures, N in crop residues and mineralized N from soil organic matter decomposition” IPCC (2019), it can only provide an indication on the N₂O global warming potential of the BBFs. In the past, there has been minimal effort to quantify emissions from organic fertilisers, as they were often considered as biogenic and assumed to have no effect on global warming. Moreover, there is currently little consensus in the literature on whether organic amendments lead to higher or lower N₂O emissions compared to synthetic fertilisers (Walling & Vaneeckhaute, 2020). Most studies focused

³⁰ The EF factor used in the sensitivity analysis is relatively close to this value (46% of TAN applied) and was selected instead since it had a valid application scope beyond animal manures.

³¹ pH, NH_4^+ -N, NO_3^- -N, DM and C:N ratio

on determining the N_2O emissions that derived from manures, which can vary between 0.1 and 3.3% of total N applied due to large differences in the composition and type of manures, soil type, climate and management. By using the Tier 1 emission factor from the IPCC 2019, important factors such as the soil type, organic resource type and application method are not accounted for, leading to high uncertainties of the respective N_2O emission factors (Velthof et al., 2024).

Therefore, to give a rough estimation on the accuracy of the N_2O emissions from the application of BBFs, site-specific N_2O emission factors from the Broccoli field trial in Estonia were calculated based on cumulative N_2O flux ($\mu\text{g m}^{-2}$) over a period of 3 months. The results showed emission factors for the BBFs between 0.003% (Bokashi Granules) and 0.008% (Pelleted fish sludge) of the total nitrogen of 120 kg ha^{-1} applied, which were significantly smaller than the IPCC 2019 default value of 0.6%. A reason for that could be the limited measurement period of three months, not yet representing the full N_2O emission potential of the BBFs. The mineralisation of nitrogen from organic fertilisers can require a long time, depending the source of organic fertiliser as well as environmental factors. Thus, a build-up of N_2O emissions in the broccoli experiment might take a longer period than only three months. Moreover, as the emission factor from the broccoli field experiment was only calculated for the experimental period of three months during summer and not on an annual basis as the IPCC value, it does not represent the yearly N_2O fluxes caused by seasonal changes such as fluctuations in temperature or rainfall. Especially the lack of the latter (and therefore decreased soil moisture and resulting aerobic conditions) could have led to lower emissions.

Nevertheless, the calculated emission factors from the broccoli experiment confirm the findings in the literature that more research on emission factors for new organic residue streams such as the bio-based fertilisers is needed to more precisely model global warming impacts. In general, it is expected that compost from vegetable, garden waste and fruit as well as sewage sludge and meals from bone and meat produce low N_2O emissions due to a smaller mineral nitrogen content (Velthof et al., 2024). This might also be applicable to BBFs, as the agronomic performance of the fertiliser sources was generally lower than the mineral fertiliser reference.

To mitigate overall environmental impacts from emissions related to reactive nitrogen, it is important to investigate possible **trade-offs**, such as **between NH_3 and N_2O losses**. In this context, pollution swapping needs to be assessed carefully. Studies have shown that an injection of organic fertilisers (manure) significantly reduces NH_3 emissions, while N_2O emissions might be increased (Velthof & Mosquera, 2011). Moreover, the 4R nutrient

management strategy (Right source, Right rate, Right time, Right place; Johnston & Bruulsema, 2014) might be an effective strategy in reducing N_2O emission from BBFs due to a better balance between nitrogen inputs and outputs. In terms of the right timing of organic fertilisation, avoiding wet conditions, applying the nutrients in accordance to the plant growth rate, and limiting excess of soil nitrogen is crucial. This might consequently reduce NO_3^- in the soil, which in turn serve as an indirect source of N_2O emissions (Velthof et al., 2024).

6.2.3.3 Mineral fertiliser benchmarks

In addition to the uncertainties concerning the production phase of standard ecoinvent mineral fertiliser inventories outlined in section 6.1.4, the results (i.e. Terrestrial acidification) proved to be sensitive for the type of fertiliser applied, dependent on its share of urea. However, this uncertainty cannot be precisely quantified since this would require the agronomic performance data of a second, alternative mineral fertiliser containing urea. This could be interesting for future field trials to better quantify the uncertainty related to the reference mineral fertilisers.

6.2.3.4 Impact assessment

This study focused on five environmental impact categories (see section 2.2.3). For Global Warming, changes of **soil organic carbon** were not considered, as the same tillage operations were assumed for the BBFs and mineral fertiliser reference with no expected differences in soil management on soil organic carbon stocks and thus Global warming impacts. Other beneficial impacts of organic fertilisation on soil health or the mitigation of extreme weather events were not considered here either, but would be important to assess in future studies. Organic fertilisers are known for their ability to enhance soil carbon, nutrient availability, microbial diversity and activity, as well as overall biodiversity. They achieve this by providing a wider range of compounds, such as carbon and humic acids, which are lacking in synthetic fertilisers (Jannoura et al., 2014; Yuan et al., 2017). In terms of soil organic carbon, the use of organic fertilisers such as BBFs can enhance soil organic carbon levels and thus increase the overall soil organic matter contents. Depending on the C:N ratio of the fertilisers, organic fertilisers such as compost, which can contain a high carbon content and a high C:N ratio (> 20), can support soil organic matter build-up compared to fertilisers with a low C:N ratio (< 15) or mineral fertilisers (Niggli et al., 2024). The tested BBFs in this study contained high organic carbon contents of 62 to 84% (dry weight), which might enhance the soil organic matter content in the soil. Several studies on compost application reported an increase in soil organic carbon stocks after the application of compost (Ding et al., 2012; Li & Han, 2016; Tian et al., 2009;

Xin et al., 2016). In terms of soil carbon sequestration potential, the use of fertilisers can enhance carbon storage in the soil by increasing biomass production and contributing to the return of crop residues like roots, stubble, and straw, potentially reducing atmospheric CO₂ concentrations (Jensen et al., 2020a). However, the soil carbon sequestration potential needs to be evaluated carefully, as it is often difficult to differentiate whether the carbon input comes from external added organic fertilisers or a smaller native soil organic carbon decomposition (Jiang et al., 2021). Building-up soil organic matter through the use of organic fertilisers can help mitigate the effects of increasingly extreme weather events, such as heavy rainfall and prolonged droughts caused by climate change. This practice reduces the risk of soil fertility loss due to erosion from heavy rains and helps prevent crop losses by retaining water in the soil during extended drought periods.

In addition of not covering soil carbon in the environmental impact assessment, the potential toxicity impacts of heavy metals contained in the BBFs (Zhang et al., 2023) have not been modelled and assessed. Although heavy metal concentrations were within the legal limits for all BBFs assessed (Zhang & Akyol, 2023), such an assessment could contribute to a more complete picture of environmental impacts of the BBF.

7 Conclusions

This study assessed environmental impacts of five BBFs produced from different waste streams of the fish industry. Four BBFs showed a high agronomic performance and their environmental impacts during application were considered. The hotspots of BBFs production as well as during BBF application were identified.

Both, the BBF production, but also their application showed to be very relevant: for the impact categories Global warming and Mineral Resources use, a reduction of impacts in production potentially leads to a substantial overall reduction in impacts. However, it is important to note that assumed upscaling efficiencies from current pilot BBF production to potential future industrial production were comparably low. The share of BBFs production contributing to total impacts of crop fertilisation could thus become smaller if more efficiency gains will be realized. In general, BBF production could be further optimized by avoiding intense processing of side-streams (unless they considerably increase agronomic performance), using efficient drying technologies and renewable energies as well as optimizing transport distances and packaging. On the other hand, the emissions during fertiliser application dominated Freshwater and Marine

Eutrophication impacts with the agronomic performance of BBFs as one of the key determinants. It is therefore central to reduce environmental impacts of novel BFF by testing them in the field under different conditions and with different target crops and application scenarios to provide recommendations on the optimal use with the highest agronomic performance.

The BBFs that showed high agronomic performances were generally able to compete with mineral fertilisers for certain environmental impacts. However, there were large differences in performance between trials and BBF. Generally high AMFEs in the ryegrass pot trials (substituting P fertiliser) led to comparably low impacts for BBFs with one fertiliser (Solid BBF) having lower impacts in all impact categories. For the three trials for substituting N mineral fertilisers (wheat pot and two broccoli field trials), BBFs, if applied as fertilizer based on N-equivalence, showed similar to higher environmental impacts for Global Warming and Mineral resources and mostly higher environmental impacts for Terrestrial and Freshwater Eutrophication because of the dominating background emissions and lower yields in case of BBF. For Terrestrial acidification, the used emission factor turned out to be very sensitive for the comparison.

However, these results strongly depend on the assumptions taken for upscaling, the agronomic conditions fertilisers were tested under and on the assumption, that BBF production does not compete with an alternative valorisation of side-streams (basic, simplified assumption of this study). If there are alternative uses of side-streams, they could be accounted for by (1) assigning the side-streams an economic value (and environmental impacts) or (2) accounting for the environmental impacts and other unwanted effects of substitutes for those alternatives. However, with this, the comparison between fertilisers will likely become less transparent. Yet, in a circular economy, it is necessary to account for competing uses and undesired side effects from valorising side-streams that are already valorised differently. The use of non-valorised waste (if suitable for BBFs production) should be priority.

The methodological choices in this study exposed quite some uncertainties and knowledge gaps with regard to LCA of BBFs: on the one hand, generic emission models (and factors) do not yet cover the complexity of various forms of BBFs and require refinements based on field-measurements in the future. On the other hand, there is a need for open, standardized methods on how to interpret chemical characteristics (e.g. N:P ratio) to predict most efficient use and environmental impacts as well as approaches to assess agronomic performance of slow-releasing BBFs including their comparison against mineral fertilisers.

It is important to note that because of the finite P resources, there is no alternative in using organic fertilisers and novel BBFs to substitute mineral P fertilisers. Even under these conditions, it remains key to optimize the production, agronomic performance and field emissions of BBFs (accounting for pollution-swapping effects) to reduce their environmental impacts and effects. Finally, the analysis in step 2 also showed that BBF impacts are only one part of environmental impacts of farming. Consequently, in addition to implementing good agricultural practice for the application of BBFs (e.g. focus of P-fertilisation on P-responsive soils), their application should be combined with agro-ecological practices to further reduce environmental impacts of the food produced.

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10 Appendix

10.1 Methods

10.1.1 ecoinvent input data used across case study

Water: Tap water {Europe without Switzerland} | market for | Cut-off, U

Electricity: Low voltage market electricity mix is assumed as input (market for). It should be differentiated based on country mix.

Enzymes: Enzymes {GLO} | market for enzymes | Cut-off, U

Natural gas: High pressure natural gas is assumed as input (market for). It should be differentiated based on country mix. A caloric value of 39 MJ/m³ is assumed (in line with ecoinvent).

Transport with lorry is distinguished by cooling:

- **No cooling:** Transport, freight, lorry, unspecified {RER} | market for transport, freight, lorry, unspecified | Cut-off, U
- **Cooled:** Transport, freight, lorry with refrigeration machine, cooling {GLO} | market for | Cut-off, U (only GLO process available)
- **Frozen:** Transport, freight, lorry with refrigeration machine, freezing {GLO} | market for | Cut-off, U (only GLO process available)

10.1.2 Buildings

10.1.2.1 Pilot scale

- Inclusion of "Building, hall {GLO} | market for | Cut-off, U" (in m²) in inventory of final BBF.
- Area: Total building area dedicated to BBF production [m²] / total yearly production volume of all BBFs [kg] (if it would be operated without interruptions) / [lifetime of building (50 a)]
- Use economic allocation to allocate total impact to single BBF's

10.1.2.2 Industrial scale

- If reliable estimates or the production area are not available (Adriatic Sea): Assumption of 4*10-10 units of "chemical factory, organics" (slightly adapted to not contain any machinery) per kg of BBFs (same assumption as for many

chemicals in ecoinvent, including ammonia; factory with 50'000 t/a production volume * 50 years lifetime). This process contains 50% building hall and 50% multi-storey building and surrounding areas (Piccinno et al. 2016)

- If reliable estimates are available (all other case studies): Same approach as at pilot scale but adding 15m³ of "building, multi-storey {RER}" per m² of building hall.³²
 - Exception: Because of larger areas needed for composting, the Baltic Sea case study used the same amount "building, multi-storey {RER}" per kg of output as for other ecoinvent fertilisers.

10.1.3 Packaging

Primary data was used where available (Baltic Sea and North Sea). Otherwise, a default process from ecoinvent was chosen (per kg of packaged product):

- Solid fertiliser: "Packaging, for fertilisers or pesticides {GLO}| packaging production for **solid** fertiliser or pesticide, per kilogram of packed product | Cut-off, U". → packaging material that is needed to store 1 kg of solid fertilisers in a 50kg plastic bag.
- Liquid fertiliser: "Packaging, for fertilisers or pesticides {GLO}| packaging production for **liquid** fertiliser or pesticide, per kilogram of packed product | Cut-off, U". → packaging material that is needed to store 1 kg of liquid fertilisers in a 20 liter plastic container.

10.1.4 Selection of fertiliser for comparison

Illustration of the range of impacts by different multi- and single nutrient fertilisers in ecoinvent:

³² In the case of the Cantabrian Sea case study, "building, multi-storey {GLO}" was used. A sensitivity analysis showed that changes in production impacts were below 1% due to this deviation (and accordingly even less for the whole life cycle including the use phase).

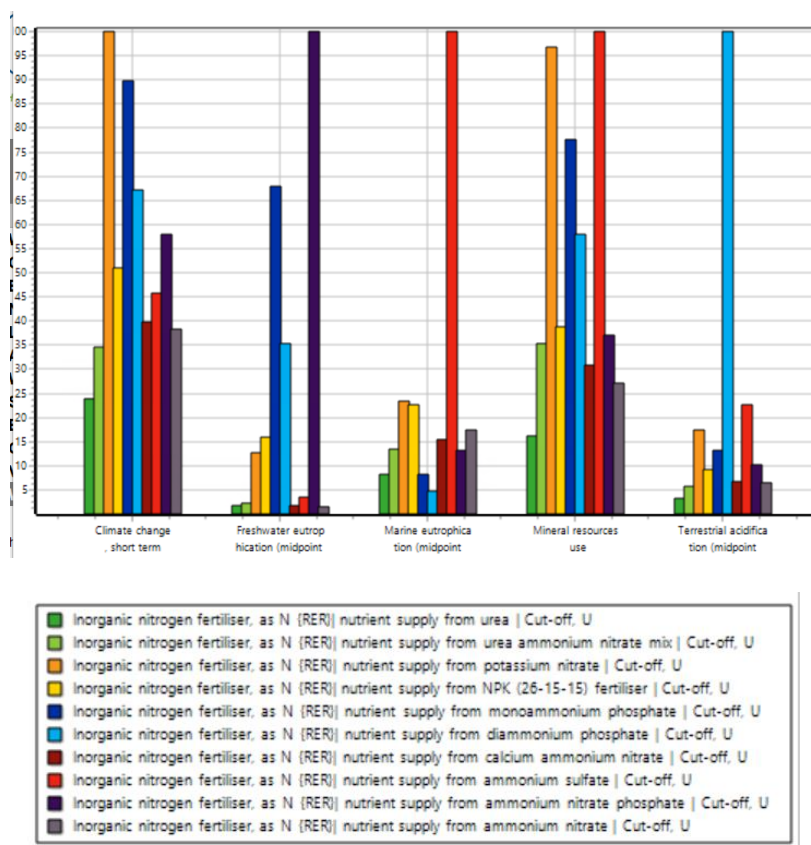


Figure 33. Comparison of environmental impacts of different mineral N fertilizers fromecoinvent per kg N (relative to fertilizer with highest impact per category (=100%))

Table 41 Average Consumption of different types of N fertiliser (2010-2021) summed for West and Central Europe, in 1000 t N. (IFA, 2023)

Type of N-Fertiliser	Average Consumption, in 1000t N	Market share of each N-fertiliser
Ammonium Nitrate, AN	2 906	25%
Calcium Ammonium Nitrate, CAN	3 002	26%
Urea	5 742	49%
Sum	11 650	100%

10.2 Environmental impacts per ha

10.2.1 Wheat: impact per ha

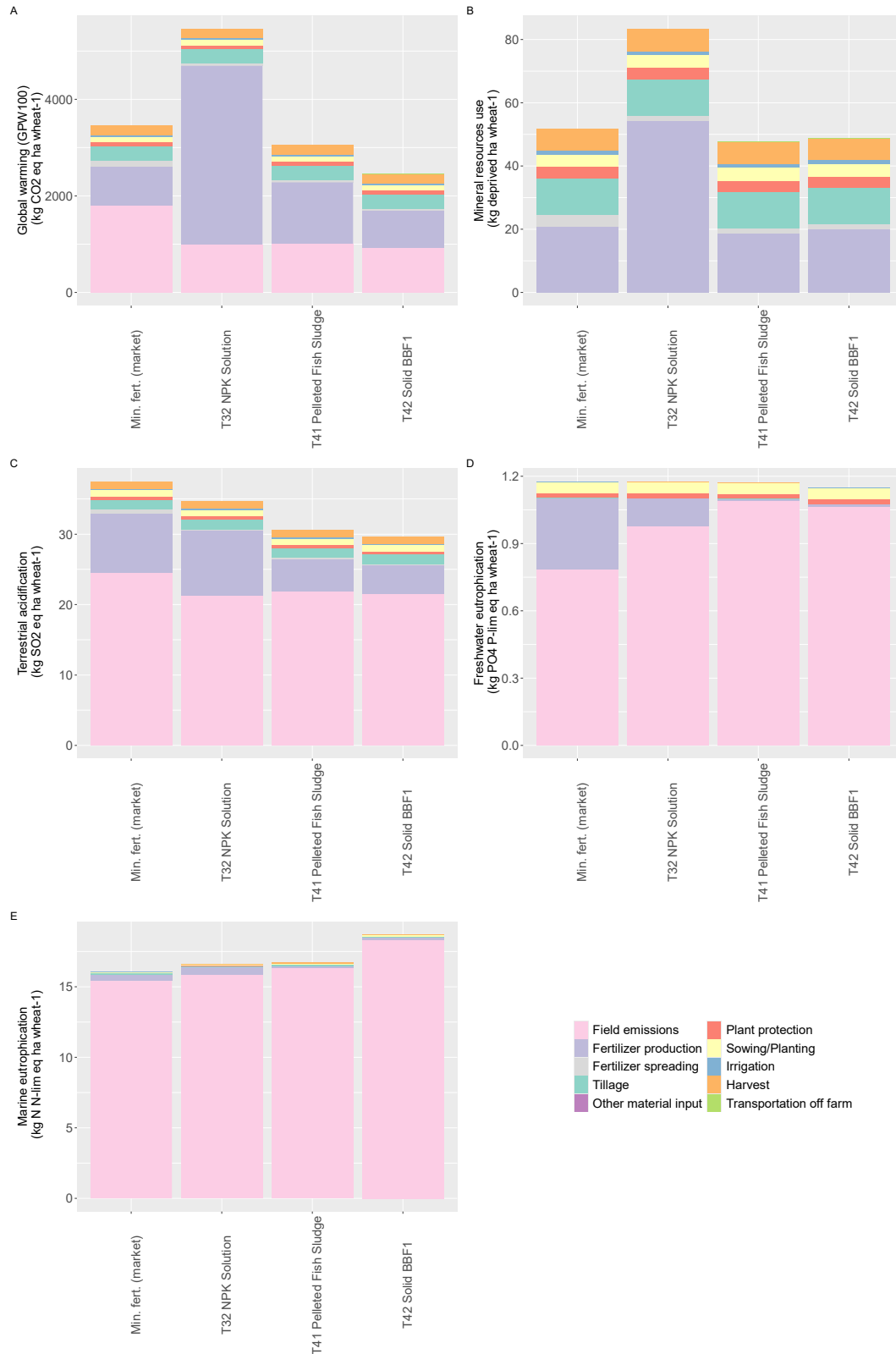


Figure 34 Environmental impacts of producing 1 ha of *wheat*, based on agronomic data from pot trials.

10.2.2 Ryegrass: impact per ha

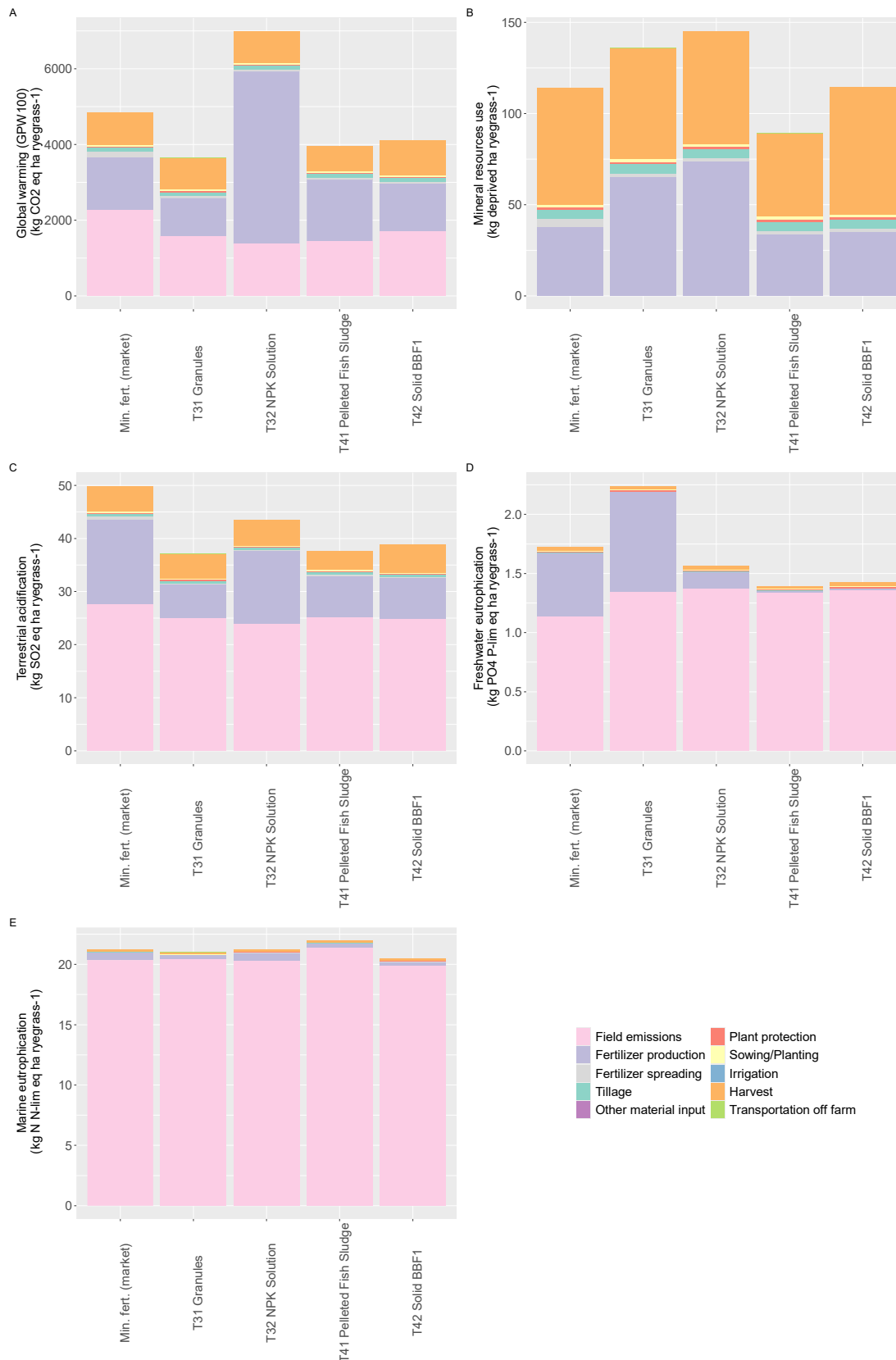


Figure 35 Environmental impacts of producing 1 ha of ryegrass, based on agronomic data from pot trials.

10.2.3 Broccoli in Estonia, season 2023: impact per ha

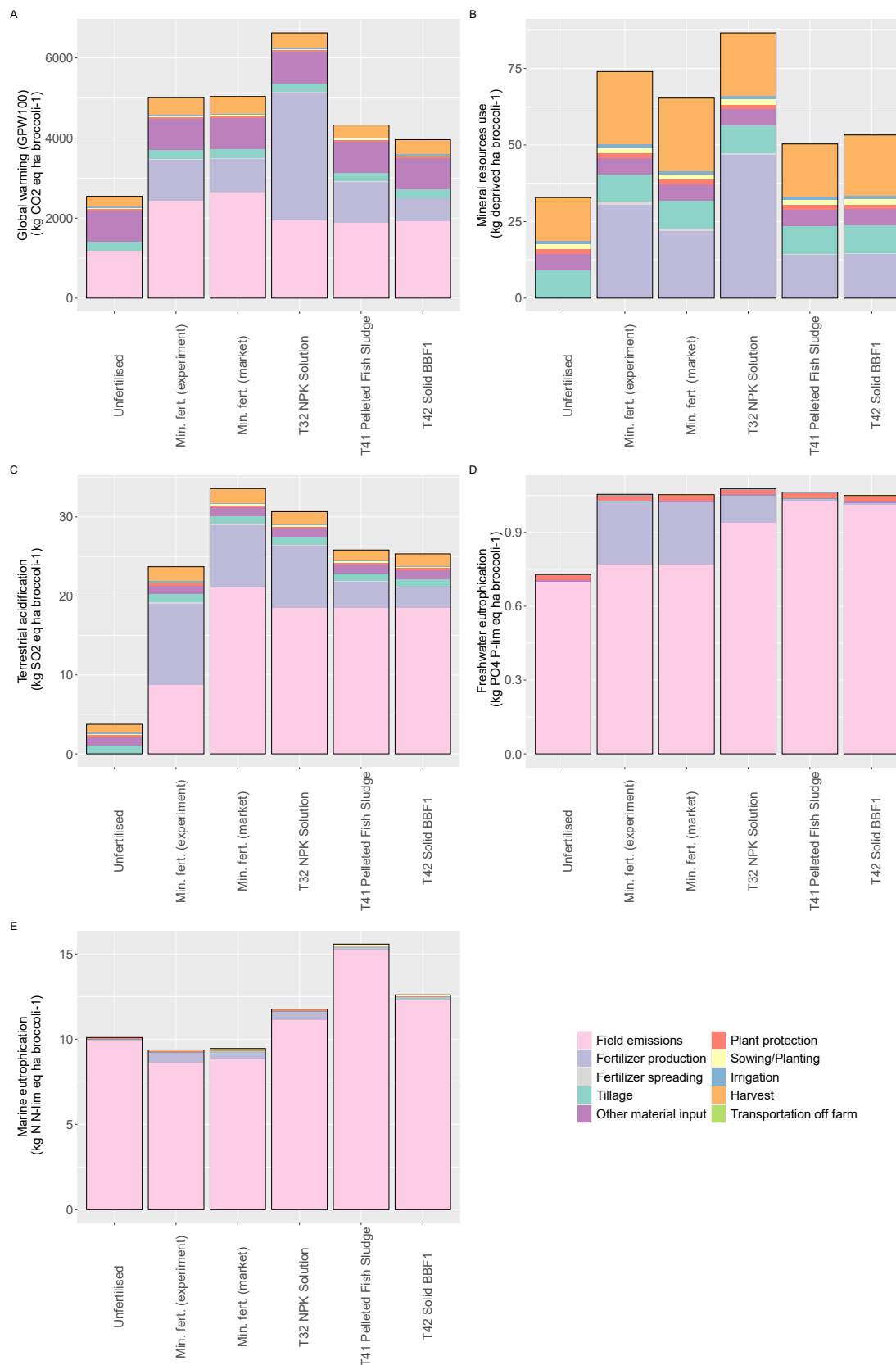


Figure 36 Environmental impacts of producing 1 ha of broccoli, based on agronomic data from the field trial in Estonia.

10.2.4 Broccoli in Spain, season 2024: impact per ha

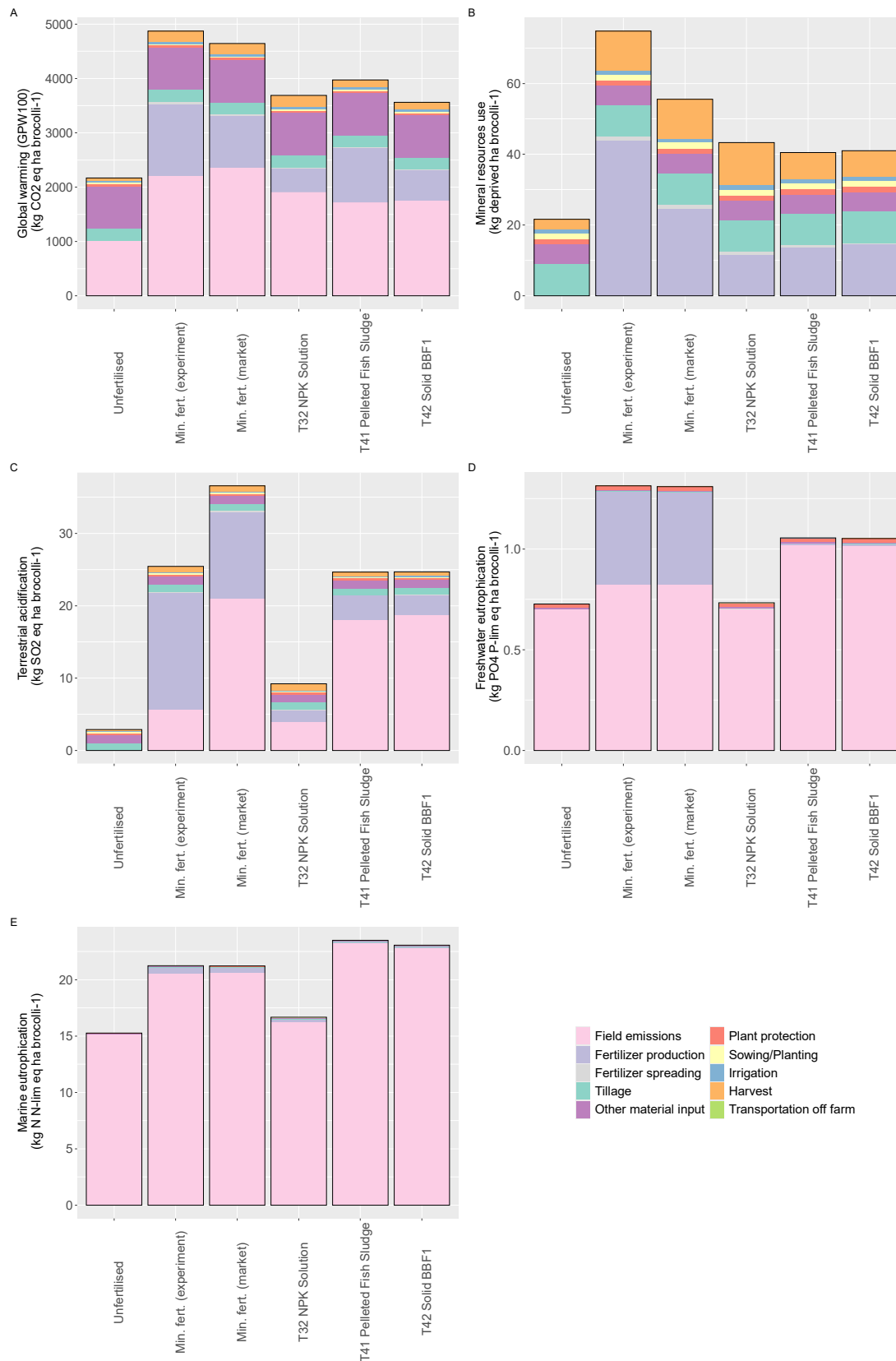


Figure 37 Environmental impacts of producing 1 ha of broccoli, based on agronomic data from the field trial in Spain.

10.3 Sensitivity analysis for broccoli field trials

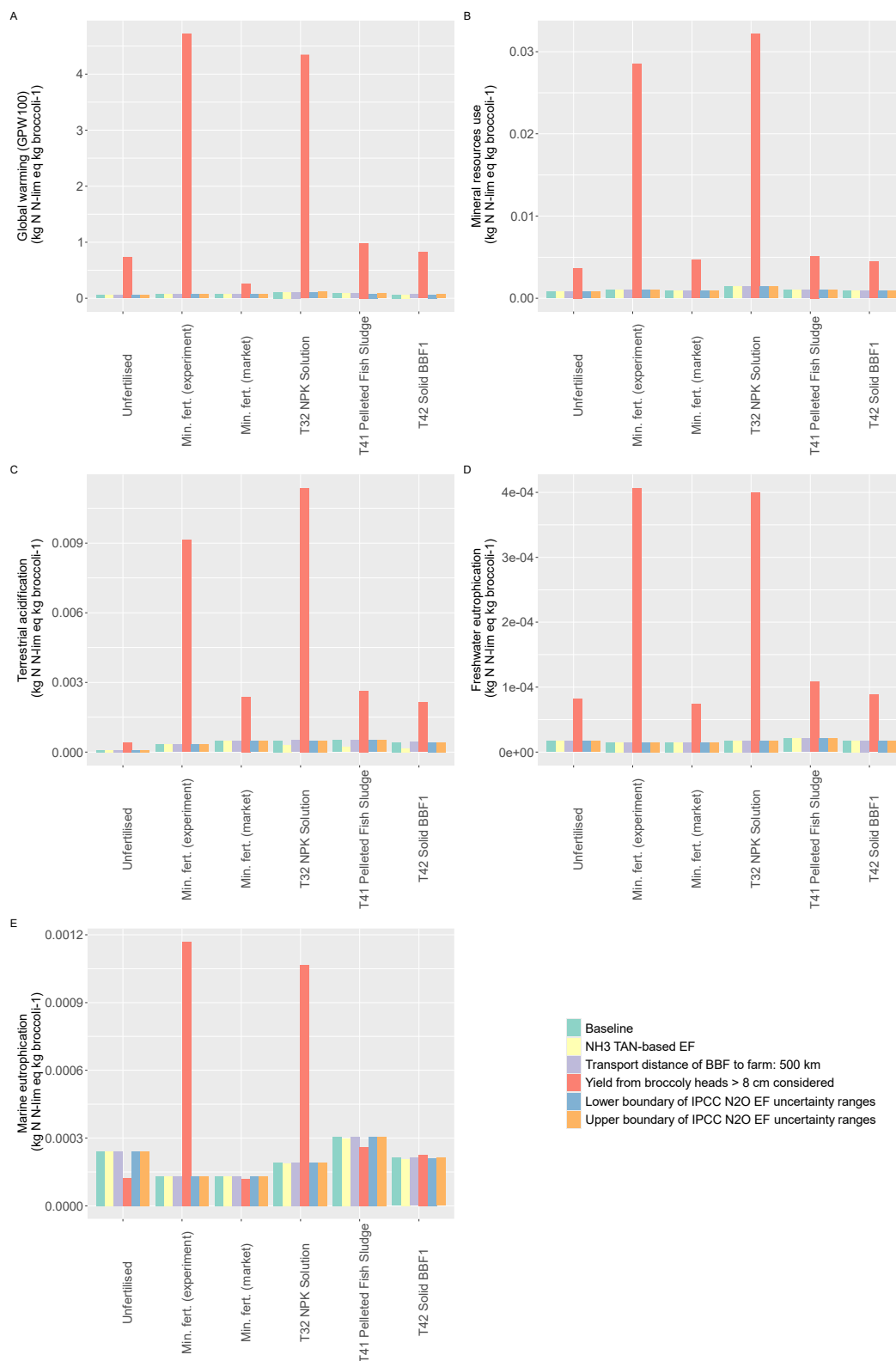


Figure 38 Sensitivity analysis for broccoli (Estonian field trial)

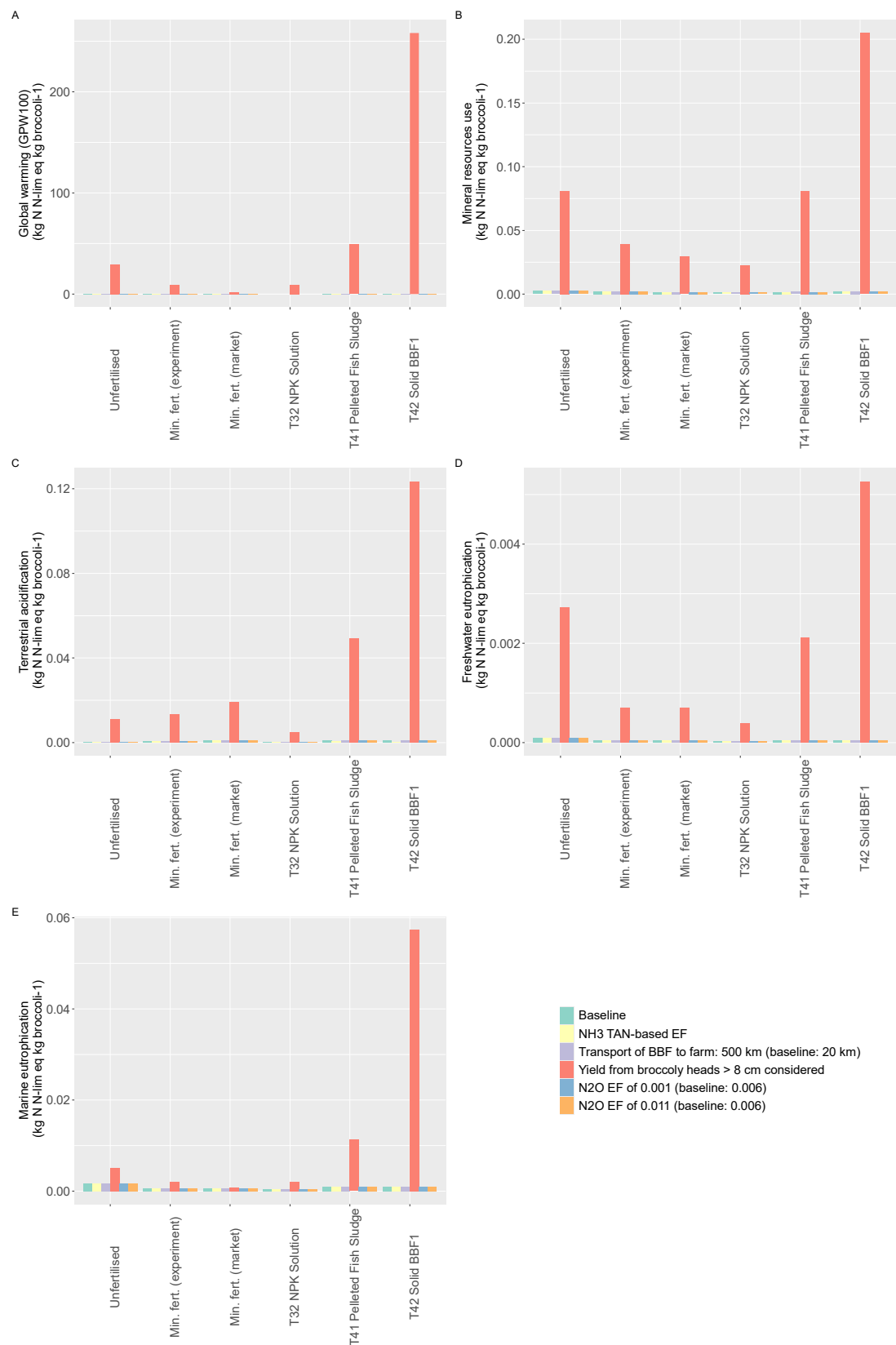


Figure 39 Sensitivity analysis for broccoli (Spanish field trial, season 2024)

SEALAND



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