Horizon 2020 Programme
Research and Innovation Action

*This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme, under Grant Agreement **No 773649**.*

Efficient Carbon, Nitrogen and Phosphorus cycling in the European Agri-food System and related up- and down-stream processes to mitigate emissions

Start date of project: 2018-09-01

Duration: 54 months

D5.2. Environmental profile of agro-ecosystems and of the food value chain

Deliverable details	
Deliverable number	*D5.2*
Revision number	
Author(s)	Florian Grassauer, Markus Herndl (AREC); Laura Iten, Martin Stüssi, Robin Harder, Gérard Gaillard (AGRO); Fabian Kraus (KWB)
Due date	2022-04-30
Delivered date	
Reviewed by	
Dissemination level	Public
Contact person EC	Johanna Schepers

Contributing partners	
1.	AREC
2.	AGRO
3.	KWB
4.	Case study leaders: IRTA, WUR, FCSR, IASP, ASIO

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EXECUTIVE SUMMARY

Satisfying the ever-growing global food demand was traditionally done by expanding and intensifying agricultural production. However, these practices led to considerable environmental impacts as the food value chain nowadays accounts for considerable amounts of greenhouse gas emissions (~26 % of global anthropogenic emissions) and eutrophication (~78 % of global emissions).

Therefore, the project Circular Agronomics aims at the assessment of practical and technical solutions to improve the current carbon (C), nitrogen (N), and phosphorus (P) cycling in European agro-ecosystems and related up- and downstream processes within the food supply chain. The project comprises six case studies from different regions in the European Union (i.e., Catalunia, Spain; Brandenburg, Germany; Lungau, Austria; Emilia-Romagna, Italy; Gelderland, Netherlands; South Moravia, Czech Republic) that planned to conduct ten different experiments in order to test the practical and technical solutions by either a combination of a technical sub-system with a subsequent agricultural field experiment or a sole agricultural field experiment. However, different restraints led to waiver or postponement of certain traits of some experiments. Therefore, the data collection only yielded seven experiments with complete data. Regarding the other three experiments, at least data on the respective technical sub-systems could be collected.

The experiments were subsequently assigned to three innovative strategies which aim at different compartments of agricultural production (i.e., (1) nutrient management in crop production, (2) nutrient management in livestock production, (3) and waste management and nutrient/carbon recovery).

The different experiments were analyzed according to their respective system description and in compliance with the methodology as outlined in Deliverable 5.1. Moreover, abiotic resource depletion was added as an environmental impact category due to its relevance for experiments that focus on mineral fertilizer as impacts from background processes such as mining.

The strategy of nutrient management in crop production comprised three experiments that investigated different management parameters to increase the nutrient efficiency in crop production. The results show that increasing levels of N fertilization leads to higher yields and increases emissions (abiotic resource depletion and eutrophication), which is even more pronounced under a dry climate. Regarding the timing of fertilization, four weeks after sowing showed the least emissions, which can be explained by the higher N demand of the plants at this stage. Moreover, the test of different tillage regimes indicated the no-tillage variant to be favorable in terms of environmental impacts per kg crop.

Results of two experiments assigned to the innovative strategy of nutrient management in livestock production showed the beneficial effects of precision feeding in terms of mitigating greenhouse gas emissions and eutrophication due to a needs-oriented supply of nutrients that leads to lower losses. It could further be shown that the extensive management of organic dairy farms can be very efficient in terms of eutrophication if the management intensity matches the natural production potential of the agricultural area of the farm.

The remaining five experiments examined improvements in waste management and carbon/nutrient recovery by using waste streams as potential sources of nutrients or reducing emissions by capturing nutrients. Regarding three investigated digestate treatment concepts, microfiltration/ microsieving revealed the lowest environmental impacts. Regarding capturing nutrients, the struvite technology can recover and subsequently recycle these nutrients in a comparably clean and plant available form from soybean wastewater treatment with low environmental impacts. The membrane technology seems to be an electricity-saving alternative compound for whey thickening compared to centrifuges.

Overall, it could be shown that the innovative technical sub-systems cause additional efforts (such as electricity consumption) and corresponding additional impacts. However, the subsequent farming systems should be able to achieve reduced emissions. Regarding the non-renewable energy demand and global warming potential of the observed systems, it seems rather unlikely that a corresponding reduction in emissions by farming systems can be realized. Conversely, it is more likely that this trade-off can be achieved for acidification and eutrophication (especially ammonia emissions), where agriculture has a crucial role. The report shows particular areas of improvement for process engineers focusing on optimization of technologies and farmers/agricultural researchers for optimization of their nutrient management behaviors. From the comparison, particular done for one experiment and separated assessments done for others and incomplete data-sets for several technical and farming systems, we only can state that such a hybrid out of technology and agriculture may reduce environmental impacts if it is well applied, however there it is unlikely that it is always well applied. Nonetheless, this aspect of dedicated nutrient management and emission mitigation should be investigated further.

1. INTRODUCTION

1.1 Background

Human societies face many grand challenges in the near future and are therefore pursuing solutions to problems such as climate change, energy and food security, health, and industrial reconstruction (Bugge et al., 2016; Ollikainen, 2014; Pülzl et al., 2014; Richardson, 2012). Regarding the agricultural sector, a key challenge is the nutrition of the growing world population. According to the UN (2017), the growth of the world population is predicted to reach 9.7 billion people by 2050. The demand for food accompanying this growth is estimated to increase by 70 % compared to the 2005-2007 level (FAO, 2012). Meeting this growing demand is traditionally done by expanding and intensifying agricultural production (Godfray et al., 2010; Tilman et al., 2011). However, these practices also have considerable impacts on the environment.

Currently, the food supply chain accounts for approximately 26 % of the global anthropogenic greenhouse gas (GHG) emissions (Poore and Nemecek, 2018), primarily resulting from the agricultural phase of production (i.e., land clearing, fertilization, and crop- and livestock production) (Burney et al., 2010; Fantin et al., 2017; Longo et al., 2017), and is therefore considered a significant contributor to climate change (FAO, 2018). Further, the food supply chain contributes about 78 % to the global eutrophication of aquatic and terrestrial ecosystems (Poore and Nemecek, 2018). Similar to the GHG emissions, large parts of the eutrophication also originate from the agricultural production phase. This can be related to the high amounts of fertilizers used in agricultural production, as the global use of fertilizers increased by 700 % from 1965 to 2005 (Matson et al., 1997; Tilman et al., 2001). Considering these severe impacts on the environment, modern agriculture faces the challenge of producing more food to nourish the ever-growing global population without intensifying the pressure on limited resources and the environment (Sutton et al., 2013).

1.2 Objectives

Therefore, the European research project Circular Agronomics aims at a comprehensive synthesis of practical and technical solutions to improve the current carbon (C), nitrogen (N), and phosphorus (P) cycling in European agro-ecosystems and related up- and downstream processes within the food value chain. The practical solutions are tested within six case studies around the European Union (i.e., Catalunia, Spain; Brandenburg, Germany; Lungau, Austria; Emilia-Romagna, Italy; Gelderland, Netherlands; South Moravia, Czech Republic) comprising ten different experiments as described in D5.1 (Wollmann et al. 2020).

1.3 Summary of experiments

In five of the ten experiments, novel technical sub-systems are analyzed and tested in agricultural field experiments afterwards, whereas the other five experiments solely consist of agricultural field experiments (see Table 1). However, due to severe constraints related to Covid 19, the conduction of certain traits of multiple experiments was postponed or even waived. Therefore, the data collection process yielded only seven experiments with complete data (Experiments 1, 2, 3, 4, 5, 9, 10), whereas the agricultural field experiment data are missing in three experiments (Experiments 6, 7, and 8).

Table 1. Ten experiments from six different case studies, their respective inclusion of (A) a technical sub-system and (B) an agricultural field experiment, and the status of data collection (gray shading indicates no available data from the agricultural field experiment).

Experiment No.	Case Study	Short experiment description	Technical sub-system included (A)	Agricultural field experiment included (B)	Data collected from
1	Germany/Czech Republic	N-use efficiency in winter wheat	no	yes	B
2	Germany	Slurry application techniques	no	yes	B
3	Italy	Conservation tillage	no	yes	B
4A	Spain	Solar dried fertilizers in crop rotations	no	yes	B
4B	Spain	Digestate acidification and solar drying	yes	no	A
5A	Italy	Fertigation with microfiltered digestate	no	yes	B
5B	Italy	Digestate microfiltration/microsieving	yes	no	A
6	Germany/Netherlands	Digestate vacuum degasification	yes	yes	A
7	Netherlands	Phosphate from soybean wastewater	yes	yes	A
8	Czech Republic	Acid whey thickening	yes	yes	A
9	Spain	Precision feeding	no	yes	B
10	Austria	Extensively managed dairy farms	no	yes	B

1.4. Assignment of the experiments to three innovative strategies

The ten considered experiments contribute to three innovative strategies developed within the course of the project, which aim at different compartments of agricultural production (i.e., (1) nutrient management in crop production, (2) nutrient management in livestock production, (3) and waste management and nutrient/carbon recovery). Therefore, every experiment is related to one innovative strategy and has the potential to reduce the impacts on the environment and improve the abiotic resource depletion efficiency of agricultural production systems and the overall food value chain.

Experiments 1, 2, and 3 aim at the innovative strategy of improving nutrient management in crop production by exploring the N-use efficiency of different winter wheat cultivars under different N dressings and weather simulations (Experiment 1), testing different slurry application techniques at different stages of crop development and even before sowing (Experiment 2), and comparing different tillage regimes (Experiment 3). Experiments 9 and 10 try to improve the nutrient management in livestock production via testing different feeding strategies (Experiment 9) and applying extensive management of dairy farms in a less favorable production area (Experiment 10). Finally, the remaining five experiments (4, 5, 6, 7, 8) aim to optimize waste management and nutrient/carbon recovery by conducting different novel and innovative techniques, including solar drying (Experiment 4), microfiltration (Experiment 5), or vacuum degasification (Experiment 6) of digestate, phosphate recovery from soybean wastewater (Experiment 7), and acid whey thickening with a membrane treatment (Experiment 8).

1.5 Structure of the report

The purpose of this deliverable report is to show and discuss the results of the environmental assessments of the considered experiments within the Circular Agronomics project. The environmental assessments were conducted using life cycle assessment (LCA), which is commonly used to evaluate and describe environmental impacts and abiotic resource depletion of agricultural production processes from a cradle to farm-gate perspective (Klöpffer and Grahl, 2009; Rebitzer et al., 2004). LCA is standardized by an international framework (ISO, 2006a, b) and follows four steps: (1) the definition of goal and scope, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) the interpretation of results. As the definition of goal and scope was already elaborated in D5.1, this report focuses only on steps 2-4.

Due to the missing data on the agricultural field experiments in the abovementioned experiments, we separately look at the methodology and results of the LCA of the agricultural field experiments and the LCA of the technical sub-systems in the methodology and results sections of this deliverable. In the discussion section, we discuss the results of the experiments and further synthesize them in relation to their respectively assigned innovative strategy (i.e., (1) nutrient management in crop production, (2) nutrient management in livestock production, and (3) waste management and nutrient/carbon recovery). Section 5 finally concludes the deliverable.

2. METHODOLOGY

2.1. General Methodology

The proposed methodology was detailed described in D5.1.

An addition in terms of impact categories was made: abiotic resource depletion was added as an additional impact category. D5.1 proposed to show abiotic resource depletion in the aggregated category “Exergy.” The abiotic resource depletion category is especially relevant for experiments that focus on the impacts from mineral fertilizer from background processes such as mining, which is a key lever for mitigating the potential impact in this category.

Abiotic resource depletion: This impact category includes metal and mineral resources from CML 2001 (Guinée et al., 2001), corresponding to the ILCD 2011 recommendation. The method characterizes current consumption and the available reserves and is an indicator of the scarcity of metals and minerals.

Phosphorus and Potassium are included in the mineral resources, while energy resources are not included in order to avoid overlaps with the CED.

Due to the lack of data regarding the data of the agricultural field experiments in several case studies, the technical sub-systems were assessed separately with the flow modeling software Umberto LCA+ using the ecoinvent database version 3.6. Therefore, deviating from the proposed plan outlined in D5.1, not only the collection of life cycle inventory (LCI) data but also the life cycle impact assessments (LCIA) of the technical sub-systems were calculated separately for the technical sub-systems. The considered impact categories for the technical sub-systems are the same as for the agricultural field experiments. However, some aggregated impacts (exergy and normalized eutrophication) as well as the water stress index (WSI) by AWARE could not be calculated with the Umberto LCA+ software.

It should be underlined that the impact categories as global warming potential, acidification, and eutrophication potential are strongly affected by nitrogen (notably dinitrogen monoxide and ammonia) and phosphate emissions, which are very relevant in agricultural systems. The technical systems normally reveal hereby a minor or even negligible contribution for acidification or eutrophication potential. A particular focus for technical systems is set within this assessment on the non-renewable cumulative energy demand and global warming potential, which are relevant in terms of technological approaches and may offset or even enlarge corresponding hypothetic savings in the farming sector.

The data collection was done by AREC (for agricultural field experiments) and by KWB (for technical sub-systems). Based on the available data, KWB and AGRO calculated preliminary LCAs and used the results as a basis for further data collection to refine the results. KWB characterized the output of the technical system in terms of nutrient values and quantity. These flows were part of the agricultural data collection of AREC, and AGRO processed the data. Hence the technical and the agricultural system can be coupled by the functional unit chosen for the agricultural system to compare the overall systems between different experiments. The results for the technical sub-system are given per output unit (e.g., digestate) to be able to compare different technical sub-systems with each other. Five of the ten experiments (Experiments 4, 5, 6, 7, and 8) included an agricultural system as well as a technical sub-system. However, due to data availability reasons, only Experiment 5 yielded a sufficient data inventory for both systems. Therefore a comparison of, e.g., environmental drawbacks of the technical sub-system and, e.g., environmental benefits of the agricultural system could only be achieved for this particular Experiment. Thereby a relation between the reference flow of the technical system and the functional unit of the agricultural system was established to display both parts against each other among all available impact categories for both technical sub-system and agricultural system.

2.2. Description of the calculated experiments

The description of each experiment follows the description already given in D5.1. However, a change in the order of magnitudes was made for the functional units from Mg to kg. Additionally, the subsections “Hypothesis”, “Goal”, and “Strategy” are new. The “Hypothesis” gives the information on the overall aim of the experiment and the improvements that were targeted to be achieved. All indicators listed in D5.1 were calculated, of which two are discussed in more detail. These two include the main target indicator and a trade-off indicator. Other indicators are included in the annex. The “Goal” gives information on the two specific environmental indicators that were chosen to evaluate the improvements and the potential trade-offs. The findings of the experiments are aggregated on three strategy levels in the discussion section: (1) nutrient management in crop production, (2) nutrient management in livestock production, and (3) waste management and nutrient/carbon recovery. The assignment of the experiments to the three different innovative strategies was made within a workshop with all case study leaders.

Experiment 1- N use efficiency of winter wheat

System and its function

Different genotypes of winter wheat are tested for their nitrogen use efficiency (NUE) when supplied with different amounts of mineral N fertilization in 3 different weather situations (Figure 1). Several different wheat varieties are tested in the experiment. For the environmental evaluation, a selection of three genotypes was assessed (one cultivar with a high / medium / low NUE, respectively). There are five different levels of N fertilization (0% N, 50% N, 75% N, 100% N, 125% N) and three different weather conditions (non-irrigated in Germany, irrigated in Germany, non-irrigated in the Czech Republic). The function of the system lies in the production of wheat grain, with two main outputs: wheat grain (main product) and wheat straw (co-product).

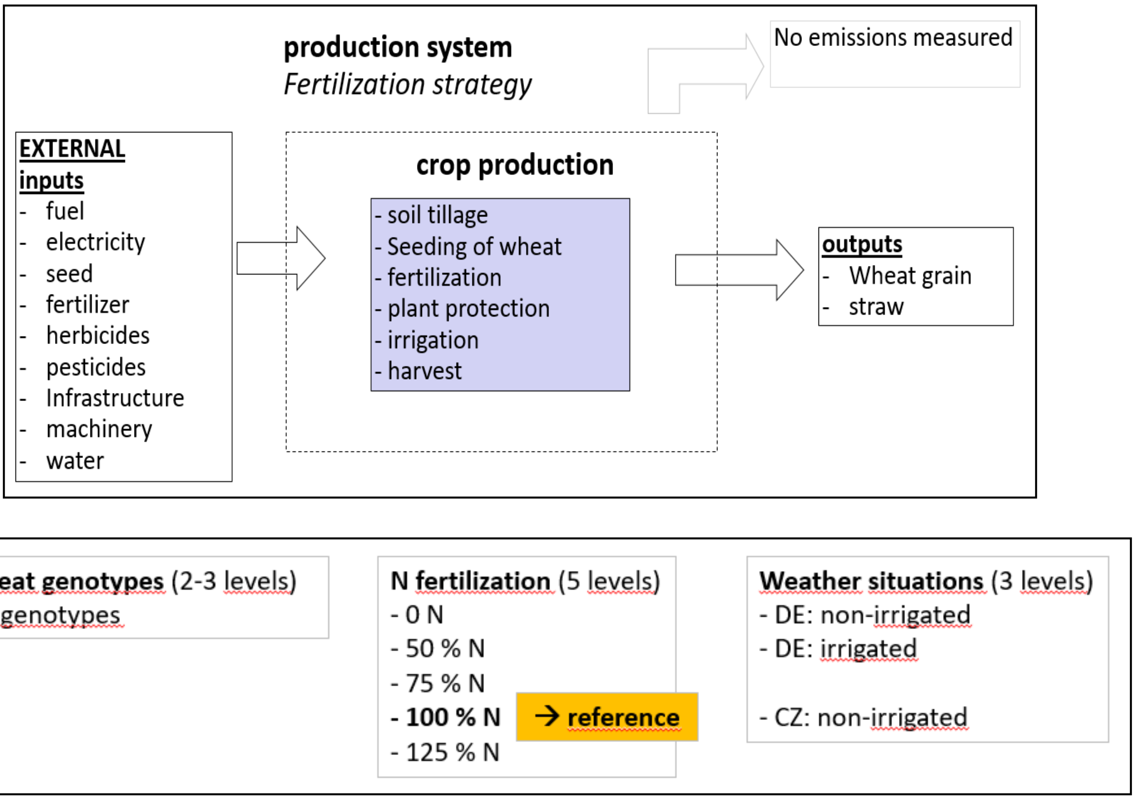

Figure 1. System description and considered scenarios of Experiment 1.

Reference

100% N fertilization for 3 genotypes, non-irrigated conditions in DE and CZ (=BAU (business as usual) in DE and CZ).

System Boundaries

Field level. From the harvest of pre-crop until the harvest of wheat. (Pre crops: seed wheat (DE) and maize grain (CZ)).

Functional Unit

1 kg of wheat grain (86% Dry Matter, protein content or given protein yield).

Allocation

- Germany: no allocation (100% straw remains on the field)

- CZ: 50% of the straw remains on the field, 50% is used externally as animal bedding. There is no allocation for the straw that remains on the field. Allocation is based on monetary criteria for the part of the straw used externally.

Hypothesis

N uptake is dependent on weather conditions (water availability) and thus, N fertilization should be adapted to minimize losses.

Goal

The goal is to reduce abiotic resource depletion (by optimizing the dose of mineral fertilizer) and eutrophication potential (through less emissions from fertilization surplus).

Assigned innovative strategy

Nutrient management in crop production

Experiment 2 - Slurry application techniques

System and its function

Different slurry application techniques are tested with nitrification inhibitors (NI) in a field experiment with maize to reduce field NH_3 emissions. Experimental conditions spanned three different application times (i.e., four weeks before sowing, one day before sowing, and four weeks after sowing) and three different application techniques (i.e., broad spread with subsequent incorporation into the soil, direct injection into the soil, and row application with subsequent incorporation into the soil). Incorporation of slurry into the soil upon the broad spread of slurry is only possible before seeding. After seeding, incorporation into the soil is no longer possible. This experiment was not conducted because spreading without incorporation into the soil would be against good farming practices on arable land. Similarly, direct placement in 15-20 cm soil depth (under the seed) through direct injection is only possible before seeding. Therefore, for the third timing variant (i.e., four weeks after sowing), placing in rows between the plants and subsequent incorporation was chosen. All application times and techniques are combined with three levels of NI (no NI, the NI containing product PIADIN® and the NI substance DMPSA (3,4-DIMETHYLPYRAZOLE-SUCCINIC acid)), see Figure 2.

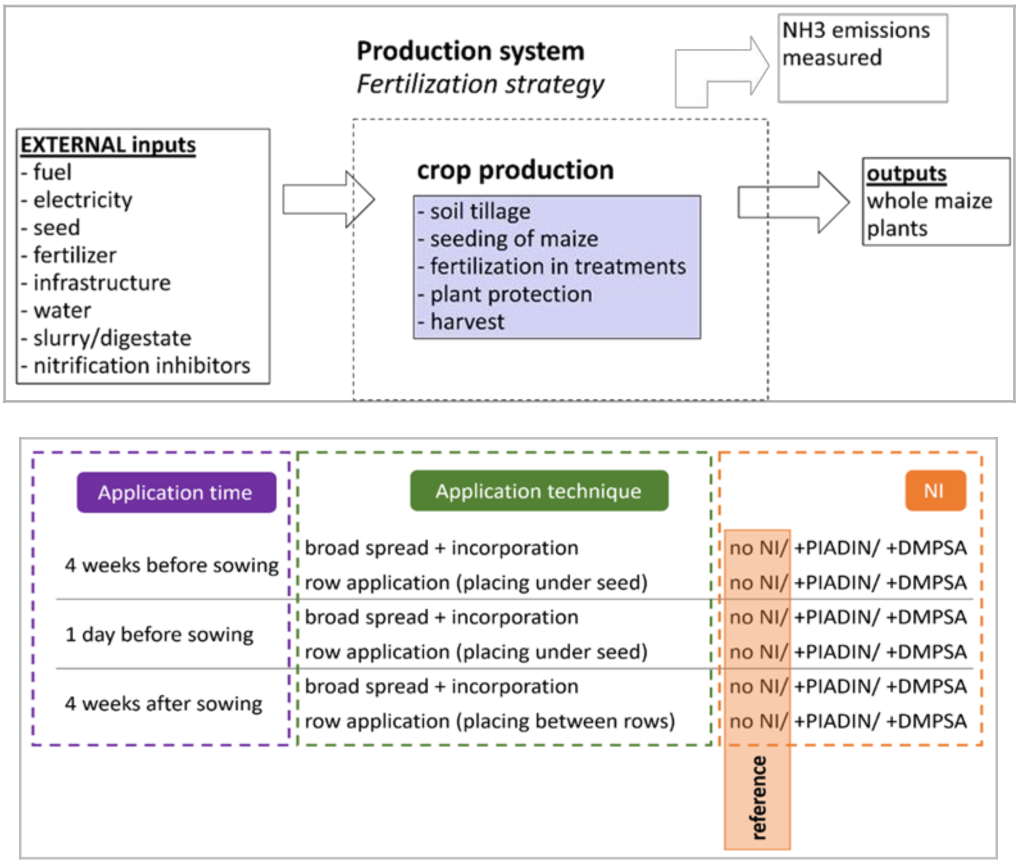

Figure 2. System description and considered scenarios of Experiment 2.

Reference

Separately for each application time:

- Broad spread application without NI, 4 weeks before sowing
- Broad spread application without NI, 1 day before sowing
- Broad spread application without NI, 4 weeks after sowing

Then: comparison of different application times (= important factor to determine maize yield).

System Boundaries

Field level. From the harvest of pre-crop (oats, 2018) until the harvest of maize.

Functional Unit

1 kg of whole maize plants (dry matter)

Allocation

No allocation. Whole maize plants are harvested for biogas production.

Hypothesis

The innovative application technique can reduce direct emissions. The timing of the application and the addition of a nitrification inhibitor can further increase fertilizer uptake and minimize losses.

Goal

The goal is to reduce potential effects on global warming, firstly during and shortly after applying fertilizer by adapted technique and timing, and secondly, reduce emissions by an adapted release of nitrogen. As a secondary effect, it should also decrease the potential for eutrophication.

Important notes for the interpretation of the results: To our knowledge, there are no independent data available on the emission reduction potential of nitrification inhibitors. Based on expert knowledge, the emission reduction is estimated between 20 and 40% for nitrogen oxides. In order to get an idea of the potential of this technology, two hypothetical NI were modeled (with 40% reduction and with 20% reduction).

Assigned innovative strategy

Nutrient management in crop production

Experiment 3 – Conservation tillage

System and its function

Three different tillage systems are compared for their effects on yield, crop quality, soil quality characteristics, and water- and nutrient use efficiency in a wheat – rapeseed rotation (Figure 3). The three tillage systems comprise the BAU treatment conventional tillage (30-35 cm plowing, harrowing, and hoeing), minimum tillage (15-20 cm harrowing and hoeing), and no-tillage (direct seeding on residues of previous crops). The experiment is conducted under farming conditions on a 2 ha field for each tested tillage system. Before the field experiment started, there was a four-year period of no-tillage on all fields.

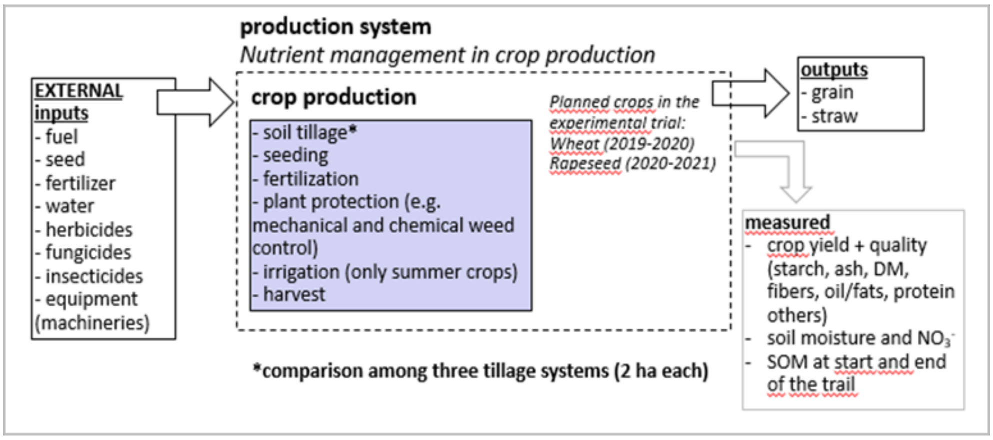

Figure 3. System description and considered scenarios of Experiment 3.

Reference

Conventional tillage (= BAU: 30-35 cm plowing, harrowing, and hoeing).

System Boundaries

Field level. From the harvest of pre-crop (maize, 2019) until the harvest of wheat (2020) and rapeseed (2021).

Functional Unit

1 kg of crop yield (wheat/rapeseed).

Allocation

Depending on the tillage system:

Conventional tillage: Allocation based on monetary criteria for wheat straw (used externally as animal bedding). No allocation for rapeseed straw (remains on the field).

Minimum / no-tillage: No allocation. All straw remains on the field.

Hypothesis

Conservation tillage can increase water- and nutrient use efficiency and has a positive effect on soil quality characteristics (e.g., C content)

Goal

The goal is to decrease the potential effects of global warming by reducing the losses of carbon and enhance the increase and storage of SOC by forgoing conventional tillage. As a second indicator, ecotoxicity was chosen as a potential trade-off indicator due to pesticide use needed for the minimum tillage and no-tillage regimes.

Assigned innovative strategy

Nutrient management in crop production

Experiment 4A – Test of solar-dried fertilizers in crop rotations

System and its function

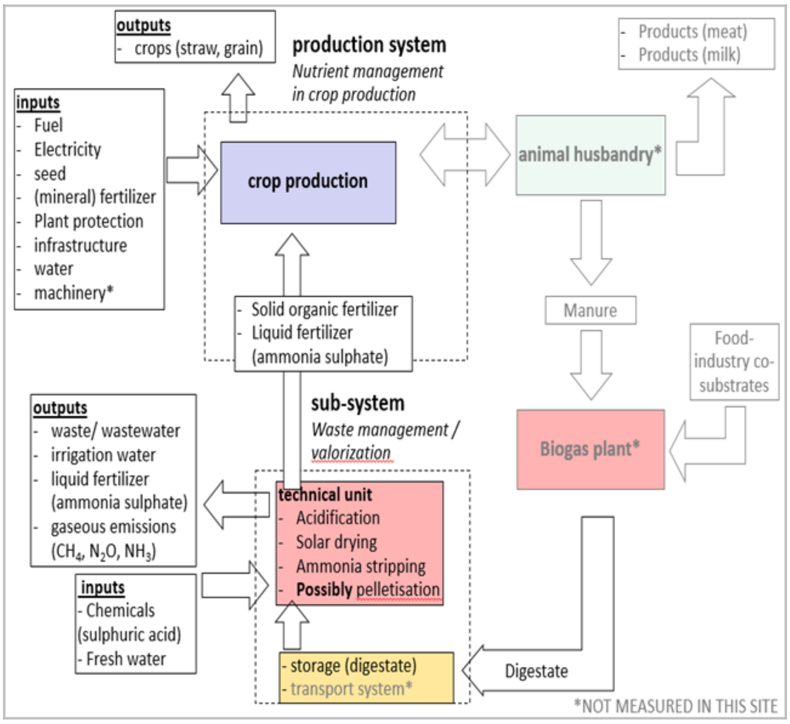

Figure 4. System description of Experiment 4.

Experiment 4 tests the use of solar-dried digestate as fertilizers in two field crop rotations: (1) a cereal-based crop rotation (wheat-barley-triticale) and (2) a non-cereal-based crop rotation (canola-pea-wheat) (**Fehler! Verweisquelle konnte nicht gefunden werden.**). The fertilizer efficacy of dried concentrated digestate is compared to fresh, untreated digestate. Nitrogen fertilization is applied per crop, but overall, the same amount of N is applied in each crop rotation. The FU is “1 Mg of crop yield”. Thus, the two crop rotations cannot directly be compared with each other, as the yield of the different crops is not comparable. This issue will be addressed using a system expansion procedure. Means of the crop rotations will be evaluated separately from each other for their environmental impacts.

Reference

Application of raw digestate for each crop rotation.

System Boundaries

Field level (crop production) and digestate treatment.

- Animal husbandry is not part of the system; the milk yield is not measured in the experiment.
- The biogas plant is not part of the system, as the biogas yield is co-dependent on other inputs.

Functional Unit

1 kg of crop yield for the mean of each crop rotation.

Allocation

- Cereal-based crop rotation: Allocation is based on monetary criteria. The straw of all cereal crops is used externally in animal husbandry.

- Non-cereal-based crop rotation: no allocation for canola and pea; plant residues stay on the field and are incorporated. Allocation is based on monetary criteria for wheat straw, which is used externally in animal husbandry.

Hypothesis

Increased nutrient valorization

Goal

The goal is to decrease abiotic resource depletion due to a more efficient system. As an additional indicator, eutrophication is discussed.

Assigned innovative strategy

Waste management and nutrient/carbon recovery

Experiment 4B – Digestate acidification and solar drying – technical sub-system

System and its function

The technical sub-system under study is a treatment process for agricultural digestate from a biogas plant in Catalonia, Spain, including an upstream solid-liquid separation, an acidification step, and solar drying (**Fehler! Verweisquelle konnte nicht gefunden werden.**). The further valorization of the substrate or its fraction is excluded from the system under study. The function of this sub-system is the treatment of digestate or its solid fraction to a certain dry matter due to the solar drying process.

Reference

The reference sub-system is characterized by untreated agricultural digestate. Hence the sub-system only describes the impacts associated with the technical digestate treatment. The reference system without a technical treatment has zero impact within this analysis. Obviously, the use or storage of digestate has environmental impacts. However, this is excluded from this sub-system.

System boundaries

The sub-system boundaries include the technical treatment and background system (Figure 5). However, due to a lack of data, emissions to air from the drying process had not been considered. Therefore, any follow-up valorization of the digestate in agriculture is excluded from the assessment.

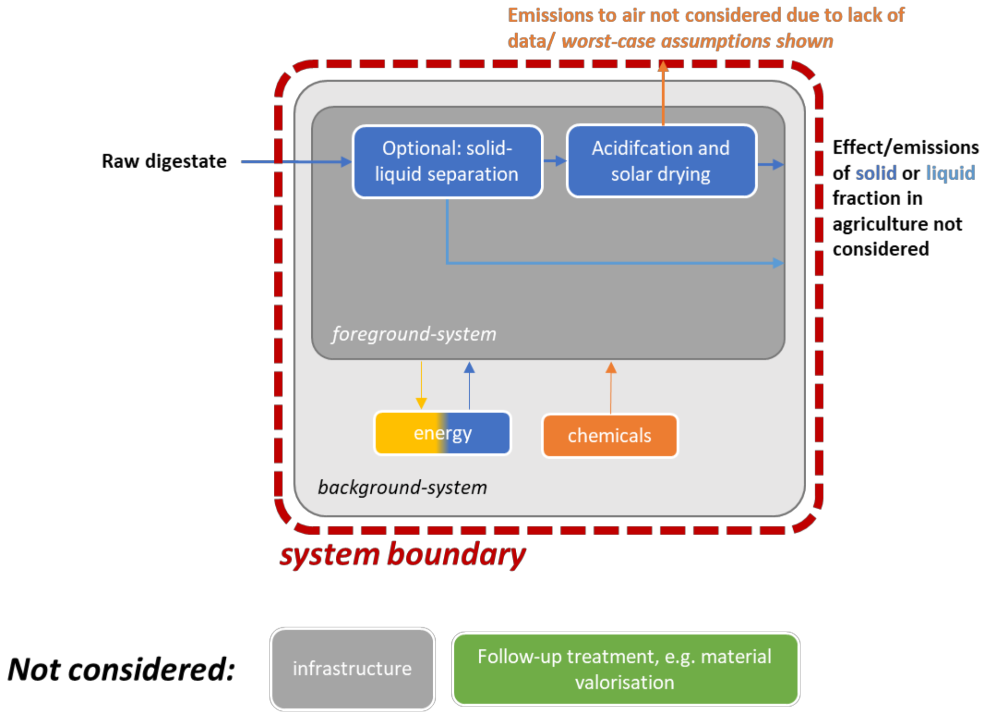

Figure 5. System boundaries of the technical sub-system (i.e., digestate acidification and solar drying) of Experiment 4B.

Functional unit/Relation for comparison

According to the system's function, the impacts are related to the reference flow of raw digestate. Potential environmental impacts will be described as “Impact (e.g., kg CO_2-Eq)/m³ digestate treated”. Due to the inequivalence of resulting products, the comparison related to the reference flow has certain limitations (see below).

Allocation

All related impacts due to changes in operation (e.g., acid consumption for acidification) are allocated to the reference flow. Therefore, no allocation procedures are necessary within this scope.

Hypothesis

Mitigation of emissions through a pre-treatment of agricultural digestate.

Goal

The goal is to mitigate emissions (e.g., ammonia) in agricultural digestate applications due to a technical pre-treatment. Due to delays in the commissioning of the stripping unit, the comparison is reduced to two scenarios (treatment of raw digestate and treatment of solid fraction after solid-liquid separation (centrifuge) with a combination of acidification and solar drying).

Assigned innovative strategy

Waste management and nutrient/carbon recovery

Experiment 5A – Fertigation with microfiltered digestate

System and its function

Raw digestate is separated into solid and liquid fractions. The liquid fraction is microfiltered, and the microfiltrate is used in the fertigation of energy crops to test its fertilizer efficacy. There are two levels of different fertilizers: raw digestate and microfiltered digestate. The application of raw digestate is followed by plowing and combined with mineral fertilization and sprinkler irrigation (= BAU treatment). The microfiltered fraction of digestate is applied by fertigation through drip line irrigation and combined with the solid/dense fraction of raw, separated digestate (Figure 6).

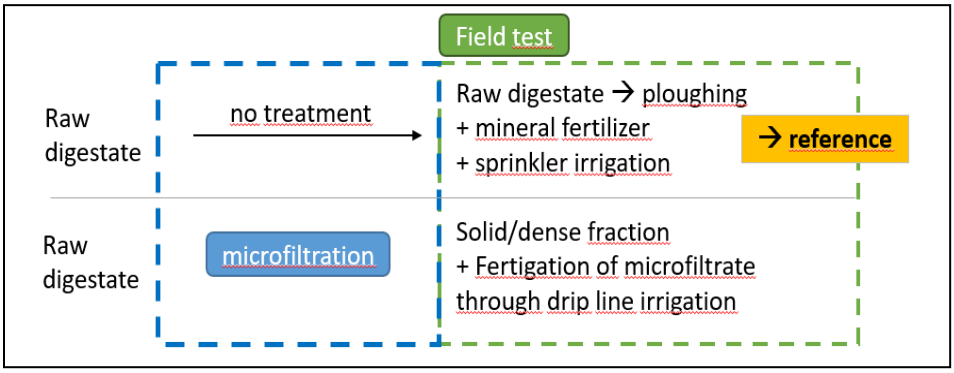

Figure 6. Considered scenarios of Experiment 5A.

Reference

Application of raw digestate, followed by plowing and combined with mineral fertilization and sprinkler irrigation (= BAU treatment).

System Boundaries:

Field level. From the harvest of soybean (2018) until the harvest of maize (2019) and sorghum (2020) and microfiltrate production.

No significant influence on crop yield and biogas yield is expected through the microfiltrate fertigation to plants, compared with BAU (at least in the first years of application), and the biogas yield also depends on other external inputs (e.g., cattle manure, wine production residues). That is why it was decided in agreement with the case study leader (CSL) to leave the biogas plant out of the considered system.

Functional Unit

1 Mg of whole crop yield: maize (2019), sorghum (2020).

Allocation

No allocation. Whole plants are harvested for their use in energy production.

Hypothesis

Microfiltered digestate applied by fertigation (drip line) allows for reduced N fertilization

Goal

Decrease abiotic resource depletion (by using less mineral fertilizer) and decrease potential effects on global warming (by burning less diesel and by plowing less).

Assigned innovative strategy

Waste management and nutrient/carbon recovery

Experiment 5B – Digestate microfiltration/microsieving - technical sub-system

System and its function

The technical sub-system under study is a treatment process for agricultural digestate from a biogas plant in Emilia-Romagna, Italy, including a solid-liquid separation and a microfilter/microsieve of the liquid fraction. The further valorization of the substrate or its fractions is excluded from the system under study. The function of this sub-system is the treatment of digestate towards a certain maximum tolerable particle size so that it can be used in the drip-line fertigation system (Figure 7).

Reference

The reference sub-system is characterized by untreated agricultural digestate. Hence the sub-system only describes the impacts associated with the technical digestate treatment. The reference system without a technical treatment has zero impact within this analysis. Obviously, the use or storage of digestate has environmental impacts. However, this is excluded from this sub-system.

System boundaries

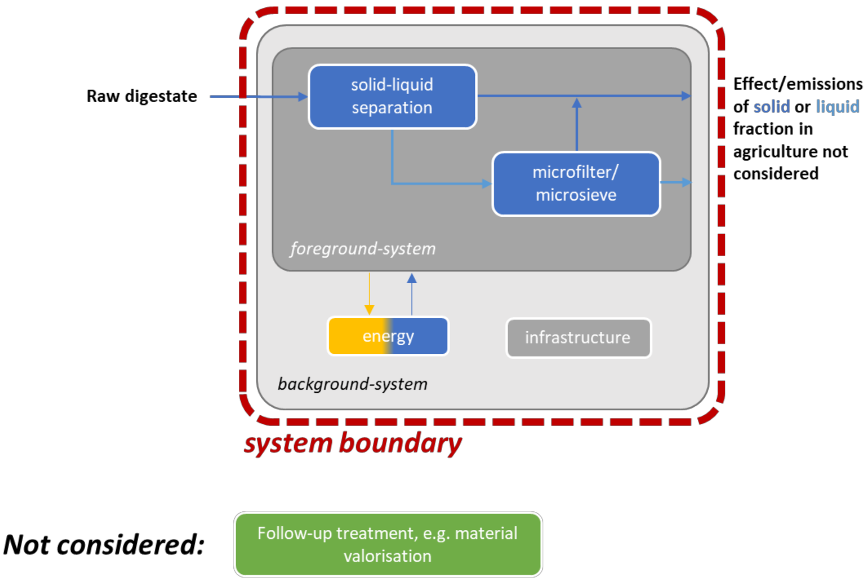

Figure 7. System boundaries of the technical sub-system (i.e., digestate microfiltration/microsieving) of Experiment 5B.

Functional unit/Relation for comparison

According to the system's function, the impacts are related to the reference flow of raw digestate. Potential environmental impacts will be described as “Impact (e.g., kg CO_2-Eq)/m³ digestate treated”.

Allocation

All related impacts due to changes in operation (e.g., energy consumption for microsieving) are allocated to the reference flow. Therefore, no allocation procedures are necessary within this scope.

Hypothesis

Mitigation of emissions through a drip-line irrigation/fertigation of agricultural digestate.

Goal

The goal is to mitigate emissions (e.g., ammonia) in agricultural digestate applications due to a drip-line irrigation/ fertigation system. To achieve this, a certain maximum tolerable particle size in the liquid digestate needs to be achieved to prevent the driplines from clogging. The maximum tolerable particle size in the (liquid) digestate is achieved by combining solid-liquid-separation (screw press) and microsieving the liquid fraction.

Assigned innovative strategy

Waste management and nutrient/carbon recovery

Experiment 6 – Digestate vacuum degasification for nitrogen recovery

System and its function

The sub-system under study is a treatment process for agricultural digestate from a biogas plant in Brandenburg, Germany, including CO_2 and NH_3 removal and recovery by vacuum stripping. The further valorization of the substrate or the corresponding mineral ammonium fertilizer is excluded from the system under study. The function of this sub-system is to treat the digestate to a certain ammonium content due to the vacuum stripping process (80 % NH_4-N recovery).

Reference

The reference sub-system is characterized by untreated agricultural digestate. Hence the sub-system only describes the impacts associated with the technical digestate treatment. The reference system without a technical treatment has zero impact within this analysis. Obviously, the use or storage of digestate has environmental impacts. However, this is excluded from this sub-system.

System boundaries

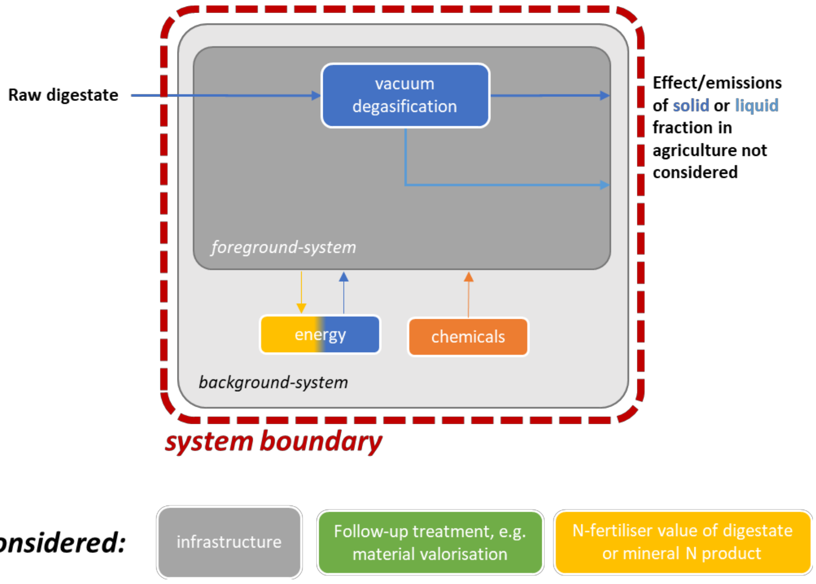

Figure 8. System boundaries of the technical sub-system (i.e., digestate vacuum degasification for N recovery) of Experiment 6.

The N-fertilizer value of the digestate/ N-depleted digestate of the mineral N product is excluded from the balance. It is assumed that the depleted digestate has a reduced fertilizing efficiency. However, the mineral N product compensates for this lower value. Reliable data for gained flexibility in N valorization and/or reduced emissions could not be provided in time. The exclusion can be estimated as a worst-case assumption; hence it is neglected that agricultural digestate and the mineral N product might have different fertilizing values or emission profiles. The sub-system is therefore limited to consumables such as energy and chemicals.

Functional unit/Relation for comparison

According to the system's function, the impacts are related to the reference flow of raw digestate. Potential environmental impacts will be described as “Impact (e.g., kg CO_2-Eq)/m³ digestate treated”.

Allocation

All related impacts due to changes in operation (e.g., energy consumption for vacuum degasification) are allocated to the reference flow. Therefore, no allocation procedures are necessary within this scope. The N-fertilizer value of digestate/ N-depleted digestate or mineral N product is excluded.

Hypothesis

Mitigation of ammonia emissions through vacuum degasification of agricultural digestate.

Goal

The goal is to mitigate emissions (e.g., ammonia) in agricultural digestate application due to a temporal distinguished and demand-orientated application of mineral nitrogen as a conventional fertilizer decoupled from digestate valorization. The technical sub-system under study aims for a technical process low in consumables and corresponding impacts.

Assigned innovative strategy

Waste management and nutrient/carbon recovery

Experiment 7 – Phosphate recovery from soybean wastewater

System and its function

The technical sub-system under study is a soybean wastewater treatment plant in Belgium, including an anaerobic followed by an aerobic treatment (Figure 9). Excess sludge from the aerobic treatment is dewatered and composted. The function of this sub-system is the treatment of soybean wastewater in-line with the present legal standards.

Reference

The reference system is characterized by the soybean wastewater treatment plant without a phosphate recovery unit. This reference scenario (baseline) is displayed in the comparison.

System boundaries

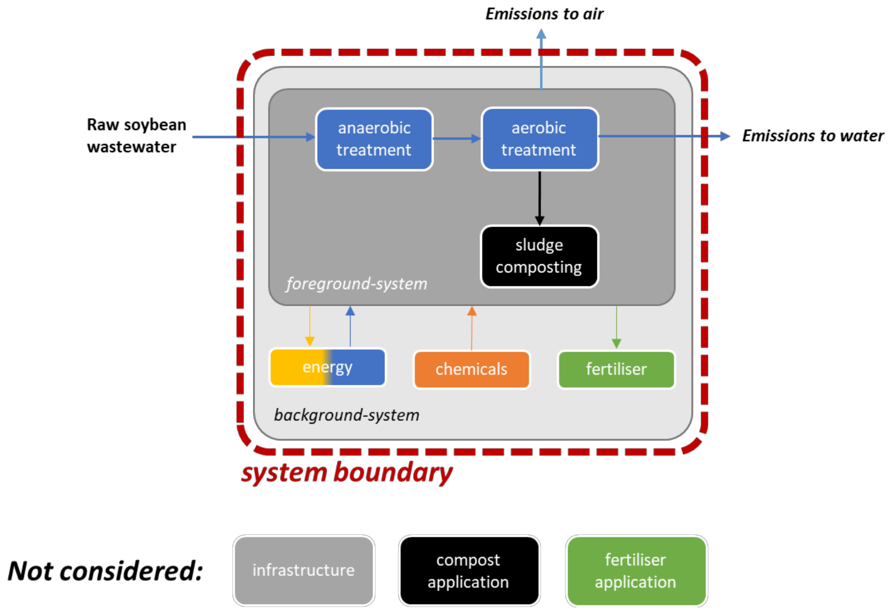

Figure 9. System boundaries of the technical sub-system (i.e., P recovery from soybean wastewater) of Experiment 7.

Functional unit/Relation for comparison

According to the system's function, the impacts are related to the reference flow of soybean wastewater. Potential environmental impacts will be described as "Impact (e.g., kg CO_2-Eq)/m³ wastewater treated".

Allocation

All related impacts due to changes in operation (e.g., the integration of struvite recovery) are allocated to the reference flow. Therefore, no allocation procedures are necessary.

Hypothesis

P recovery from wastewater and agricultural reuse in the form of struvite may substitute conventional P fertilizers at low environmental costs in production.

Goal

The goal is to recover phosphate (and nitrogen or potassium) from the wastewater treatment process in a mineral and plant-available form of struvite for potential reuse in agriculture and contribute to the circularity of the critical resource phosphorus.

Assigned innovative strategy

Waste management and nutrient/carbon recovery

Experiment 8 – Acid whey thickening with membrane treatment

System and its function

The technical sub-system under study is a thickening process for a dairy plant in the Czech Republic, including a pre-treatment followed by thickening with nanofiltration (NF) and NF permeate treatment with reverse osmosis to recover water for cleaning in place (Figure 10). The further treatment of thickened whey is excluded from the system under study. The function of this system is the treatment of raw acid whey towards a certain dry matter required by the follow-up treatment (e.g., anaerobic digestion)

Reference

The reference system is characterized by a present acid whey thickening process using a centrifuge for pre-thickening. This reference scenario (baseline) is displayed in the comparison.

System boundaries

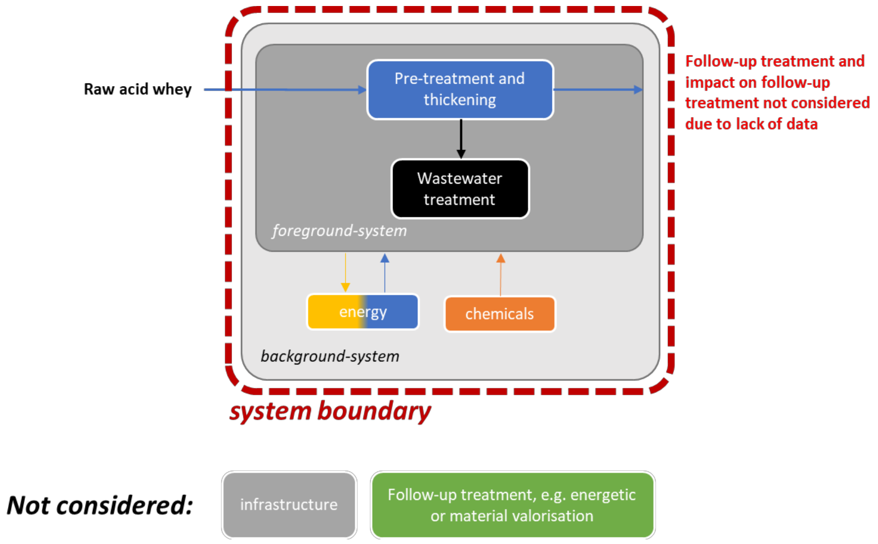

Figure 10. System boundaries of the technical sub-system (i.e., acid whey thickening with membrane treatment) of Experiment 8.

Functional unit/Relation for comparison

The impacts are related to the reference flow of acid whey to be treated according to the system's function. Potential environmental impacts will be described as "Impact (e.g., kg CO_2-Eq)/m^3 acid whey treated".

Allocation

All related impacts due to changes in operation (e.g., exchange of centrifuge by Electrospun-nanofibrous membrane (ENM)) are allocated to the reference flow. Therefore no allocation procedures are necessary.

Hypothesis

Utilization of a present waste stream at lower environmental costs than the current state of the art.

Goal

The goal is to utilize a present waste stream (acid whey) in a more efficient way than currently realized. Different valorization routes (energetic and agricultural valorization) were investigated. However, no accurate data were available; therefore, this balance only focuses on consumables (e.g., energy, chemicals).

Assigned innovative strategy

Waste management and nutrient/carbon recovery

Experiment 9 – Precision feeding and fertilization strategies

System and its function

The effect of precision feeding versus conventional feeding of cows on milk production is tested to reduce mineral N fertilization. There are two different feeding regimes: conventional feeding (= ad libitum fodder range for cows, BAU treatment) and precision feeding (diet is individually adapted to the physiological condition of the single animal). The slurry from both different feeding strategies is collected separately and used for fertilizer forage crops to test its N use efficiency. In addition, for each slurry, there are two different application times tested: a single application at the full rate before sowing (= BAU) and two applications (splitted application) (Figure 11). The nutrient (N) content of both slurries is expected to be different (reduced nutrient content in slurry from precision feeding). Thus, the same amount of N will be applied to each plot, but not the same total amount of slurry.

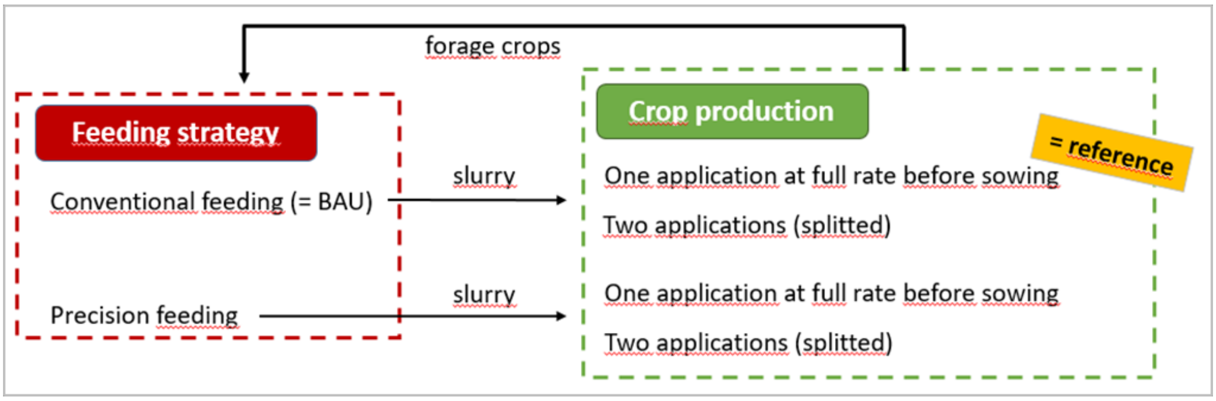

Figure 11. Considered scenarios of Experiment 9.

Reference

Single application of slurry from conventional feeding at the full rate before sowing (= BAU).

System Boundaries

Farm gate.

Functional Unit

1 kg energy corrected milk (ECM)

Allocation

Biophysical allocation. Main product = milk; co-product = meat.

Hypothesis

- Precision feeding of cows will decrease the demand for feed
- Fertilization with slurry will reduce the demand for N mineral fertilizer

Goal

- Reduce abiotic resource depletion associated with feed production, and decrease potential effects on global warming potential (GWP) related to slurry storage (to be verified).
- Reduce abiotic resource depletion (mineral fertilizer).

Strategy

Nutrient management in livestock production

Experiment 10 – Extensive management of organic dairy farms in the Lungau region

System and its function

The 20 organic dairy farms of the Austrian study region Lungau are characterized by extensive management and the regional purchase of feedstuffs, animals, and seeds. The feed ration of the dairy cows consists approximately of > 90 % roughage and 5 % concentrates. Due to the different site conditions (cutting frequencies of grassland and different amount of arable land on each farm), there are huge differences in the average milk yield between the farms. These extensively managed farms of the study region Lungau are compared to an average Austrian organically managed model dairy farm (MDF). The more extensive management in the Lungau region is the innovation to be assessed compared to a comparable average Austrian dairy farm.

Reference

Average Austrian organically managed model dairy farm (MDF). The input and output data of the MDF were derived from (i) national databases and were complemented by additional data based on (ii) specific models and (iii) expert judgments. For a more detailed description of the MDF, please see Grassauer et al. (2022).

System Boundaries

The considered system boundaries of the Lungau farms are set at the farm gate (i.e., from cradle to farm gate) (Figure 12) and include the whole farm area dedicated to milk production (physical limit) and cover one calendar year (temporal limit). Indirect emissions from upstream processes of the purchased inputs (e.g., production, transportation) were considered through eco-inventories from the SALCA and ecoinvent databases. However, due to the Lungau production regulations, feedstuffs, animals, and organic fertilizers must be purchased from the Lungau region. Therefore, and to depict the extensive management of the Lungau farms, we adapted six existing eco-inventories for organic agriculture (i.e., eco-inventories for purchased wheat grain, barley grain, rye grain, grass silage, hay, and calves) based on primary data from the Lungau farms. Detailed information on the amended eco-inventories is given in the supplementary material of Grassauer et al. (2022).

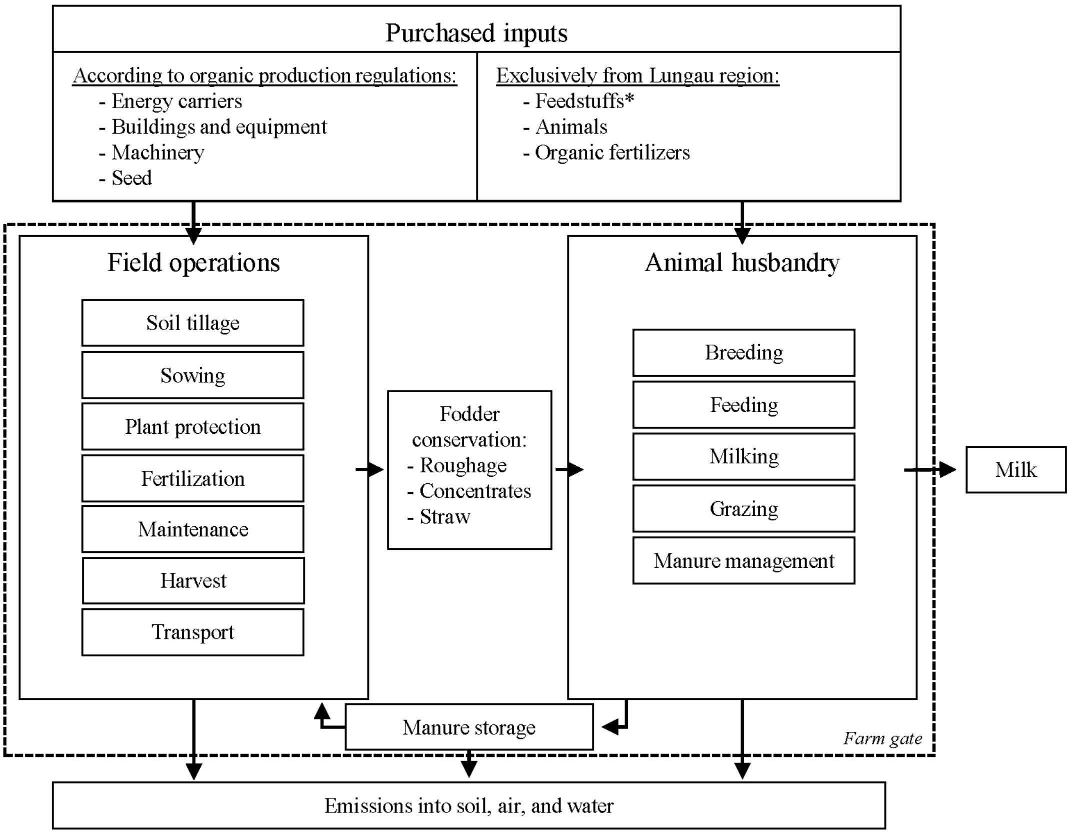

Figure 12. System description of Experiment 10. Adapted from Grassauer et al. (2022). *Except for feeding lime, cattle salt, and mineral feed.

Functional Unit

1 kg ECM

Allocation

Allocation is based on a hierarchical process consisting of physical and monetary criteria. Please see Pedolin et al. (2021) for a detailed description.

Hypothesis

Through the extensive management in a less favorable production area, the Lungau farms practice site-adapted agriculture and, therefore, can contribute to food production in an environmentally competitive manner.

Goal

Show the environmental performance of a set of Austrian organic dairy farms that produce milk in a less favorable production area compared to a typical Austria organic dairy farm.

Strategy

Nutrient management in livestock production

3. RESULTS

For each experiment, the chosen indicators (see 2.2. Description of the calculated experiments, subsection "Assigned innovative strategy") are depicted in an overall graphic that shows their total impact and an absolute contribution analysis for each stage of the life cycle. An absolute contribution analysis shows the total impact of a certain life cycle indicator (e.g., global warming potential) of a certain product divided into its different contributing sources (e.g., agricultural machinery, chemicals, or energy carriers). The legend of the contribution analysis differentiates between the different experiments.

Transport: all transport emissions (e.g., distribution of fertilizers from plant to storage)
Fertilizers: emissions related to the production of fertilizers (e.g., mining activities)
Energy Carriers: emissions related to the combustion of energy carriers (e.g., diesel combustion in tractor)
Chemicals, at regional storehouse: emissions related to the production of chemicals (e.g., production of pesticides)
Agriculture, production: direct emissions from agricultural production (e.g., direct emissions from fertilization)
Agricultural machinery, production: emissions from the production of agricultural machinery (e.g., tractor production)

Experiment 1 – N use efficiency of winter wheat

Results for selected indicators

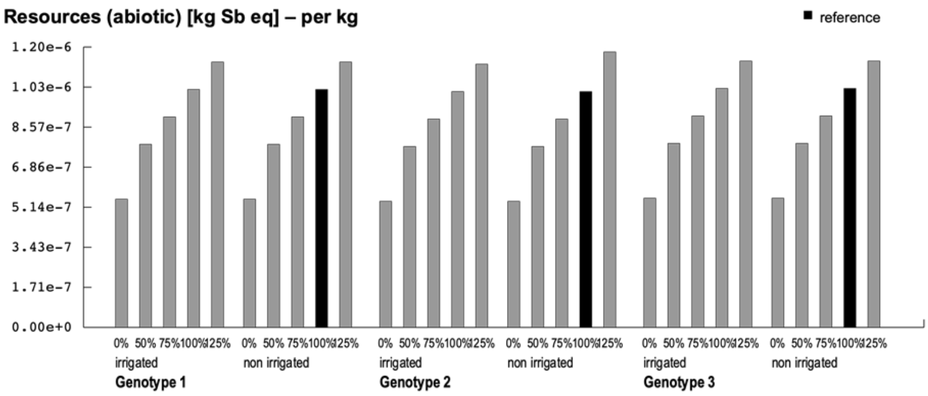

Figure 13. Abiotic resource potential per kg wheat grain of three different genotypes, two (simulated) weather conditions, and five N fertilization levels of Experiment 1.

The results in Figure 13 show the impact on abiotic resource depletion per kg of winter wheat grain in terms of kg Sb-Eq. There is no difference between the three genotypes and no difference between irrigated and non-irrigated farming. The impact increases with the level of N fertilization. The background processes in the mining ores are the main contributors to abiotic resource use.

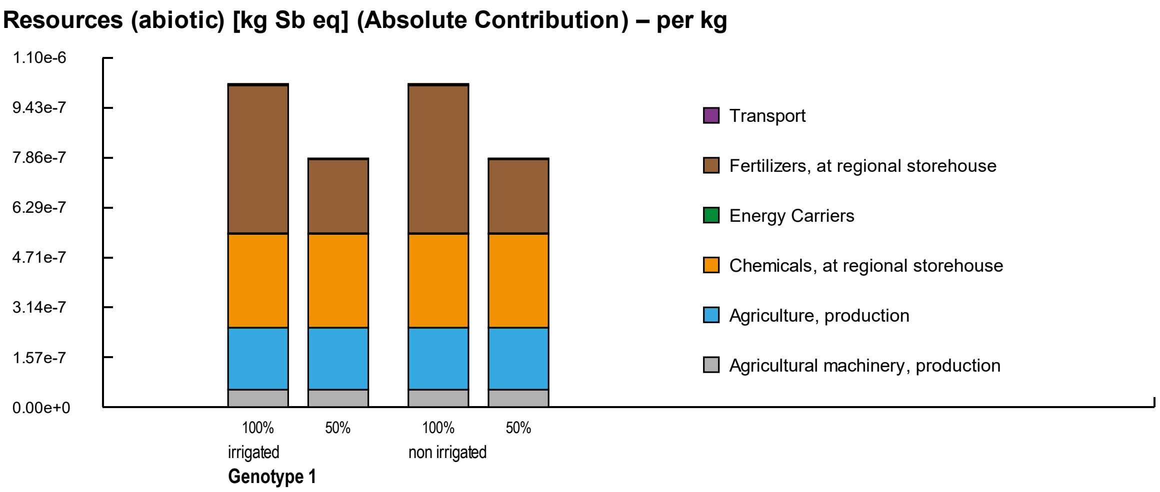

Figure 14. Absolute contribution analysis of the abiotic resource potential per kg wheat grain of one genotype, two (simulated) weather conditions, and two fertilization levels of Experiment 1.

Figure 14 shows the absolute contribution analysis of the abiotic resource potential per kg of wheat grain. The contribution of the agricultural machinery, the agricultural production, the used chemicals, the energy carriers, and the transport is the same for all scenarios. The differences in total impact are due to the emissions from the fertilizers, which are higher for the fertilization level of 100% and only half for the fertilization level of 50%.

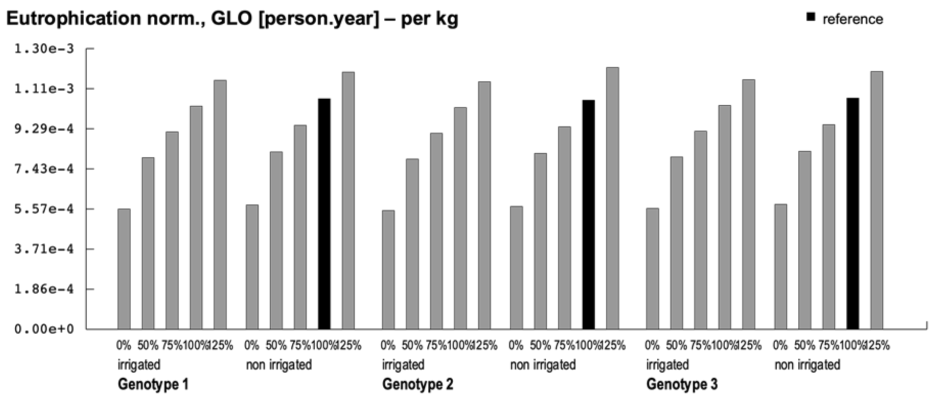

Figure 15. Eutrophication per kg wheat grain of three different genotypes, two (simulated) weather conditions, and five N fertilization levels of Experiment 1.

The impact on the eutrophication potential per functional unit (1kg of wheat grain) shows no difference between the three genotypes and no difference between irrigated and non-irrigated farming (Figure 15). The impact increases with the level of N fertilization. About 90% of the entire impact on eutrophication is due to the direct emissions of the agricultural process. The background processes play a minor role. The main emissions are nitrate, followed by ammonia and nitrogen oxides.

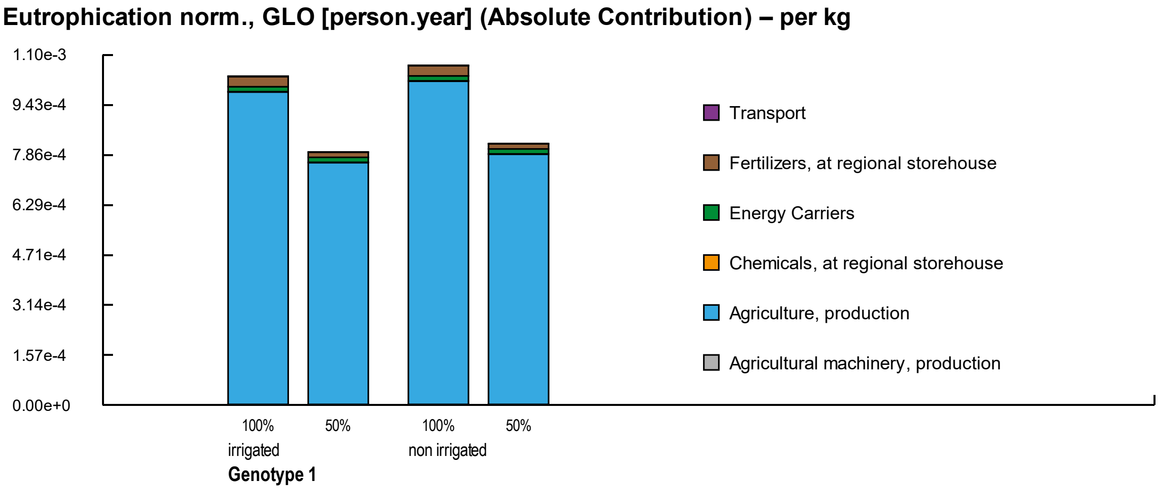

Figure 16. Absolute contribution analysis of the eutrophication per kg wheat grain of 3 different genotypes, two (simulated) weather conditions, and two fertilization levels of Experiment 1.

The differences in total impact for the absolute contribution analysis of the eutrophication potential per kg of wheat grain (Figure 16) are mainly due to the emissions from agricultural production, which are higher for the fertilization level of 100% and lower for the fertilization level of 50%.

The experiment shows that there is an optimal point for fertilization and excess fertilization leads to higher resource depletion and higher eutrophication that cannot be counter-balanced with a higher yield.

Experiment 2 – Slurry application techniques

Results for selected indicators

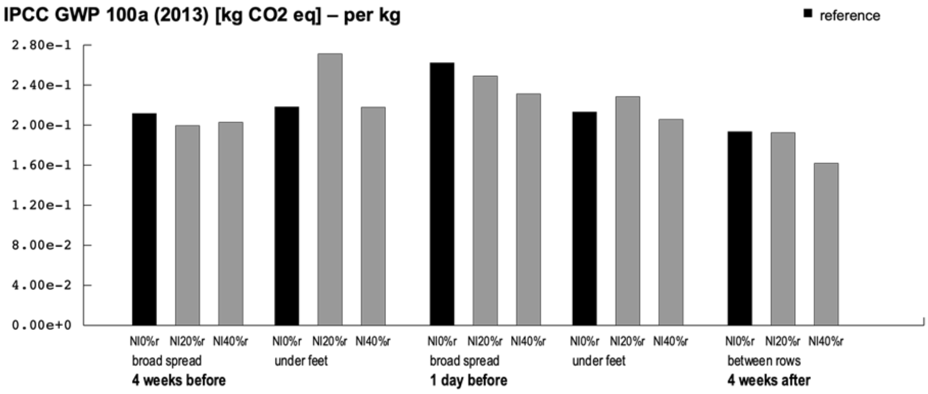

Figure 17. Global warming potential per kg of whole maize using three different timings for fertilization, two different application techniques, and two different levels of nitrification inhibition of Experiment 2.

Figure 17 shows the results for global warming potential in terms of kg CO_2-Eq per kg of whole maize. The slurry application yields the lowest emissions when applied "4 weeks after" sowing and most "1 day before". Under feet application yields lower emissions for the case of "1 day before", the inverse is true for the case of "4 weeks before". There is a tendency for lower emissions with increasing inhibition of nitrification. Slightly below 40% of the emissions are direct emissions from the agricultural process. The other main contributor is the production of fertilizers.

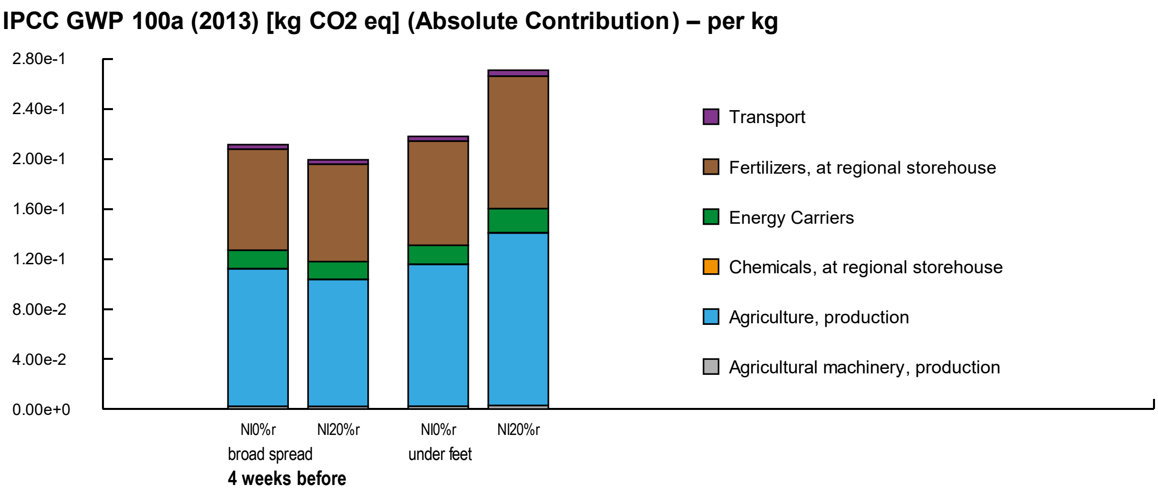

Figure 18. Absolute contribution analysis of global warming potential per kg of whole maize using three different timings for fertilization, two different application techniques, and two different levels of nitrification inhibition of Experiment 2.

The absolute contribution analysis of global warming potential per kg of whole maize (Figure 18) shows that the differences in total impact are due to an increase of emissions of all life cycle stages in a proportional manner.

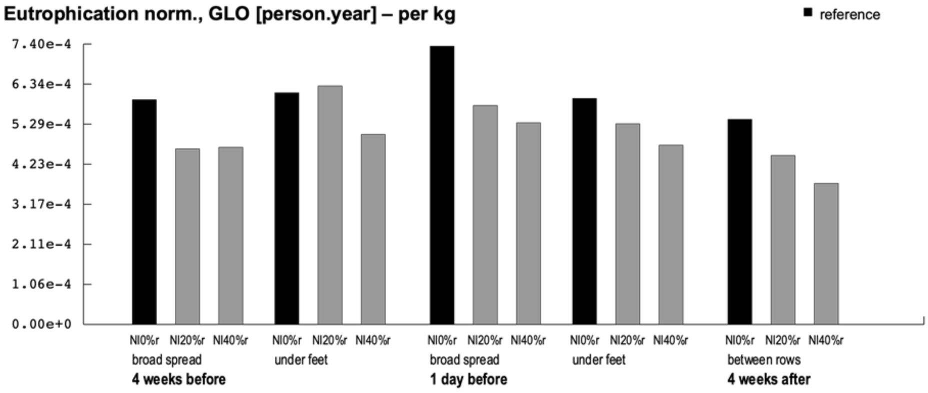

Figure 19. Eutrophication per kg of whole maize using three different timings for fertilization, two different application techniques, and two different levels of nitrification inhibition of Experiment 2.

The results for eutrophication in terms of person*year in terms of kg whole maize in Figure 19 show the slurry application yields the lowest emissions when applied 4 weeks after sowing and most 1 day before. The application technique yielding the lowest emissions is unclear as the ranking changes. Generally, the higher the reduction of nitrification, the lower the emissions. The main contributor to the emissions is the agricultural process which leads to mainly nitrate and ammonia emissions.

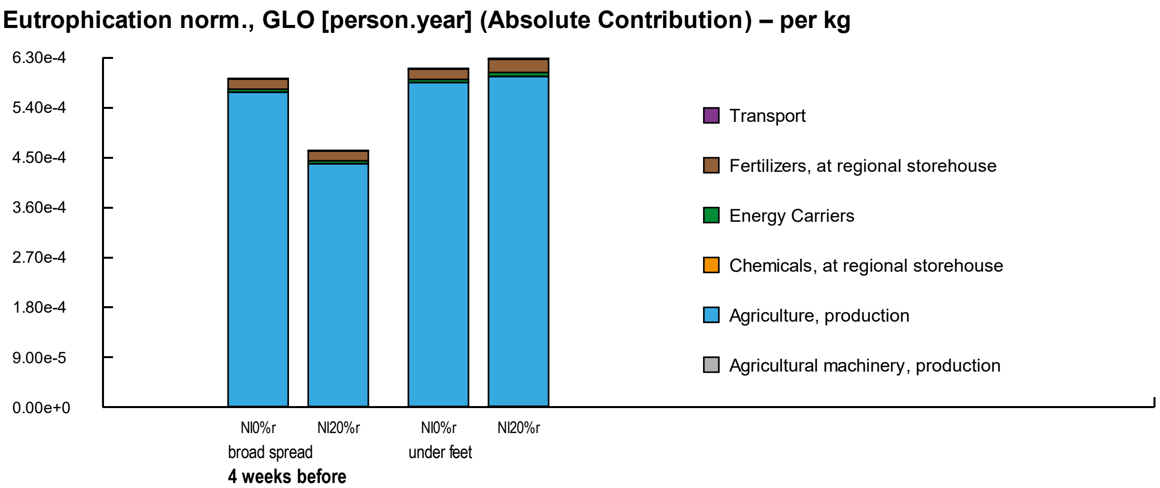

Figure 20. Absolute contribution analysis of eutrophication per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

Figure 20 shows the results for the absolute contribution analysis of eutrophication per kg of whole maize. The differences in total impact are due to an increase of emissions of all life cycle stages in a proportional matter.

Experiment 3 – Conservation tillage

Results for selected indicators

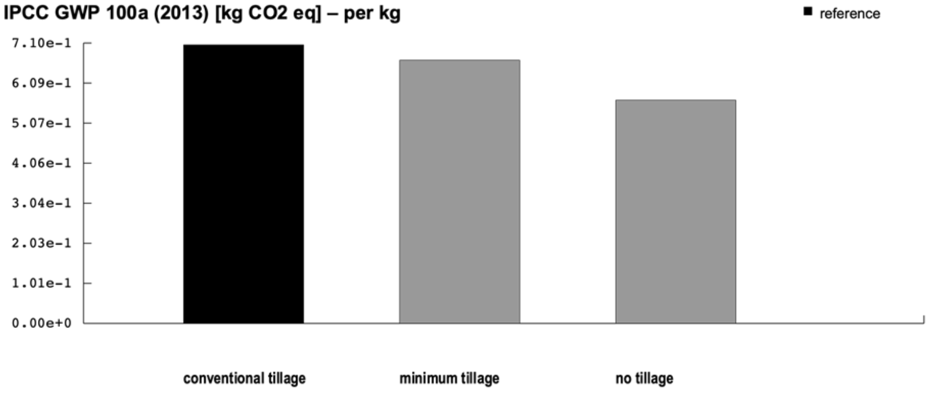

Figure 21. Global warming potential per kg of wheat using three different tillage systems of Experiment 3.

Conventional tillage yields the highest emissions, followed by minimum tillage and no-tillage in terms of kg CO_2-Eq per kg of wheat (global warming potential, Figure 21). The direct emissions of the agricultural process mount up to 50%, including the diesel combustion of the tractor. Other emissions come from background processes of fertilization production, for example, the heat consumption in the production plant.

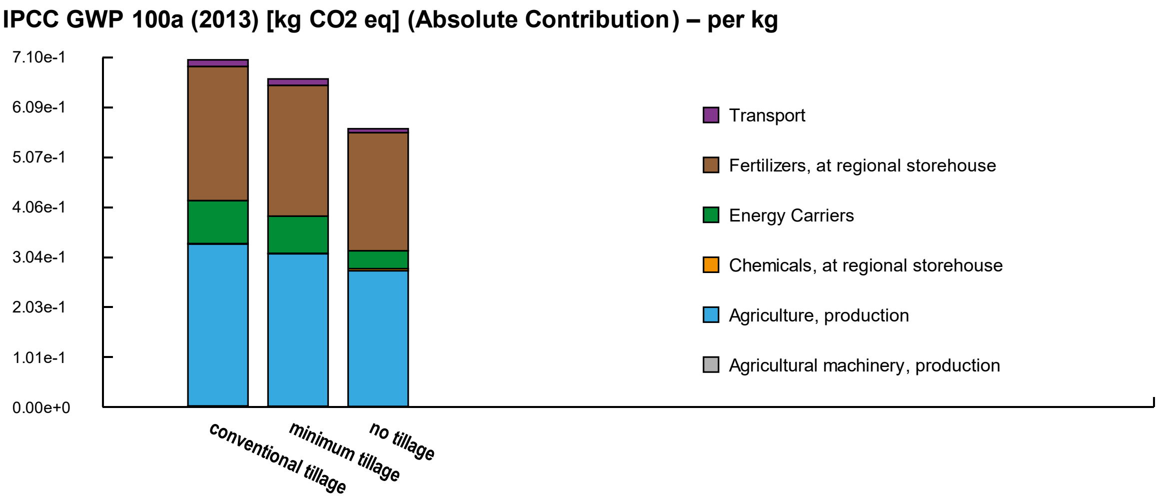

Figure 22. Absolute contribution analysis of global warming potential per kg of wheat using three different tillage systems of Experiment 3.

Figure 22 shows the results for the absolute contribution analysis of global warming potential per kg of whole maize. The differences in total impact are due to an increase in emissions of all life cycle stages, but the increase is not equal in all stages – hence it deserves closer investigation.

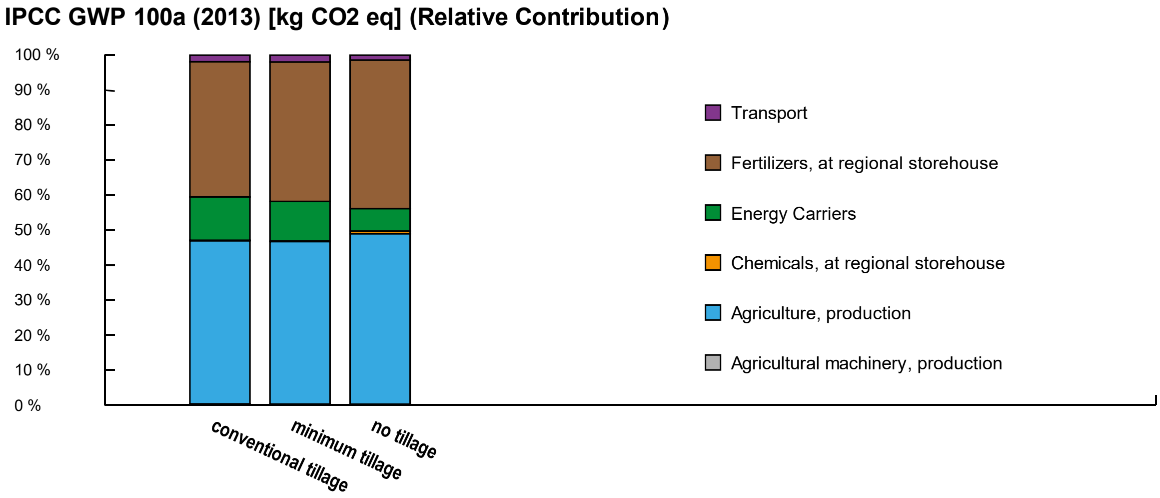

Figure 23. Relative contribution analysis of global warming potential per kg of wheat using three different tillage regimes of Experiment 3.

In order to see the partitioning clearer, Figure 23 shows the relative contribution analysis. The difference in overall impact between conventional and minimum tillage is explained by a rather proportional difference (the relative contribution between all life cycle stages stays rather constant). A more pronounced change is visible for the no-tillage scenario, where the energy carrier contributes less to the overall impact than for the other two scenarios. However, a small (compared to the overall impact) contribution of the chemicals (pesticides, namely glyphosate) is detectable.

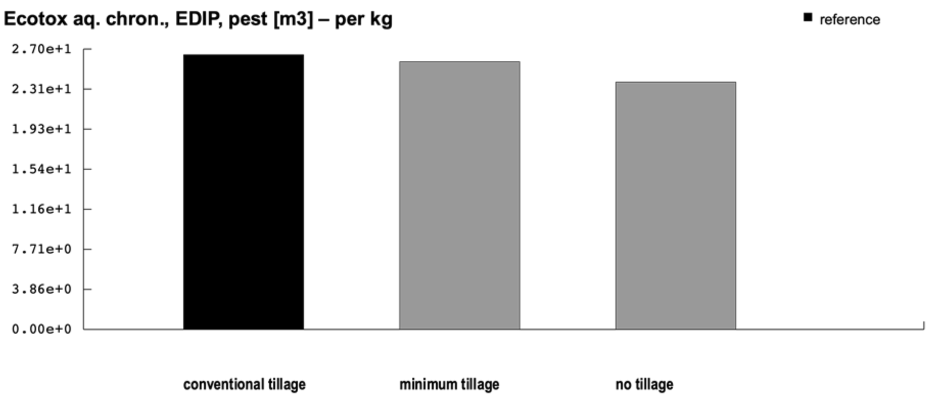

Figure 24. Aquatic ecotoxicity per kg of wheat using three different soil treatments of Experiment 3.

Figure 24 shows the results for ecotoxicity in terms of kg CO_2-Eq per kg of wheat. Conventional tillage yields the highest emissions, followed by minimum tillage and no-tillage. The direct emissions of the agricultural process due to the application of pesticides dominate the impacts on aquatic ecotoxicity.

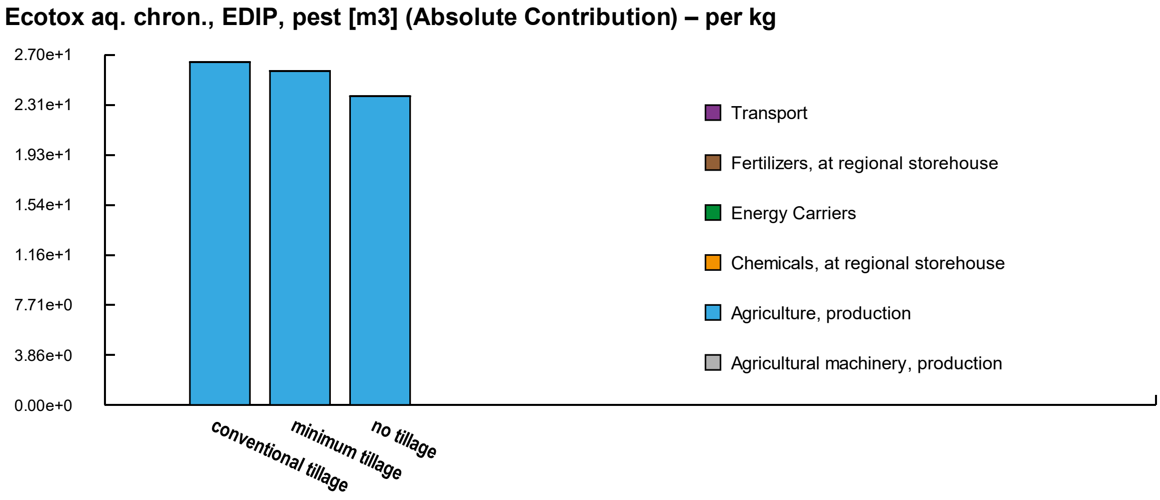

Figure 25. Absolute contribution analysis of aquatic ecotoxicity per kg of wheat using three different soil treatments of Experiment 3.

The absolute contribution analysis of ecotoxicity per kg of whole maize (Figure 25) shows that the impact is characterized by the life cycle stage of agricultural production only. Differences in total impact are due to an increase in emissions of all life cycle stages, but the increase is not proportional.

Experiment 4A – Test of solar-dried fertilizers in crop rotations

Results for selected indicators

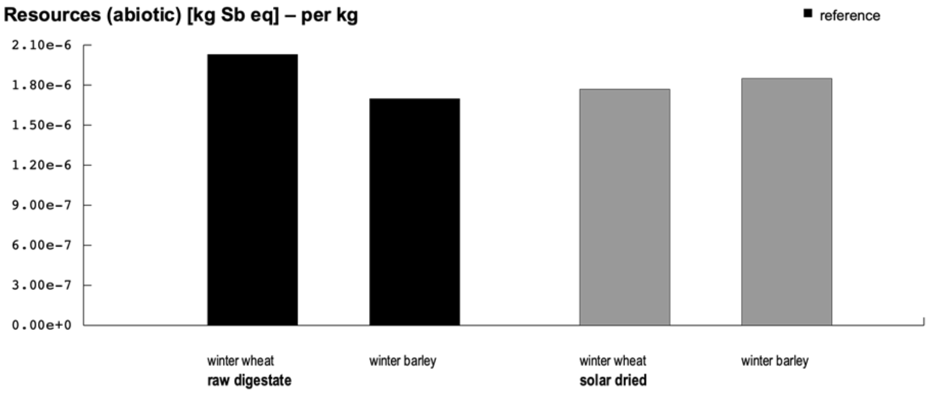

Figure 26. Abiotic resource depletion per kg of crop yield using two different fertilizers of Experiment 4A.

Figure 26 shows the results for abiotic resource depletion in kg Sb-Eq per kg of crop yield. For winter wheat, the raw digestate has higher emissions than the solar-dried scenario, while for winter wheat, the opposite is true.

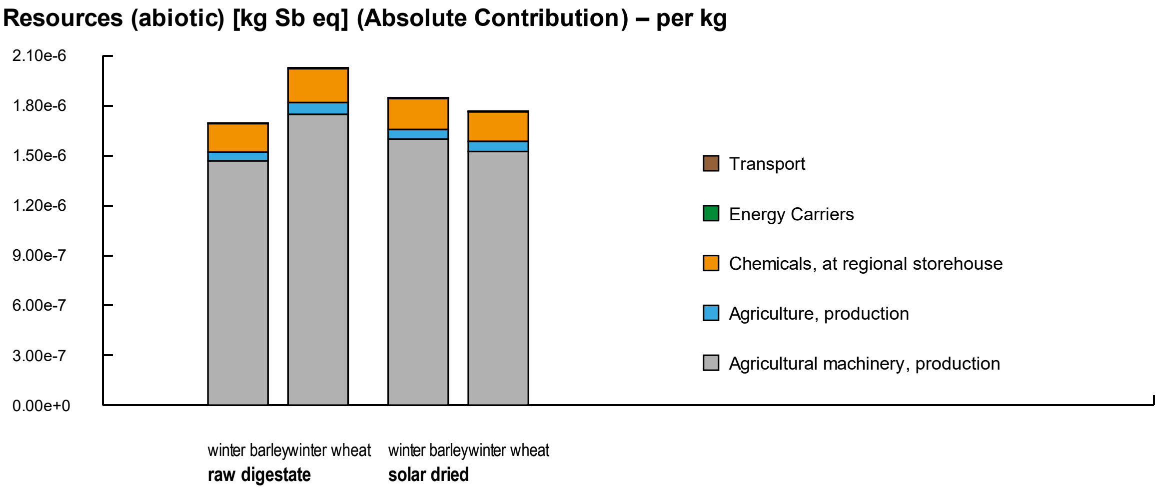

Figure 27. Absolute contribution analysis of abiotic resource depletion per kg of crop yield using two different fertilizers of Experiment 4A.

The differences in the impact are due to a proportional increase or decrease of impact across all life cycle stages, as shown in Figure 27 (the absolute contribution analysis of abiotic resource use per kg of crop yield).

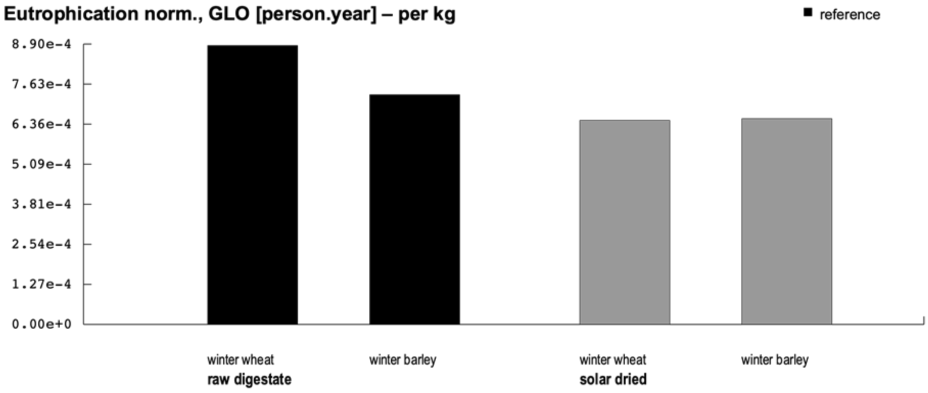

Figure 28. Eutrophication per kg of crop yield using two different fertilizers of Experiment 4A.

Figure 28 shows the results for eutrophication in kg Sb-Eq per kg of crop yield. For winter wheat, the raw digestate has higher emissions than the solar-dried scenario, while for winter wheat, the opposite is the case.

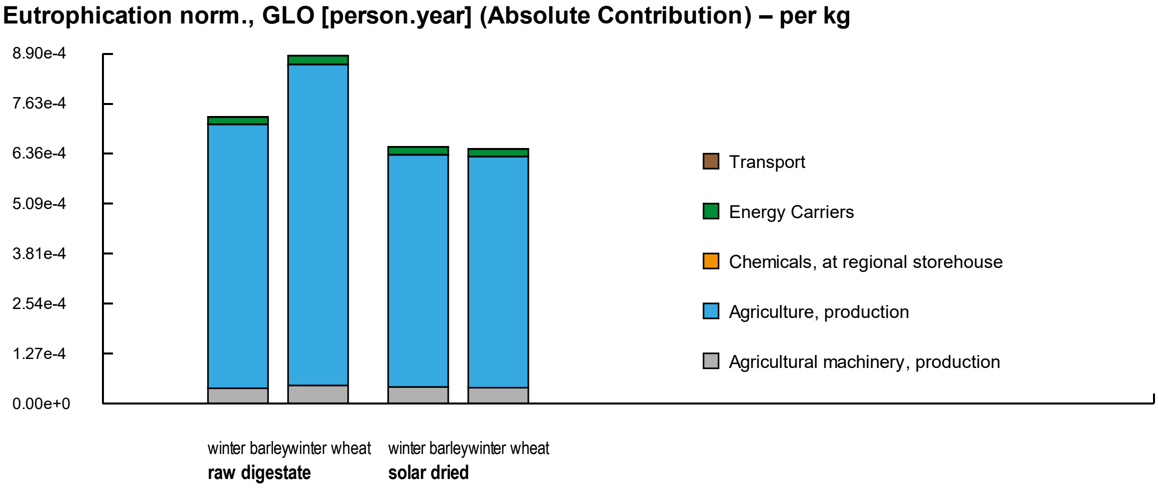

Figure 29. Absolute contribution analysis of eutrophication per kg of crop yield using two different fertilizers of Experiment 4A.

The absolute contribution analysis of eutrophication per kg of crop yield in Figure 29 shows the differences in impact are due to an increase in impact in the agricultural production stage while the other life cycle stages stay almost constant.

Experiment 4B - Digestate acidification and solar drying – technical sub-system

Results for selected impact categories

As indicated in Figure 30, the overall sulfuric acid consumption for raw digestate acidification is significant and shows a high impact contribution in all related impact categories. This results from fossil sulfur consumption in the production of sulfuric acid. The solid-liquid separation prior to acidification and solar drying reduces the acid demand significantly. Electricity and polymer are associated with lower efforts in all impact categories. However, the liquid fraction of the digestate remains untreated.

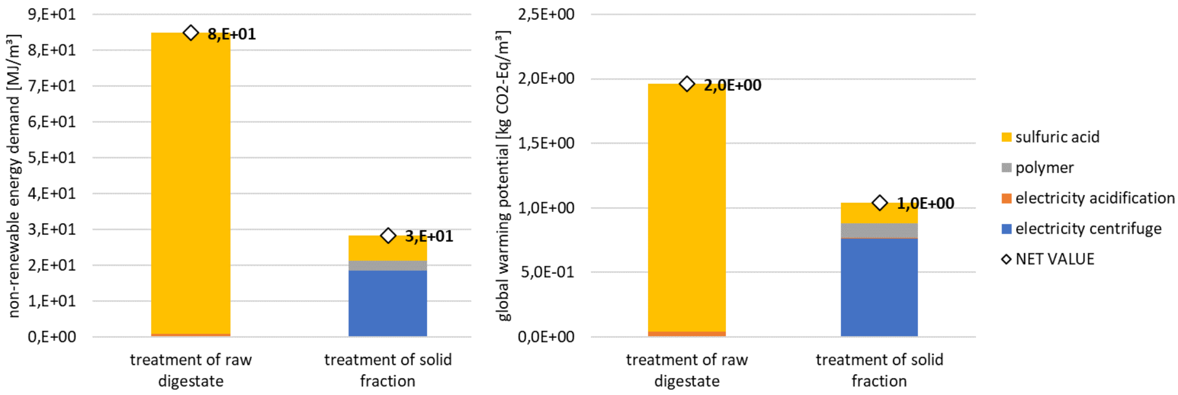

Figure 30. Non-renewable cumulative energy demand and global warming potential for the different technical sub-systems involving acidification and solar drying of Experiment 4B. Further impact categories are shown in the annex.

Experiment 5A – Fertigation with microfiltered digestate

Results for selected indicators

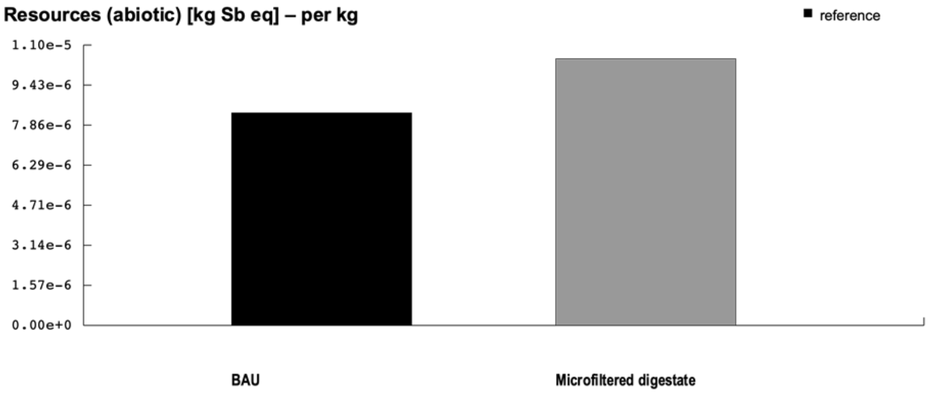

Figure 31. Abiotic resource depletion per kg of crop yield using two different fertilization schemes of Experiment 5A.

The business-as-usual scenario performs better than the microfiltered digestate in terms of impact on abiotic resource depletion in kg Sb-Eq per kg of crop yield, as shown in Figure 31.

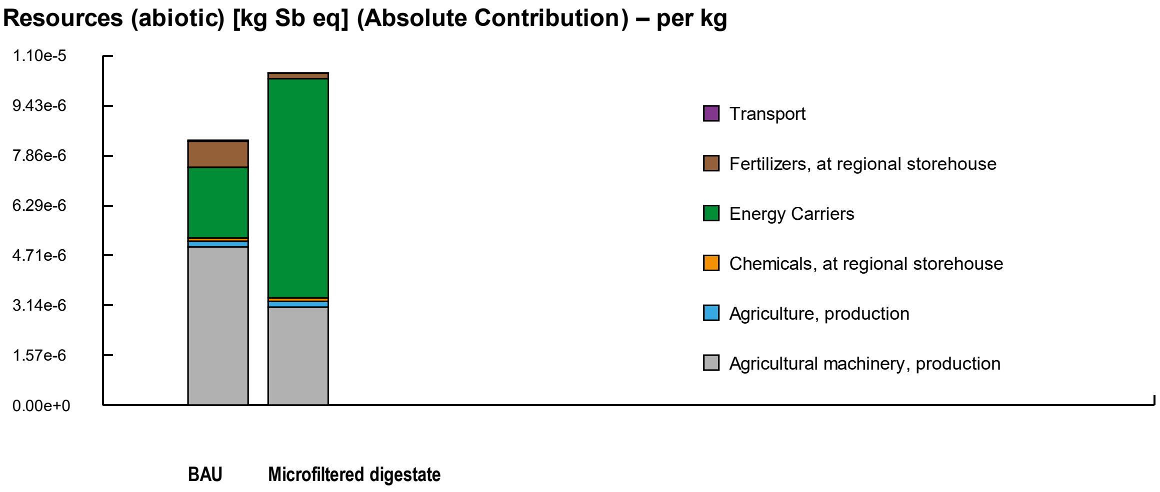

Figure 32. Absolute contribution analysis of abiotic resource depletion per kg of crop yield using two different fertilization schemes of Experiment 5A.

Figure 32 shows the results for the absolute contribution analysis of abiotic resource depletion per kg of crop yield. The differences in impact are due to an increased need for energy carriers in the case of the microfiltered digestate, which is larger than the decrease in impacts from the agricultural machinery.

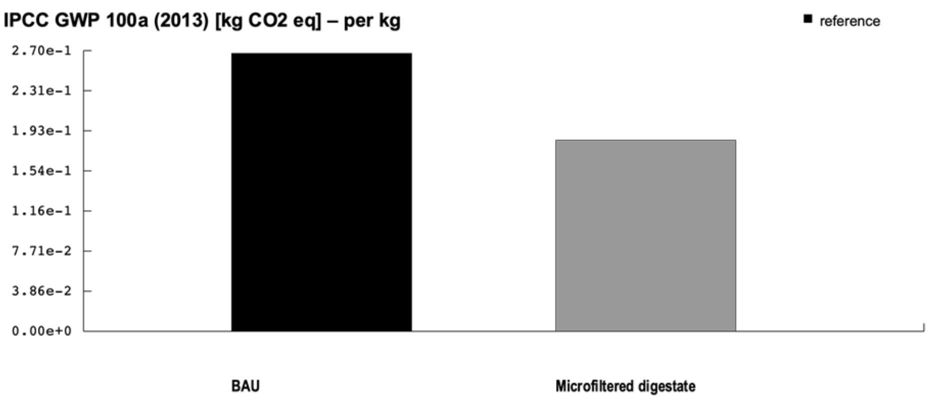

Figure 33. Global warming potential per kg of crop yield using two different fertilization schemes of Experiment 5A.

The business-as-usual scenario produces higher emissions related to global warming potential than the microfiltered digestate (results shown in Figure 33, in kg CO_2-Eq per kg of crop yield). The emissions are mainly carbon dioxide and dinitrogen monoxide.

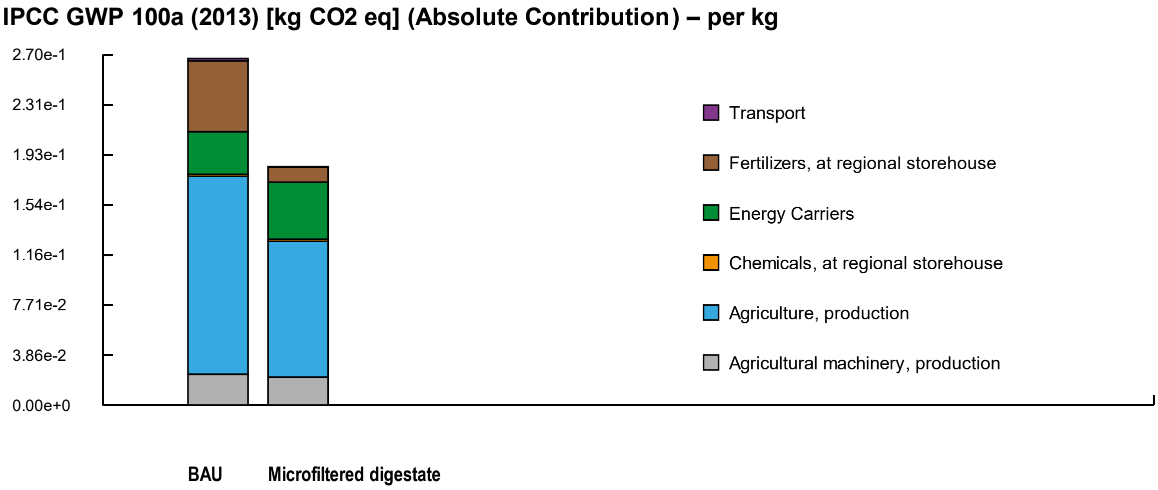

Figure 34. Absolute contribution analysis of global warming potential per kg of crop yield using two different fertilization schemes of Experiment 5A.

Figure 34 shows the results for the absolute contribution analysis of global warming potential per kg of crop yield. The impact difference is due to a decrease in the direct emissions from agricultural production for the innovative system and the need for fertilizers in the BAU scenario.

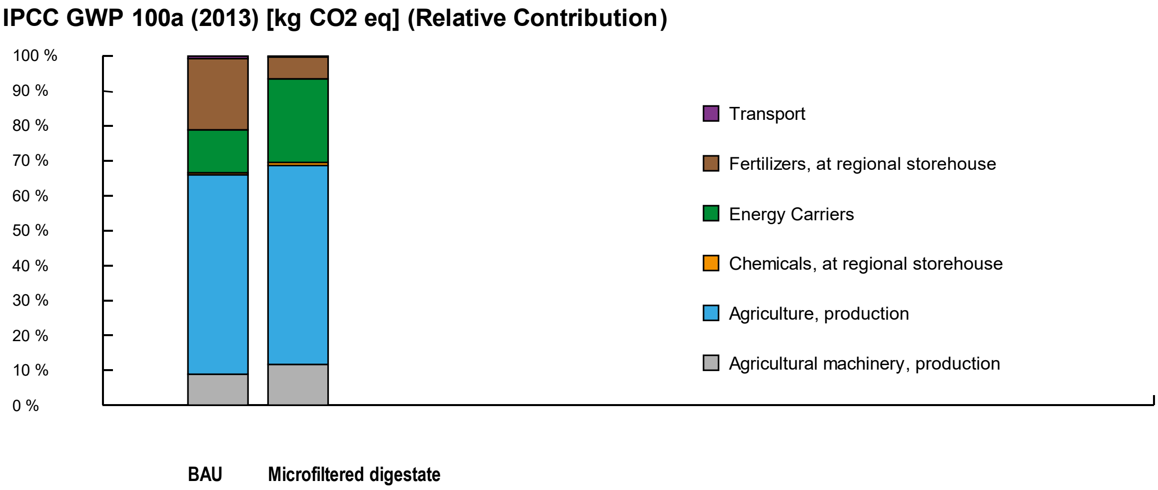

Figure 35. Relative contribution analysis of global warming potential per kg of crop yield using two different fertilization schemes of Experiment 5A.

The results for the relative contribution analysis of global warming potential per kg of crop yield (Figure 35) show the total composition of the impact between the two scenarios is rather similar except for the energy carriers, which are higher for the microfiltered digestate, and for the fertilizers, which are higher for the BAU case.

Experiment 5B - Digestate microfiltration/microsieving - technical sub-system

Results for selected impact categories

The results for cumulative energy demand and global warming potential (Figure 36) indicate a high contribution for electricity of the screw press and the microfilter (microsieve) compared to the efforts estimated for infrastructure (e.g., steel, piping).

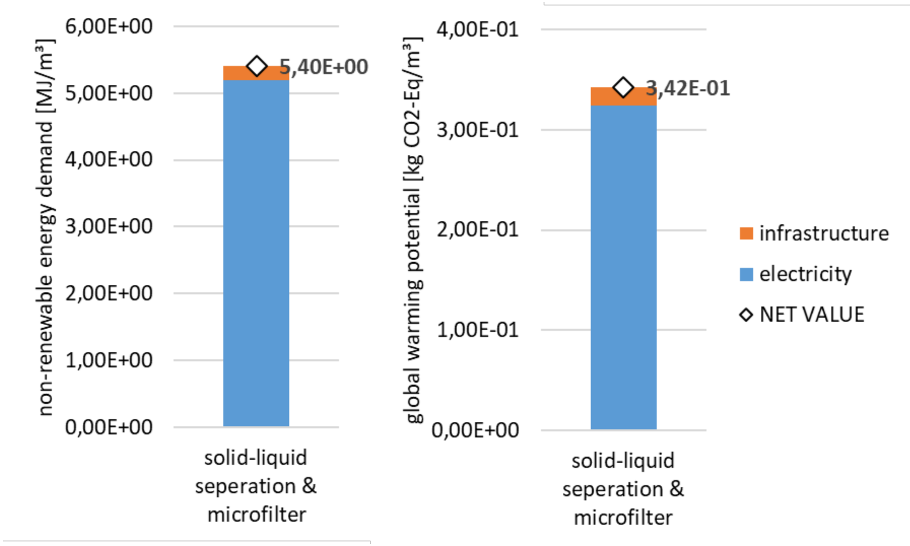

Figure 36. Non-renewable cumulative energy demand and global warming potential for the technical sub-system with microsieving of Experiment 5B. Further impact categories are shown in the annex.

Experiment 6 - Digestate vacuum degasification for nitrogen recovery

Results for selected impact categories

The four scenarios represent different developmental stages during the project. The initial operations suffer from extensive heat consumption, influencing the energy demand and the global warming potential. Also, the use of caustic soda and sulfuric acid show relevant contributions to the overall energy demand, while caustic soda usage is also relevant for the global warming potential. Due to optimization steps, caustic soda consumption and especially heat consumption could be reduced separately, which led to a significant reduction in terms of energy demand and global warming potential (Figure 37).

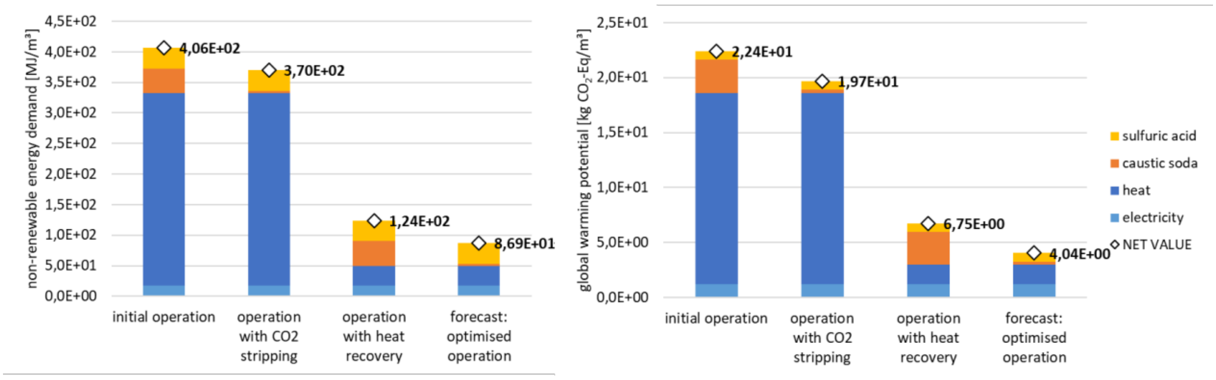

Figure 37. Non-renewable cumulative energy demand and global warming potential for the technical sub-system with vacuum degasification for different operating modes of Experiment 6. Further impact categories are shown in the annex.

Experiment 7 - Phosphate recovery from soybean wastewater

Results for selected impact categories

Three different recovery scenarios were considered besides the baseline (soybean WWTP) (Figure 38). The soybean WWTP (baseline scenario)) is energy positive and carbon-neutral due to the high quantity of biogas produced in the anaerobic wastewater treatment prior to aerobic wastewater treatment. Using phytase treatment prior to anaerobic treatment to release phosphate, bio-acidification prior to anaerobic treatment to release phosphate, and recovery of K-struvite in the post-treatment of aerobic treatment, the P-recovery rates are approximately 30-40 % of the P influent, dependent on the treatment strategy. All three strategies increase the energy demand and the global warming potential of the entire treatment.

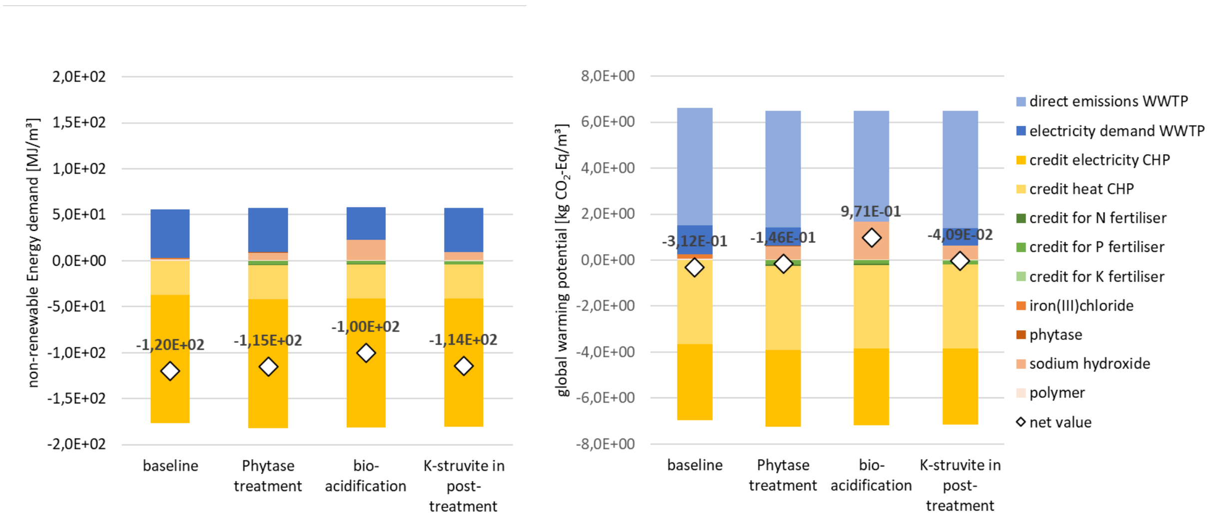

Figure 38. Non-renewable cumulative energy demand and global warming potential for the technical sub-system with phosphate recovery for different approaches/strategies of Experiment 7. Further impact categories are shown in the annex.

Experiment 8 - Acid whey thickening with membrane treatment

Results for selected impact categories

The results (Figure 39) indicate that at least two-thirds of energy demand and global warming potential is contributed by electricity consumption of the pre-thickening and thickening of whey. The energetic efforts and climate-relevant contributions of the sludge and brine treatment in wastewater treatment are expected to be similar for both treatment steps. Overall the novel treatment with Electrospun-nanofibrous membrane (ENM) reveals an advantage due to the reduction of electricity consumption compared to a centrifuge, while the impact contribution of chemicals production for membrane cleaning increase only slightly.

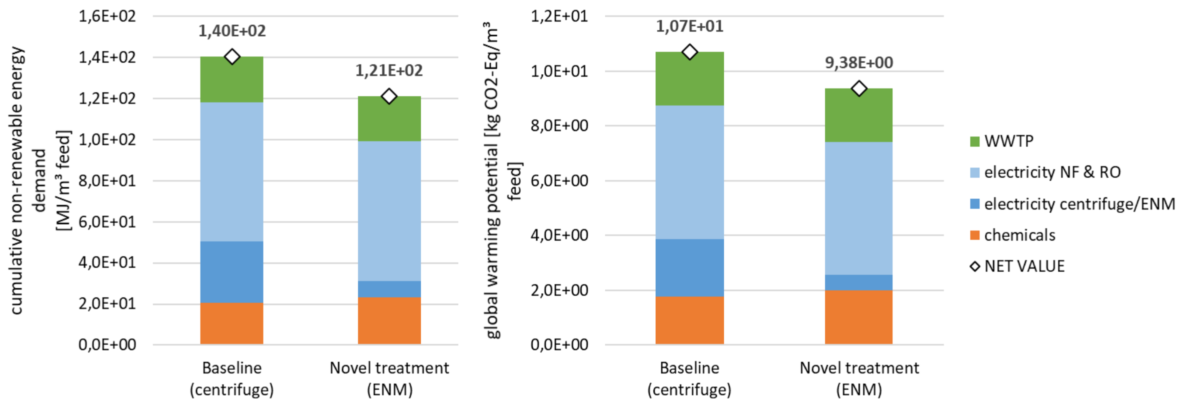

Figure 39. Non-renewable cumulative energy demand and global warming potential for the technical sub-system with acid whey thickening with membrane treatment of Experiment 8. Further impact categories are shown in the annex.

Experiment 9 – Precision feeding and fertilization strategies

Results for selected indicators

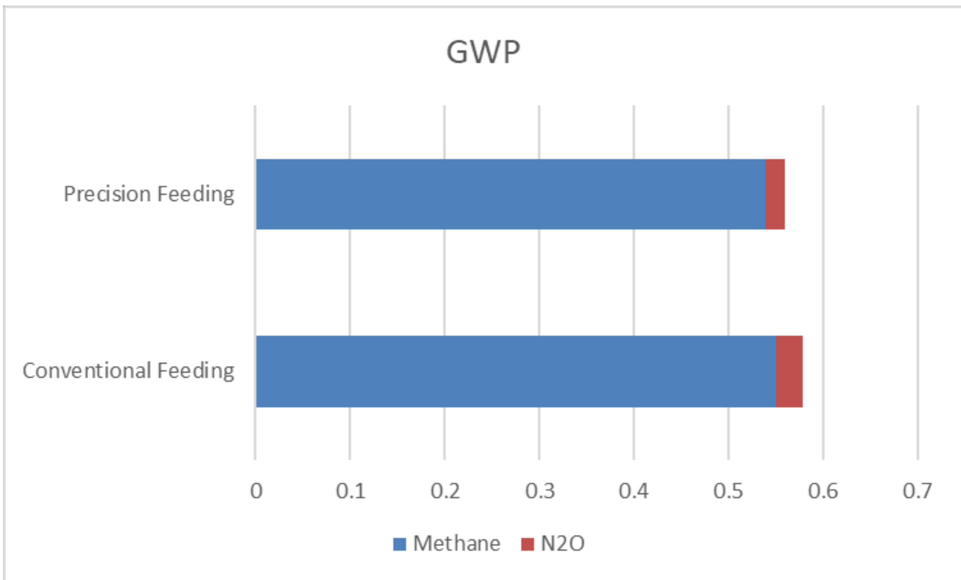

Figure 40. Global warming potential per kg of ECM using two different feeding schemes of Experiment 9.

The results are shown in Figure 40 for the global warming potential per kg of milk as an absolute contribution analysis based on the gases emitted. Methane is the main contributor to both precision and conventional feeding.

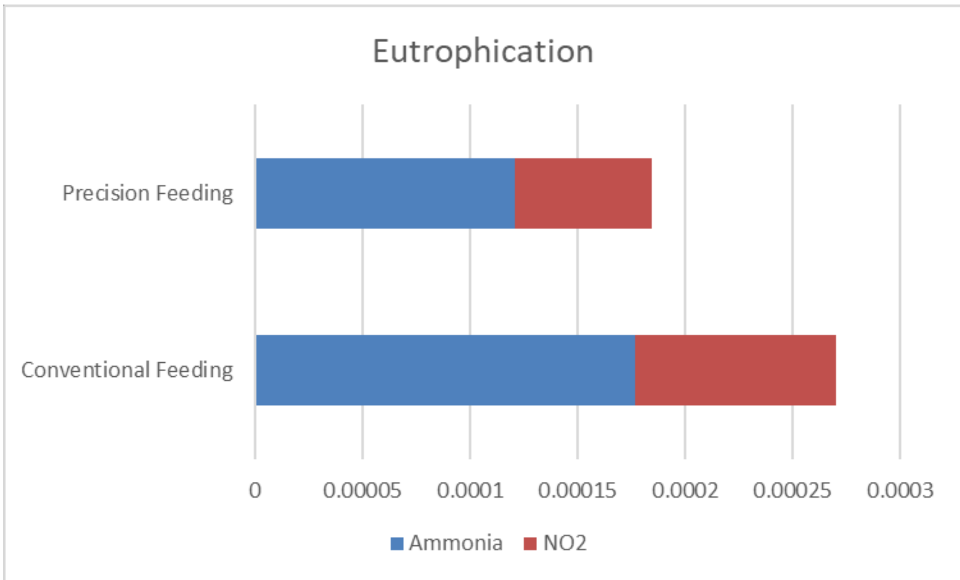

Figure 41. Eutrophication per kg of ECM using two different feeding schemes of Experiment 9.

The results are shown in Figure 41 for the eutrophication potential per kg of milk as an absolute contribution analysis based on the gases emitted. The absolute contribution is higher for both gases in the conventional feeding.

Experiment 10 – Extensive management of organic dairy farms in the Lungau region

Results for selected indicators

Figure 42 presents the global warming potential per kg ECM of the 20 Lungau farms compared to the model dairy farm (MDF). The MDF emits 1.3 kg CO_2-Eq per kg ECM, whereas the Lungau farms cause a mean of 1.6 (within a range of 0.8 to 2.5) kg CO_2-Eq per kg ECM. The absolute and relative contribution analyses (Figure 43) revealed "Agriculture, production" as the main contributor to GWP, comprising on-farm emissions like, e.g., CH_4 from enteric fermentation and manure storage or N_2O from manure application.

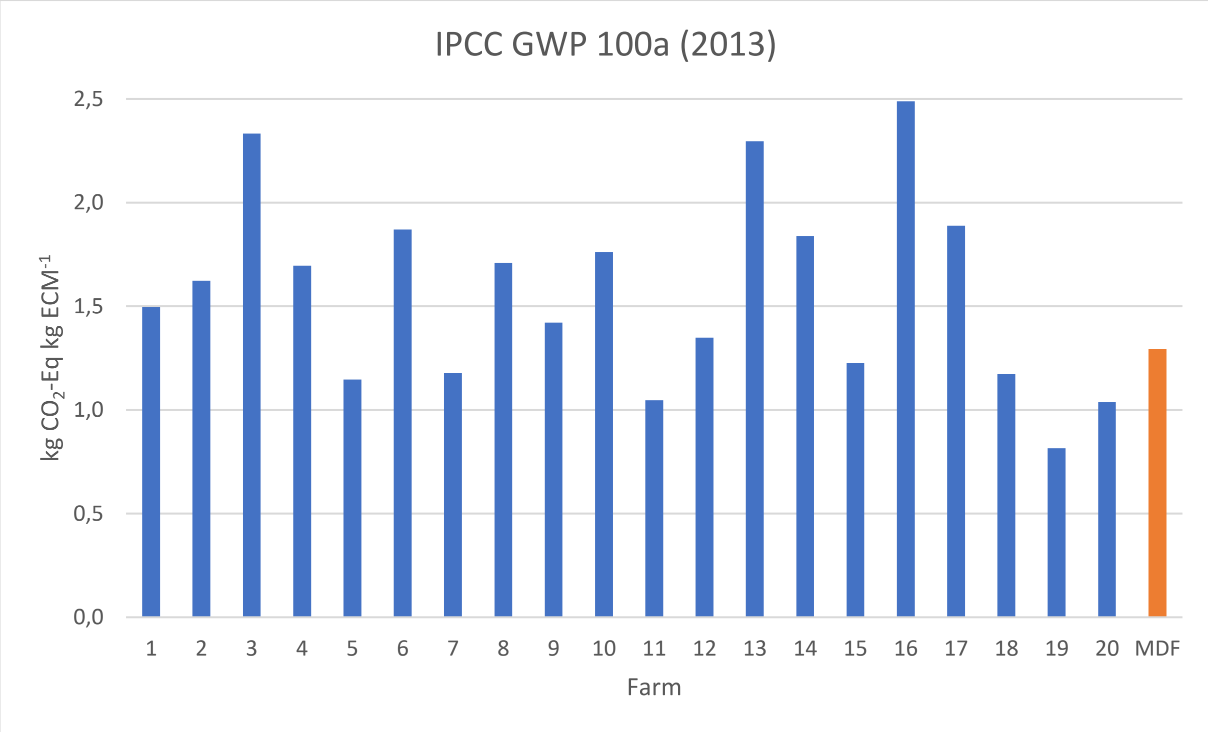

Figure 42. Global warming potential per kg ECM of the 20 Lungau farms and the MDF of Experiment 10.

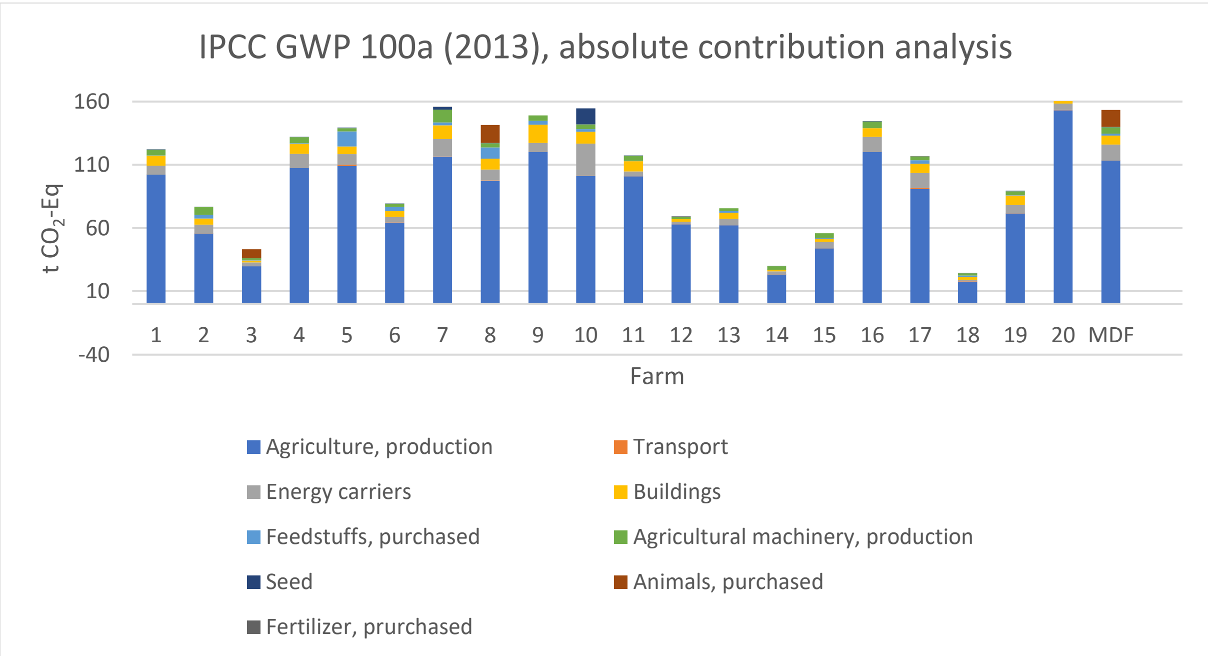

Figure 43. Absolute contribution analysis of the global warming potential of the 20 Lungau farms and the MDF of Experiment 10.

The results for the normalized eutrophication of the 20 Lungau farms and the MDF are depicted in Figure 44. The Lungau farms' normalized eutrophication ranges from 0.0006 to 0.0026 person $year^{-1}$ per kg ECM, with a mean value of 0.0013 person $year^{-1}$ per ECM. Again the absolute contribution analysis revealed "Agriculture, production" to be the main contributor to the eutrophying emissions, which can be related to nitrate leaching and aquatic and terrestrial P emissions (Figure 45).

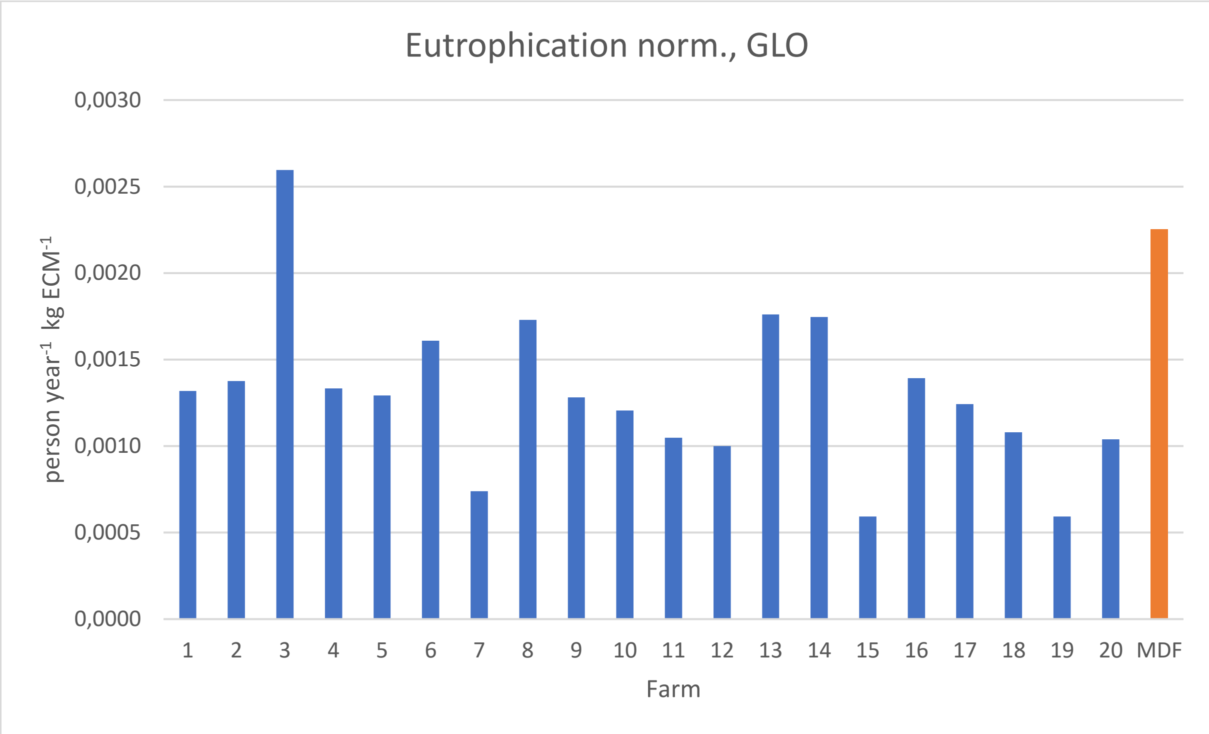

Figure 44. Normalized eutrophication per kg ECM of the 20 Lungau farms and the MDF of Experiment 10.

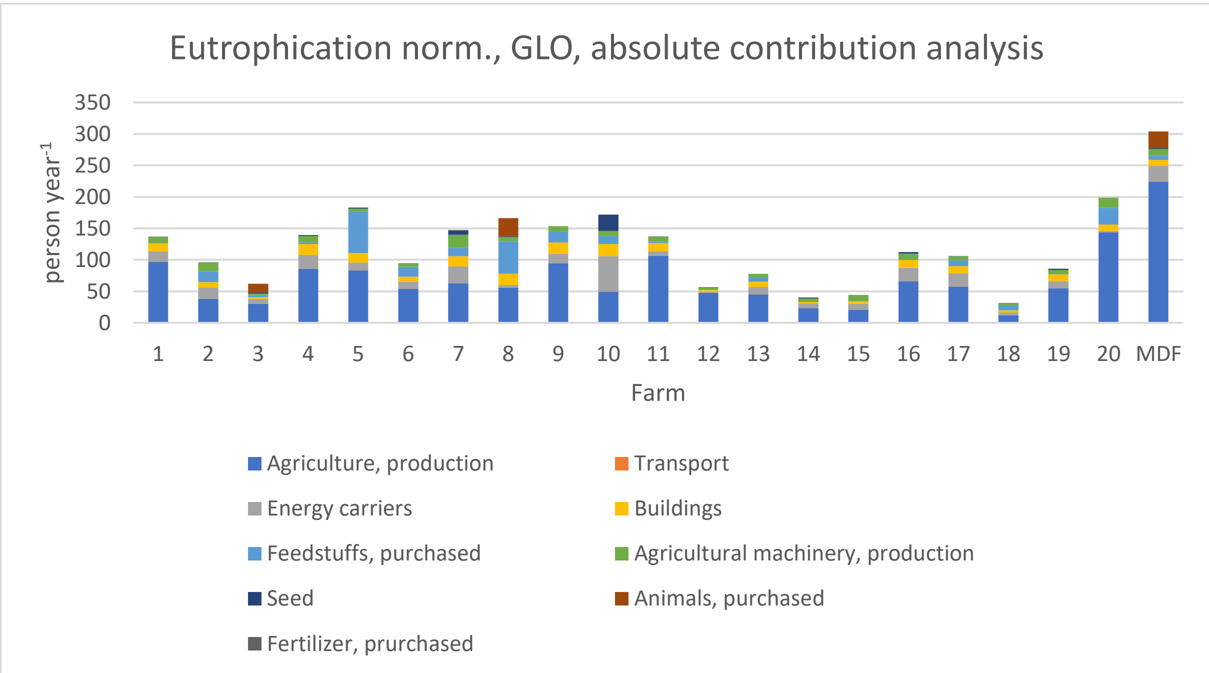

Figure 45. Absolute contribution analysis of the normalized eutrophication of the 20 Lungau farms and the MDF of Experiment 10.

4. DISCUSSION

4.1 Discussion of the experiments

Experiment 1 – N use efficiency of winter wheat

Eutrophication and resource depletion are influenced by N fertilization levels but not by the other two parameters, i.e., genotype and weather condition. The absolute contribution analysis confirms the correlation of increasing resource depletion with increasing levels of N fertilization as well as the absence of correlation for the two other variables because the differences in scenarios are mainly related to the "Fertilizers" category. For eutrophication, the increase in impact is linked to all stages of the life cycle, but the contribution analysis reveals that the bulk part of the emissions is due to the agricultural production stage.

Overall, there is a linear relationship between increased abiotic resource reuse and increased levels of N fertilization as well as increased eutrophication. This suggests that one can expect a surplus of nitrogen for those scenarios where higher levels of N fertilization are applied. If there was no surplus of nitrogen, the yield (denominator of the impact) would increase, and hence there would not be a relative increase of impact per functional unit. In order to test this hypothesis, a nitrogen balance was calculated.

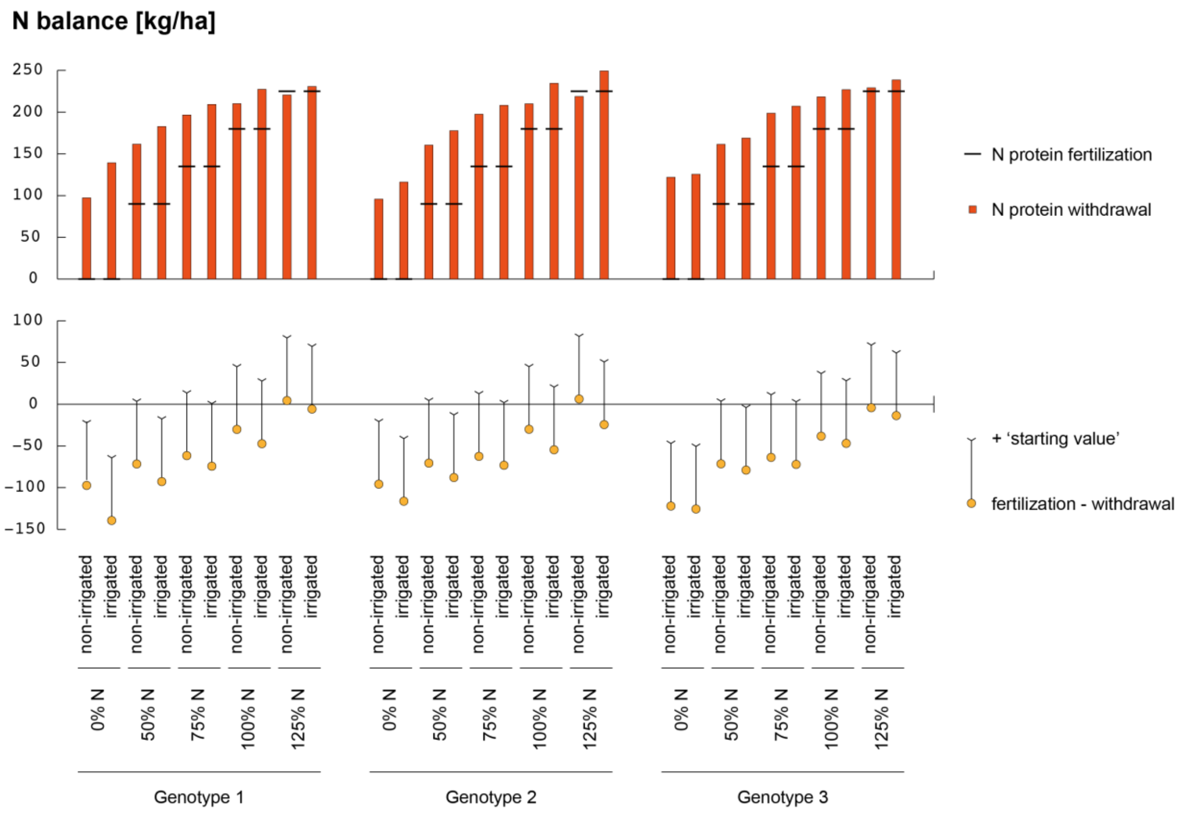

Figure 46. Nitrogen balance of the fields used for the experiments with three different wheat genotypes, two (simulated) weather conditions, and five fertilization levels.

Figure 46 shows the results for the nitrogen balance. The top graph shows the N protein fertilization and the N protein withdrawal, which both tend to be higher with higher fertilization levels. While the fertilizer level is the same for the irrigated and non-irrigated scenarios, the withdrawal tends to be higher for the non-irrigated and 0-75% N fertilization scenarios but lower for the non-irrigated 100-125% N fertilization scenarios. The lower graph shows the initial N value and the resulting value (starting value + fertilizer – withdrawal). The surplus is higher for the non-irrigated scenarios.

The results suggest that the impact is higher with increasing N fertilization levels, which is more pronounced under dry conditions. Hence, the surplus of nitrogen for the scenarios with a higher application of N is confirmed by the nitrogen balance.

The experiment was made in the region of Berlin Brandenburg and is extendable to other regions that experience similar amounts of rainfall. The findings, however, cannot be extended to N-sensitive zones. In terms of crops, the findings are extendable to barley. For winter rye, the findings are expected to have the same tendency. However, the yield would be expected to be lower.

Experiment 2 – Slurry application techniques

The results did not yield a clearly detectable trend for the parameters under study, which motivated us to investigate the influence of the yield.

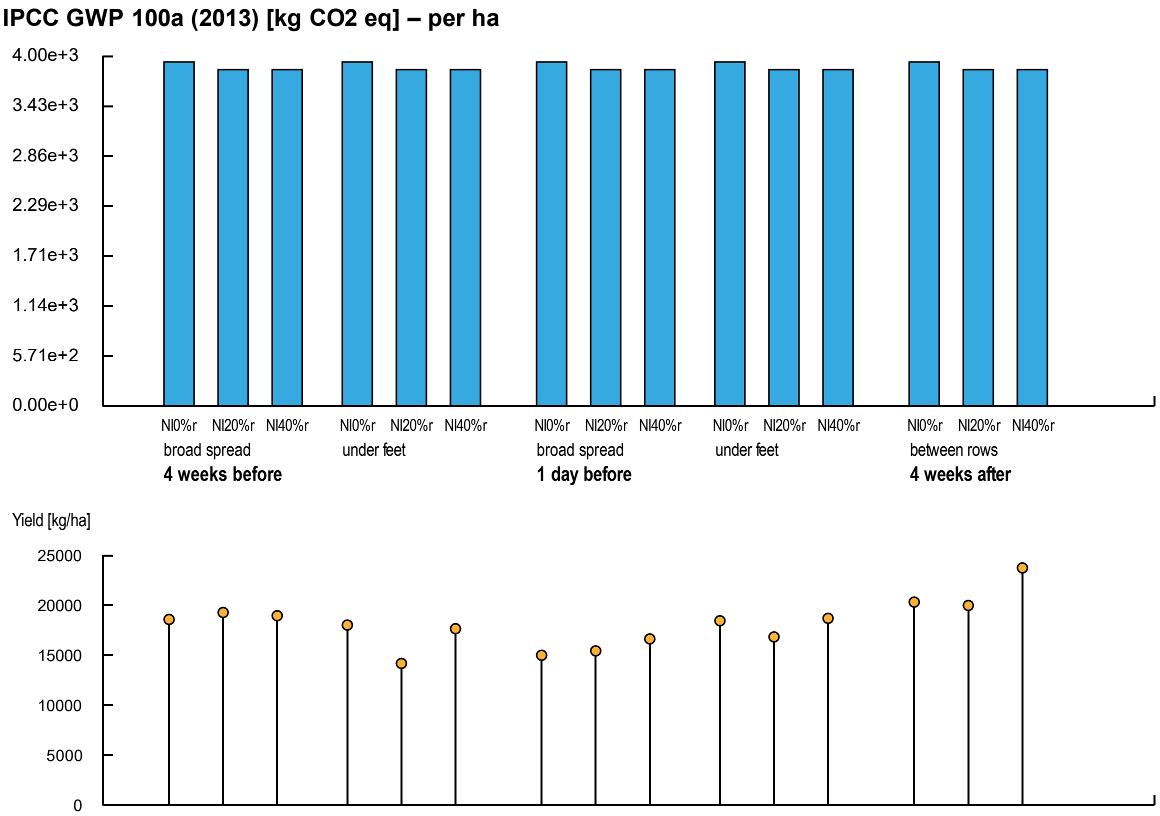

Figure 47. Global warming potential per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors multiplied by the yield and yield per ha.

Figure 47 shows the yield of kg whole maize per ha in the lower plot and the results for global warming potential per ha in the upper plot

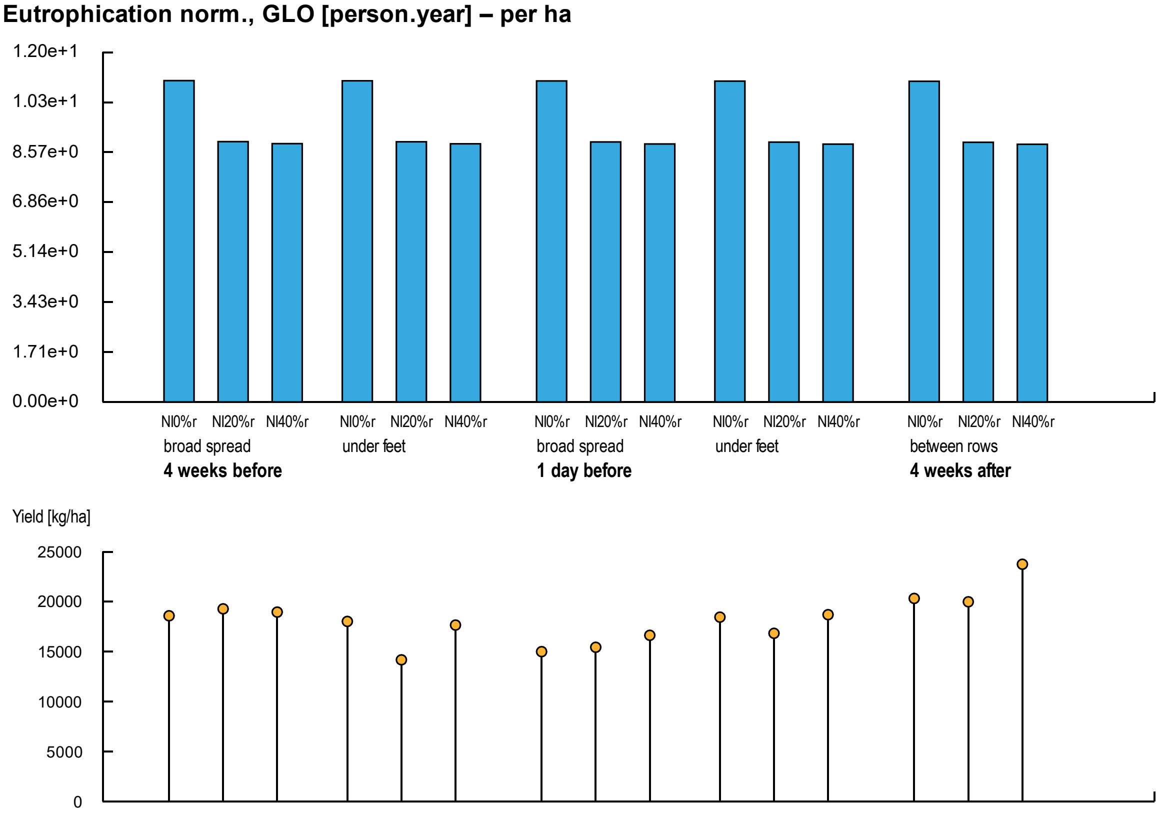

Figure 48. Eutrophication per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors multiplied by the yield and yield per ha.

Figure 48 shows the yield of kg whole maize per ha in the lower plot and the results for eutrophication per ha in the upper plot. No apparent difference between the timing of the fertilization and the technique can be seen in either of the two indicators. However, this statement may be due to the limitations of both model and data. Much more detailed data for field emissions, data on the plant growth, and N uptake would have to be measured and incorporated. Especially the gaseous emissions would have to be closely monitored as well as the nitrate leaching. The literature, to our knowledge, does not provide independently established numbers for the reduction of emissions due to the use of nitrification inhibitors.

Ideally, an ANOVA analysis would be performed based on more data than currently available to identify the main drivers and levers. It would also allow for a more specific analysis given the considerable variation in yield that cannot be explained univocally. The currently available data would have to be complemented by emissions measurements to air at the time of application. Additionally, a detailed N uptake in the plants would be measured to understand the potentially avoided surplus of N at the different stages of plant growth. Moreover, more years would have to be taken into account – particularly in this experiment as it looks at three parameters (technique, timing, inhibition).

Nevertheless, it can be stated that fertilization 4 weeks before sowing with an under feet application yields the lowest emissions (GWP and eutrophication). Moreover, Nitrification inhibitors can help reduce emissions, and their potential needs to be examined in more detail.

The experiment was done in the Berlin Brandenburg region, but the findings can be expanded to any location and any crop, given that it can be fertilized with the above-examined techniques without damage. The timing of fertilization and NI must be adjusted to the plant. The closeness of fertilization to the roots naturally depends on the growth stage. Consequently, under feet fertilization works for the spring crops when fertilization and planting are close in time. However, weather conditions might inhibit some technology. For example, wet soil is needed for injections.

Experiment 3 – Conservation tillage

The scenarios no-tillage, minimum tillage, and business-as-usual were examined with the main focus on increasing soil organic carbon content (SOC). However, SOC data was not measured and thus could not be taken into account. The changes in global warming potential, for instance, were simply due to less tractor use and hence less diesel used. The potential changes in SOC as a function of the applied tillage regime were not considered due to a lack of data. For the ecotoxicity indicator, the no-tillage regime has the lowest impact despite the highest input of herbicides. This can be related to the additional herbicide input being compensated by a higher yield.

When looking at the contributing process that drives the global warming indicator's impact, diesel combustion is identified as the main lever, followed by the production of nitrogen fertilizers. The impacts in the ecotoxicity indicator are driven by herbicides.

The results are expected to keep their validity on fields with a similar soil type which is regarded as more relevant than the geography per se. For pesticide use, the bans in the respective countries have to be taken into account. Here, glyphosate was used, which is under discussion for being banned, or a ban is already decided in several European countries, for instance, Germany (banned by 2024).

Direct seeding or no-tillage is not adapted for crops such as beets, potatoes, etc. An issue with direct seeding that needs further attention is the nutrient balance in the soil, which of course, is changed compared to BAU without the incorporation of residues.

Experiment 4 – Test of solar-dried fertilizers in crop rotations & Digestate acidification and solar drying

The differences in impact for both indicators (i.e., abiotic resource depletion and eutrophication) are examined in more detail. The production and machinery stages are the main contributors and change proportionally to the yield. The contribution analysis for both indicators yields the same partitioning across the scenarios. This is explicable due to the great similarities between the agricultural part of the experiment. Digestate production is where the two processes differ the most, as solar-dried digestate shows significantly lower emissions. However, the lower emissions in eutrophication of the innovative system may be offset by higher emissions to the air during solar drying. There are no measurements available that could be incorporated into the model. The solar-dried fertilizer contains less phosphate, which leads to less eutrophication. Solar drying exhibits a tendency to reduce eutrophication. This tendency is more pronounced for winter wheat than for winter barley.

For the technical part of this experiment, it can be assumed that, especially for acidification and nitrogen acidification potential (and eventually also for global warming potential), the potential direct emissions from the dryer, if they are not captured, will bring a significant contribution to the overall profile. These may extend the savings of the agricultural system. However, a definitive assessment could not be undertaken due to a lack of data for direct emissions to air from the dryer.

The entire (technical and agricultural) experiment was conducted in Spain, and the results are expected to be similar in dry regions needing irrigation. Moreover, the experiment was set up for N-vulnerable zones. In terms of crop type, there are no limitations expected. However, the digestate was produced from pig slurry, which has a specific nutrient composition, and other challenges are expected with other types of slurry, mainly due to a change in the C/N ratio. Additionally, the C/N ratio in the pig slurry used in the experiment was optimized for biogas production, not fertilization.

In terms of the technical sub-system, the scale of the pilot unit is about 2 m^3 digestate per hour, which is in the magnitude of a medium-scale biogas plant. Significant limitations regarding upscaling are not expected due to a high TRL achievement within the project. However, there are two important limitations present:

Firstly, due to the relation to the reference flow and the comparison between the treatment of the entire raw digestate and the solid fraction from the centrifuge, the liquid fraction remains in the second scenario untreated, also indicating a lower environmental impact in relation to the raw digestate. Secondly, there has been no data available on the gaseous emissions of the dryer, while the mass balance indicates ammonium losses of about 50 %.

Experiment 5 – Fertigation with microfiltered digestate & Digestate microfiltration/ microsieving

Abiotic resource depletion is somewhat higher for the microfiltration treatment compared to BAU. This is mostly because the microfiltration requires additional inputs (such as the fertigation pipelines and more agricultural machinery), which are not fully compensated by the higher yields of plots treated with the microfiltrate.

For the global warming potential, the opposite pattern is observed. The increased emissions of GHG associated with the higher energy use of microfiltration treatment are more than compensated by reduced GHG emissions stemming from a reduced fertilizer need.

Concerning technology, the treatment scheme with screw-press and microfiltration is a technical scheme with very low energetical efforts, and due to no known direct emissions of this scheme, its footprint regarding global warming potential, acidification, or eutrophication equals zero. Among all other technical schemes on digestate tested in Circular Agronomics, the scheme has the lowest environmental footprint. However, the overall concept (Biogas-Done-Right) requires additional efforts (micro filtrate pumping, driplines manufacturing, and installation) that are not considered in this technology balance.

Being a complete experiment with one complete round of data collection, the two parts (technical and agricultural sub-system) could be combined. The results are presented below.

Combination of agricultural system and technical sub-system.

Within this microfiltration scenario (= 76 %) were integrated with the dry matter crop yield per m³ substrate (conventional digestate or microfiltrate) produced. The impacts assessed in the technology LCA were, therefore, the absolute values and contribution analysis for the agricultural system from Experiment 5A and technical sub-system from Experiment 5B are shown for the energy demand (Figure 49), the global warming potential (Figure 50), and for abiotic resource depletion (Figure 51). Further calculations for other impact categories are listed in the annex.

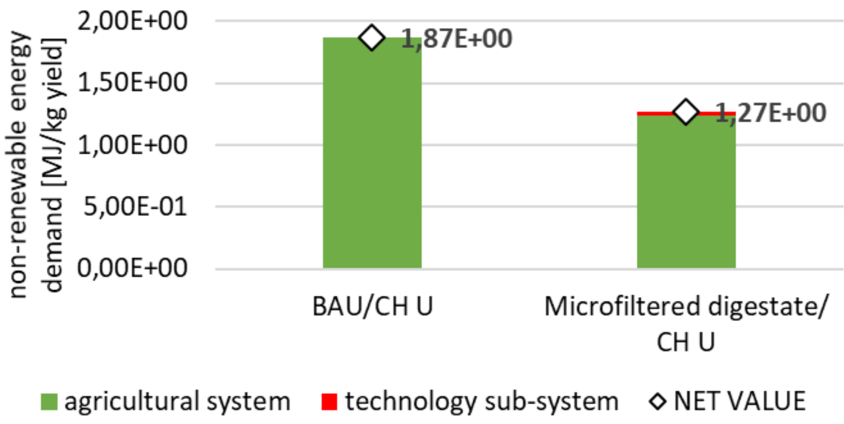

Figure 49. Non-renewable cumulative energy demand of the combined agricultural-technical system with microfiltration and fertigation

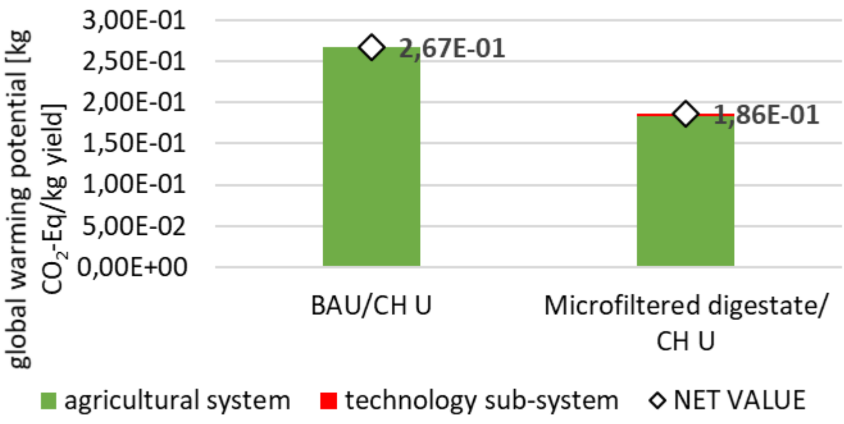

Figure 50. Global warming potential for the combined agricultural-technical system with microfiltration and fertigation

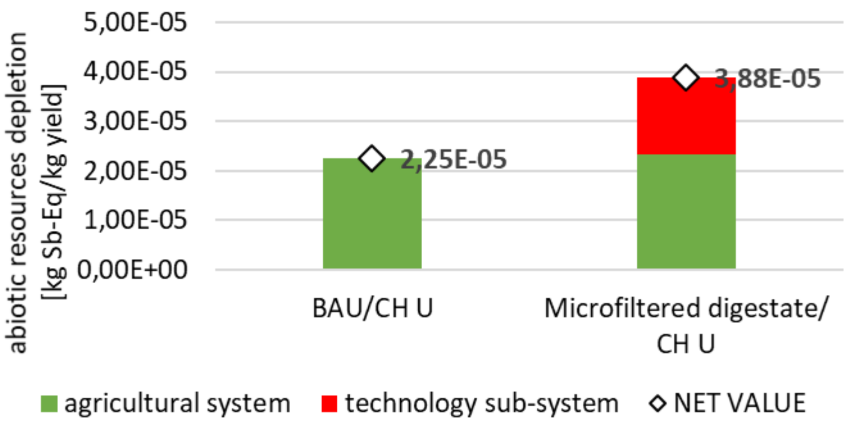

Figure 51. Abiotic resource depletion for the combined agricultural-technical system with microfiltration and fertigation

From Figure 49 and Figure 50, it becomes apparent that significant energy savings and a reduced global warming potential are a result of microfiltered digestate fertigation. The additional efforts resulting from the technical microfiltration process are responsible for 1-2 % compared of the overall impact. So, for these impact categories, it can be stated that the system considering microfiltration and fertigation will be environmentally beneficial. However, an opposite picture is given by abiotic resource depletion (Figure 51). Here the implementation of technology significantly increases the overall impact with a share of 40 % of the overall impact mainly due to the electricity production relevant for operating the screw press and the microfilter. This is associated with the depletion of fossil resources for electricity production, such as natural gas, crude oil, and coal.

The agricultural part of the experiment was conducted in Emilia-Romagna, Italy, where, due to the dry climate, fertigation makes sense. Therefore, the application of the technique and hence the extrapolation of the results make sense in similar conditions, i.e., southern European countries where several 100mm need to be irrigated. Of course, the technique only makes sense for crops that need to be irrigated. It can also be used in perennial crops such as vineyards, orchards, olives, etc. Winter crops would generally be excluded.

For the microfiltration, the digestate's level of dry matter must be 5-6% or lower to still enter the microfiltration. Technically, the scale of the pilot unit is about three m³ digestate per hour, which is in the magnitude of a medium-scale biogas plant. Significant limitations regarding upscaling are not expected due to a high TRL achievement within the project.

Experiment 6 – Digestate vacuum degasification for nitrogen recovery

Vacuum degasification initially resulted in high water evaporation due to the operating conditions near the vapor pressure curve of water. Assuming a heat supply via natural gas, this results in a very high non-renewable energy demand and corresponding GWP. However, this extraordinary high heat demand can be significantly reduced by using steam for substrate pre-heating (operation with heat recovery – 90 % of heat can be recovered). Also, caustic soda usage for pH increase could be significantly reduced via preceded CO_2 stripping. As a result, the NaOH demand could be reduced by about 90 %.

A corresponding optimized operation (reducing heat and NaOH demand) reveals a significant GWP reduction compared to the initial operation. Relating the GWP of the optimized operation of 4 kg CO_2-Eq/m³ to the mineral N product, a product-specific GWP of 2 kg CO_2-Eq/kg N can be derived. This is in the same magnitude as conventional mineral N fertilizer production via the Haber-Bosch process.

The scale of the pilot unit is about 100 L digestate per hour, which is about one magnitude lower than a small-scale biogas plant. Limitations regarding upscaling can be expected. The process has a comparably low TRL to date and is still under optimization, as shown in this analysis. A further limitation is in excluding credits for products from the balance. The 4th scenario could not be tested in the pilot unit since constructive modifications are necessary to realize heat recovery and CO_2 stripping simultaneously.

Experiment 7 – Phosphate recovery from soybean wastewater

The overall energy balance of the treatment plant is positive due to the biogas recovery in anaerobic treatment. Struvite recovery as N- or K-struvite from soybean wastewater can be realized with nearly neutral environmental impacts and a 30-40 % P-recovery rate. Since all processes are implemented in the mainstream, the caustic soda dosing rate is highly important due to the overall quantity needed. Strategies for a reduction or complete saving due to an alkalinity decrease, e.g., via CO_2-stripping, are recommended to improve results in the environmental assessment.

In comparing N and K struvite recovery, the recovery of N struvite is favored due to an N reduction and thereby a reduction of corresponding N emissions in different treatment steps post to struvite recovery (e.g., N_2O, NH_3, NH_4/NO_3), which impact several categories. The environmental impacts for the phytase production in conjunction with the low dosing rate of phytase in the phytase treatment are negligible.

The scale of the pilot unit is about 1 m³ of wastewater per hour, which is about two magnitudes lower than a corresponding full-scale plant. Therefore, limitations regarding upscaling can be expected, although the consumables are in the range of similar large-scale struvite recovery systems. Electricity and heat consumption of the wastewater treatment process (excluding the demand of the struvite and release reactor (pilot unit)) were estimated based on engineering standards. The direct emissions, especially from aerobic treatment and composting, are also calculated based on these standards. Measurements show that they vary in significant order. The environmental impacts of the additive phytase had to be estimated based on literature (Nielsen, Oxenbøll, et al. 2006, Nielsen and Wenzel 2006) since no corresponding data set is available in ecoinvent.

Experiment 8 – Acid whey thickening with membrane treatment

In both scenarios (centrifuge and filtration), overall global warming potential is in the range of 9-11 kg CO_2-Eq/m³ feed, which is in the range of hybrid membrane schemes with dense membranes working on saline fluids (Latteman 2010). The scenario with the electro-nanofibrous membrane (ENM) shows a higher chemical demand but lower electricity demand compared to centrifuge resulting in benefits for ENM treatment in almost all observed impact categories under these boundary conditions (e.g., focus on consumables and rather coal- & nuclear-based electricity mix in the Czech Republic)

It can be assumed that, especially for acidification and eutrophication potential, the emissions of the substrates on agricultural land will cause a significant contribution to the overall profile and will by far increase the impact of the technologic sub-system. Also, the impact in terms of differences in the treatment train and follow-up treatment (e.g., anaerobic digestion) have to be closely monitored since they will impact the results.

The scale of the pilot unit is about 9 m³ digestate per hour, which is the magnitude of a small-scale dairy factory in terms of acid whey production. Significant limitations regarding upscaling are not expected due to a high TRL achievement within the project. In terms of chemical use for Cleaning in Place (CiP) of membranes, the chemicals are under disclosure, as well as potential antiscalants for reverse osmosis. However, the quantity of acidic and alkaline products is known. It has therefore been assumed, based on previous experiences with LCA on membranes, that all acidic products are citric acid and all alkaline products are caustic soda. The corresponding footprints of the actual products are assumed to be in the same ranges as for these chemicals. Potential direct emissions (to air, water) from the wastewater treatment where residual waste streams from the treatment as sludge and brine are disposed of had been estimated via engineering standards.

Experiment 9 – Precision feeding and fertilization strategies

The relative changes are larger for the eutrophication potential than for the global warming potential. Due to data limitations, the calculations could be done only in a simplified manner, and no complete LCA was conducted. Nevertheless, it can be stated that precision feeding has a minor influence on GWP, whereas it leads to more pronounced reductions of the eutrophication potential. It is noteworthy that the CO_2 equivalences from CH_4

remained stable for both scenarios. The reduction was mainly due to a reduction of N_2O. For the eutrophication, both ammonia and NO_2 were reduced.

The experiment was conducted in Spain, and it is unclear to what extent the results are expandable to other regions. This is mainly because it is unclear whether certain types of concentrate are available everywhere or could be substituted with regional options. Also, the feeding ratios were adapted for milk cows and are not necessarily expandable to meat cows. Another parameter that needs precision for potential extendibility is the minimum farm and herd size required.

Experiment 10 –Extensive management of organic dairy farms in the Lungau region

The 20 Lungau farms considered in this study revealed a higher GWP per kg ECM compared to the average Austria organic dairy farm, as represented by the MDF. This is mainly related to the lower milk production caused by the extensive management and the low percentage of concentrate in the feed ration. However, considering the normalized eutrophication, the Lungau farms emit considerably lower emissions per kg ECM than the MDF. This can be explained by the lower stocking rates of the Lungau farms, which leads to less N fertilization per area and, therefore, lower emissions from nitrate leaching and terrestrial and aquatic P emissions. Please refer to Grassauer et al. (2022) for a more detailed discussion.

Limitations

The amended eco-inventories to account for the extensive management and the regional purchases of feedstuffs, animals, and organic fertilizers are based on primary data from the Lungau farms under study. They can therefore not be transferred to other farm samples.

4.2 Aggregation to strategy level

4.2.1 Nutrient management in crop production

The experiments categorized in this strategy look at different elements that could lead to more efficient nutrient management in cultivating different crops. The elements that were looked at in more detail are the dosage of fertilizer (Experiment 1), the timing, the technique, and the application of nitrification inhibitors (Experiment 2), and different tillage regimes (Experiment 3). Additionally, Experiment 1 investigated the influence of changing climatic conditions on drier soils. The experimental results revealed that, according to the law of diminishing returns by Mitscherlich (1909), increasing levels of N fertilization firstly leads to higher emissions in terms of abiotic resource depletion that cannot always be compensated by higher yields. If the nitrogen cannot be taken up, this leads to higher nutrient losses via the leaching of nitrate and increased eutrophicating emissions (O'Brien et al., 2012; Smith and Schindler, 2009). This becomes even more pronounced under a dry climate, as the nitrogen can less easily be used due to limitations in plant growth (Gonzalez-Dugo et al., 2010).

For the parameters of timing, technique, and nitrification inhibitors (NI), the timing of four weeks after sowing showed the least emissions. It is assumed that this timing was best because the plants have taken up the fertilizers best as the dressing after sowing enables nitrogen to be applied when the need for fertilizer is more assured (Strong, 1986). For the nitrification inhibitors, the more direct emissions can be reduced, the better. However, to the best of our knowledge, there are no suitable eco-inventories of the considered NIs available to date. Therefore, we could not take the emissions of producing and transporting NIs into account within the assessment.

Conservation agriculture is tested for carbon accumulation in terms of soil organic carbon (SOC). Because the data for carbon values on different time horizons were not collected, the innovative and reference systems could not be compared as intended. However, the innovative system emitted less carbon per kg of product due to a lower use of machinery and, therefore, less diesel combustion. If practices like applying nitrogen under feet or between rows and a conservation tillage regime can be combined, the emission reduction can be maximized. The findings for nutrient management in crop production show that fertilizer levels need to be adjusted to the changing climatic conditions. This is especially true for intensively managed crops like wheat and cannot necessarily be extended to nitrogen-sensitive zones. However, reductions of direct emissions are possible for every crop and every region.

4.2.2 Nutrient management in livestock production

In general, the optimization of feeding (i.e., precision feeding) leads to a needs-based supply of nutrients to livestock, thus reducing the accumulation of nutrients on farms (Cerosaletti et al., 2004) which subsequently leads to lower nutrient losses and environmental impact in the final product. In experiment 9, individual feed rations were calculated per cow, thus matching the input of nutrients with the cow´s individual needs. A full LCA could not be calculated due to a lack of data. Especially the data on the feed production based on the cows´ manure was missing. Hence the closing loop of the system (from feed to manure to feed production) could not be included. This is relevant because it is expected that the optimized feed leads to also less manure or less nutrient-rich manure. Potentially, the fertilization has to be enriched with mineral fertilizer. The feed rations included substantial amounts of concentrate, which is a change to the reference system and should be investigated as well for their effect on animal health and the lifetime of the cows. These two important parameters were excluded from the study as their inclusion would only be possible in experiments spanning longer periods of time.

In Experiment 10, we looked at the whole dairy farming system (i.e., from cradle to farm gate) of 20 organic farms via LCA. The milk production of the farms complied with the production regulations of the Lungau, which aimed to produce high-quality dairy products and keep production cycles closed within the region. Consequently, the purchase of resources (i.e., feedstuffs, animals, and organic fertilizers) was only possible within the Lungau region. Combined with the less favorable production conditions, these production regulations led to a very extensive management of the Lungau farms. Therefore, compared to the generic MDF and related to 1 kg ECM, the Lungau farms do not seem favorable regarding all considered environmental impacts. For example, as depicted in Figure 42, the mean value of the Lungau farms regarding GWP is 19 % higher than the MDF´s GWP (i.e., 1.6 and 1.3 kg CO_2-Eq per kg ECM, respectively). This is mainly related to low amounts of concentrate in the feed ration and, therefore, a lower milk yield per cow (Smith et al., 2019; Tal, 2018). However, looking at the normalized eutrophication (Figure 44), the Lungau farms seem favorable compared to the MDF, with a mean value of 0.0013 person year^{-1} compared to 0.0023 person year^{-1}. The low normalized eutrophication values of the Lungau farms can be explained by the lower stocking rates, which lead to lower nitrogen fertilization and, therefore, to lower amounts of nitrate leaching and emissions from manure application (O'Brien et al., 2012). Therefore, considering their nutrient management, the Lungau farms can be considered competitive contributors to milk production as they adapted their production intensity to (i) the specific production regulations of the regions and (ii) the less favorable production conditions, therefore practicing site adapted-agriculture.

4.2.3 Waste management and nutrient/carbon recovery

The experiments assigned to this strategy either aimed to use waste streams as potential sources of nutrients (Experiments 4 and 5) or reduce emissions by capturing nutrients (Experiments 6, 7, and 8).

Within the mentioned experiments, three digestate treatments were analyzed. However, a general comparison of these schemes is difficult due to unequal system boundaries, different assumptions in the assessment, and local boundary conditions (e.g., different electricity mixes or the usage of solar energy instead of heat from natural gas due to biogeographic differences). Nonetheless, different treatment steps to improve the present treatment schemes are discussed in the following paragraphs.

Solid-liquid separation of digestate

Two systems, “Digestate acidification and solar drying” (Experiment 4) and “Digestate microfiltration/microsieving” (Experiment 5), utilized different solid-liquid separators, resulting in different electricity consumption and consequently varying footprints. Centrifuges are designed for high capacities and consume specifically more electricity (2-3 kWh/m^3) due to their high rotation number. Screw presses consume less electricity (0.2-1 kWh/m^3) due to their low rotation number. However, screw presses are limited in capacity. For the treatment of large volumes, centrifuges are consequently preferred due to lower investment costs compared to the installation of several screw presses. However, typical agricultural biogas plants have a treatment capacity of about 1-20 m^3/h below the maximum treatment capacity of a screw press. The data on dry matter results and degree of dry matter separation from the liquid phase for both Case Studies indicate the similar performance of these separators. Consequently, screw presses may be favored within this field of application due to their lower electricity consumption resulting in lower greenhouse gas potentials.

Drying and heating of digestate

Two systems, “Digestate acidification and solar drying” (Experiment 4) and “Digestate vacuum degasification for nitrogen recovery” (Experiment 6), required heat for their treatment purpose. It became apparent that the choice of heat source and its corresponding fossil footprint is crucial for the overall footprint of the treatment train. Introducing renewable heat from the sun or waste heat from biogas valorization in a CHP is crucial for the overall footprint. The use of fossil heat sources such as natural gas significantly increases the environmental footprint. Strategies should be undertaken to a) reduce heat consumption by heat recovery and b) use renewable heat whenever possible.

pH-shifting and buffers of digestate/ chemical consumption

Agricultural digestate is characterized by two large buffer systems increasing the acid or caustic demand when the pH of digestate is shifted. The buffer equilibrium of CO_2/HCO_3^- increases the chemical demand between pH 5 and 8 significantly, while two buffer equilibria of NH_4^+/NH_3 and HCO_3^-/CO_3^{2-} increase the chemical demand between pH 8 and 12 significantly. As a result, agricultural digestate has a pH of 8, where both buffer systems accumulate at a minimum (Sommer and Husted 1995). Both buffer systems can be reduced via stripping processes since both include gaseous substances such as CO_2 and NH_3, which then, in terms of NH_3, needs to be recovered. After reducing corresponding gases, the consumption of acid or caustic chemicals can be significantly decreased, and the corresponding environmental footprints for the technology.

The importance of the type of substrate for the production of biogas and hence digestate cannot be stressed enough. When waste streams are valorized, the environmental impact can be zero or even negative (a benefit). If the substrate is generated specifically for biogas production, the environmental impact can become quite important. See figure on global warming potential of biogas of different substrates.

The experiment on solar drying of pig slurry (Experiment 4) could not be assessed completely. However, the experiment on microfiltration (Experiment 5) was complete and showed the emission reduction potential of the novel technology of fertigation. Furthermore, the findings are extendable to other regions of large-scale industrial animal farming (Experiment 4), with all crops in dry regions needing irrigation (Experiment 5).

Treatment of wastewater and waste

Two systems treated wastewater or waste streams, and the approaches under study replaced other technological units with the aim of a higher level of circularity.

The "Phosphate recovery from soybean wastewater" (Experiment 7) showed comparably low environmental efforts concerning the overall footprint of this industrial wastewater treatment plant. It became apparent that the caustic soda consumption for pH increase is relevant due to its implementation in the mainstream. It is recommended that alternative options for pH increase as CO_2 stripping are investigated to further reduce the chemical consumption and the environmental footprint. The treatment scheme in full-scale (125 m³/h) would be able to recover annually 50-60 t P (30-40% of the wastewater treatment plants' influent P), 40-50 t Mg (40-50% of the influent Mg) and either 20-30 t N (1% of the influent N) or 70 t K (5% of the influent K), which otherwise would be wasted or recycled with lower efficiency in sewage sludge (N and P), emitted as N_2 to air (N) or be discharged in the effluent (K and Mg).

The "Acid whey thickening with membrane treatment" (Experiment 8) showed lower environmental effort than its reference process using a centrifuge for pre-treatment. This technology may not directly contribute to higher nutrient use efficiency; however, corresponding environmental efforts are reduced. By exploiting the follow-up treatment (including digestion) and investigation of the nutritional value of digestates, the valuable ingredients could be recycled for agriculture. The brine from the reverse osmosis within this treatment train seems particularly interesting for the recovery of nutrients (especially potassium) due to very high concentrations (up to 5000 mg/L).

5. CONCLUSIONS

An important project goal of Circular Agronomics is to realign nutrient management in extensive farming systems to reduce nutrient surpluses, nutrient losses to air and water, and reduction of nutrient losses from nutrient-rich waste streams. Therefore, several case studies introduced a technology to treat present streams, such as digestate, to achieve a higher level of nutrient efficiency within the following farming system. Technology as such corresponds thereby with additional efforts (such as electricity consumption) and corresponding additional impacts. However, the subsequent farming systems should be able to achieve reduced emissions. In terms of the non-renewable energy demand, global warming potential, and eutrophication of the observed systems, it seems rather unlikely that a corresponding reduction in emissions by farming systems can be realized. However, it is more likely that this trade-off can be achieved for acidification and eutrophication (especially ammonia emissions), where agriculture has a crucial role. Consequently, technical systems should not directly emit corresponding emissions to air and water and should be optimized to reduce consumables and additional impacts.

The six case studies conducted within the project encompassed ten experiments that were environmentally assessed regarding their performance either in nutrient management in crop production, nutrient management in livestock production, or waste management and carbon/nutrient recovery.

Three experiments were related to nutrient management in crop production and investigated different traits to increase the efficiency of nutrient management in the cultivation of crops, such as dosage, timing, and application technique of fertilizers, different tillage regimes, application of nitrification inhibitors (NIs), different climatic conditions, and different genotypes of crops. It could be concluded that the environmental impacts (EIs) per kg crop are heavily influenced by the dosage of fertilizer, especially under dry conditions, and that different genotypes have no influence. Moreover, a fertilization four weeks before sowing combined with an under-feet application caused the lowest EIs per kg crop. Regarding tillage regimes, the no-tillage variant seemed favorable in terms of EIs per kg crop, and a higher yield could offset even the higher usage of herbicides. Finally, the experiments showed that the application of NIs tends to help reduce emissions, but their potential needs to be assessed in more detail.

Another two experiments investigated potential improvements regarding nutrient management in livestock production through precision feeding and site-adapted management of dairy farms. The results revealed that precision feeding has the potential to reduce eutrophication and greenhouse gas emissions significantly. Further, the site-adapted management of dairy farms was shown to be very efficient, as eutrophication is considered a suitable parameter to depict the nutrient management of agricultural farms.

The remaining five experiments examined improvements in waste management and carbon/nutrient recovery by using waste streams as potential sources of nutrients or reducing emissions by capturing nutrients. Thereby, special attention was dedicated to the technical sub-systems of the respective experiments. Regarding the three investigated digestate treatment concepts, the "digestate microfiltration/ microsieving" technology is by far the highest developed and energetically most optimized system and reveals the lowest environmental impacts. The "digestate acidification and solar drying" suffers from high chemical consumption and potentially relevant ammonia emissions in the dryer and should be further optimized. "Digestate vacuum degasification for nitrogen recovery" is a more high-end technology aiming for an 80 % recovery rate of the NH_4-N in the influent in mineral fertilizer form, which seems not to be completely optimized to date. Hereby the reduction of chemicals and heat recovery needs to be optimized before a potential roll-out. The struvite technology is able to recover and subsequently recycle these nutrients in a comparably clean and plant available form from soybean wastewater treatment with low environmental efforts. The membrane technology seems to be an electricity-saving alternative compound for whey thickening compared to centrifuges.

A combination of the agricultural and the technical systems for the microfiltered digestate fertigation revealed the potential of such systems. If the technology is optimized and meaningful applied and corresponding emissions relevant to global warming potential, acidification and eutrophication can be reduced. For the particular case, this report shows significant improvements in many impact categories assessed but also drawbacks in other impact categories. Some of this is directly related to today's fossil energy production and the use of natural gas, crude oil, or coal. However, these results have to be seen carefully under the circumstances. The technology and the fertigation system are optimized, which does not obviously apply to all systems investigated in Circular Agronomics. Nevertheless, the report clearly addresses particular weaknesses per experiment and Case Study and shows particular areas of improvement for process engineers focusing on optimization of technologies and farmers/agricultural researchers for optimization of their nutrient management behaviors. From the comparison, particular done for one experiment and separated assessments done for others and incomplete data-sets for several technical and farming systems, we only can state that such a hybrid out of technology and agriculture may reduce environmental impacts if it is well applied, however there it is unlikely that it is always well applied. Nonetheless, this aspect of dedicated nutrient management and emission mitigation should be investigated further.

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7. ANNEX

7.1 Agricultural experiments - Overall results per experiment

Experiment 1 – N use efficiency of Winter wheat

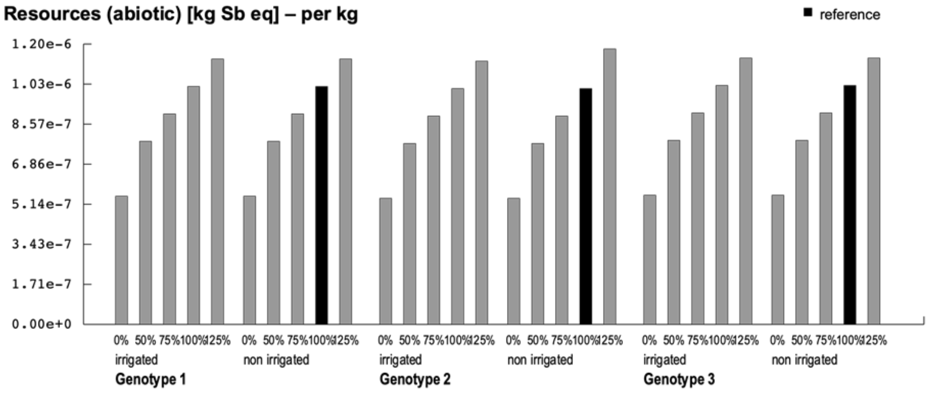

Figure 52. Abiotic resource depletion per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

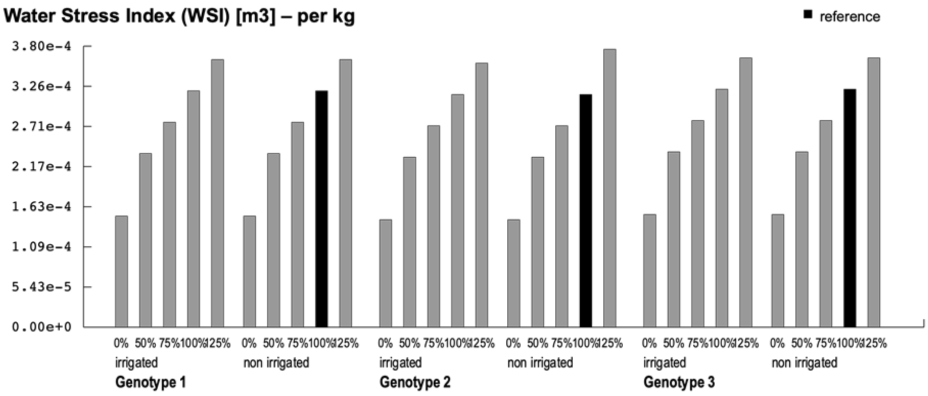

Figure 53. Water Stress Index per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

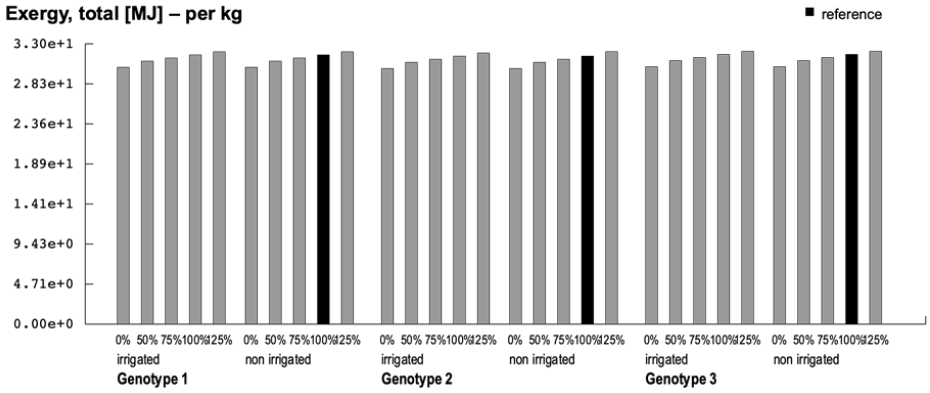

Figure 54. Total exergy per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

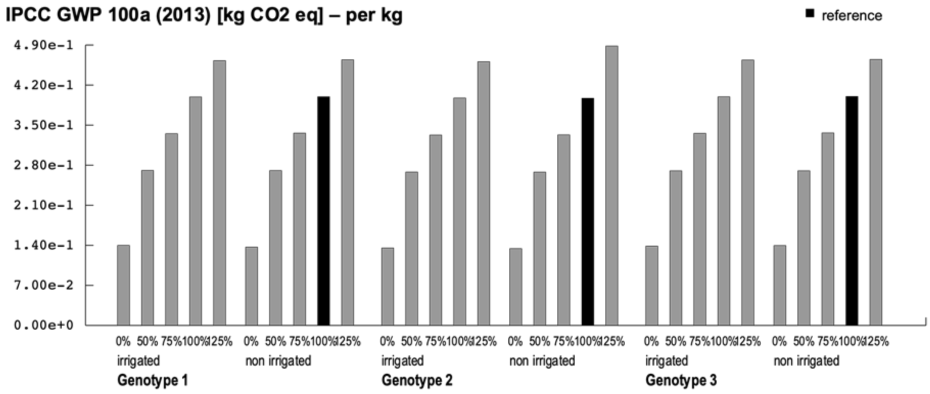

Figure 55. Global warming potential per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

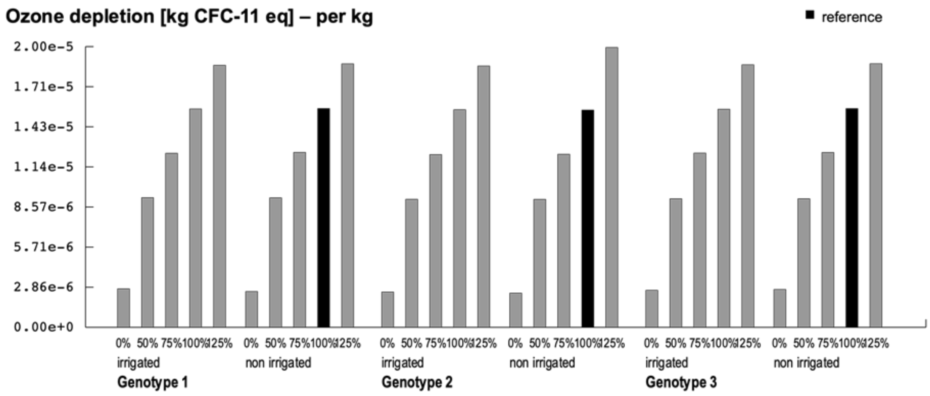

Figure 56. Ozone depletion per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

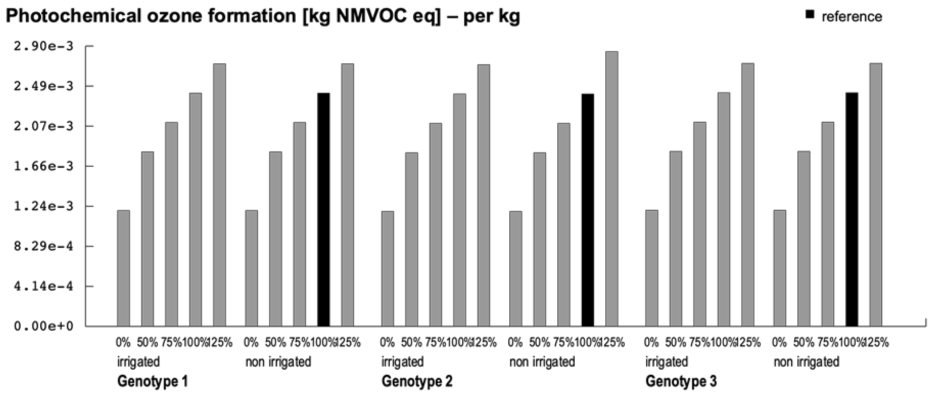

Figure 57. Photochemical ozone formation per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

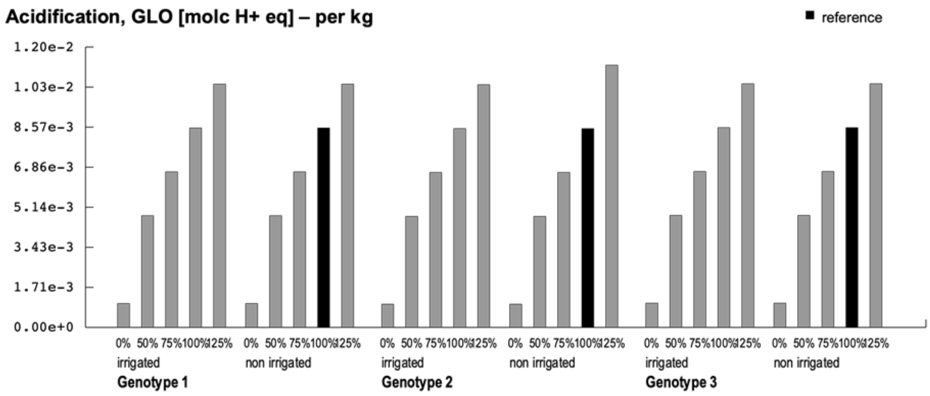

Figure 58. Acidification per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

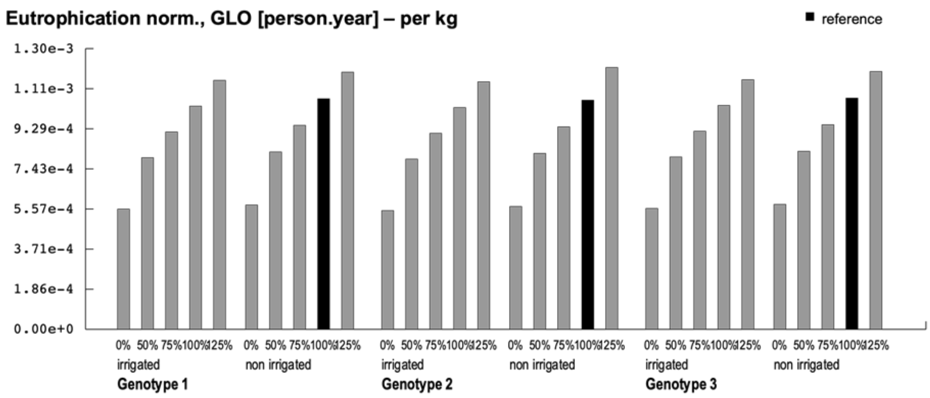

Figure 59. Eutrophication per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

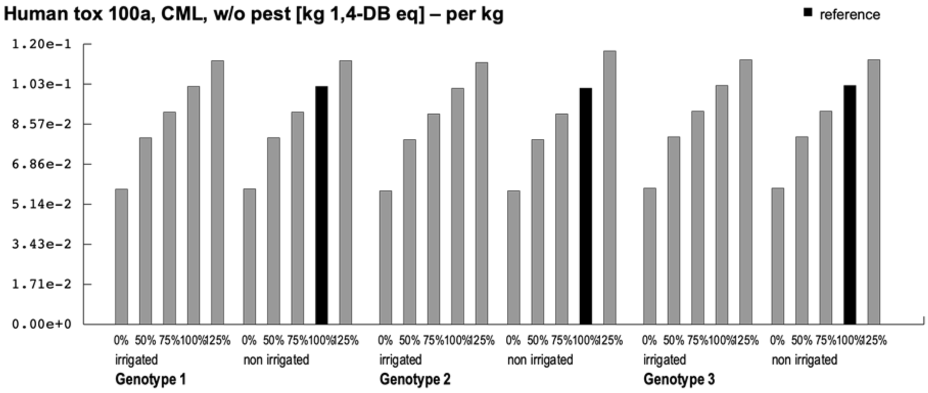

Figure 60. Human toxicity without pesticides per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

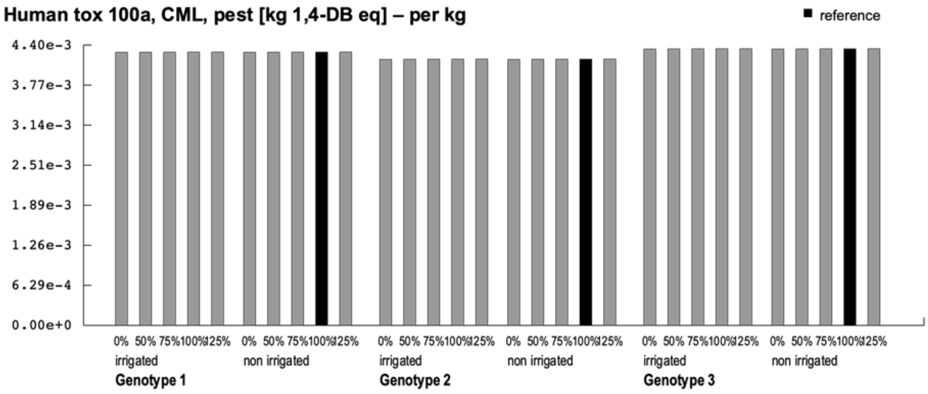

Figure 61. Human toxicity with pesticides per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

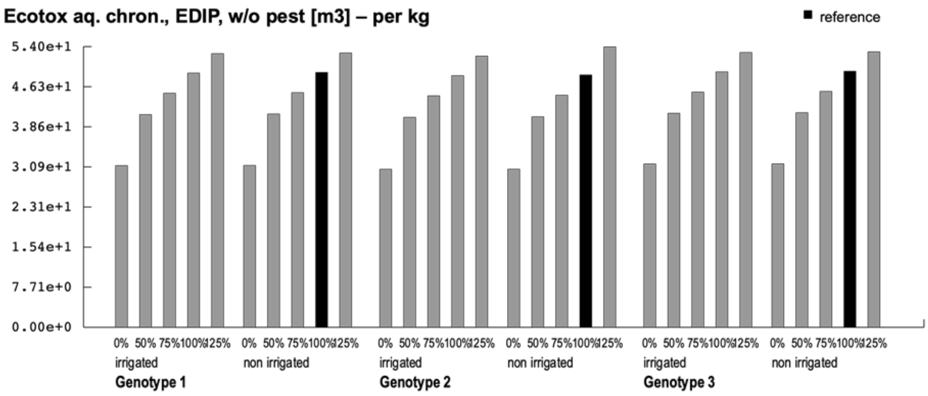

Figure 62. Aquatic ecotoxicity without pesticides per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

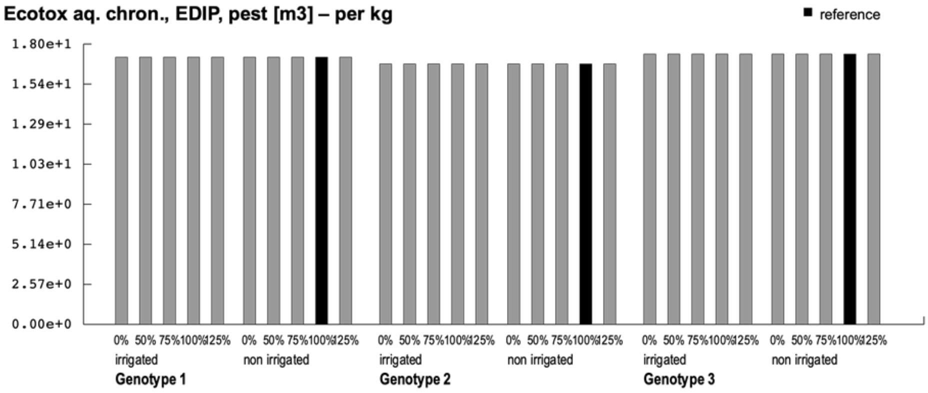

Figure 63. Aquatic ecotoxicity with pesticides per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

Experiment 2 – Slurry application techniques

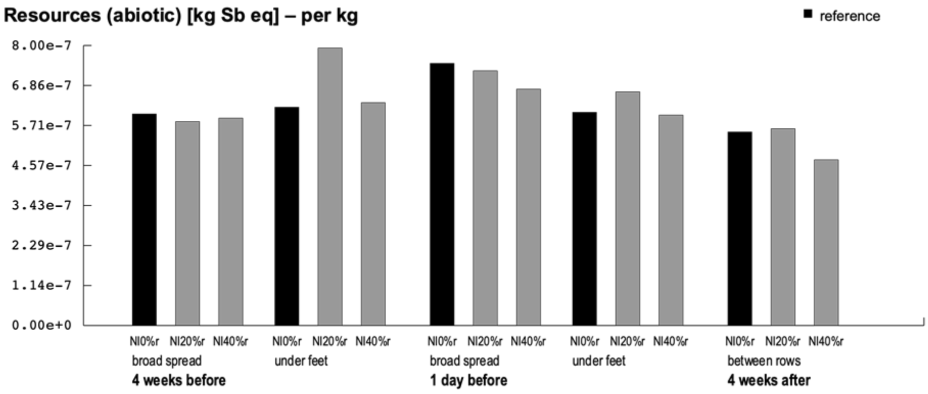

Figure 64. Abiotic resource depletion per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

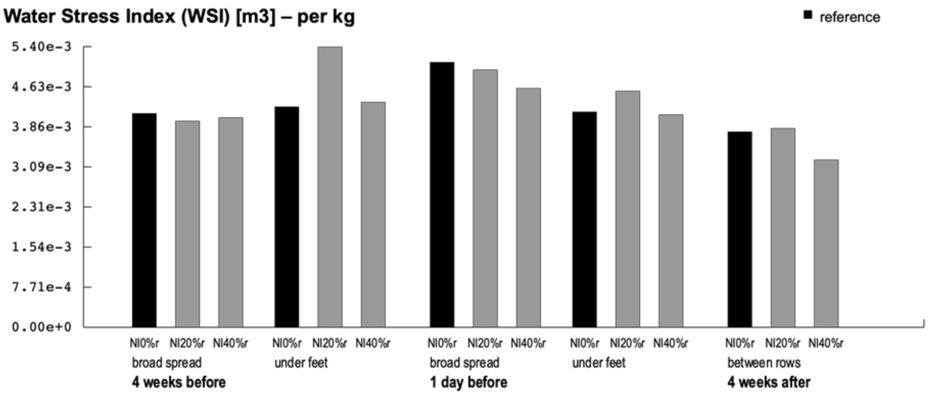

Figure 65. Water Stress Index per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

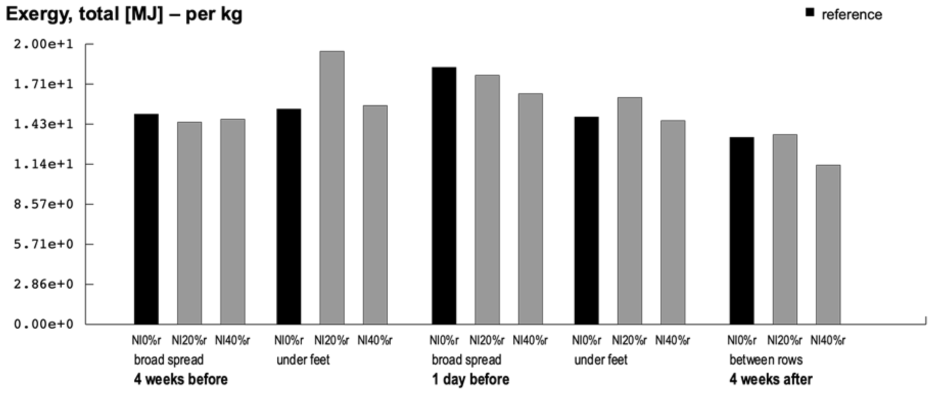

Figure 66. Total exergy per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

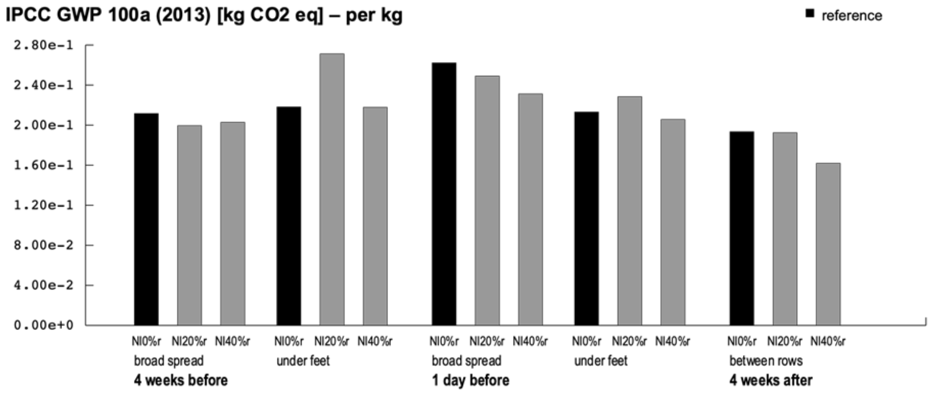

Figure 67. Global warming potential per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

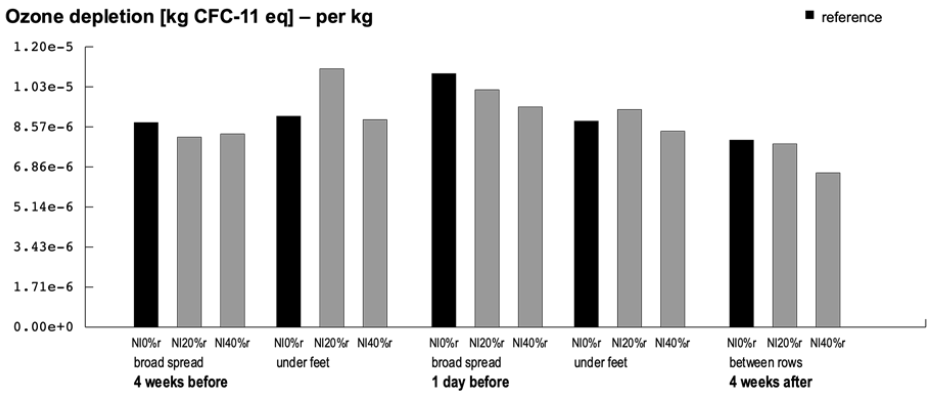

Figure 68. Ozone depletion per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

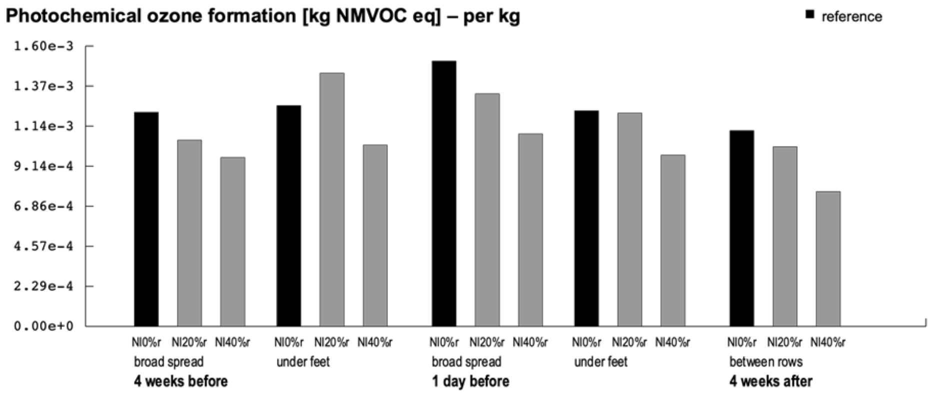

Figure 69. Photochemical ozone formation per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

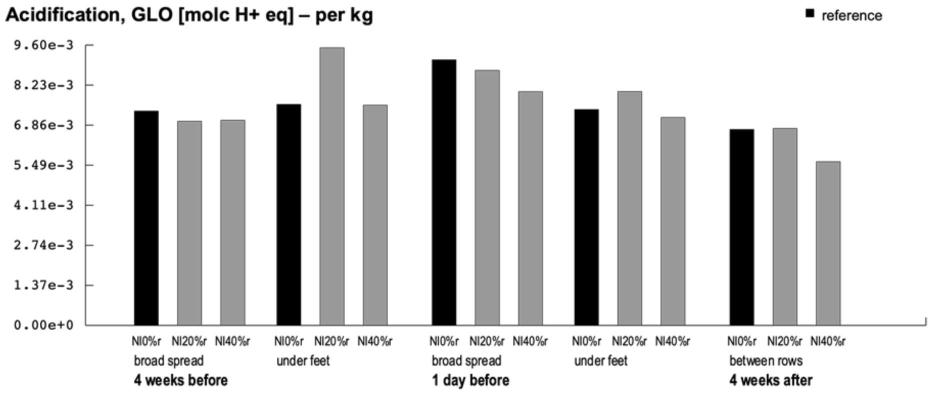

Figure 70. Acidification per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

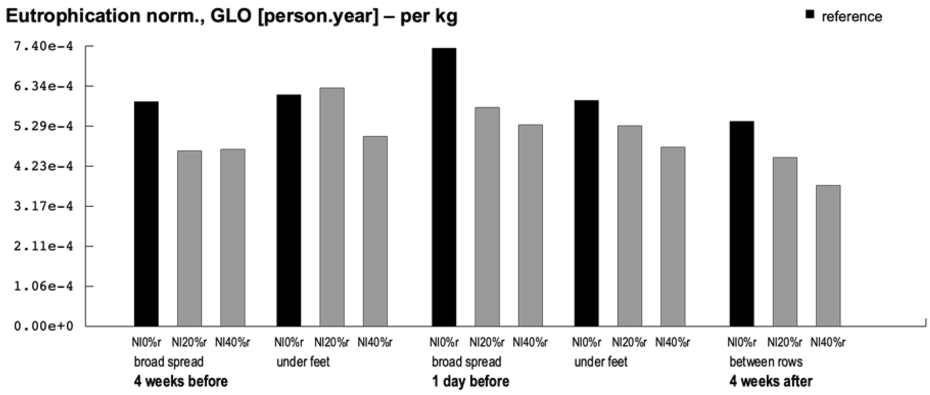

Figure 71**. Eutrophication per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors** of Experiment 2.

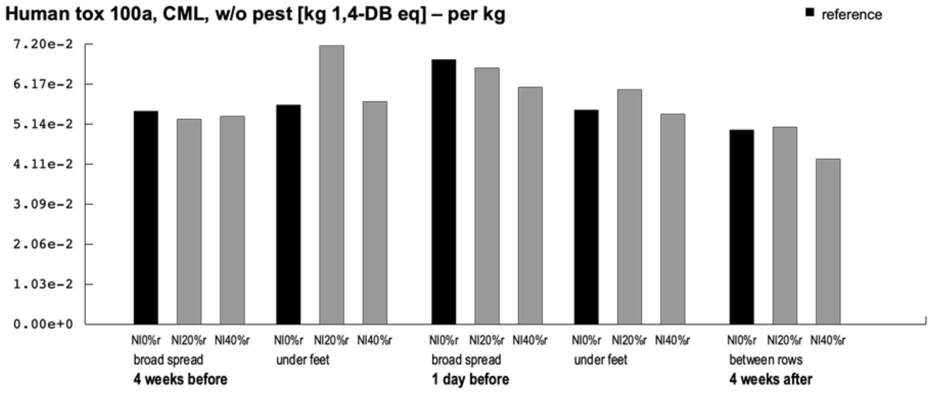

Figure 72. Human toxicity without pesticides per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

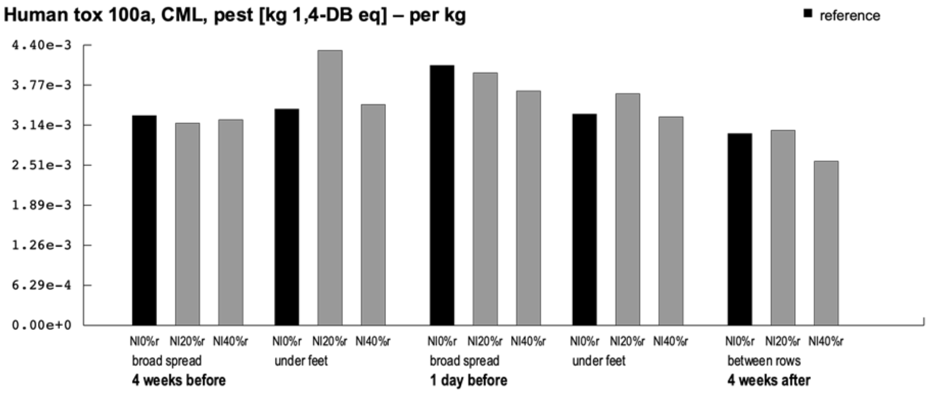

Figure 73. Human toxicity with pesticides per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

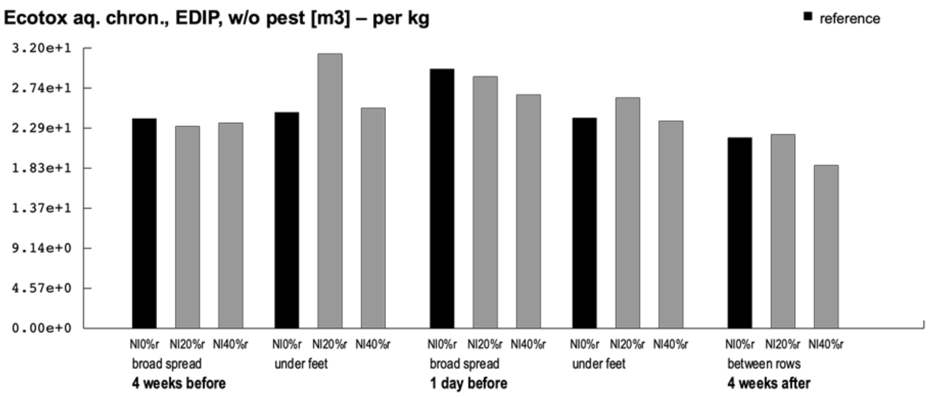

Figure 74. Aquatic ecotoxicity without pesticides per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

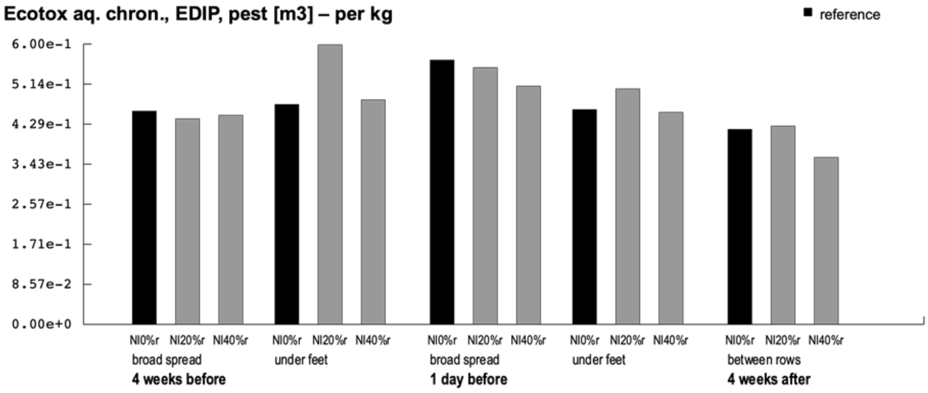

Figure 75. Aquatic ecotoxicity with pesticides per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

Experiment 3 – Conservation tillage

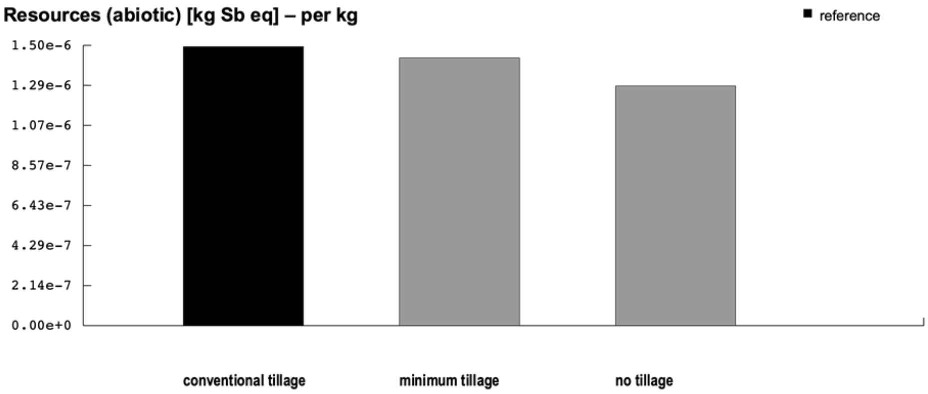

Figure 76. Abiotic resource depletion per kg of wheat using three different soil treatments of Experiment 3.

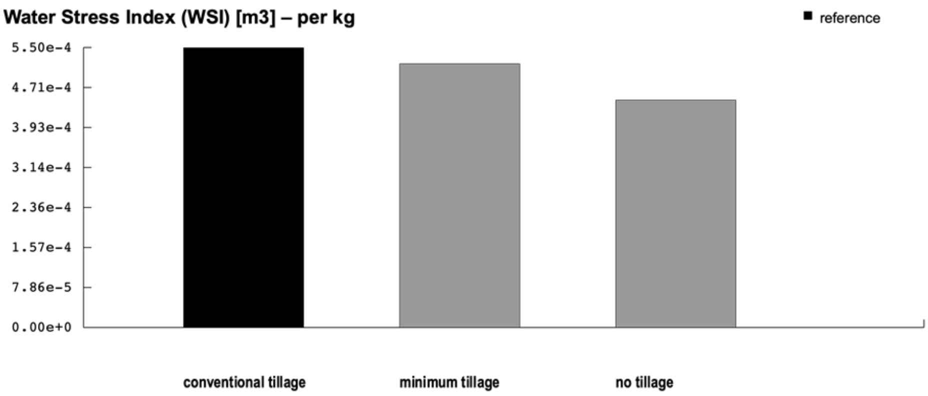

Figure 77. Water Stress Index per kg of wheat using three different soil treatments of Experiment 3.

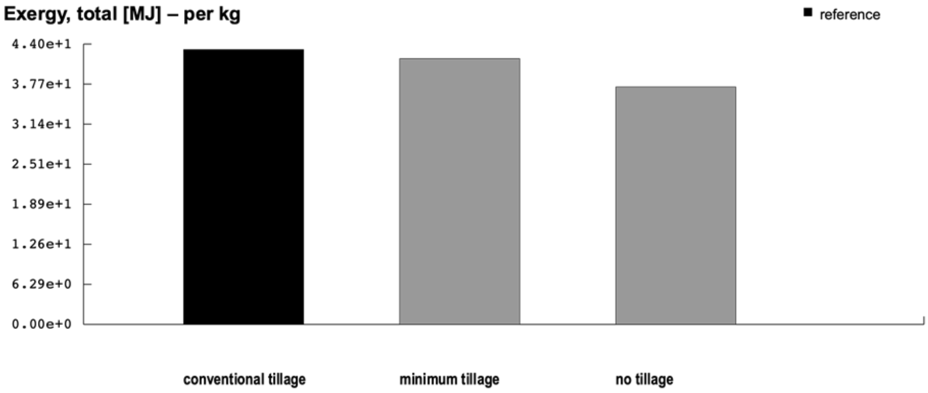

Figure 78. Total exergy per kg of wheat using three different soil treatments of Experiment 3.

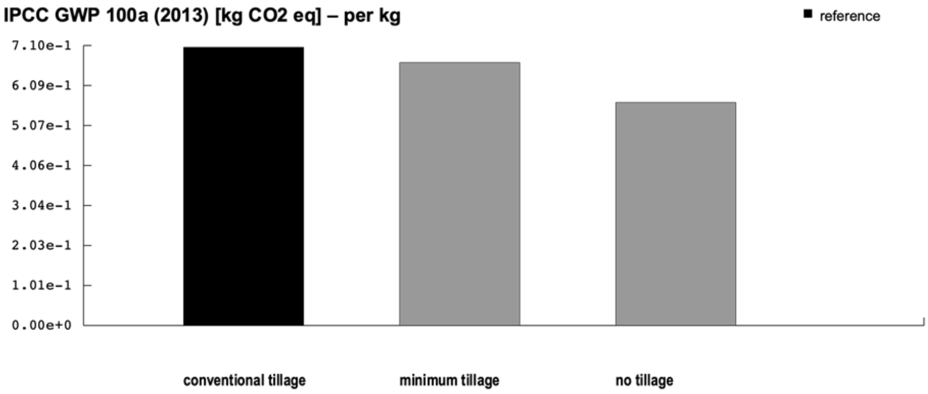

Figure 79. Global warming potential per kg of wheat using three different soil treatments of Experiment 3.

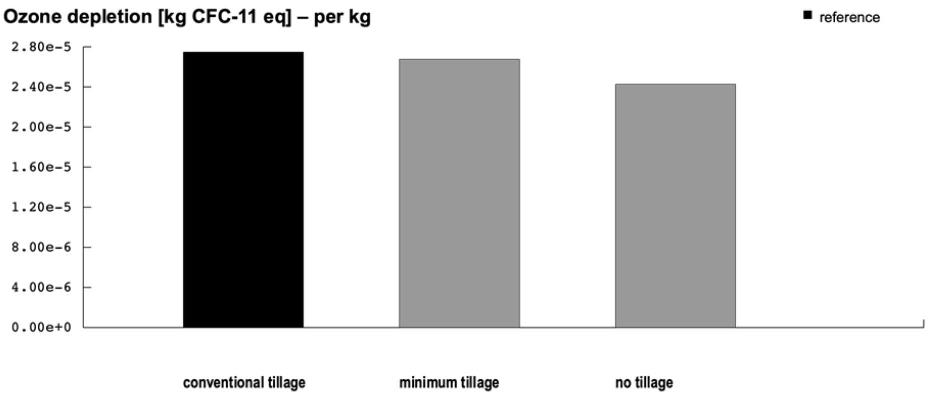

Figure 80. Ozone depletion per kg of wheat using three different soil treatments of Experiment 3.

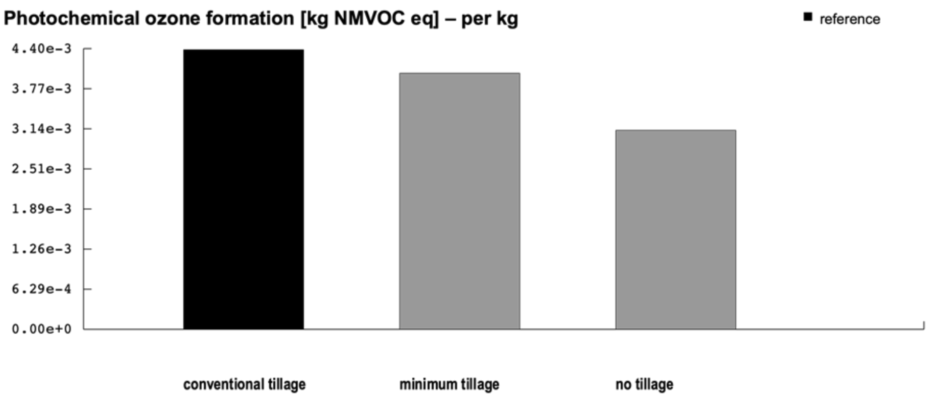

Figure 81. Photochemical ozone formation per kg of wheat using three different soil treatments of Experiment 3.

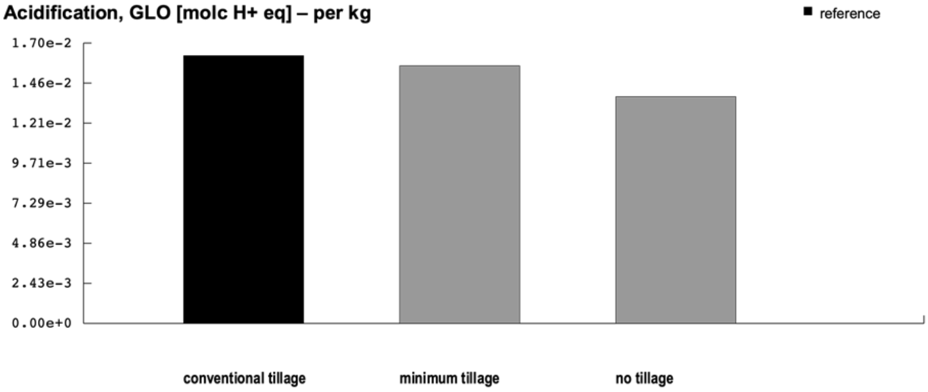

Figure 82. Acidification potential per kg of wheat using three different soil treatments of Experiment 3.

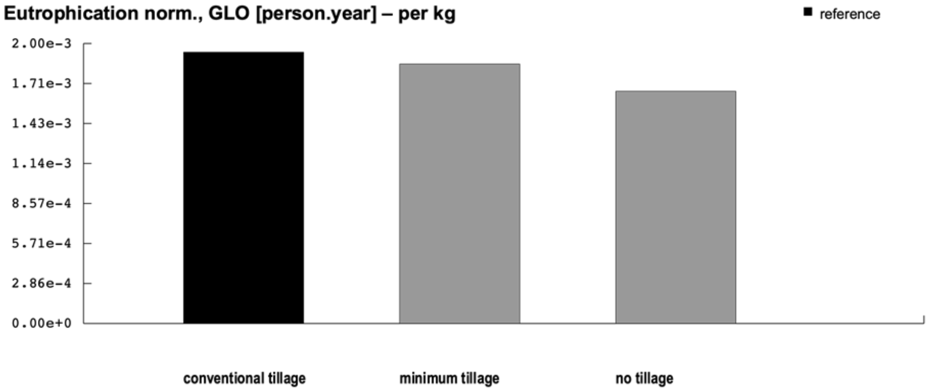

Figure 83. Eutrophication per kg of wheat using three different soil treatments of Experiment 3.

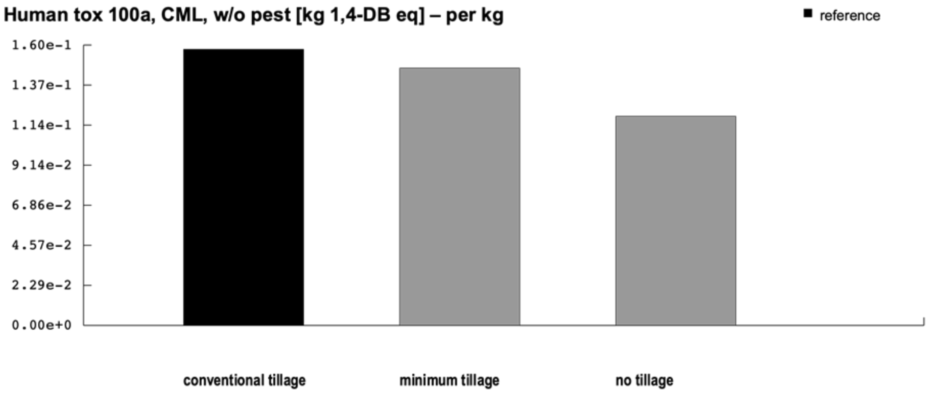

Figure 84. Human toxicity without pesticides per kg of wheat using three different soil treatments of Experiment 3.

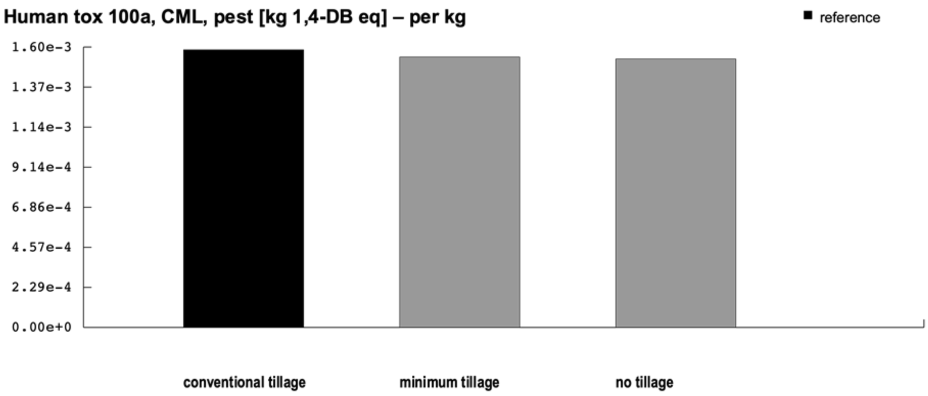

Figure 85. Human toxicity with pesticides per kg of wheat using three different soil treatments of Experiment 3.

Figure 86. Aquatic ecotoxicity without pesticides per kg of wheat using three different soil treatments of Experiment 3.

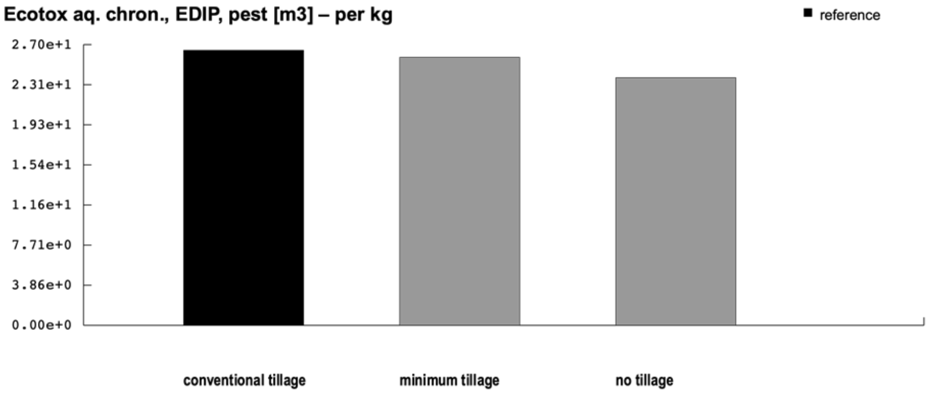

Figure 87. Aquatic ecotoxicity with pesticides per kg of wheat using three different soil treatments of Experiment 3.

Experiment 4 – Test of solar-dried fertilizers in crop rotations

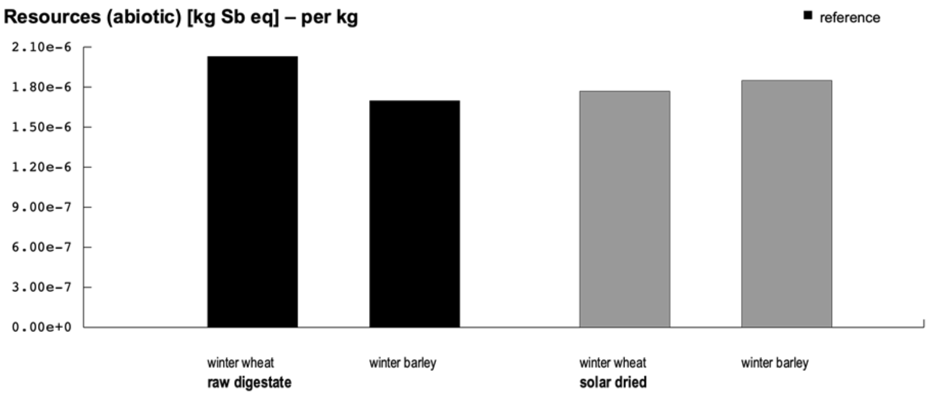

Figure 88. Abiotic resource depletion per kg of crop yield using two different fertilizers of Experiment 4.

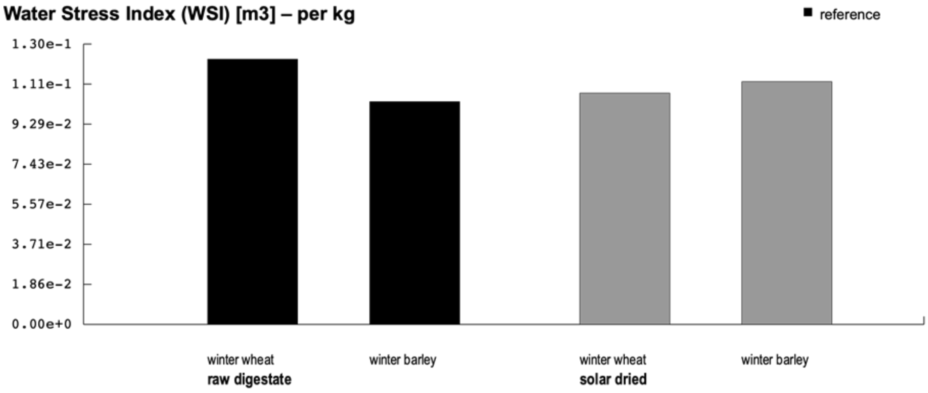

Figure 89. Water Stress Index per kg of crop yield using two different fertilizers of Experiment 4.

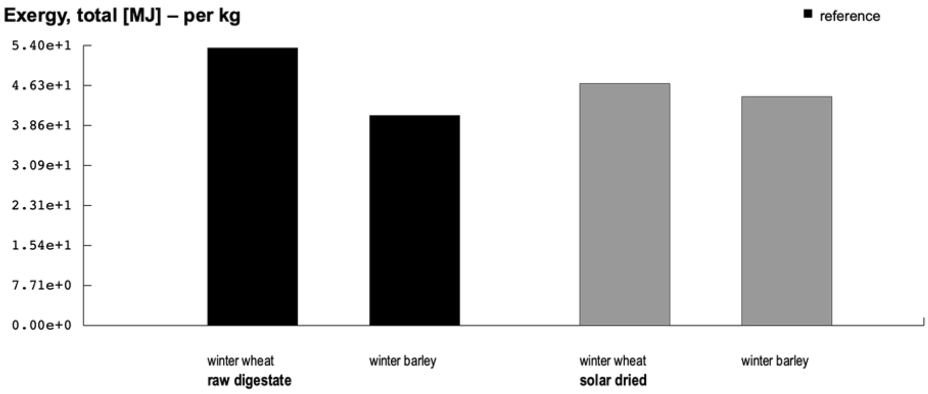

Figure 90. Total exergy per kg of crop yield using two different fertilizers of Experiment 4.

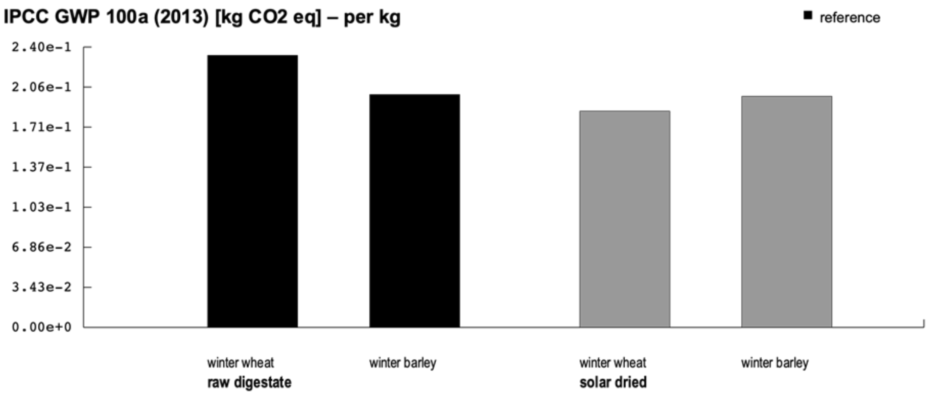

Figure 91. Global warming potential per kg of crop yield using two different fertilizers of Experiment 4.

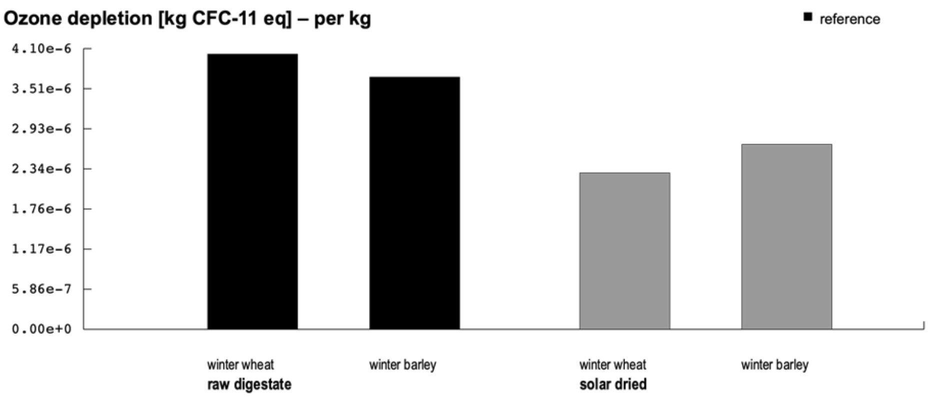

Figure 92. Ozone depletion per kg of crop yield using two different fertilizers of Experiment 4.

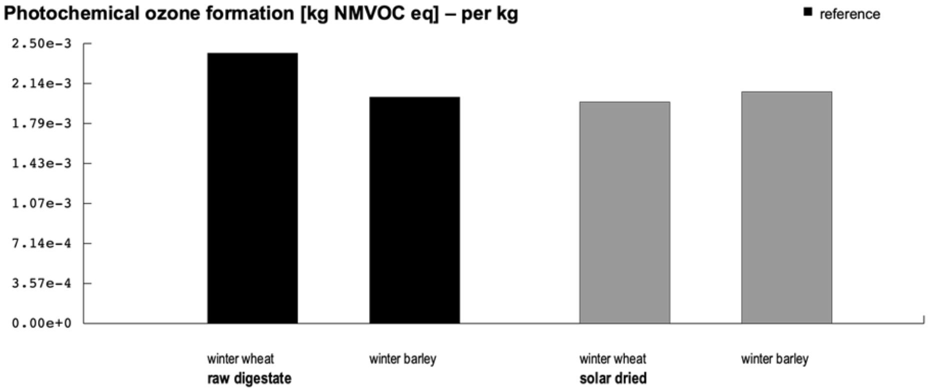

Figure 93. Photochemical ozone formation per kg of crop yield using two different fertilizers of Experiment 4.

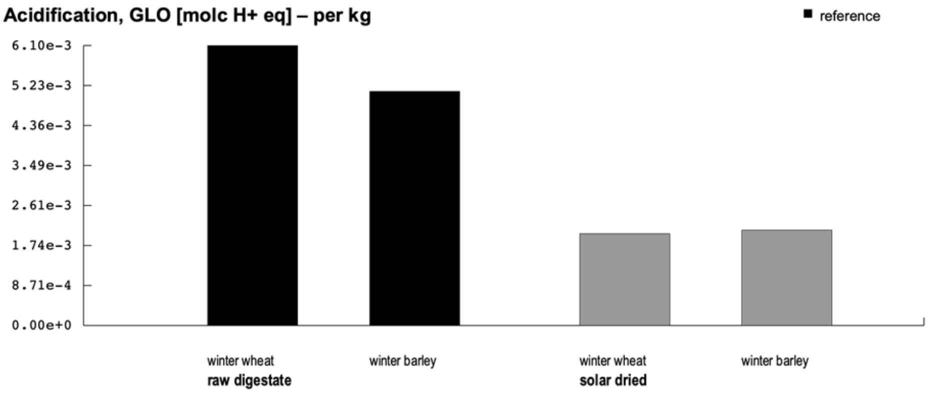

Figure 94. Acidification per kg of crop yield using two different fertilizers of Experiment 4.

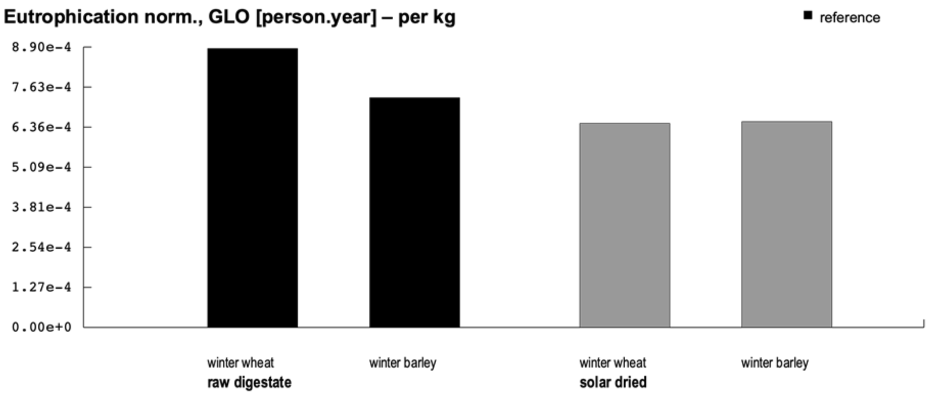

Figure 95. Eutrophication per kg of crop yield using two different fertilizers of Experiment 4.

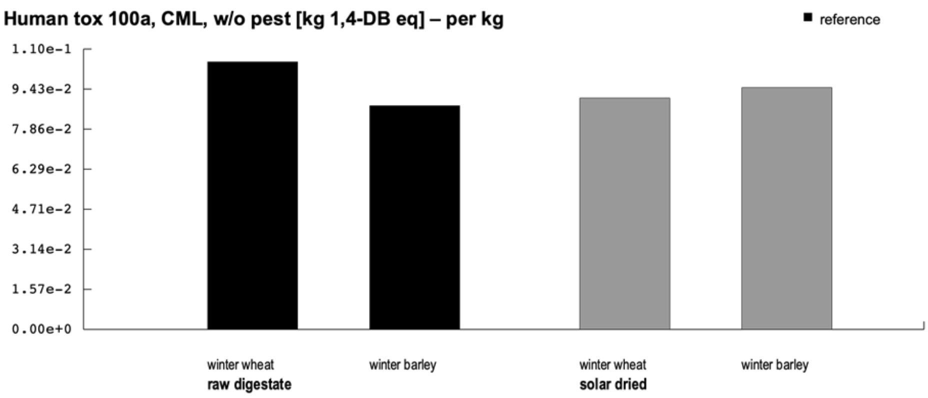

Figure 96. Human toxicity without pesticides per kg of crop yield using two different fertilizers of Experiment 4.

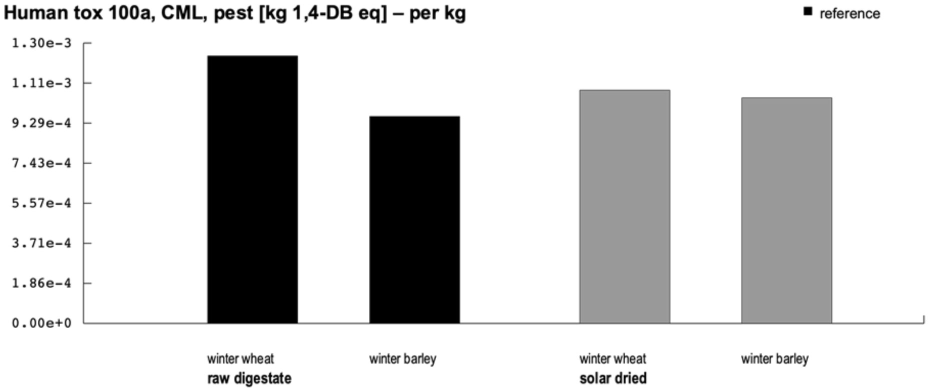

Figure 97. Human toxicity with pesticides per kg of crop yield using two different fertilizers of Experiment 4.

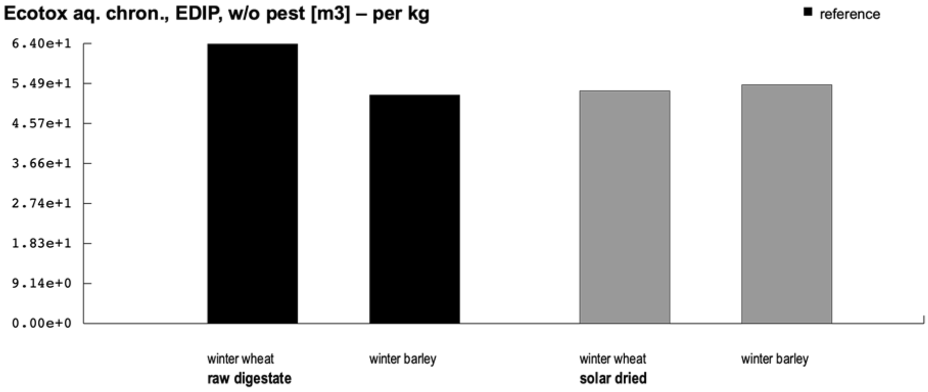

Figure 98. Aquatic ecotoxicity without pesticides per kg of crop yield using two different fertilizers of Experiment 4.

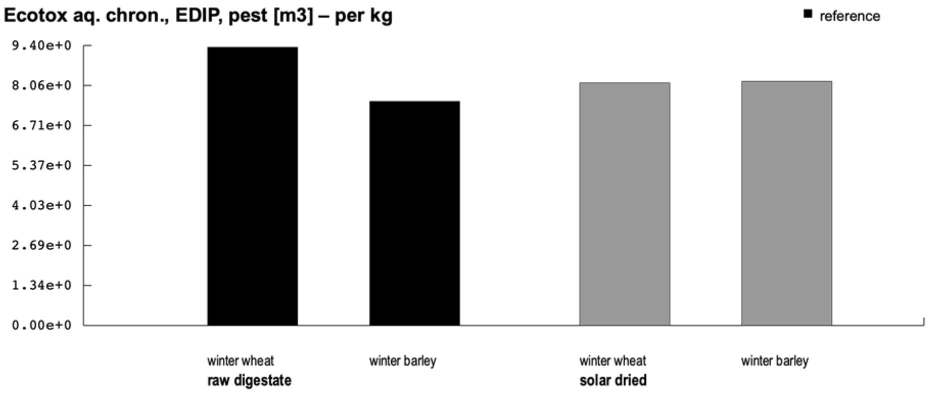

Figure 99. Aquatic ecotoxicity with pesticides per kg of crop yield using two different fertilizers of Experiment 4.

Experiment 5 – Fertigation with microfiltered digestate

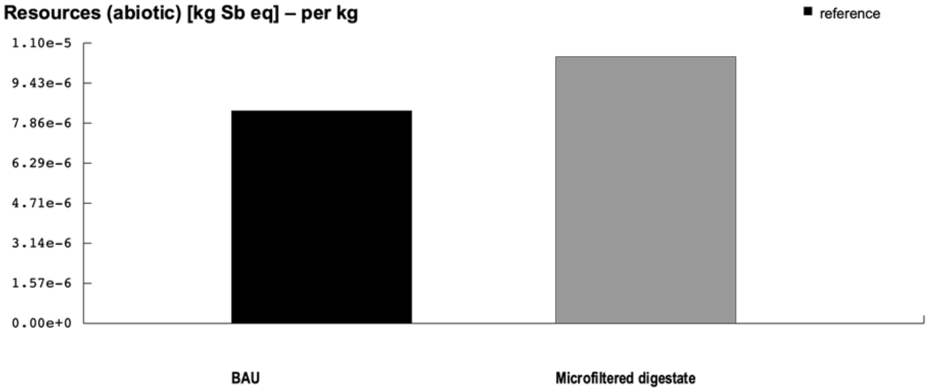

Figure 100. Abiotic resource depletion per kg of crop yield using two different fertilizers of Experiment 5.

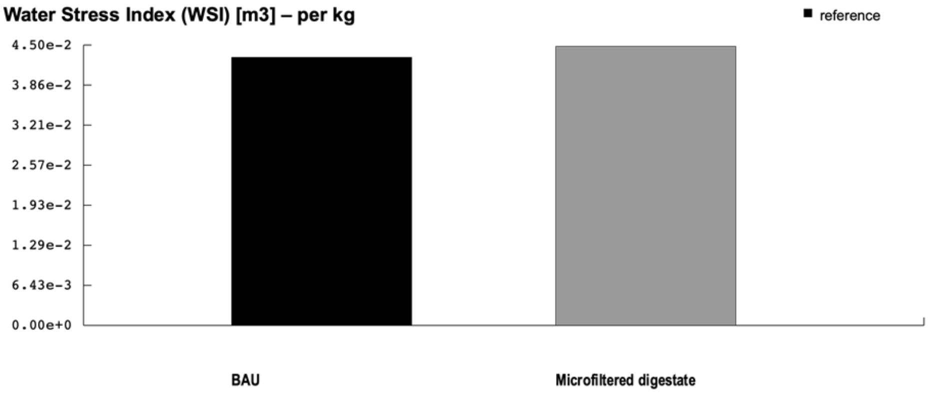

Figure 101. Water stress index per kg of crop yield using two different fertilizers of Experiment 5.

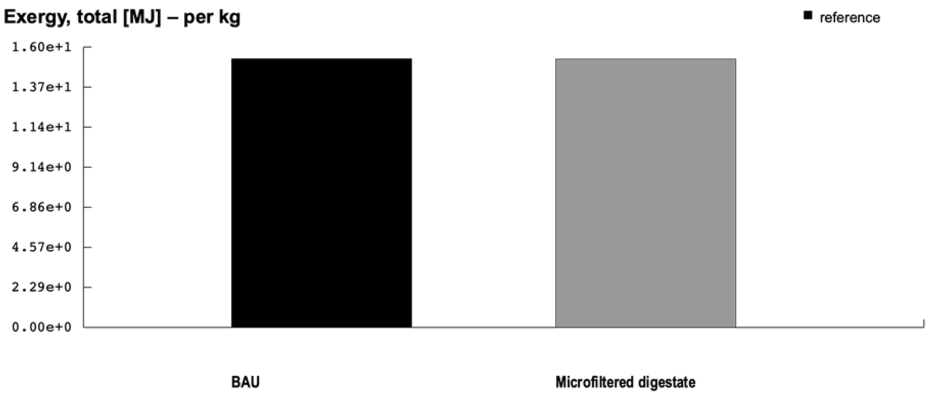

Figure 102. Total exergy per kg of crop yield using two different fertilizers of Experiment 5.

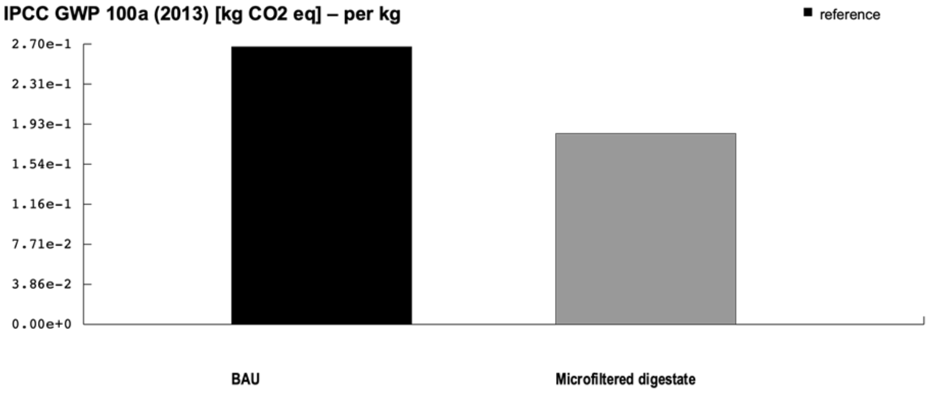

Figure 103. Global warming potential per kg of crop yield using two different fertilizers of Experiment 5.

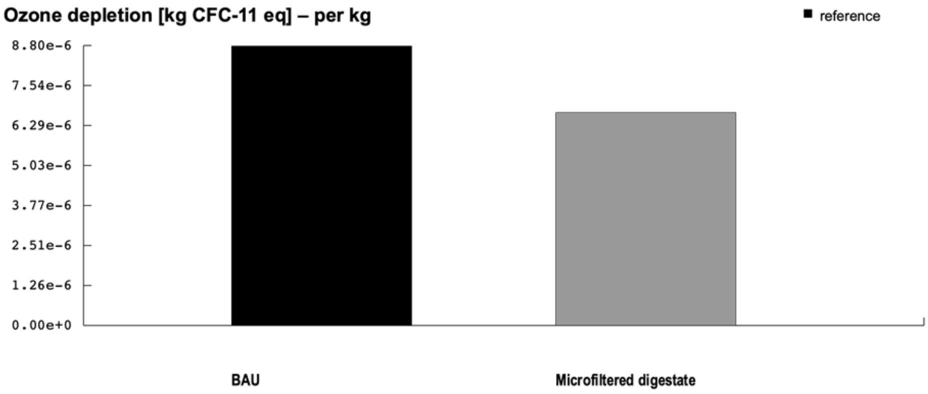

Figure 104. Ozone depletion use per kg of crop yield using two different fertilizers of Experiment 5.

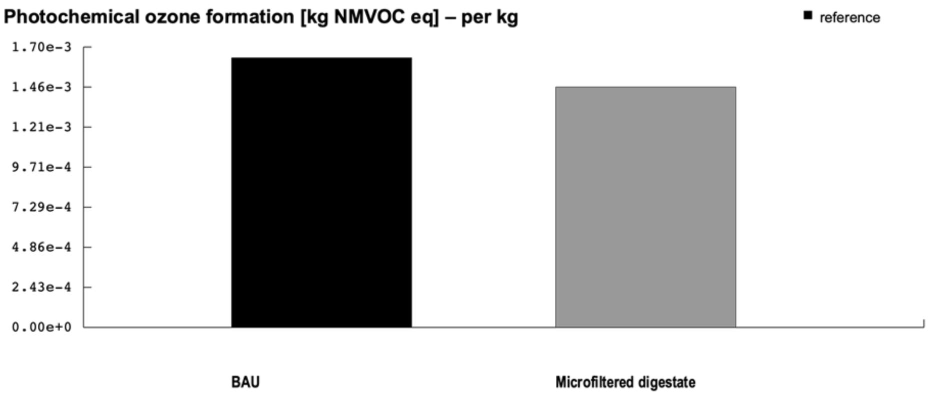

Figure 105. Photochemical ozone formation per kg of crop yield using two different fertilizers of Experiment 5.

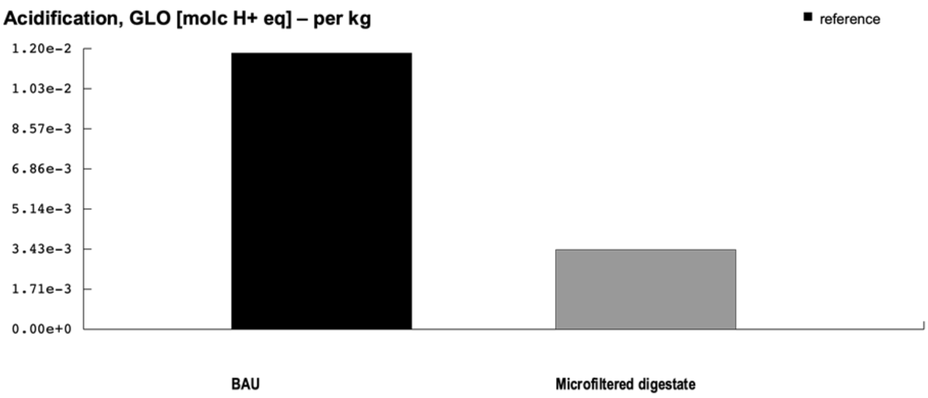

Figure 106. Acidification per kg of crop yield using two different fertilizers of Experiment 5.

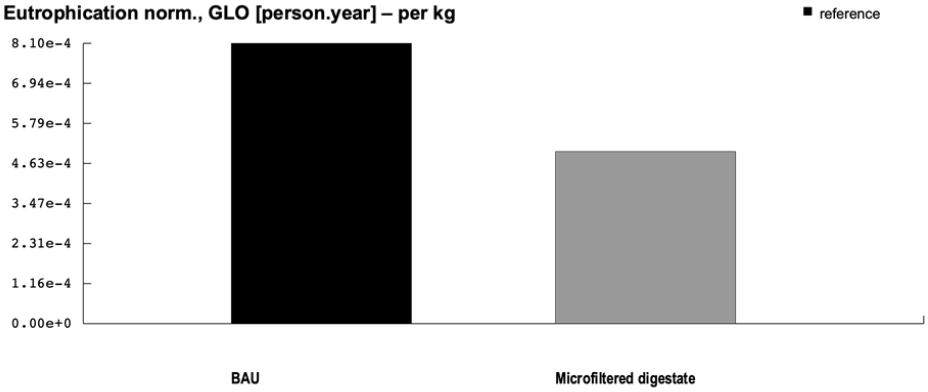

Figure 107. Eutrophication per kg of crop yield using two different fertilizers of Experiment 5.

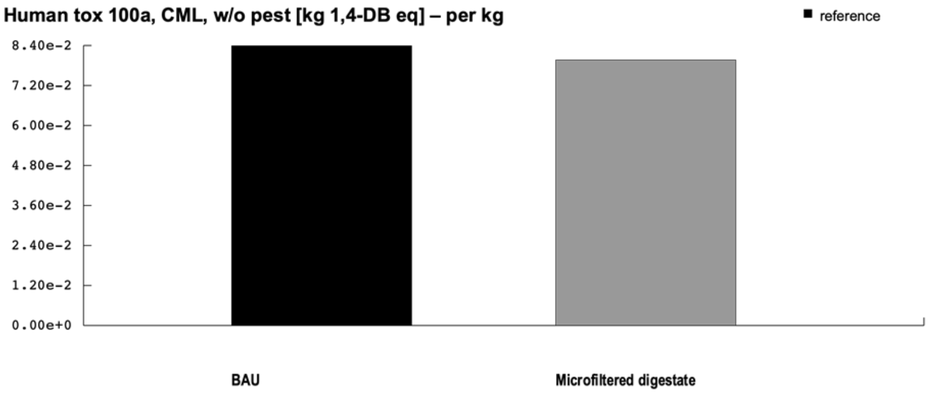

Figure 108. Human toxicity without pesticides per kg of crop yield using two different fertilizers of Experiment 5.

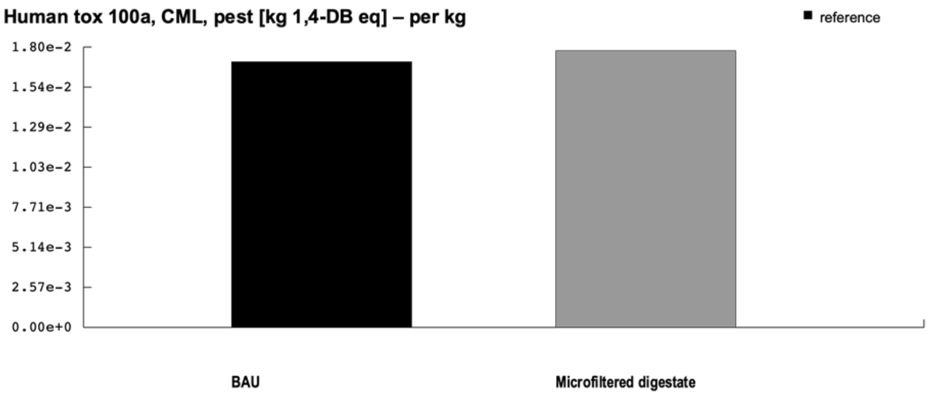

Figure 109. Human toxicity with pesticide use per kg of crop yield using two different fertilizers of Experiment 5.

Figure 110. Aquatic ecotoxicity without pesticides per kg of crop yield using two different fertilizers of Experiment 5.

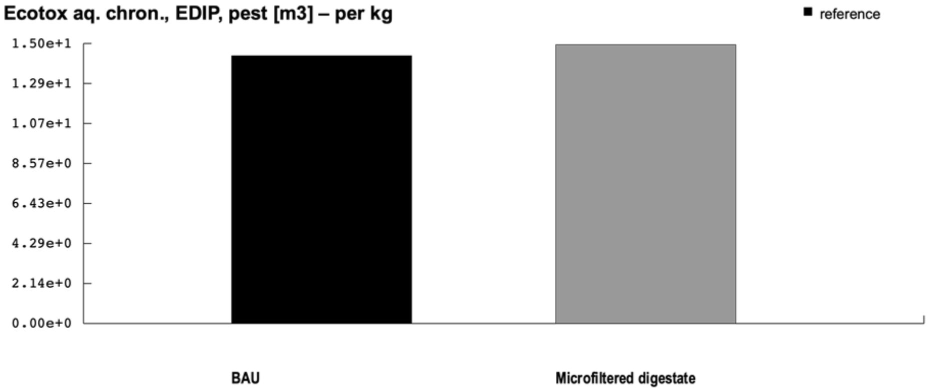

Figure 111. Aquatic ecotoxicity with pesticides per kg of crop yield using two different fertilizers of Experiment 5.

7.2 Agricultural experiments – Absolute contribution analysis per experiment

Experiment 1 – N use efficiency of Winter wheat

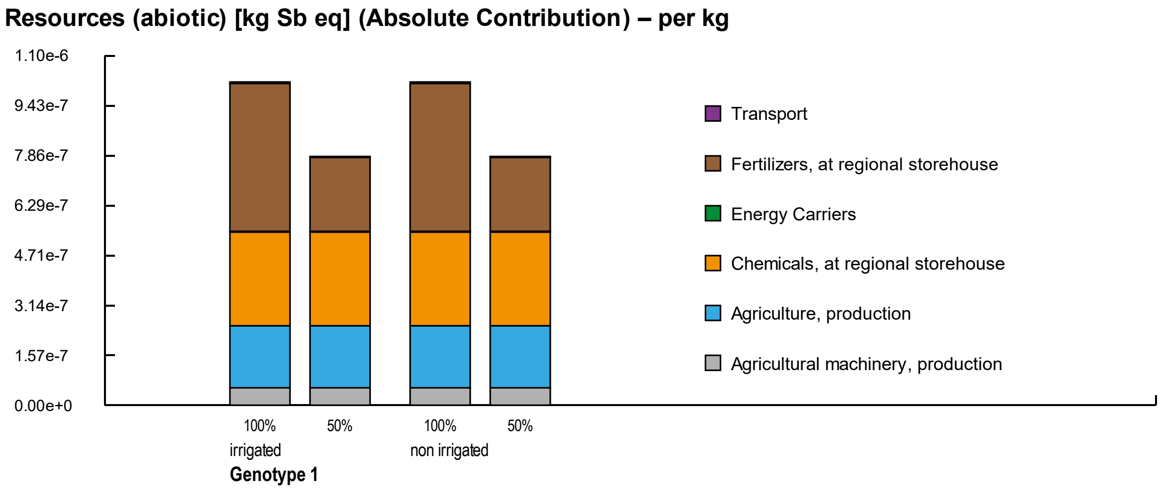

Figure 112. Absolute contribution analysis of the abiotic resource depletion per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

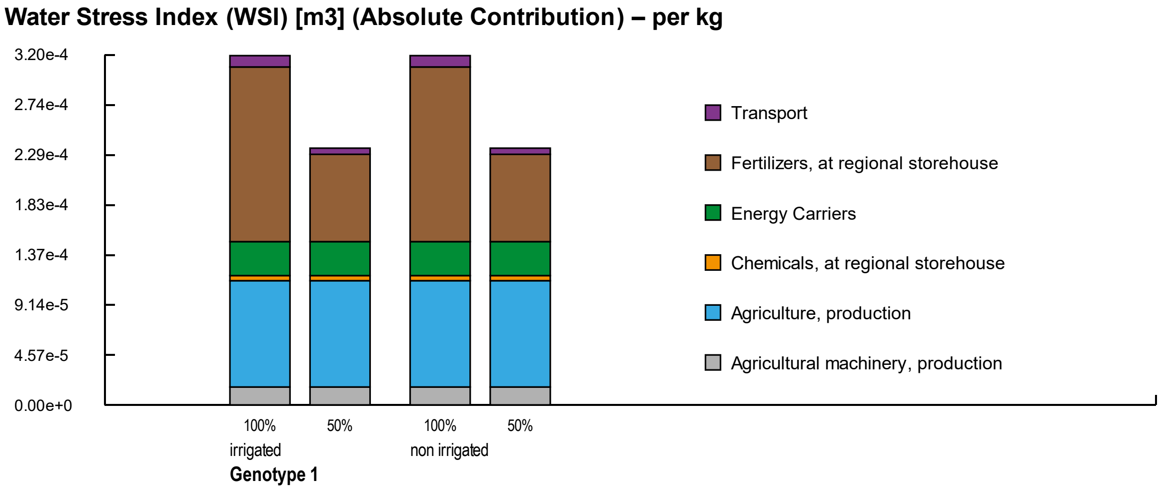

Figure 113. Absolute contribution analysis of the wáter stress index per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

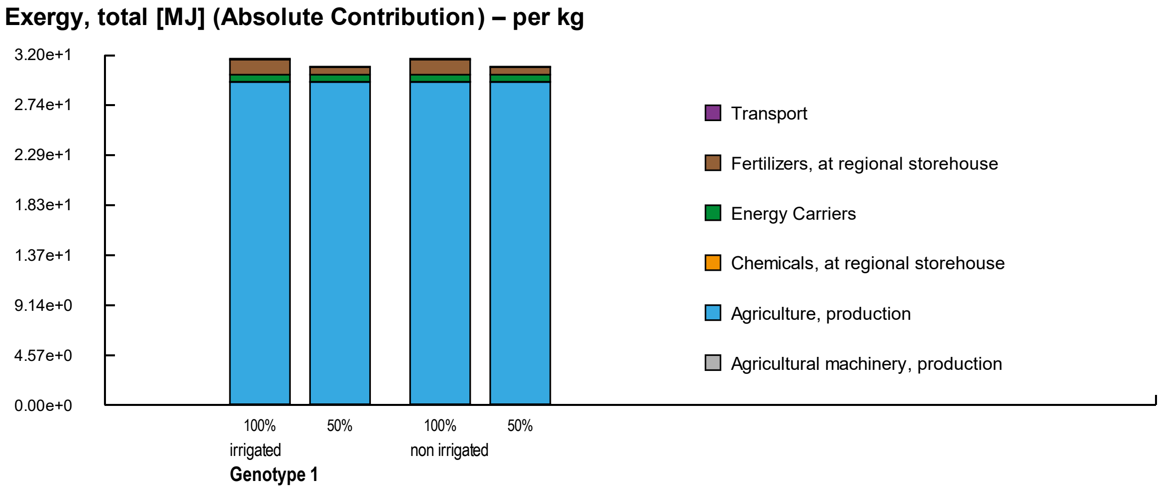

Figure 114. Absolute contribution analysis of the total exergy per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

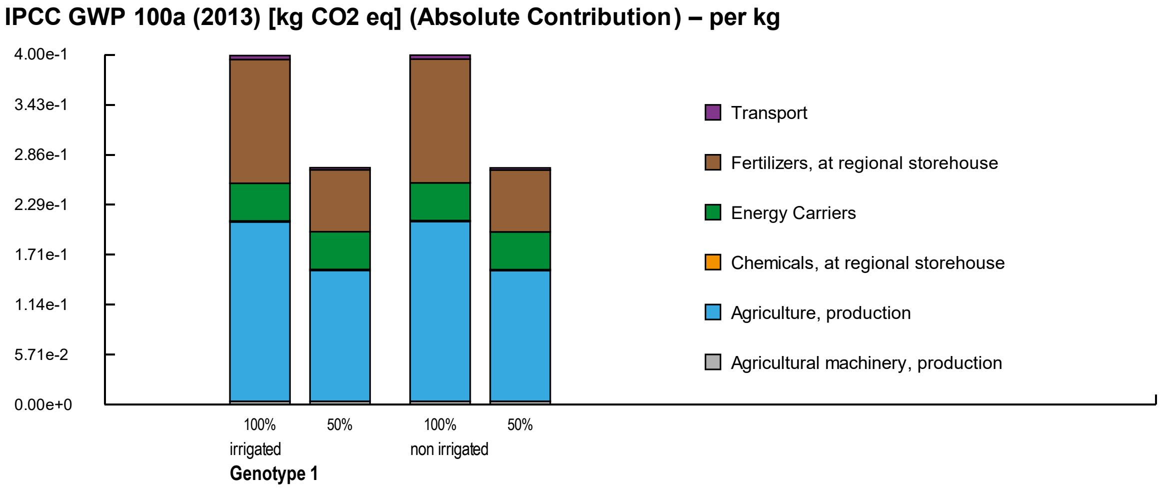

Figure 115. Absolute contribution analysis of the global warming potential per kg wheat grain of three different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

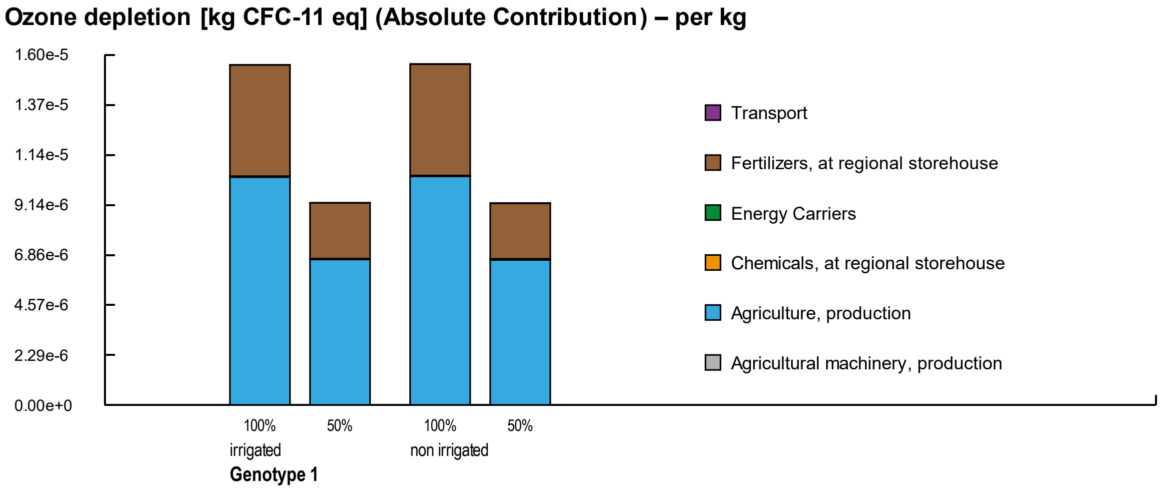

Figure 116. Absolute contribution analysis of the ozone depletion per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

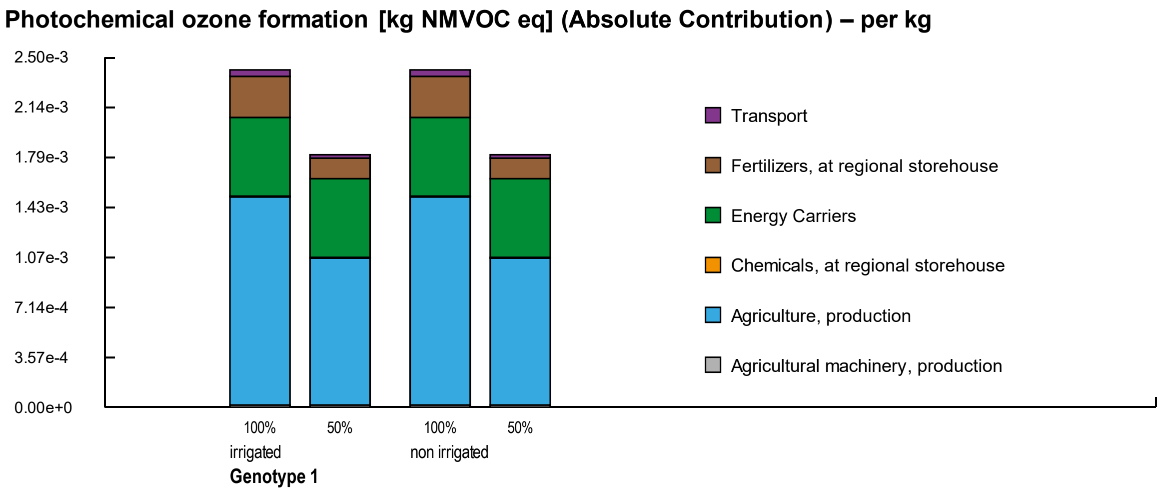

Figure 117. Absolute contribution analysis of the photochemical ozone formation per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

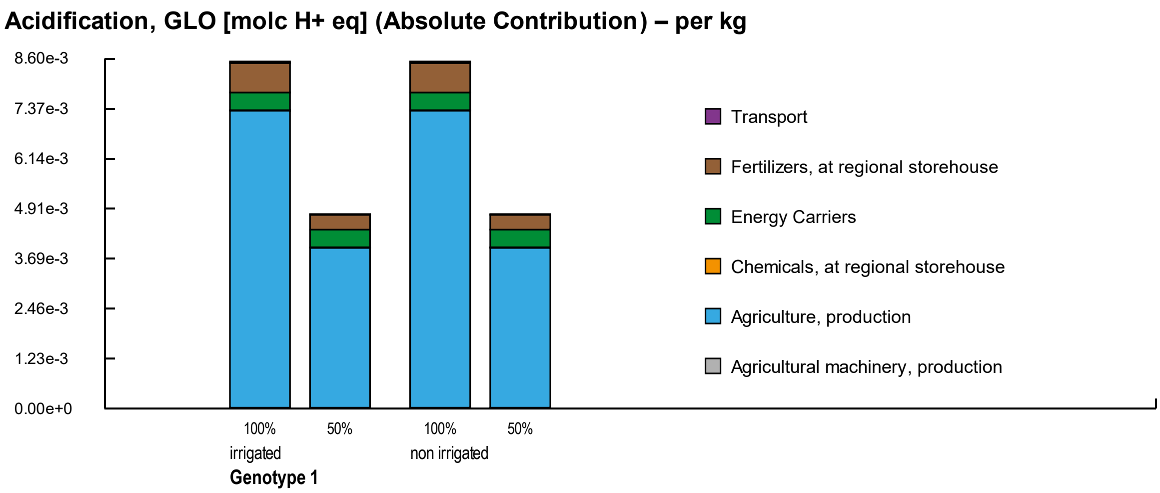

Figure 118. Absolute contribution analysis of the acidification per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

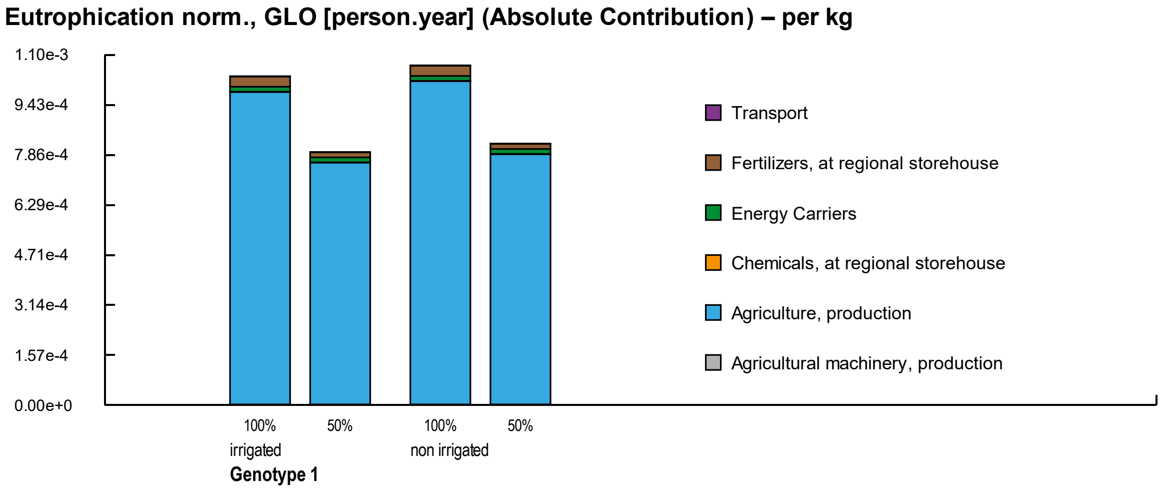

Figure 119. Absolute contribution analysis of the eutrophication per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

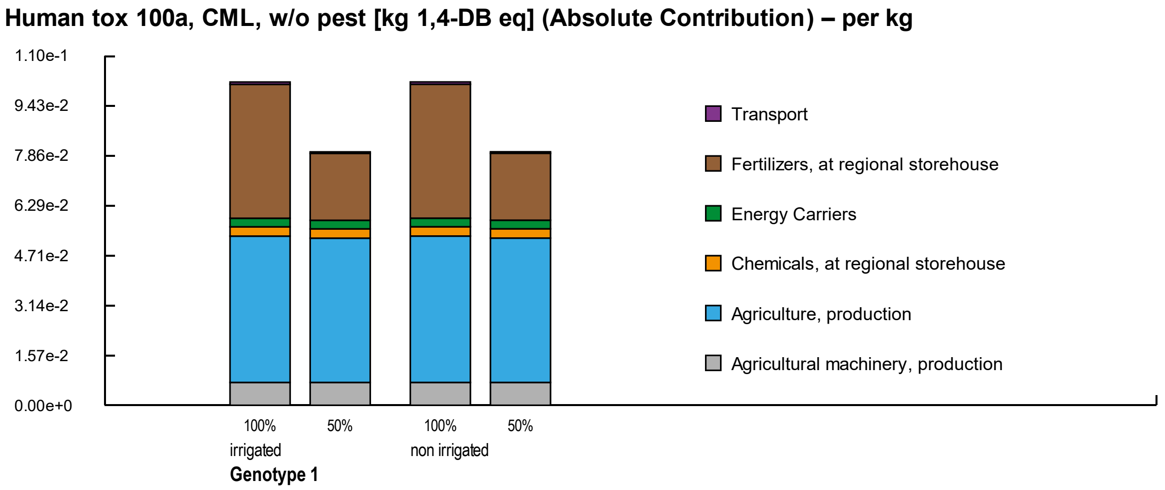

Figure 120. Absolute contribution analysis of the human toxicity without pesticides per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

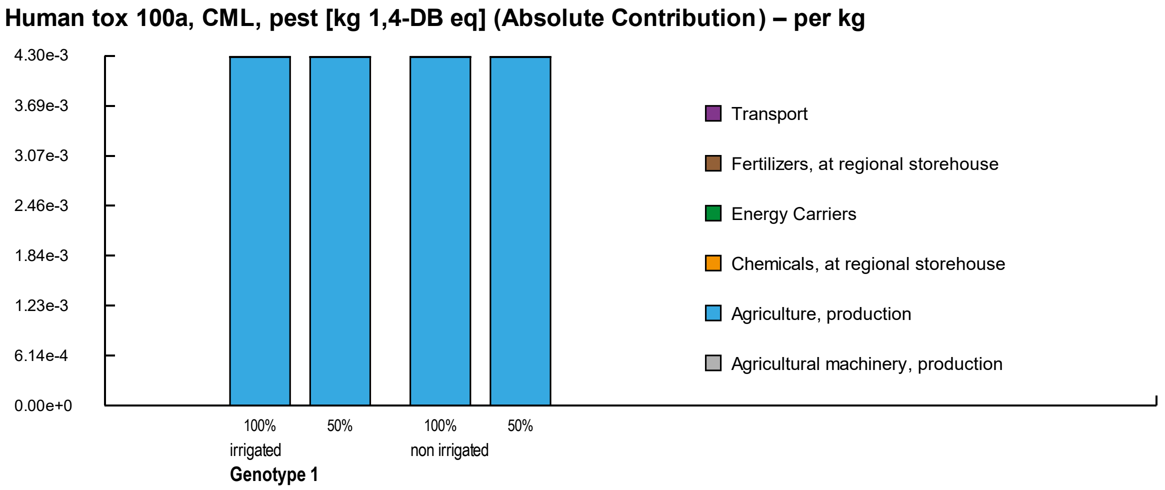

Figure 121. Absolute contribution analysis of the human toxicity with pesticides per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

Ecotox aq. chron., EDIP, w/o pest [m3] (Absolute Contribution) – per kg

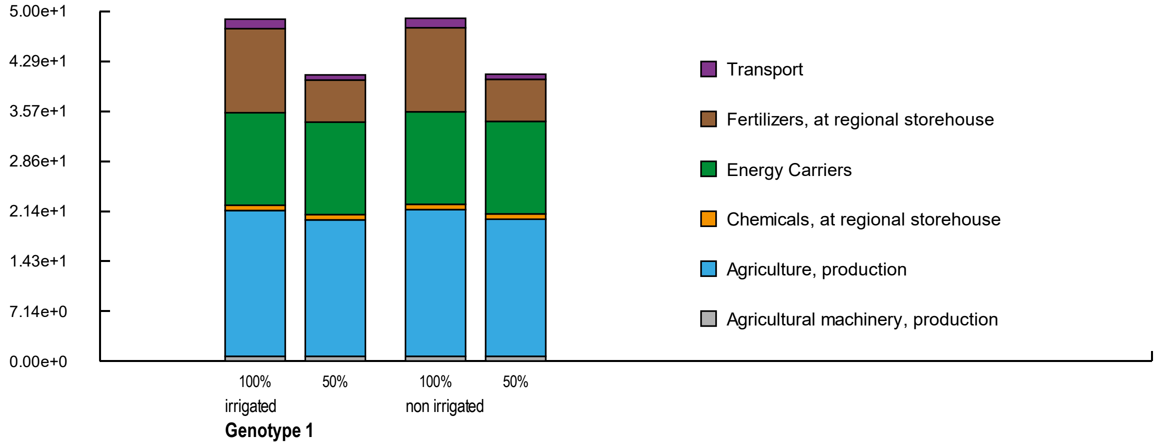

Figure 122. Absolute contribution analysis of the aquatic ecotoxicity without pesticides per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

Ecotox aq. chron., EDIP, pest [m3] (Absolute Contribution) – per kg

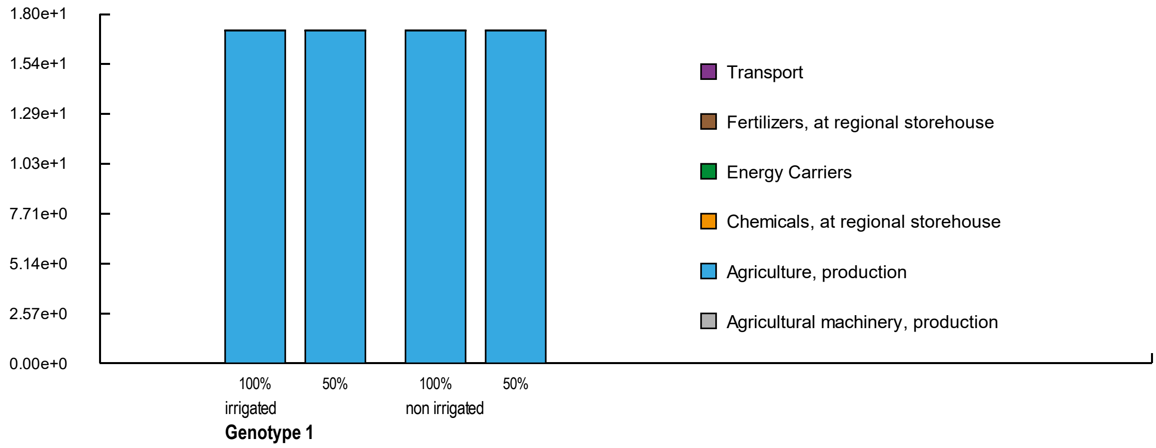

Figure 123. Absolute contribution analysis of the aquatic ecotoxicity with pesticides per kg wheat grain of 3 different genotypes, two different (simulated) weather conditions, and five fertilization levels of Experiment 1.

Experiment 2 – Slurry application techniques

Resources (abiotic) [kg Sb eq] (Absolute Contribution) – per kg

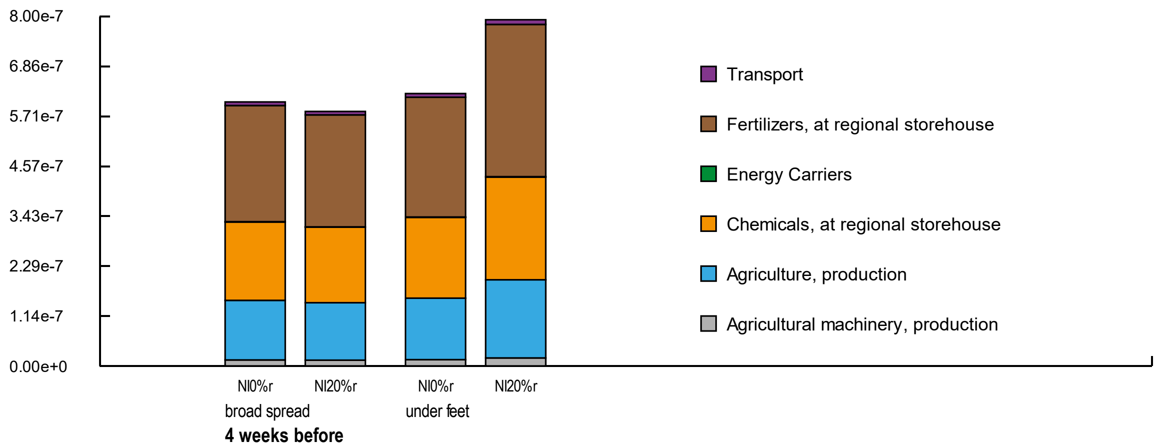

Figure 124. Absolute contribution analysis of abiotic resource depletion kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

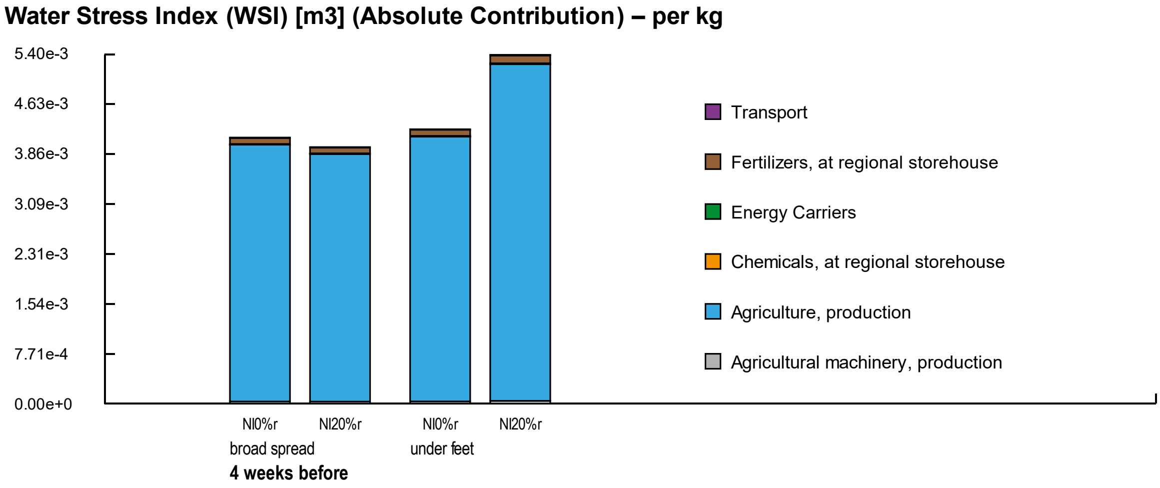

Figure 125. Absolute contribution analysis of wáter stress index per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

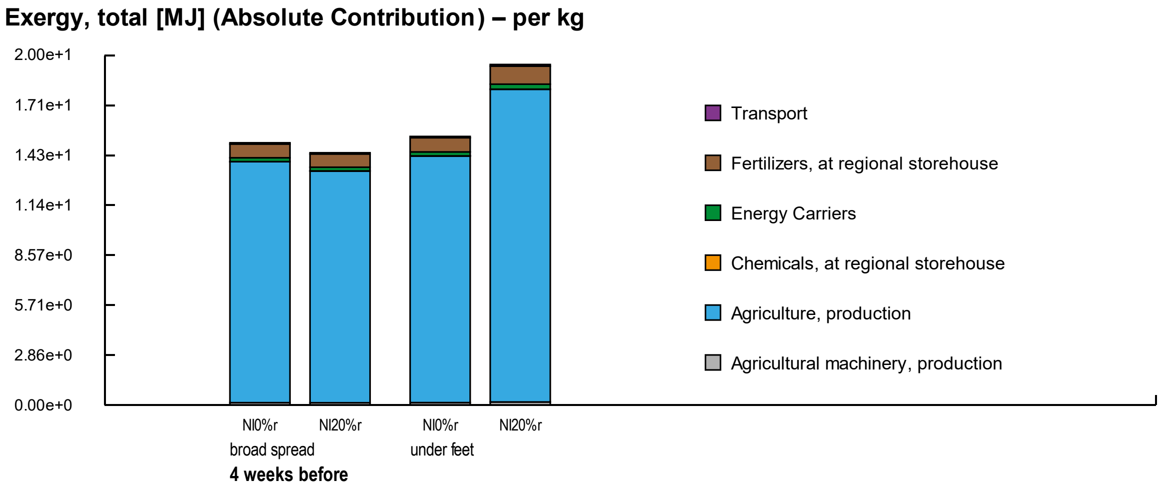

Figure 126. Absolute contribution analysis of total exergy per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

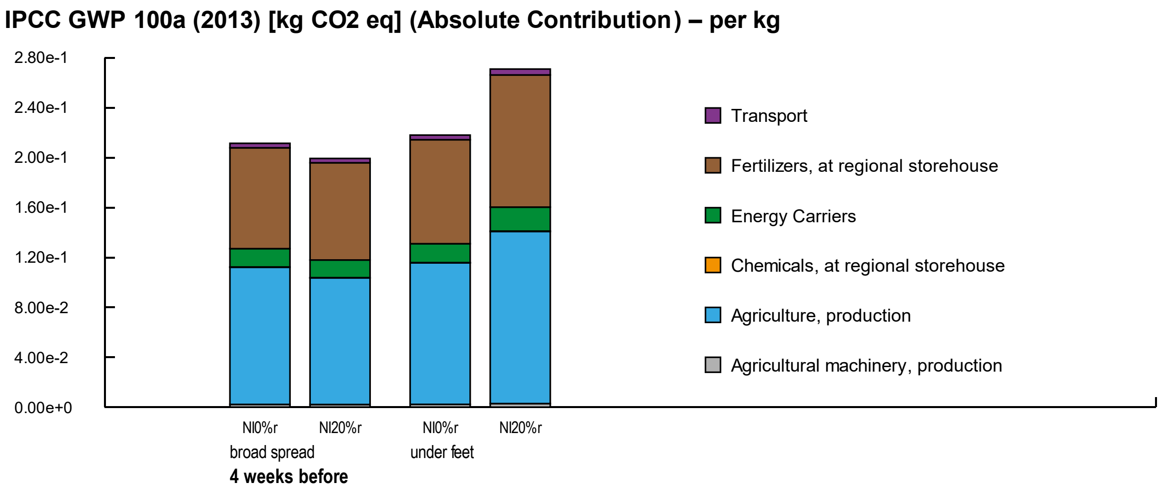

Figure 127. Absolute contribution analysis of global warming potential per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

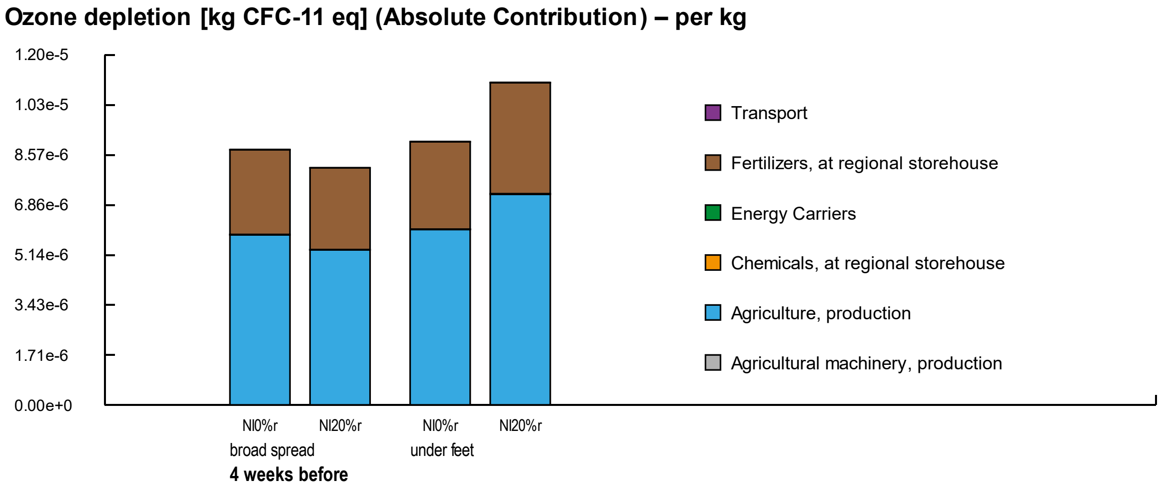

Figure 128. Absolute contribution analysis of ozone depletion per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

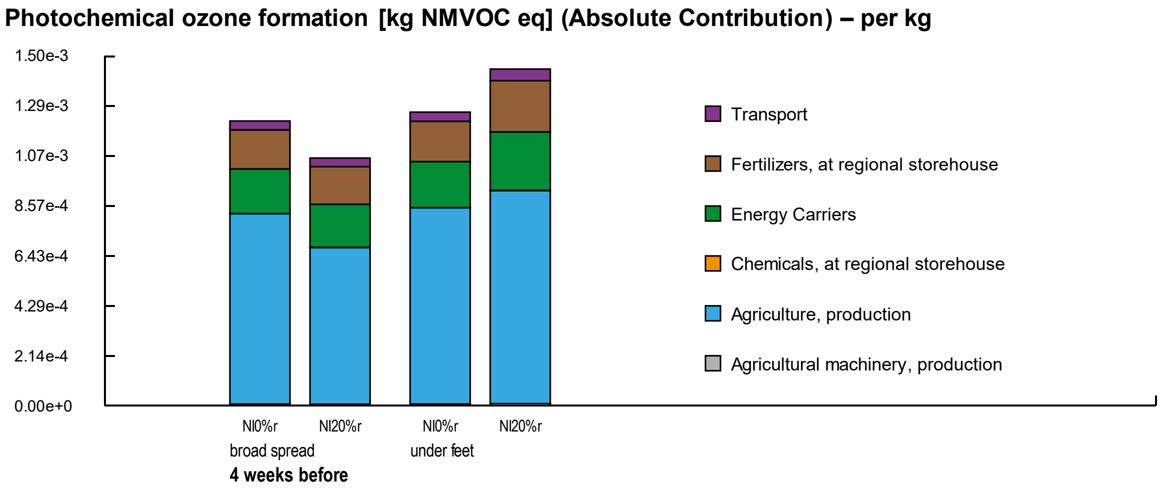

Figure 129. Absolute contribution analysis of photochemical ozone formation per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

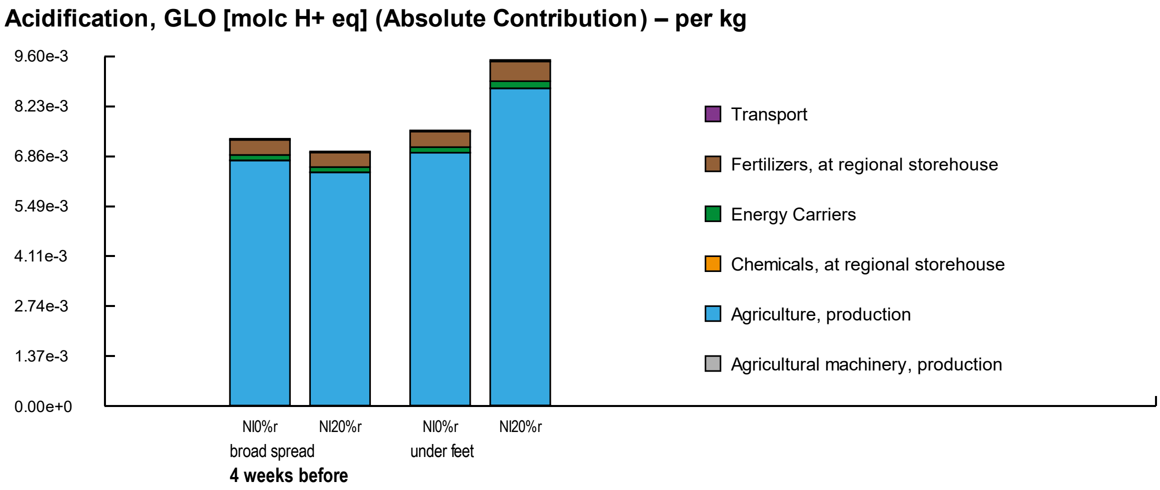

Figure 130. Absolute contribution analysis of acidification per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

Eutrophication norm., GLO [person.year] (Absolute Contribution) – per kg

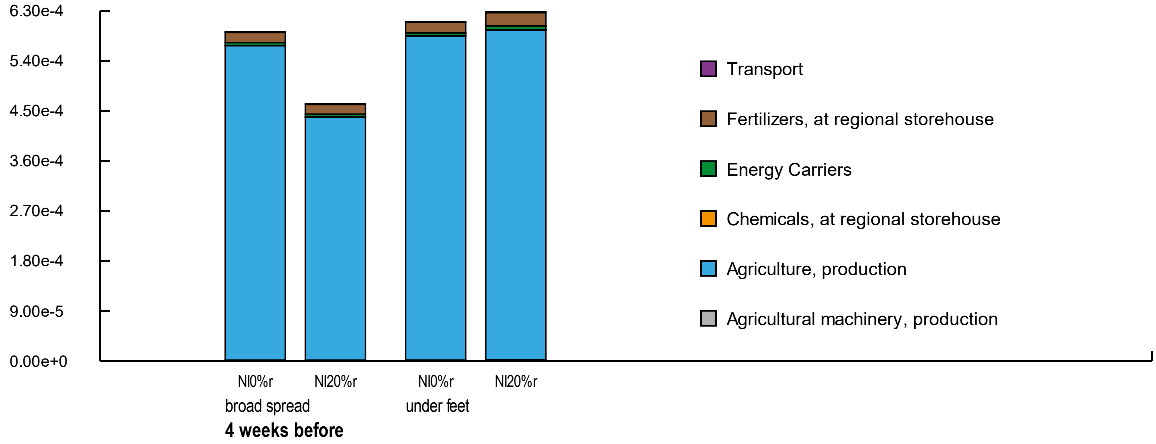

Figure 131. Absolute contribution analysis of eutrophication per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

Human tox 100a, CML, w/o pest [kg 1,4-DB eq] (Absolute Contribution) – per kg

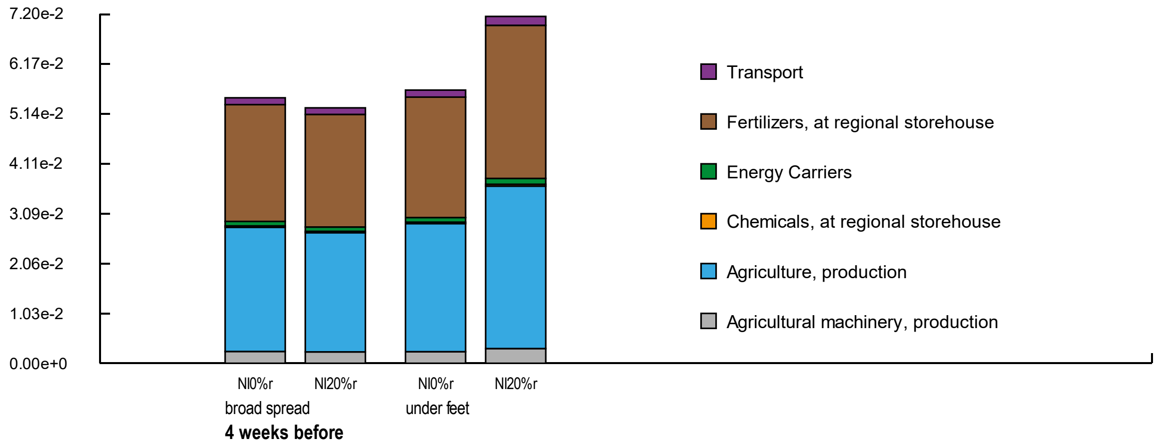

Figure 132. Absolute contribution analysis of human toxicity without pesticides per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

Human tox 100a, CML, pest [kg 1,4-DB eq] (Absolute Contribution) – per kg

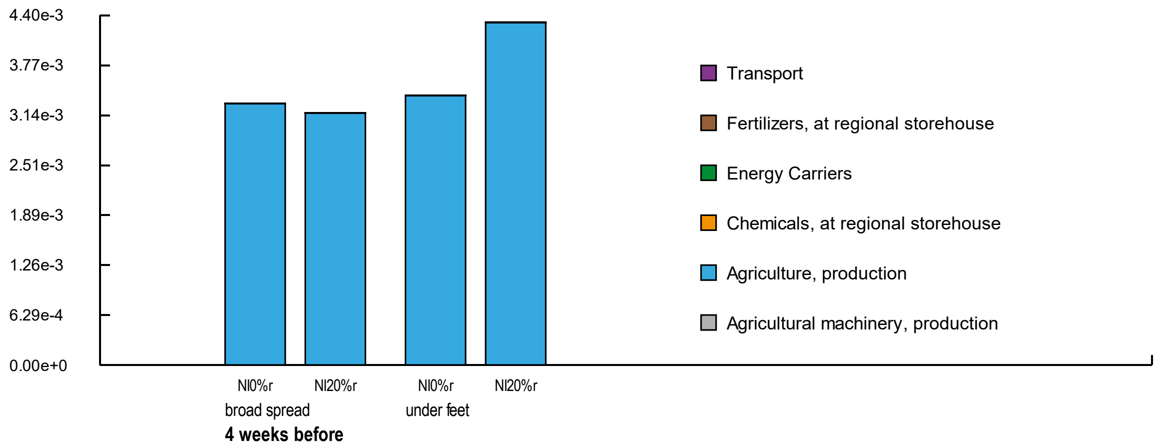

Figure 133. Absolute contribution analysis of human toxicity with pesticides per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

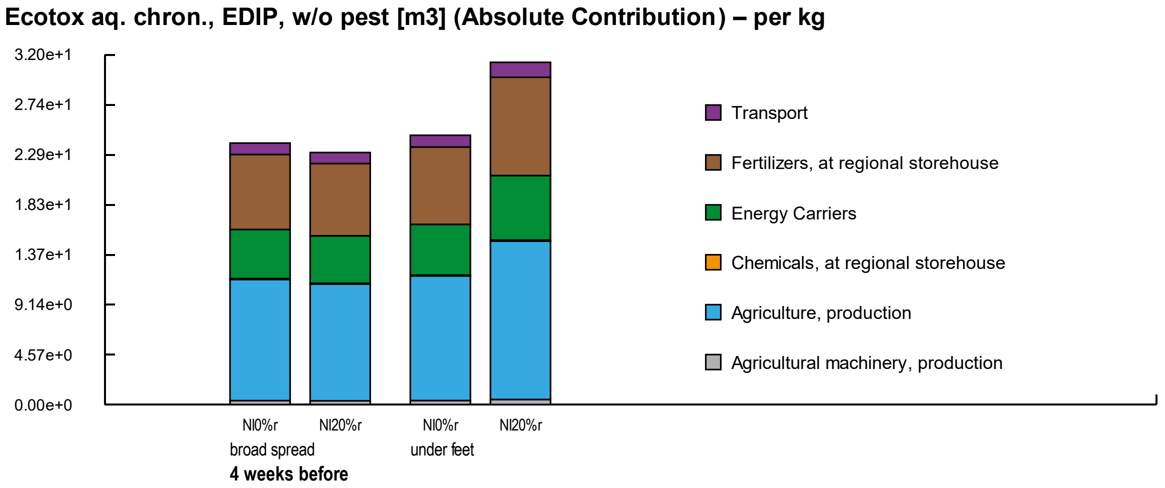

Figure 134. Absolute contribution analysis of aquatic ecotoxicity without pesticides per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

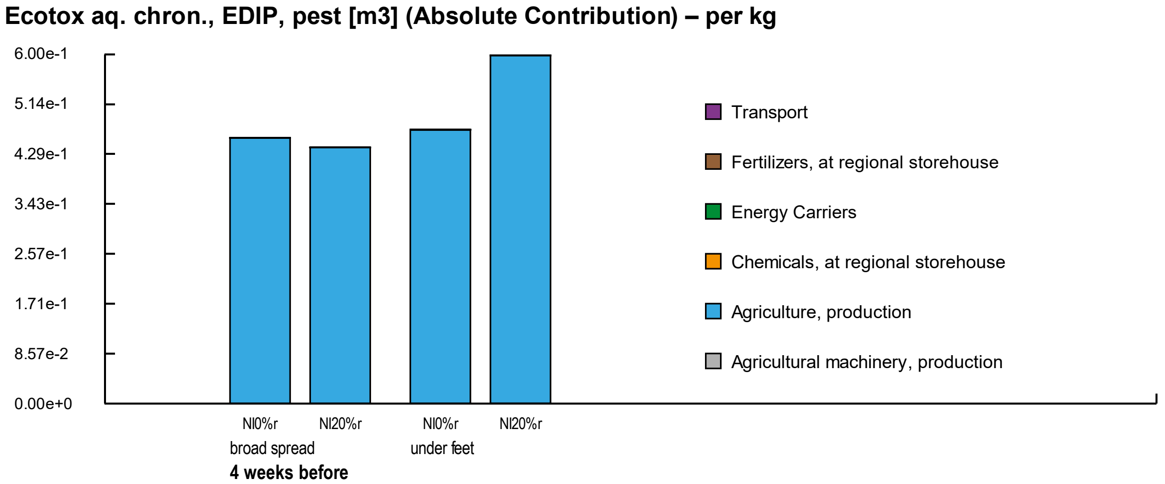

Figure 135. Absolute contribution analysis of aquatic ecotoxicity with pesticides per kg of whole maize using three different timings for fertilization, two different application techniques, and two different nitrification inhibitors of Experiment 2.

Experiment 3 – Conservation tillage

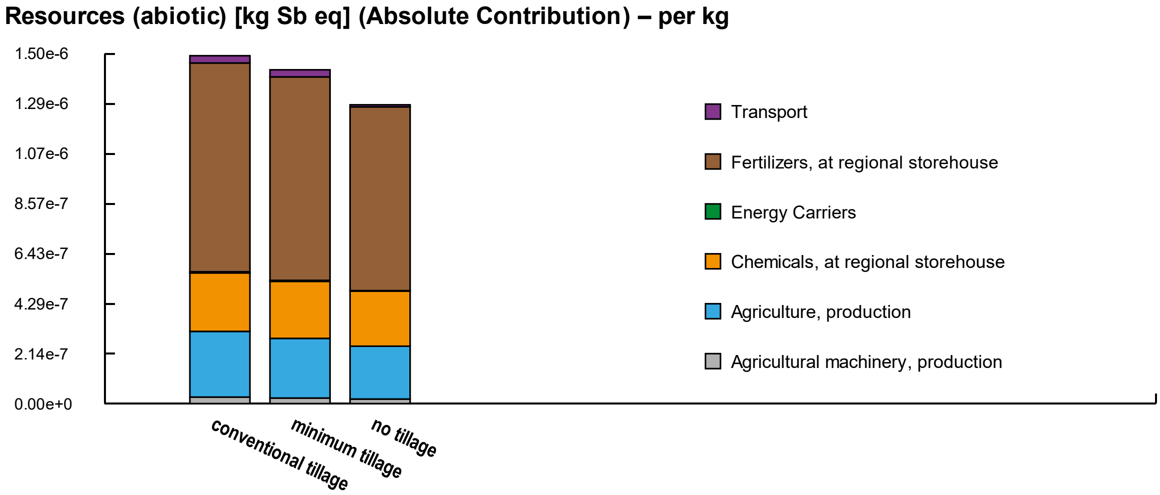

Figure 136. Absolute contribution analysis of abiotic resource depletion per kg of wheat using three different soil treatments of Experiment 3.

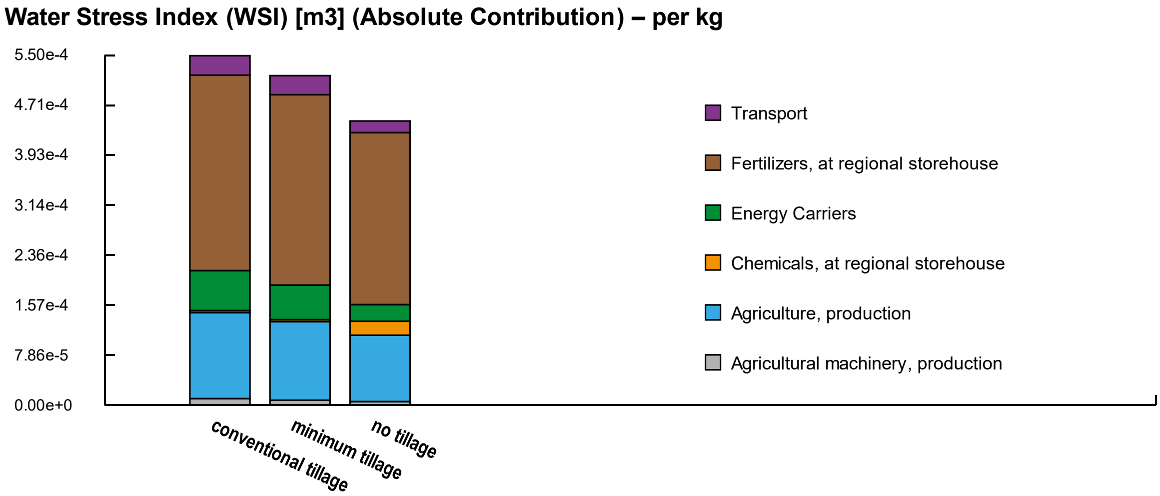

Figure 137. Absolute contribution analysis wáter stress index per kg of wheat using three different soil treatments of Experiment 3.

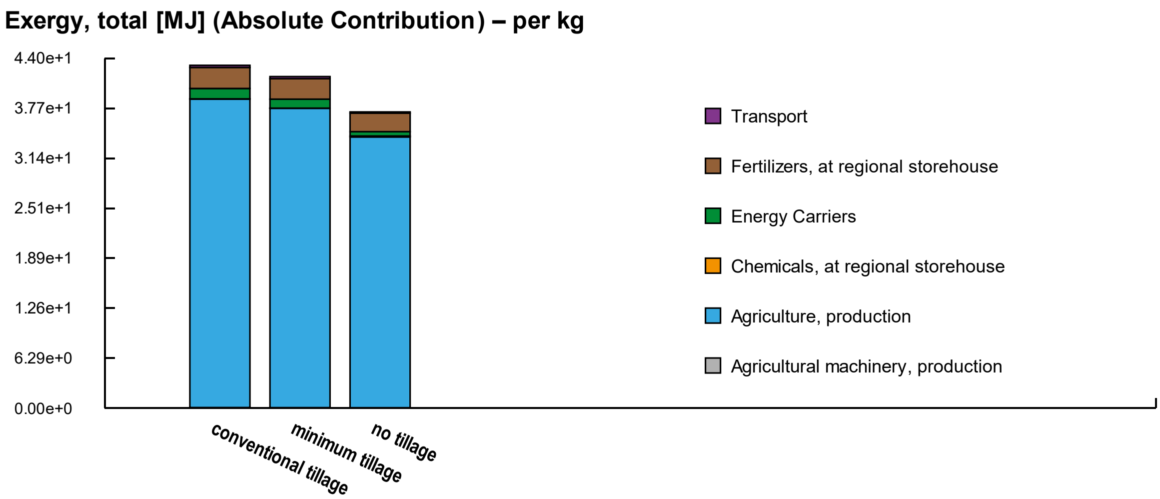

Figure 138. Absolute contribution analysis of total exergy per kg of wheat using three different soil treatments of Experiment 3.

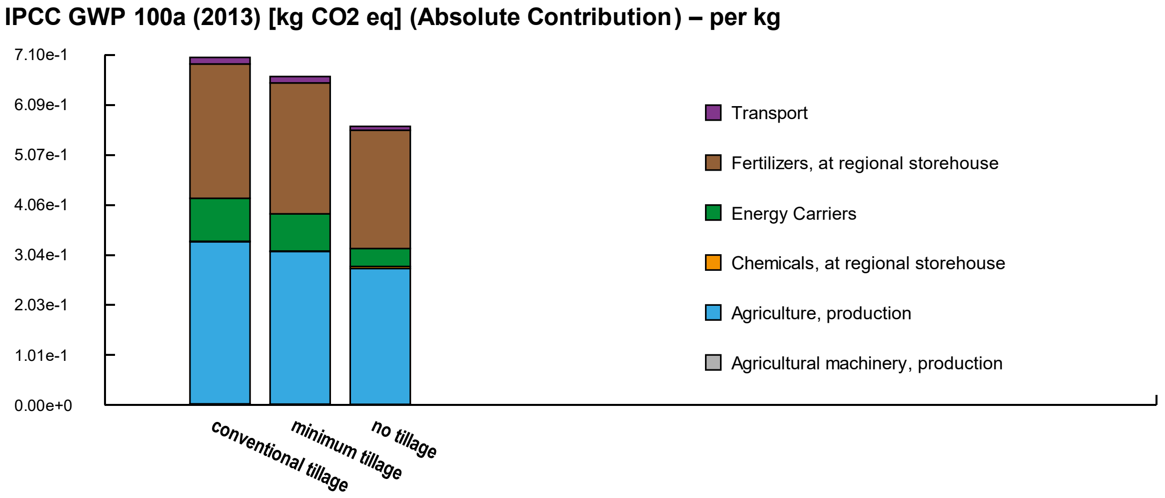

Figure 139. Absolute contribution analysis of global warming potential per kg of wheat using three different soil treatments of Experiment 3.

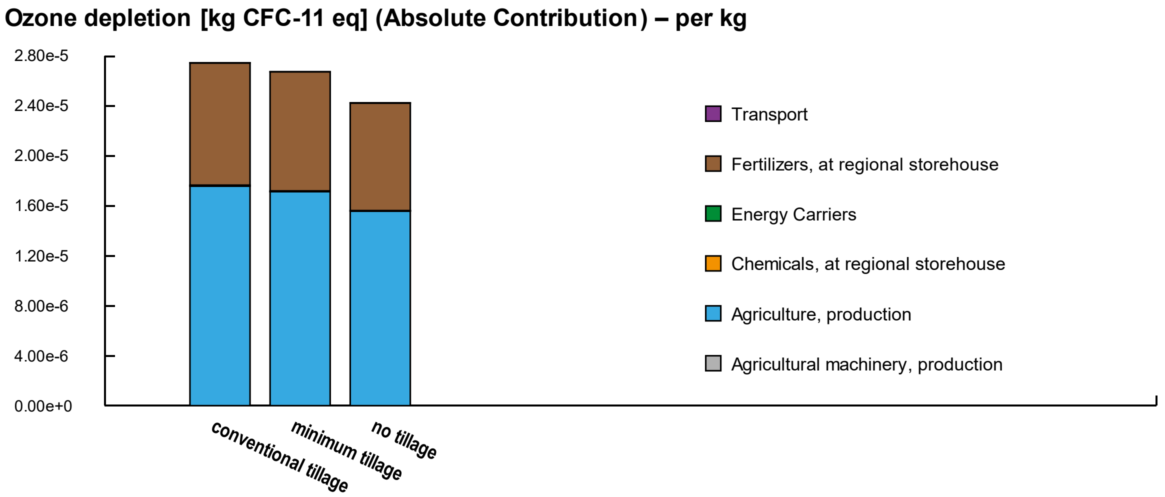

Figure 140. Absolute contribution analysis of ozone depletion per kg of wheat using three different soil treatments of Experiment 3.

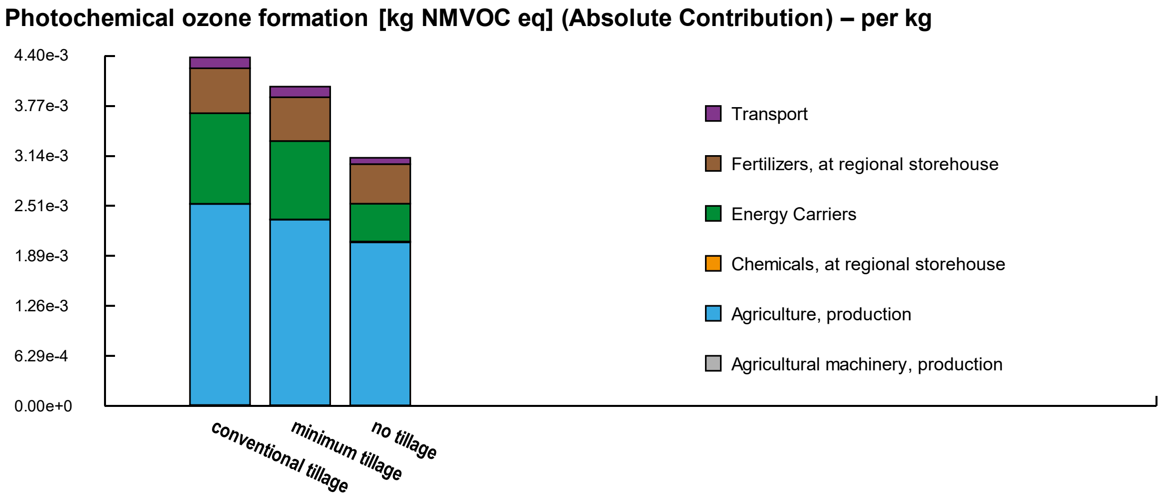

Figure 141. Absolute contribution analysis of photochemical ozone formation per kg of wheat using three different soil treatments of Experiment 3.

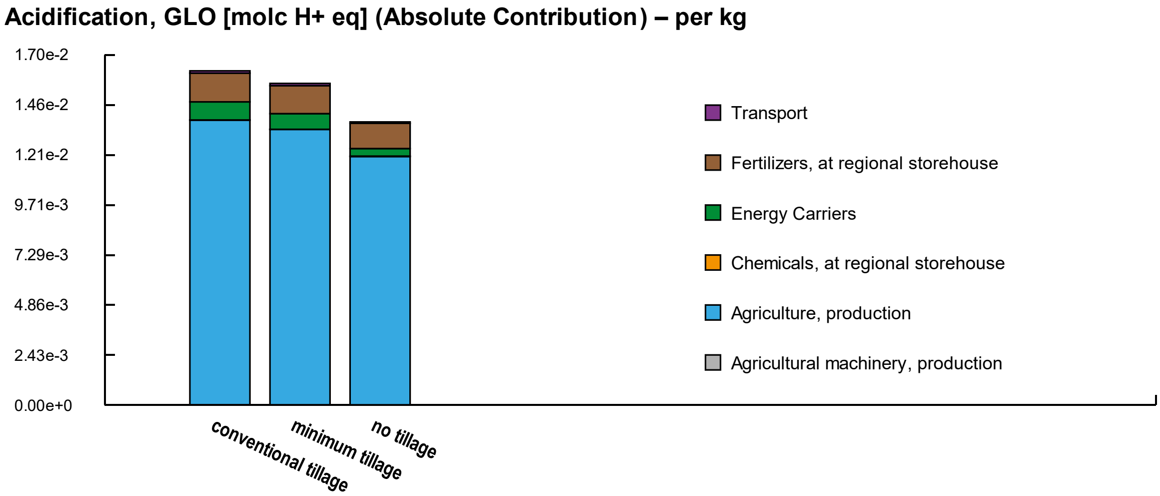

Figure 142. Absolute contribution analysis acidification per kg of wheat using three different soil treatments of Experiment 3.

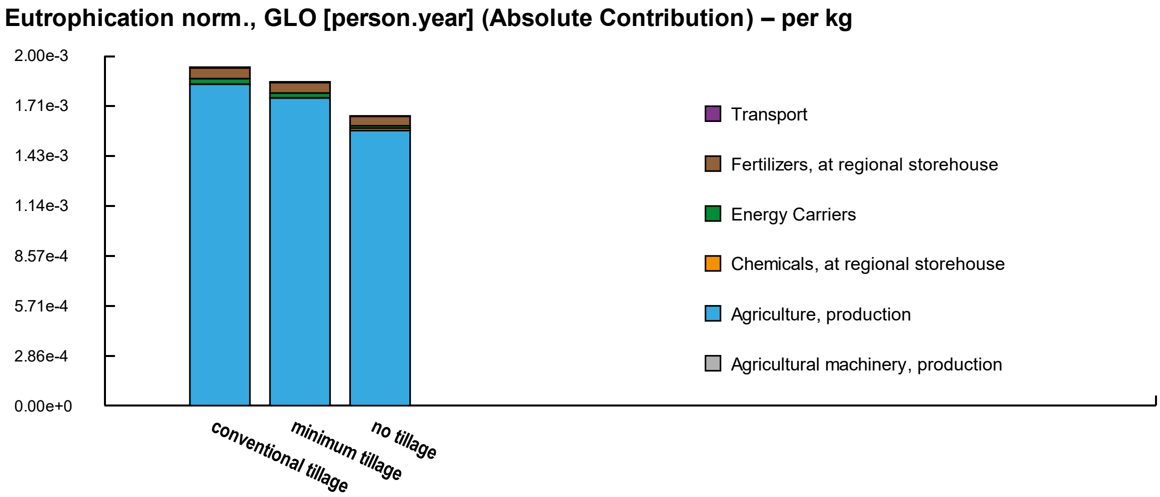

Figure 143. Absolute contribution analysis eutrophication per kg of wheat using three different soil treatments of Experiment 3.

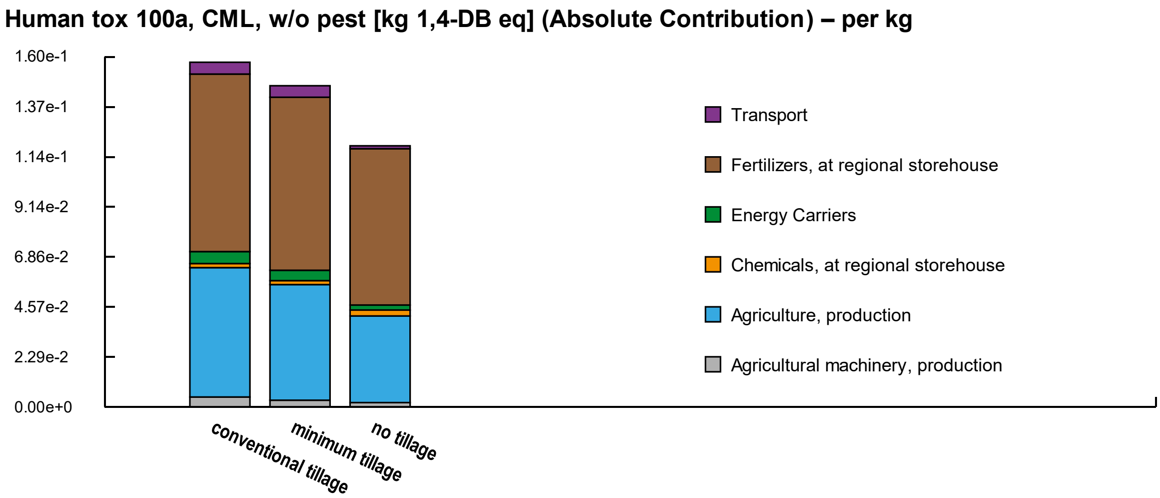

Figure 144. Absolute contribution analysis of human toxicity without pesticides per kg of wheat using three different soil treatments of Experiment 3.

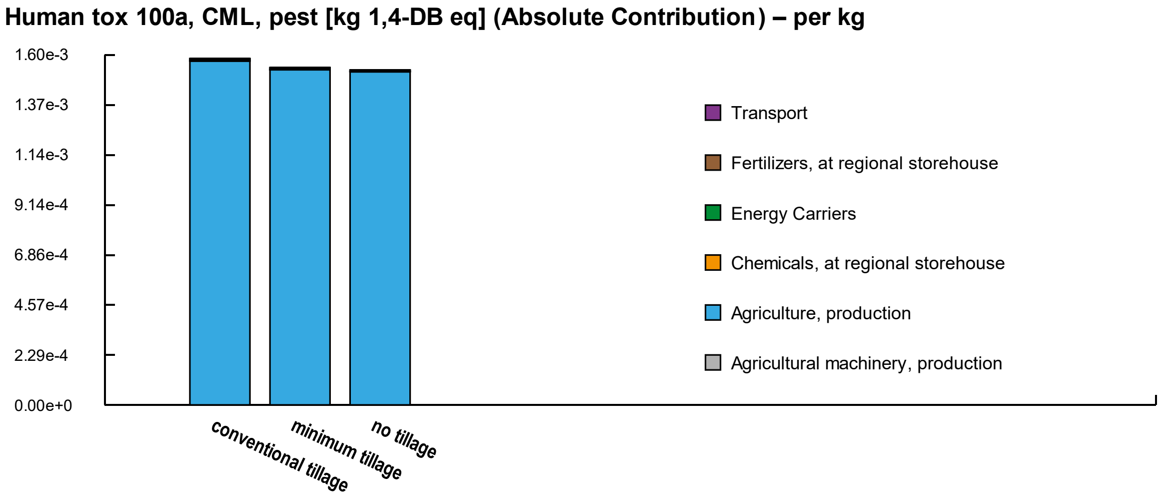

Figure 145. Absolute contribution analysis of human toxicity with pesticides per kg of wheat using three different soil treatments of Experiment 3.

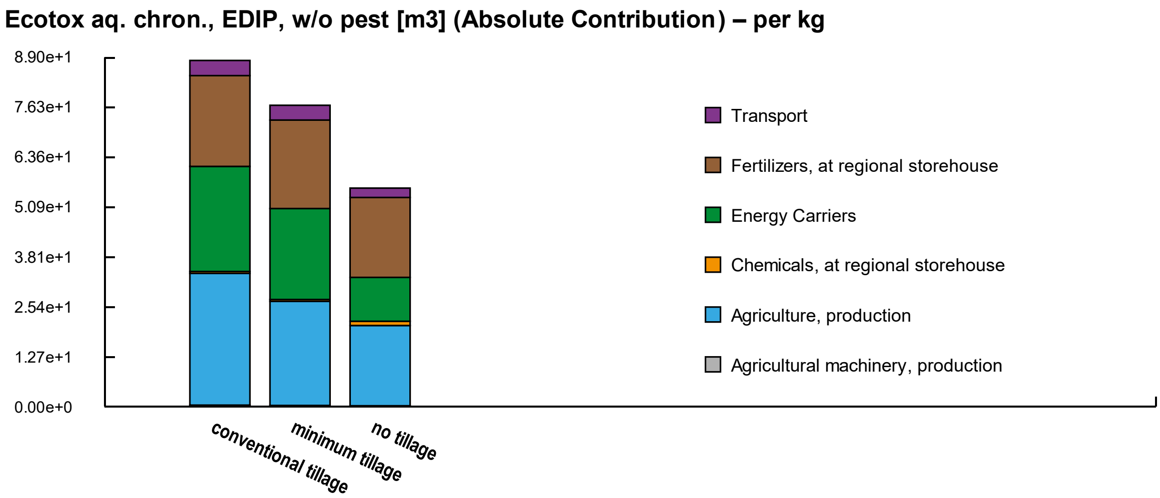

Figure 146. Absolute contribution analysis of global warming potential per kg of wheat using three different soil treatments of Experiment 3.

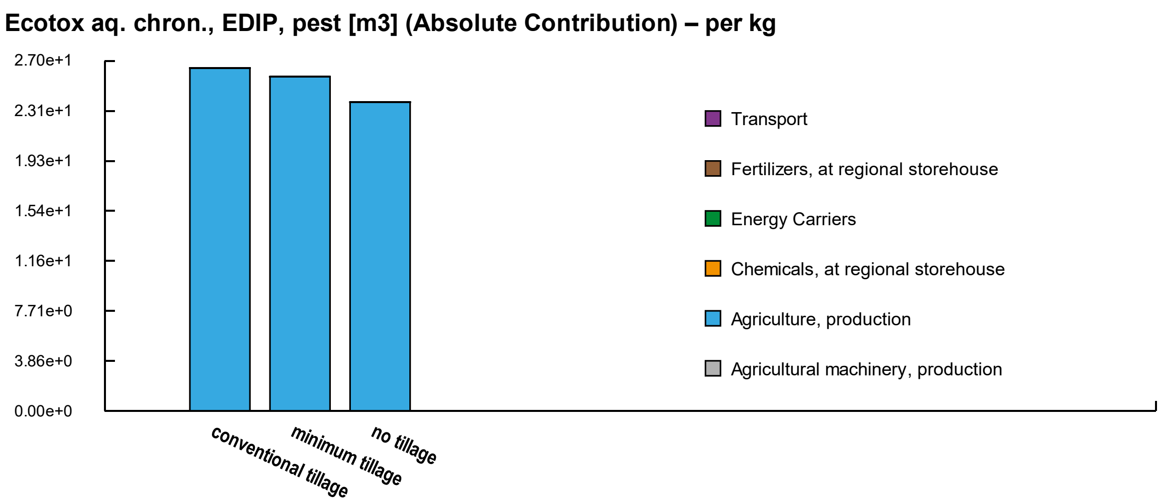

Figure 147. Absolute contribution analysis of aquatic ecotoxicity with pesticides per kg of wheat using three different soil treatments of Experiment 3.

Experiment 4 – Test of solar-dried fertilizers in crop rotations

Resources (abiotic) [kg Sb eq] (Absolute Contribution) – per kg

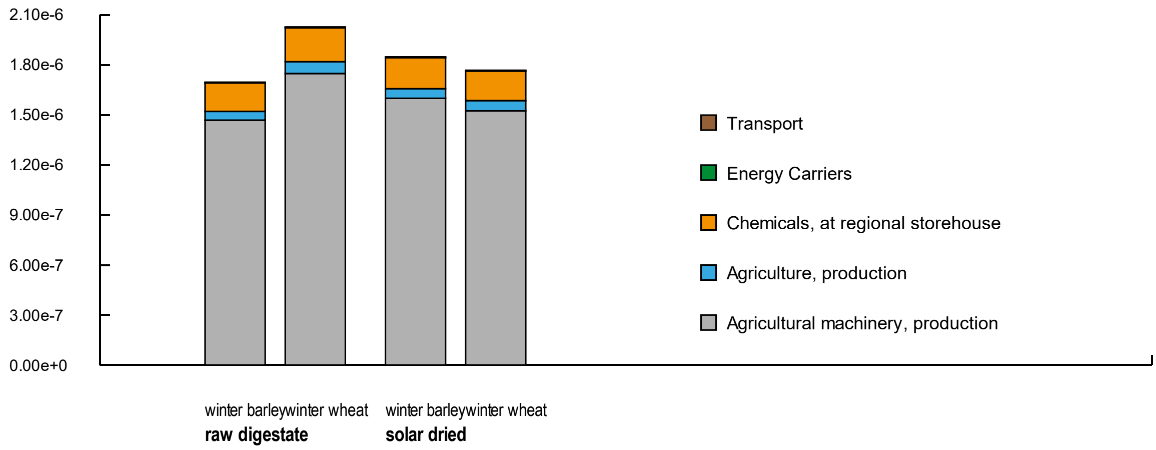

Figure 148. Absolute contribution analysis of abiotic resource depletion per kg of crop yield using two different fertilizers of Experiment 4.

Water Stress Index (WSI) [m3] (Absolute Contribution) – per kg

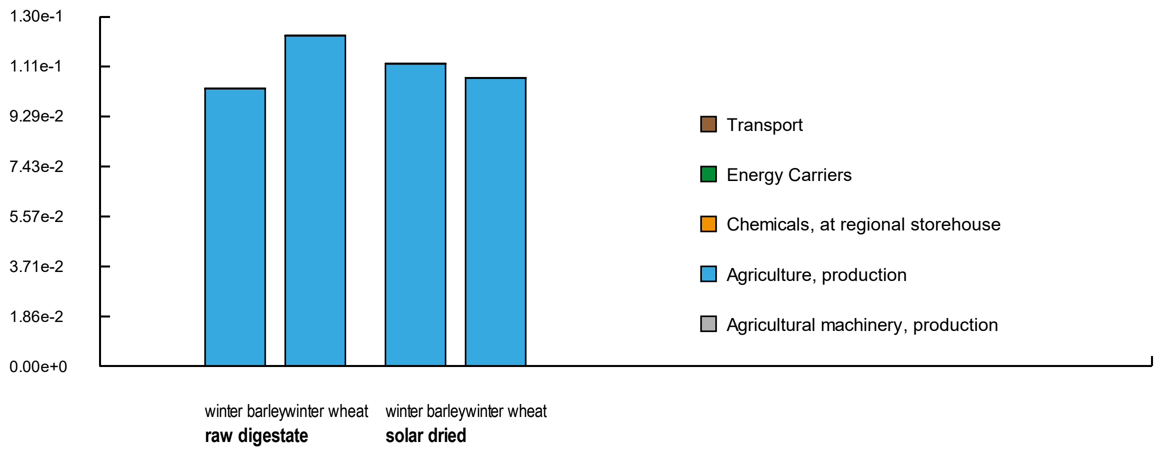

Figure 149. Absolute contribution analysis of wáter stress index per kg of crop yield using two different fertilizers of Experiment 4.

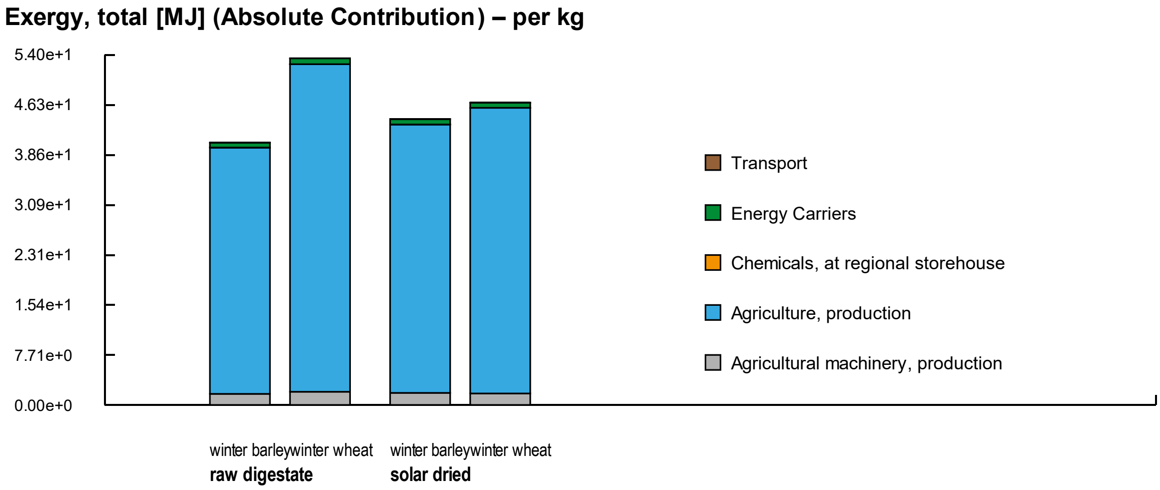

Figure 150. Absolute contribution analysis of total exergy per kg of crop yield using two different fertilizers of Experiment 4.

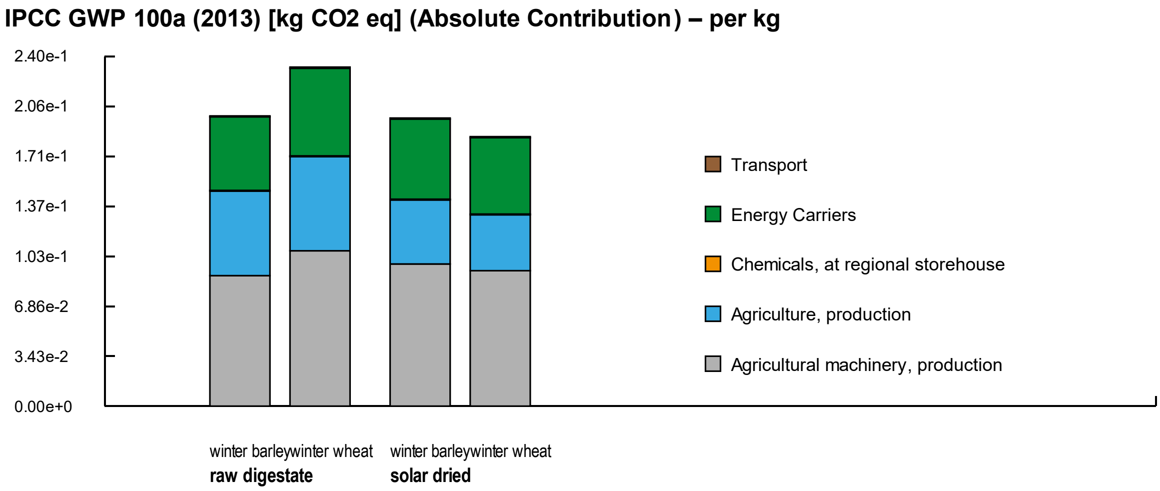

Figure 151. Absolute contribution analysis of global warming potential per kg of crop yield using two different fertilizers of Experiment 4.

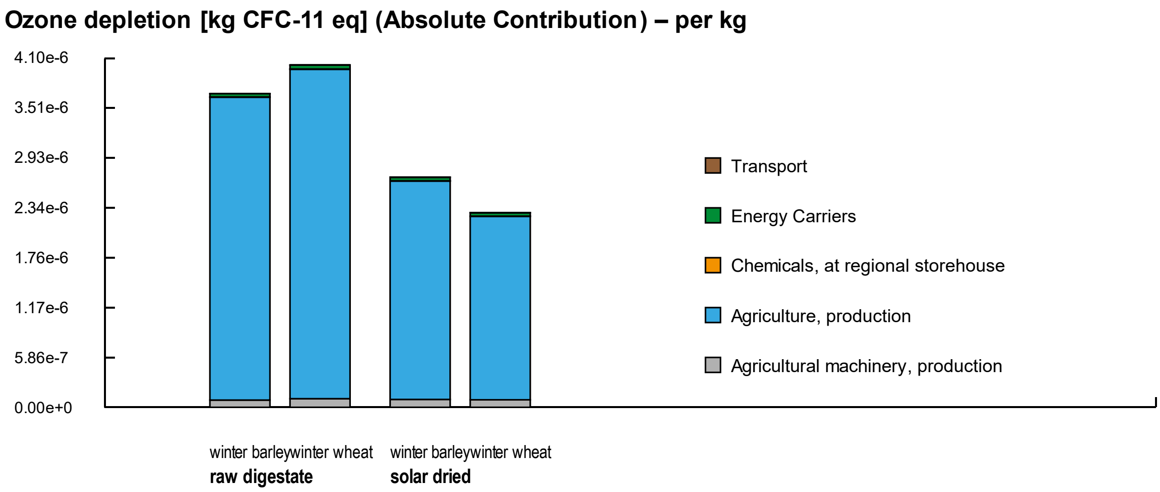

Figure 152. Absolute contribution analysis of ozone depletion per kg of crop yield using two different fertilizers of Experiment 4.

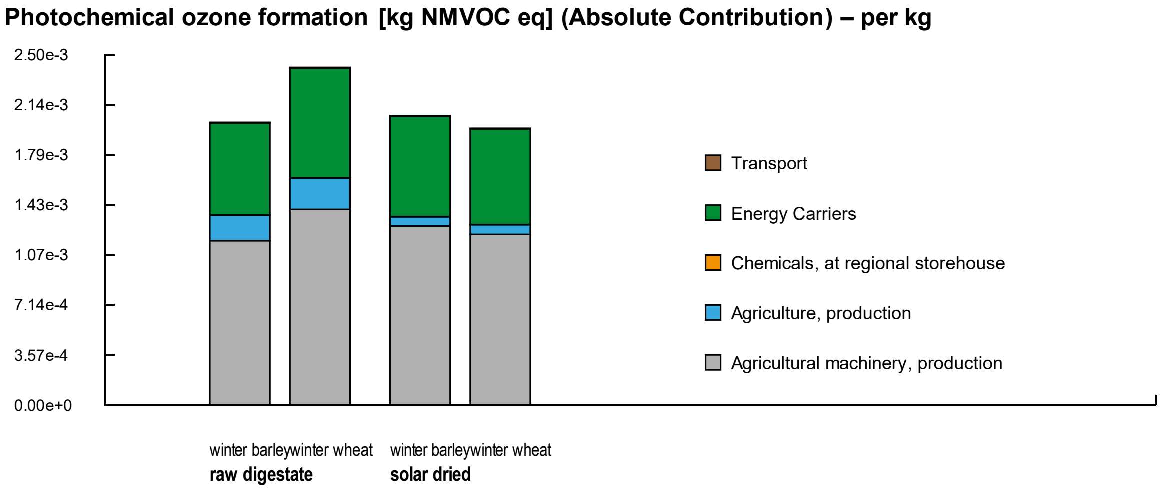

Figure 153. Absolute contribution analysis of photochemical ozone formation per kg of crop yield using two different fertilizers of Experiment 4.

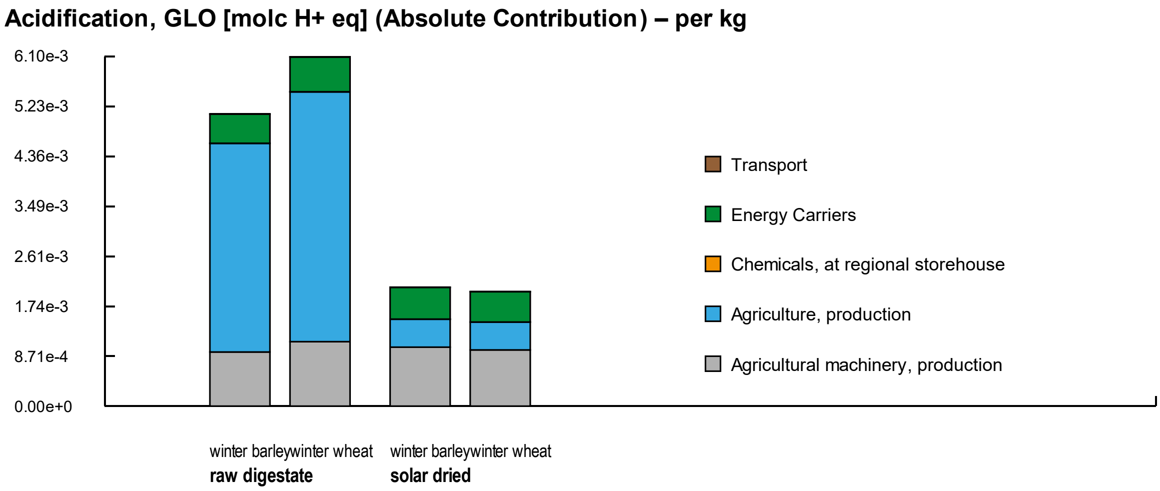

Figure 154. Absolute contribution analysis of acidification per kg of crop yield using two different fertilizers of Experiment 4.

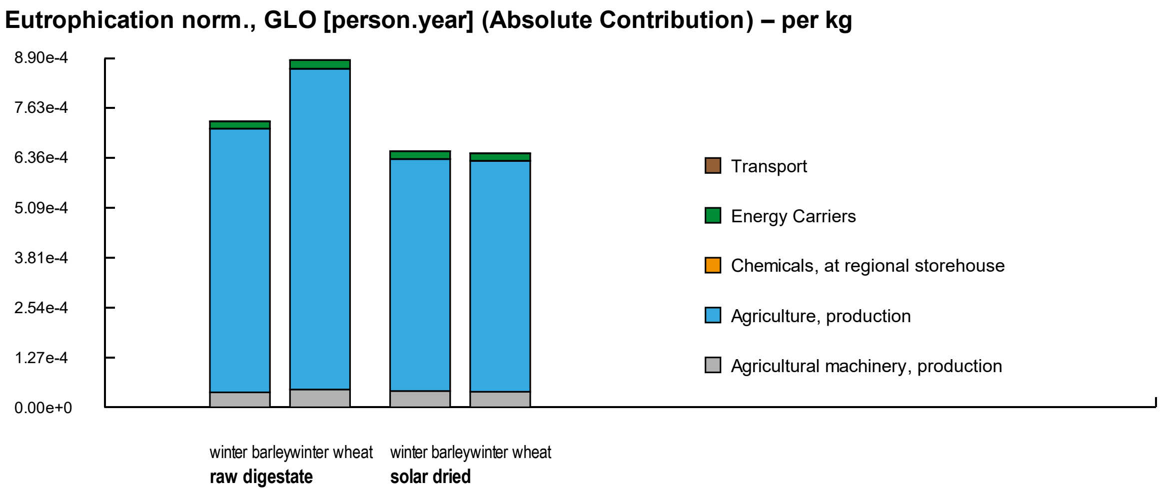

Figure 155. Absolute contribution analysis of eutrophication per kg of crop yield using two different fertilizers of Experiment 4.

Human tox 100a, CML, w/o pest [kg 1,4-DB eq] (Absolute Contribution) – per kg

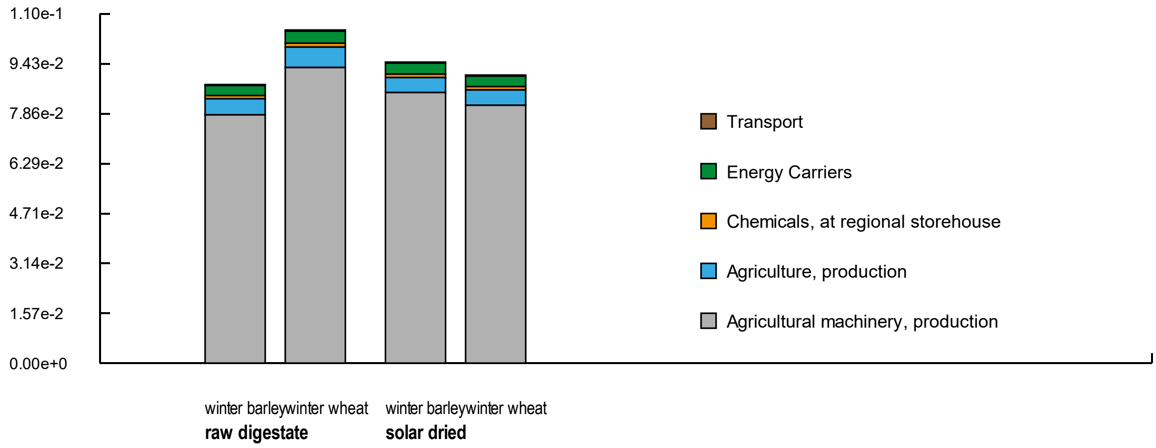

Figure 156. Absolute contribution analysis of human toxicity without pesticides per kg of crop yield using two different fertilizers of Experiment 4.

Human tox 100a, CML, pest [kg 1,4-DB eq] (Absolute Contribution) – per kg

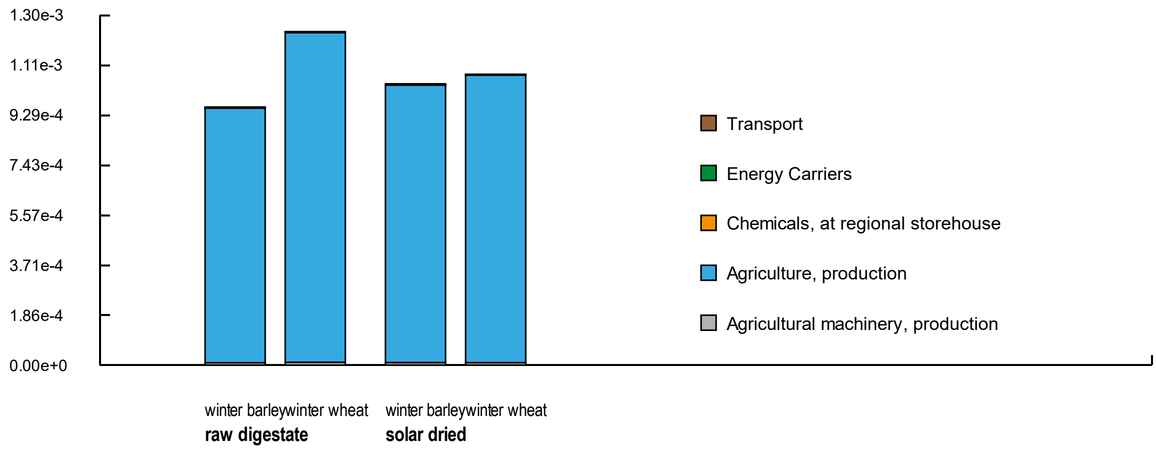

Figure 157. Absolute contribution analysis of human toxicity with pesticides per kg of crop yield using two different fertilizers of Experiment 4.

Ecotox aq. chron., EDIP, w/o pest [m3] (Absolute Contribution) – per kg

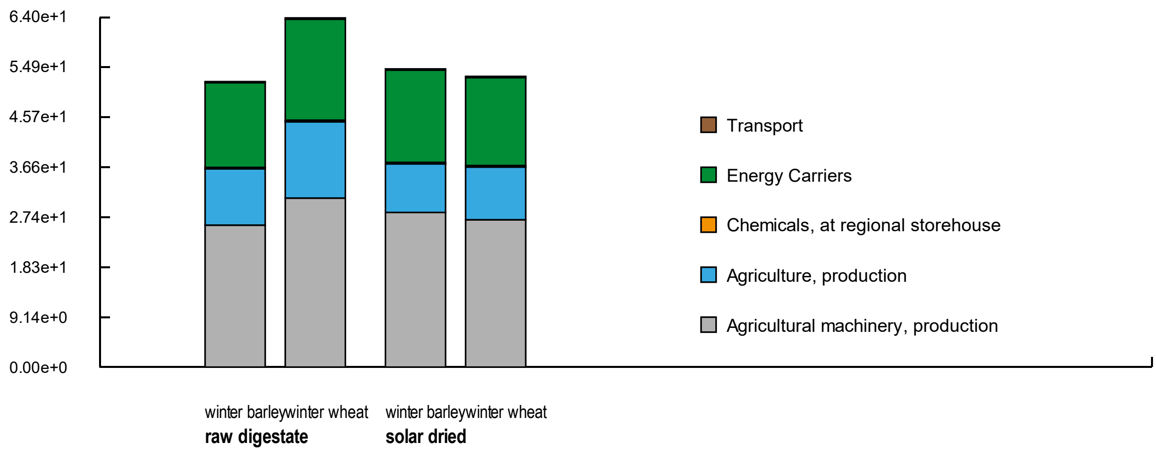

Figure 158. Absolute contribution analysis of human toxicity without pesticides per kg of crop yield using two different fertilizers of Experiment 4.

Ecotox aq. chron., EDIP, pest [m3] (Absolute Contribution) – per kg

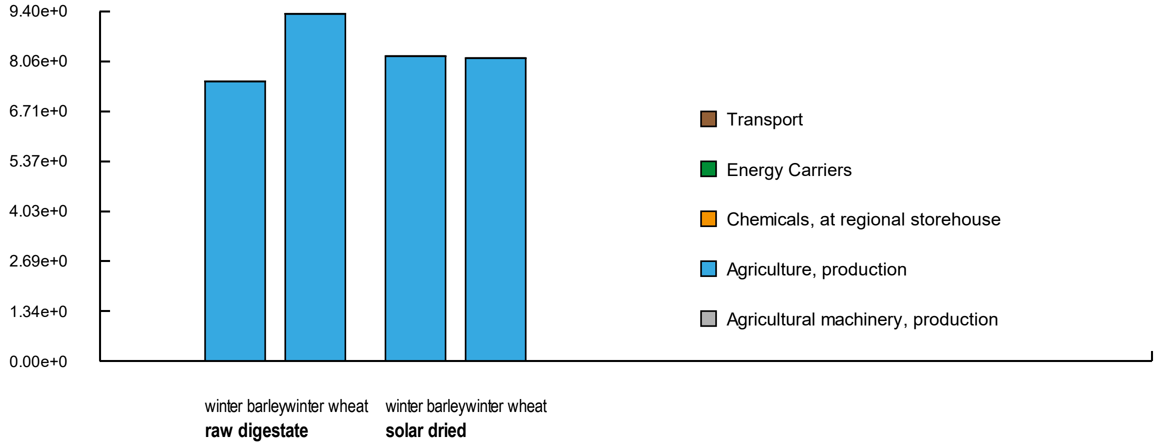

Figure 159. Absolute contribution analysis of aquatic ecotoxicity with pesticides per kg of crop yield using two different fertilizers of Experiment 4.

Experiment 5 – Fertigation with microfiltered digestate

Resources (abiotic) [kg Sb eq] (Absolute Contribution) – per kg

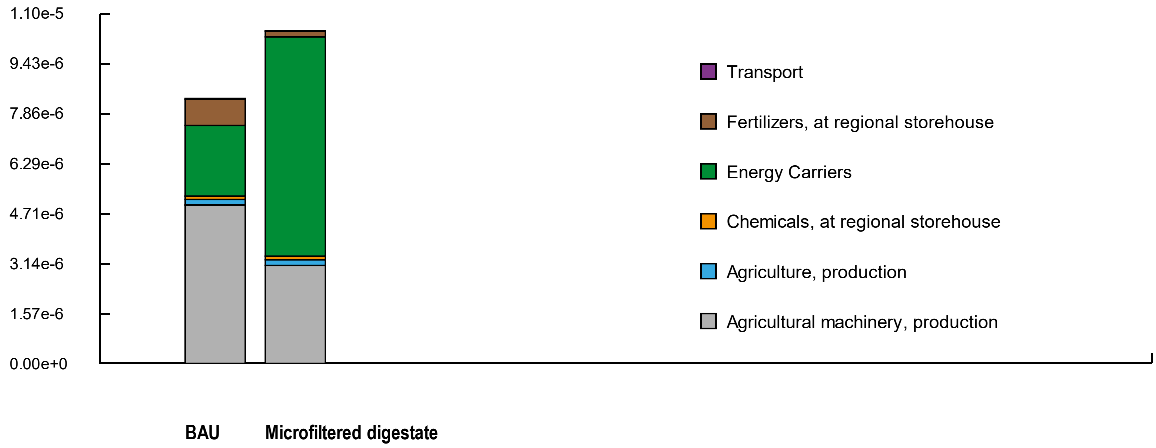

Figure 160. Absolute contribution analysis of abiotic resource depletion per kg of crop yield using two different fertilization schemes of Experiment 5.

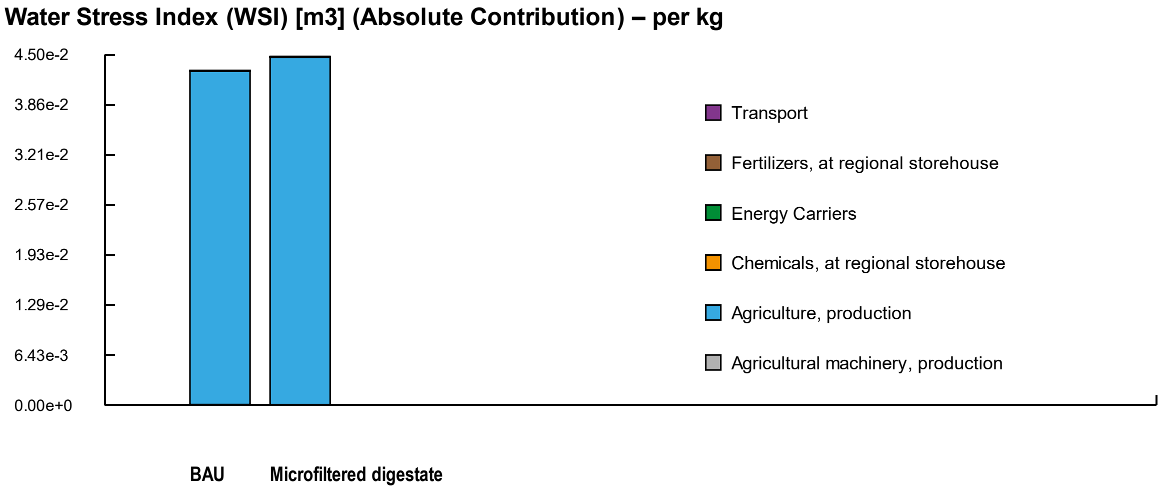

Figure 161. Absolute contribution analysis of wáter stress index per kg of crop yield using two different fertilization schemes of Experiment 5.

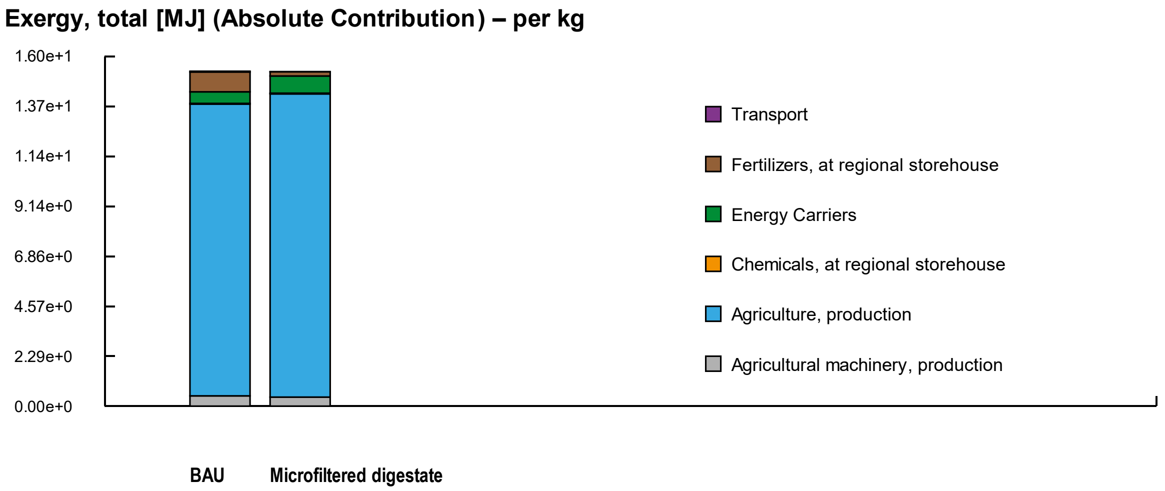

Figure 162. Absolute contribution analysis of total exergy per kg of crop yield using two different fertilization schemes of Experiment 5.

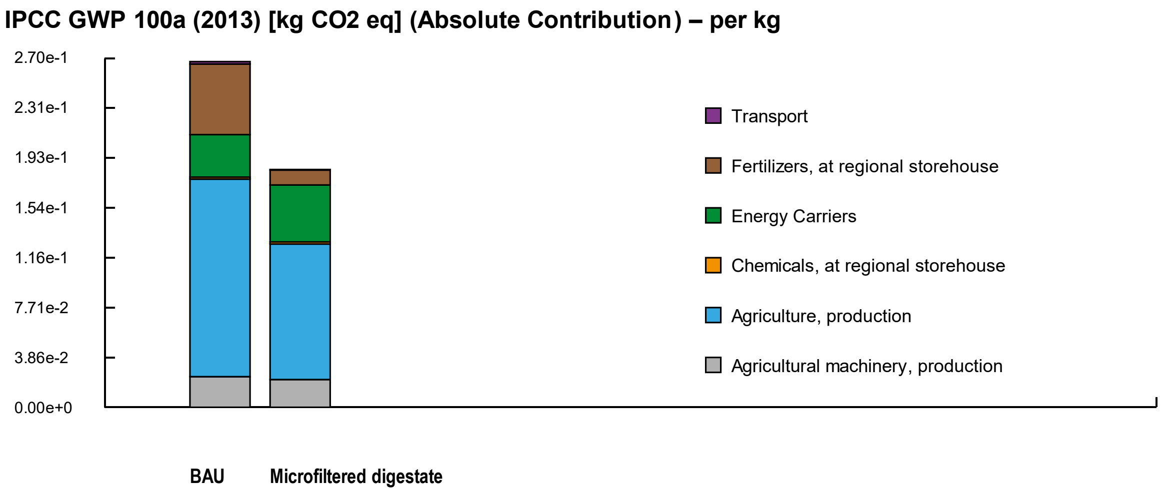

Figure 163. Absolute contribution analysis of global warming potential per kg of crop yield using two different fertilization schemes of Experiment 5.

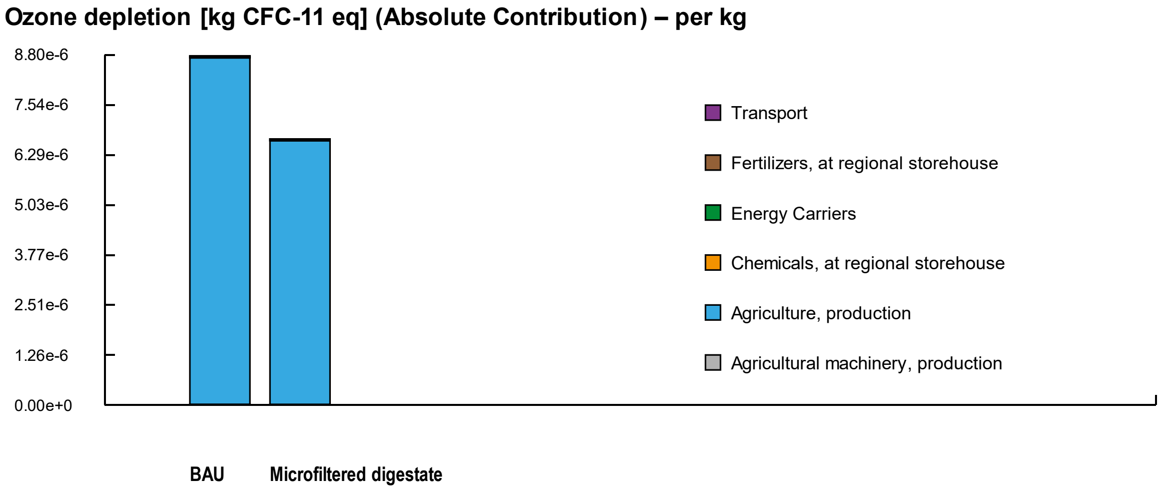

Figure 164. Absolute contribution analysis of ozone depletion per kg of crop yield using two different fertilization schemes of Experiment 5.

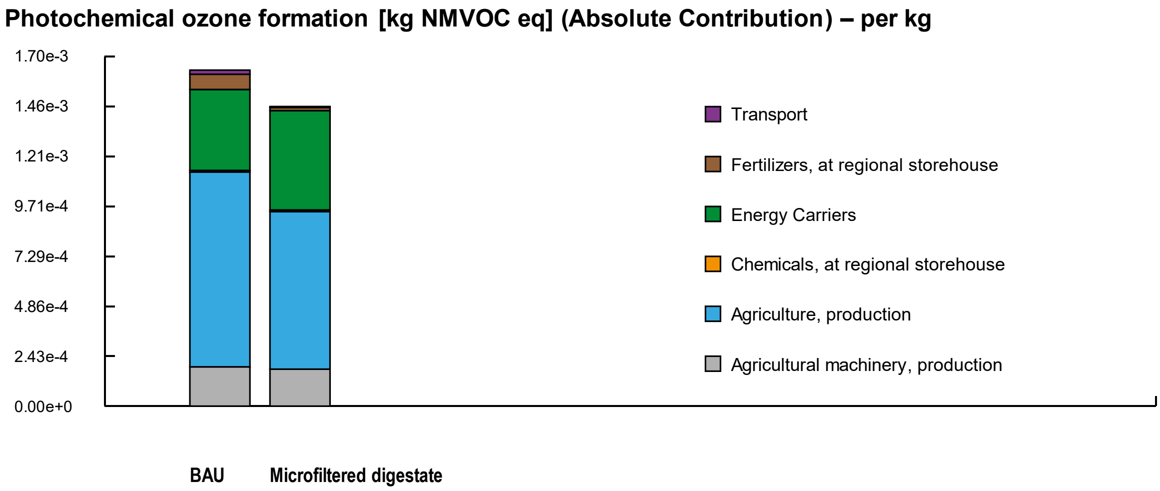

Figure 165. Absolute contribution analysis of photochemical ozone formation per kg of crop yield using two different fertilization schemes of Experiment 5.

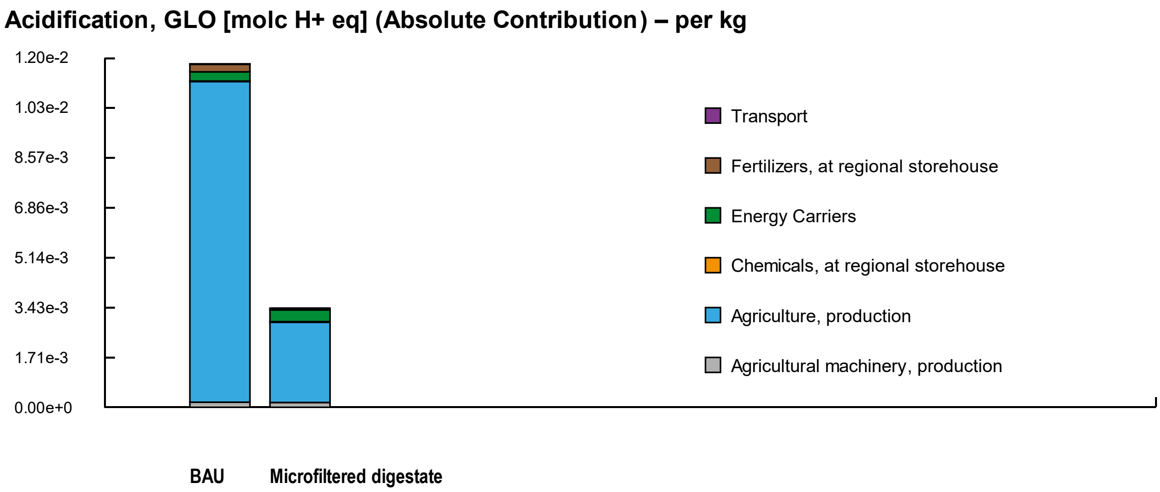

Figure 166. Absolute contribution analysis of acidification per kg of crop yield using two different fertilization schemes of Experiment 5.

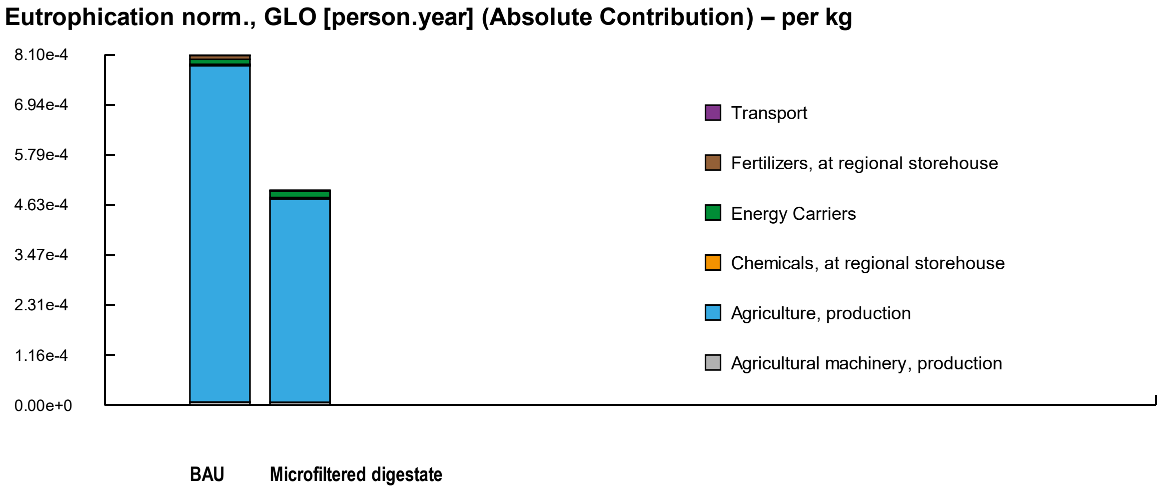

Figure 167. Absolute contribution analysis of eutrophication per kg of crop yield using two different fertilization schemes of Experiment 5.

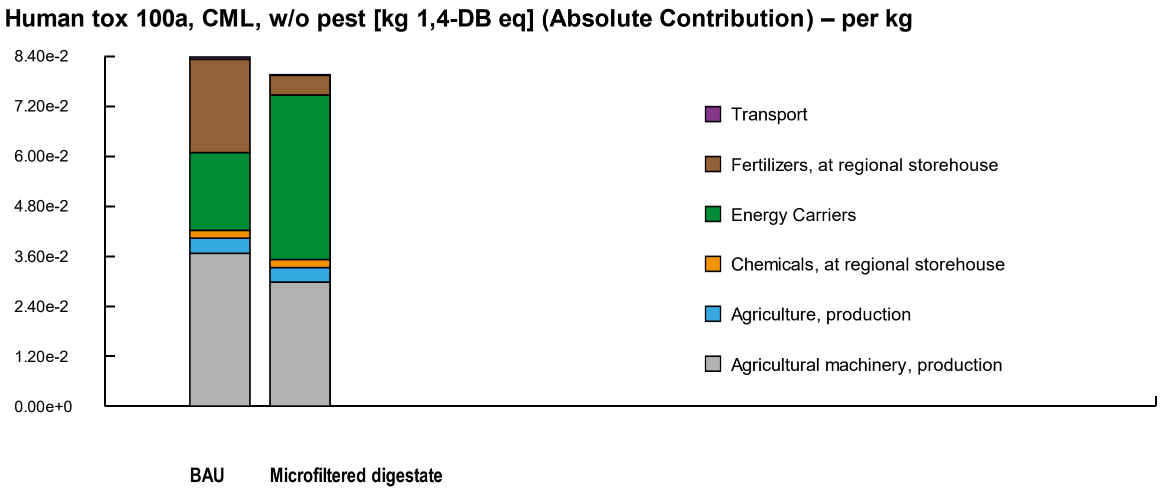

Figure 168. Absolute contribution analysis of human toxicity without pesticides per kg of crop yield using two different fertilization schemes of Experiment 5.

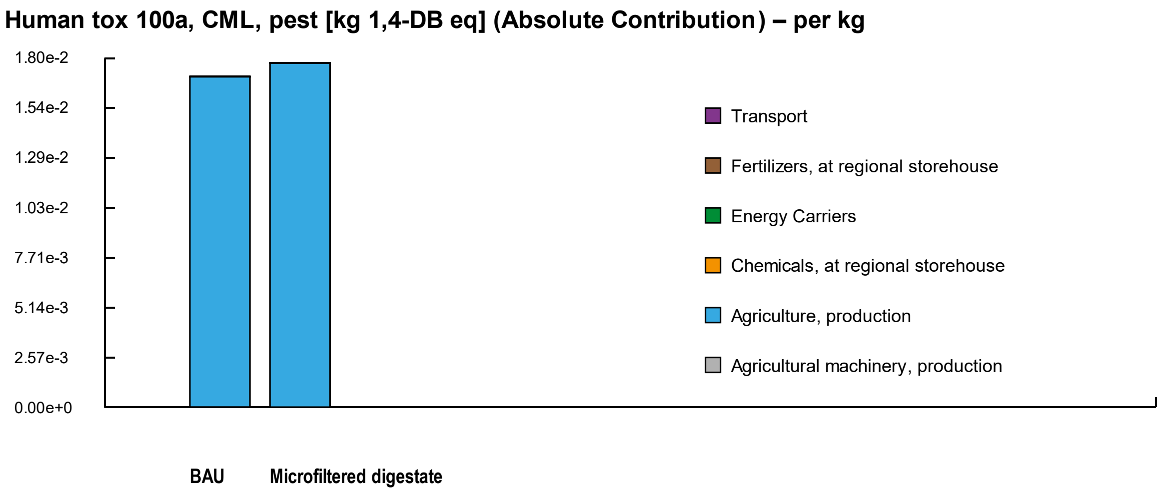

Figure 169. Absolute contribution analysis of human toxicity with pesticides per kg of crop yield using two different fertilization schemes of Experiment 5.

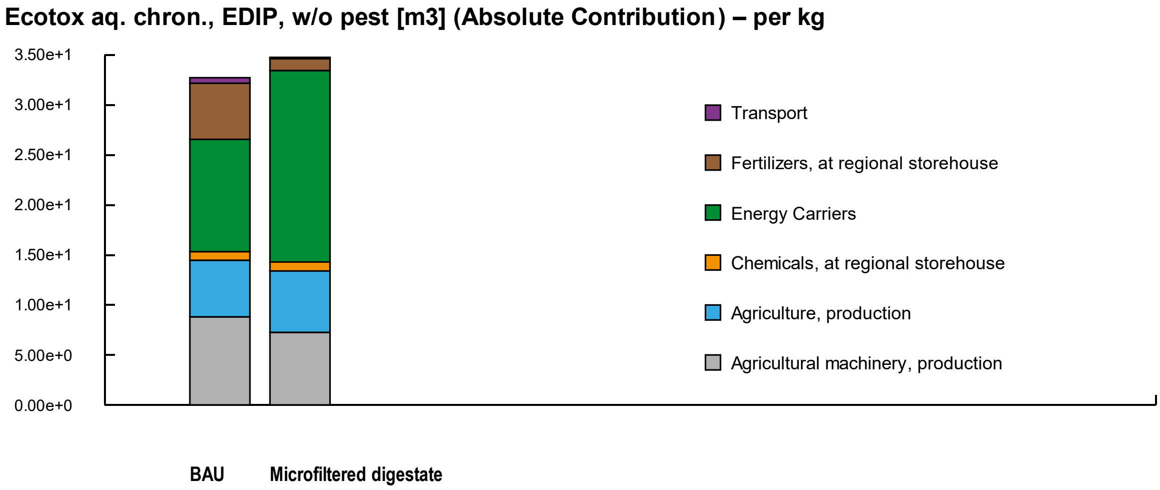

Figure 170. Absolute contribution analysis of aquatic ecotoxicity without pesticides per kg of crop yield using two different fertilization schemes of Experiment 5.

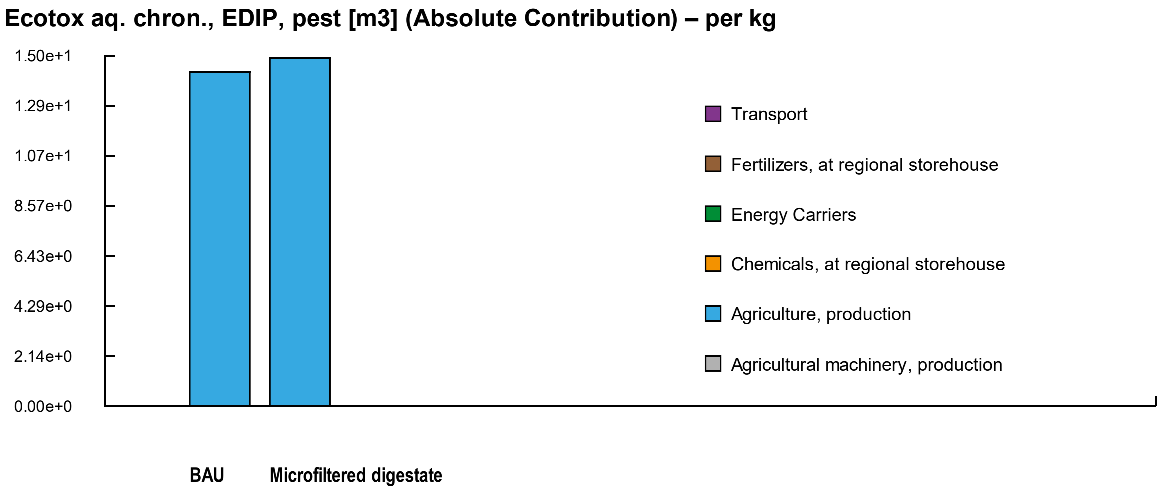

Figure 171. Absolute contribution analysis of aquatic ecotoxicity with pesticides per kg of crop yield using two different fertilization schemes of Experiment 5.

Experiment 10 - Extensive management of organic dairy farms in the Lungau region

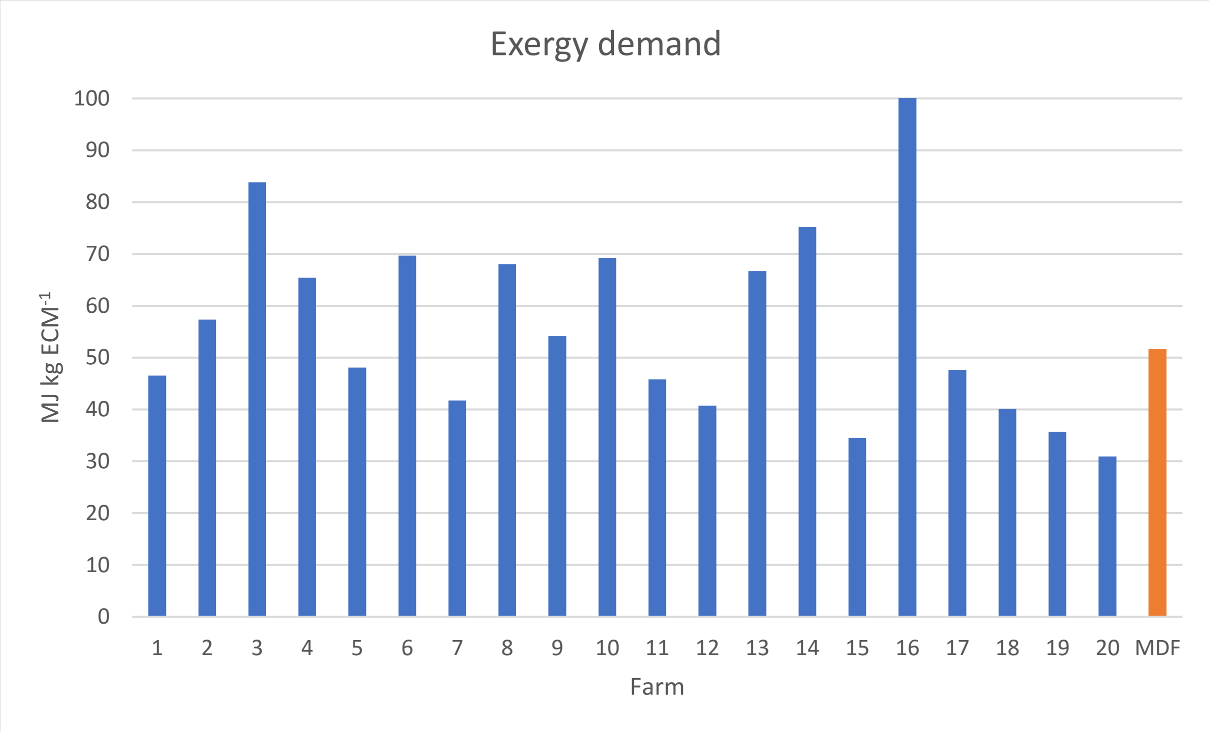

Figure 172. Exergy demand per kg ECM of the 20 Lungau farms and the MDF of Experiment 10.

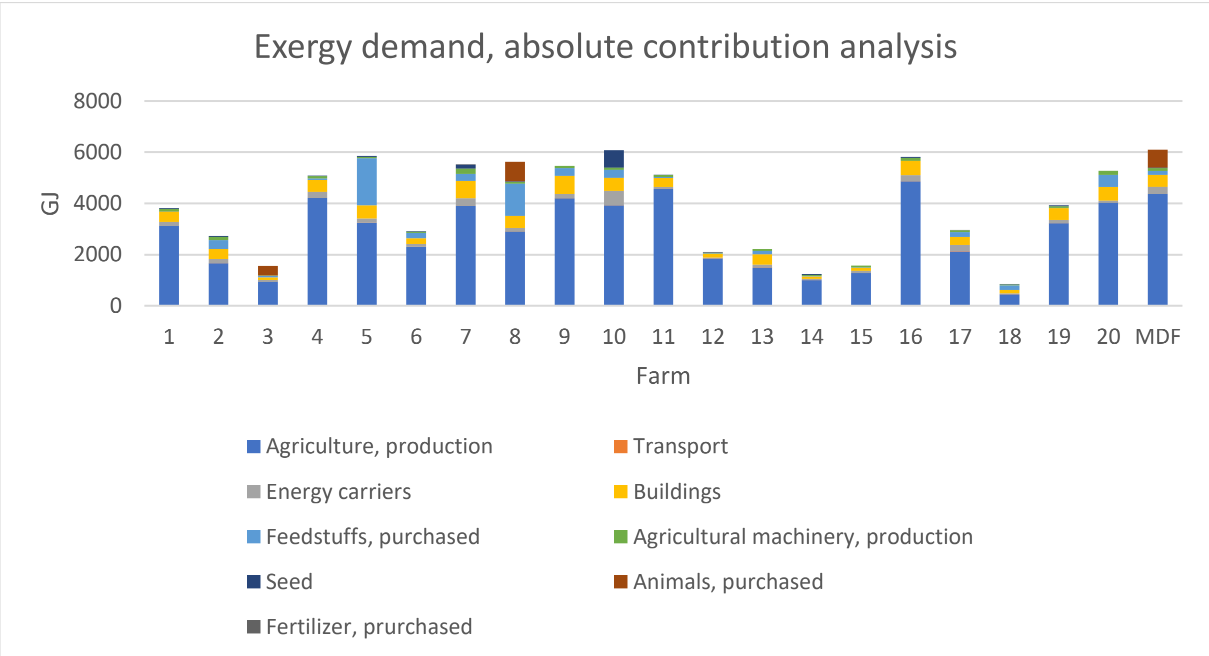

Figure 173. Absolute contribution analysis of the exergy demand of the 20 Lungau farms and the MDF of Experiment 10.

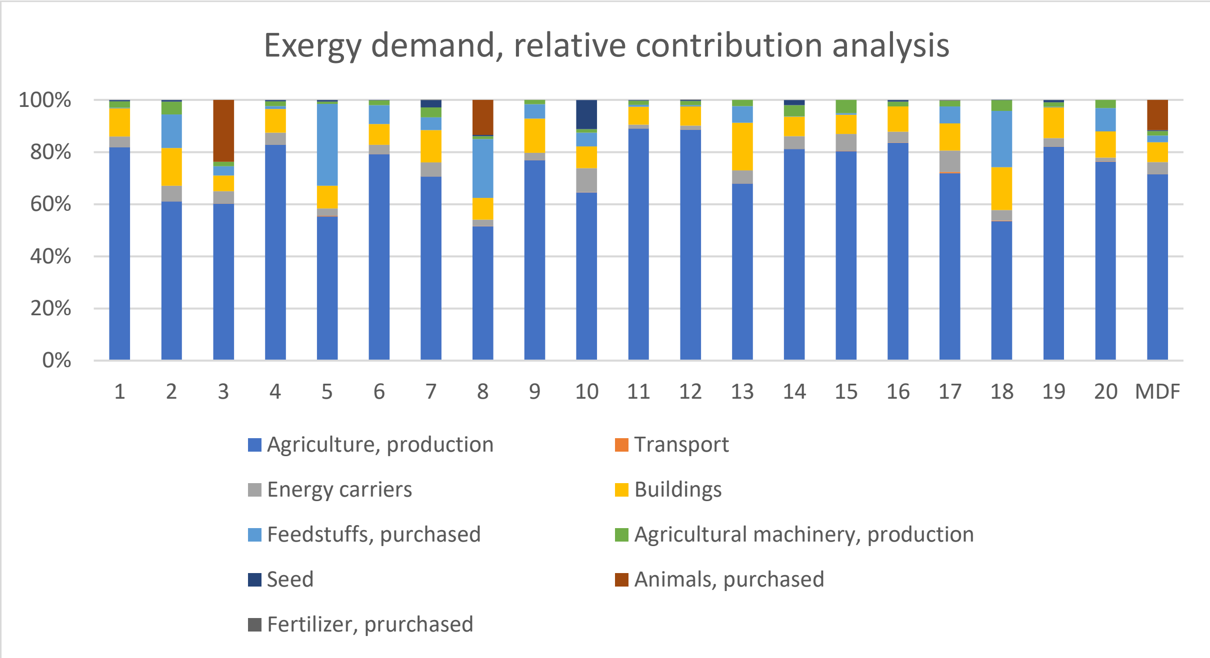

Figure 174. Relative contribution analysis of the exergy demand of the 20 Lungau farms and the MDF of Experiment 10.

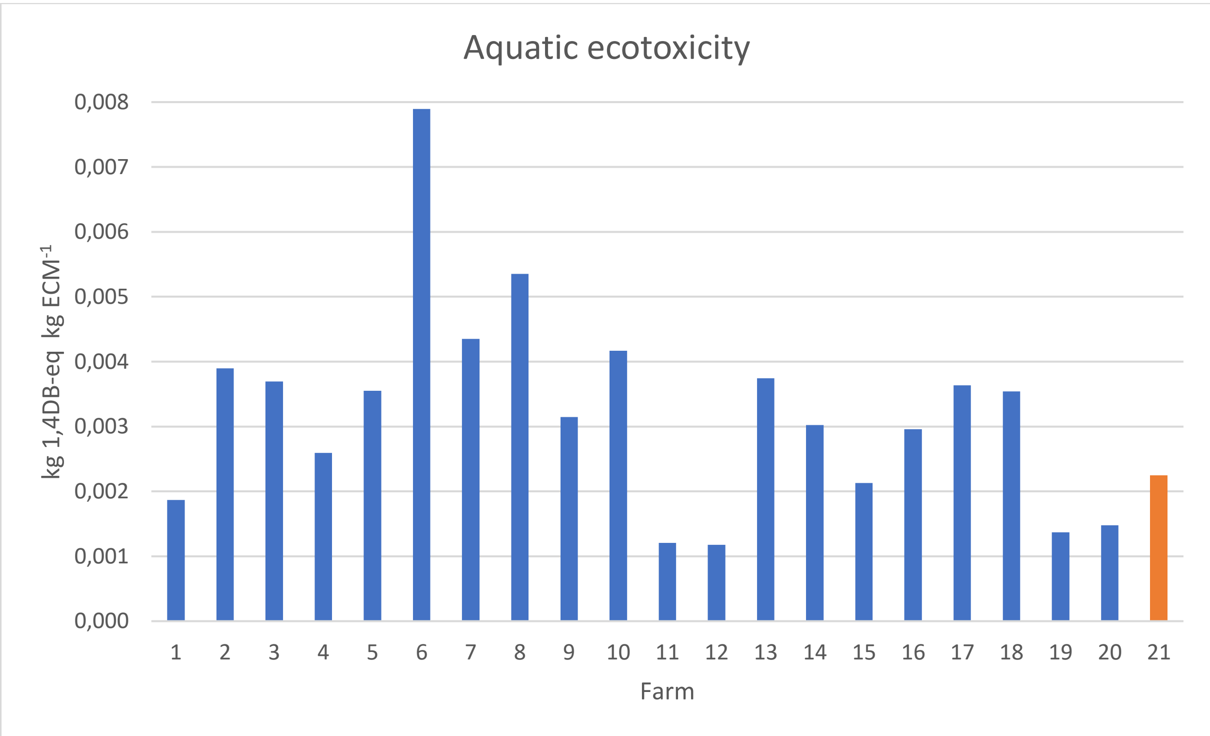

Figure 175. Aquatic ecotoxicity per kg ECM of the 20 Lungau farms and the MDF of Experiment 10.

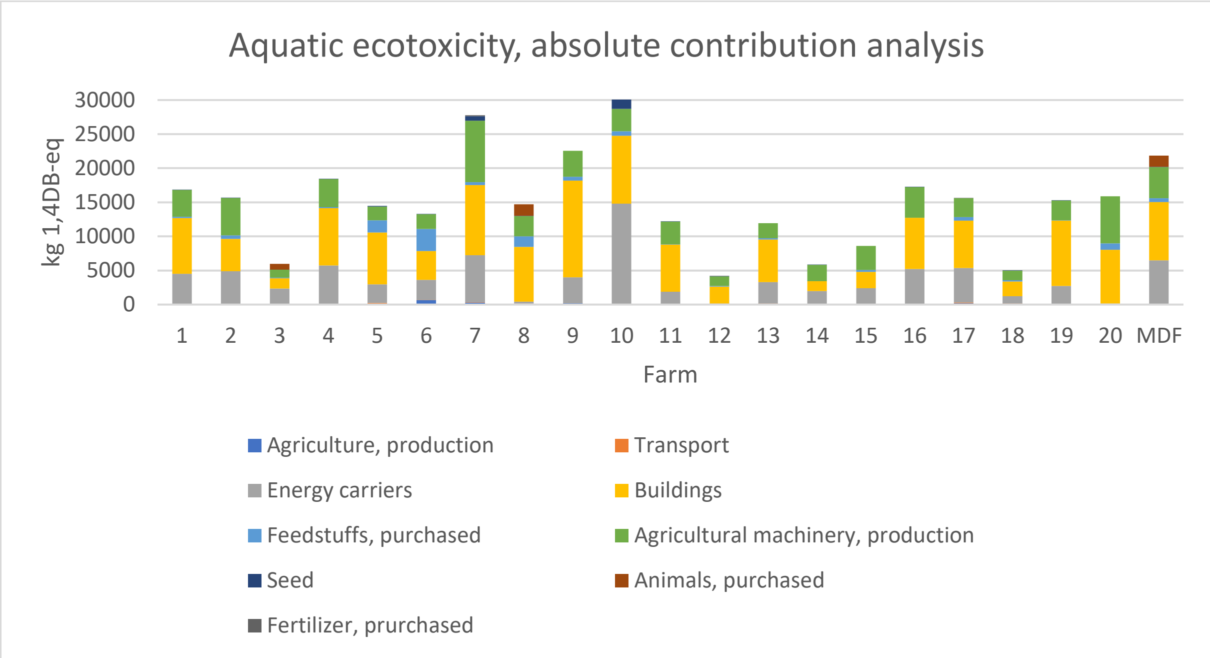

Figure 176. Absolute contribution analysis of the aquatic ecotoxicity of the 20 Lungau farms and the MDF of Experiment 10.

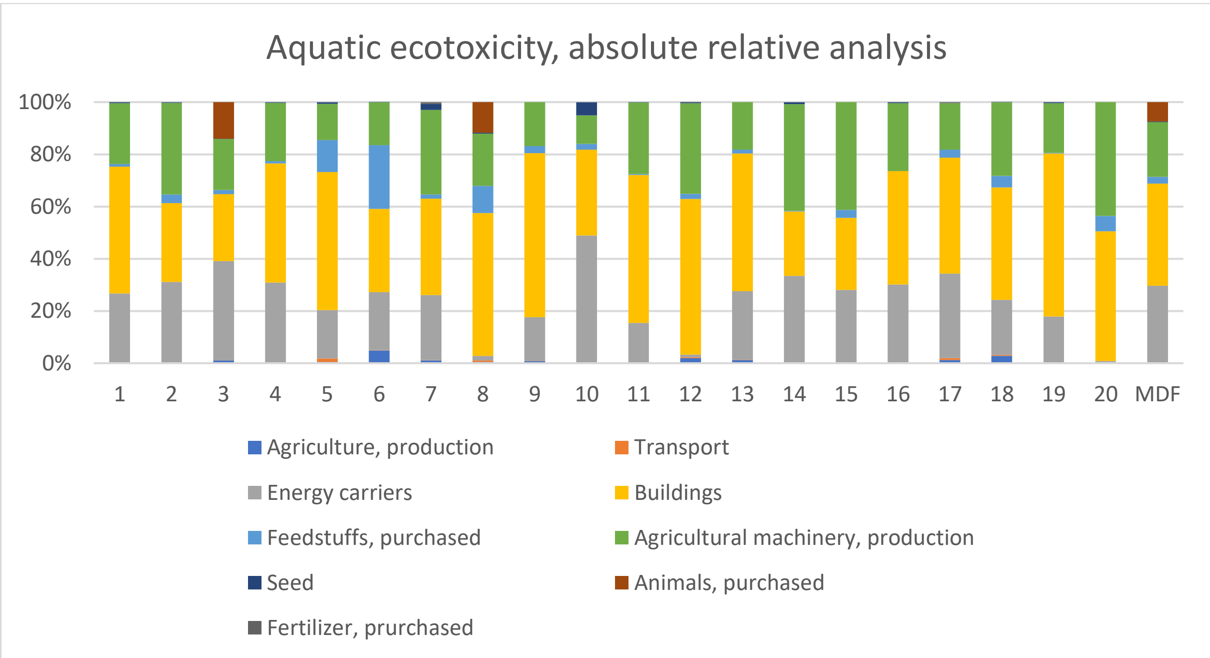

Figure 177. Relative contribution analysis of the aquatic ecotoxicity of the 20 Lungau farms and the MDF of Experiment 10.

7.3 Technical sub-systems – Results per sub-system

Experiment 4 - Digestate acidification and solar drying

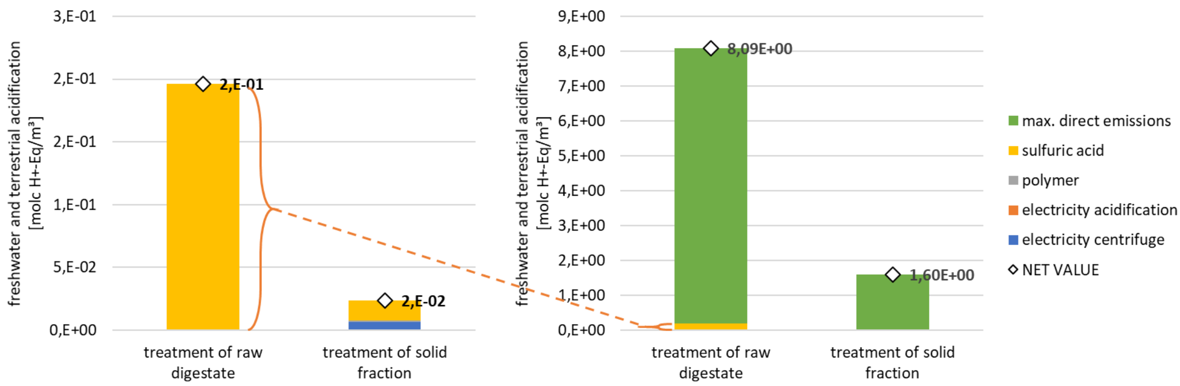

Figure 178. freshwater and terrestrial acidification for the different technical sub-systems involving acidification and solar drying (incl. sensitivity analysis: worst-case assumption for dryer) of Experiment 4

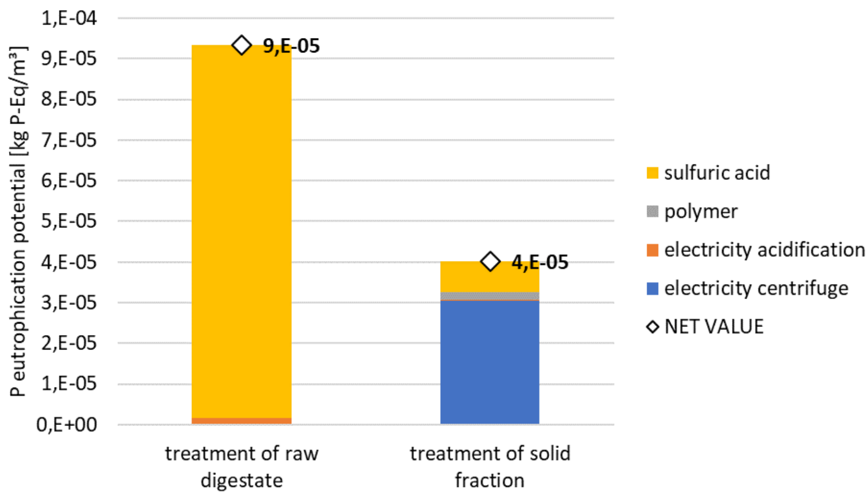

Figure 179. P eutrophication potential for the different technical sub-systems involving acidification and solar drying of Experiment 4

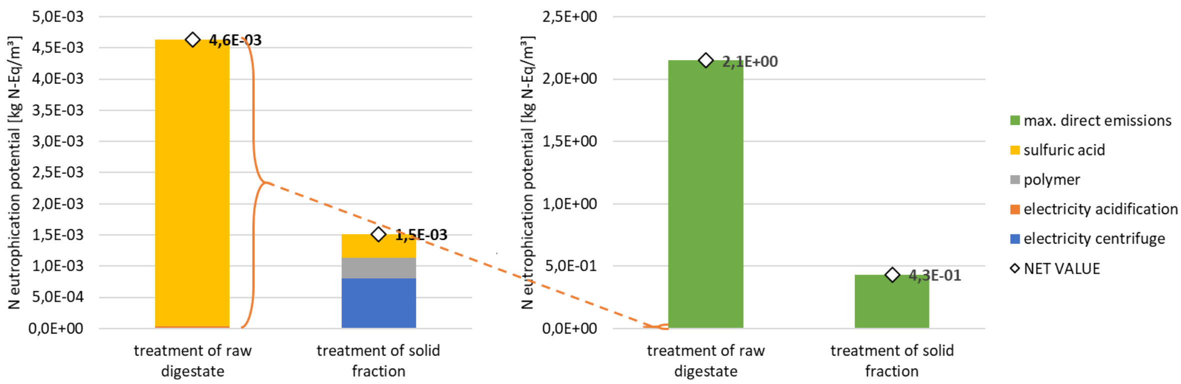

Figure 180. N eutrophication potential for the different technical sub-systems involving acidification and solar drying (incl. sensitivity analysis: worst-case assumption for dryer) of Experiment 4

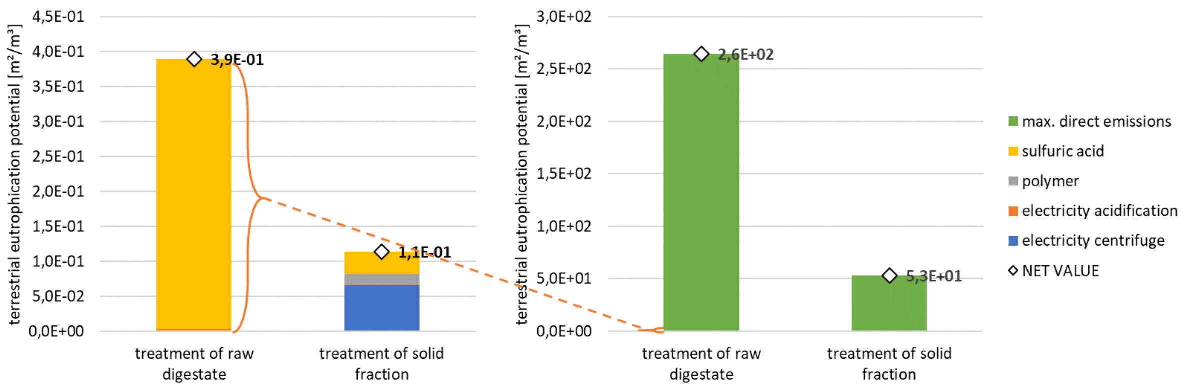

Figure 181. Terrestrial eutrophication potential for the different technical sub-systems involving acidification and solar drying (incl. sensitivity analysis: worst-case assumption for dryer) of Experiment 4

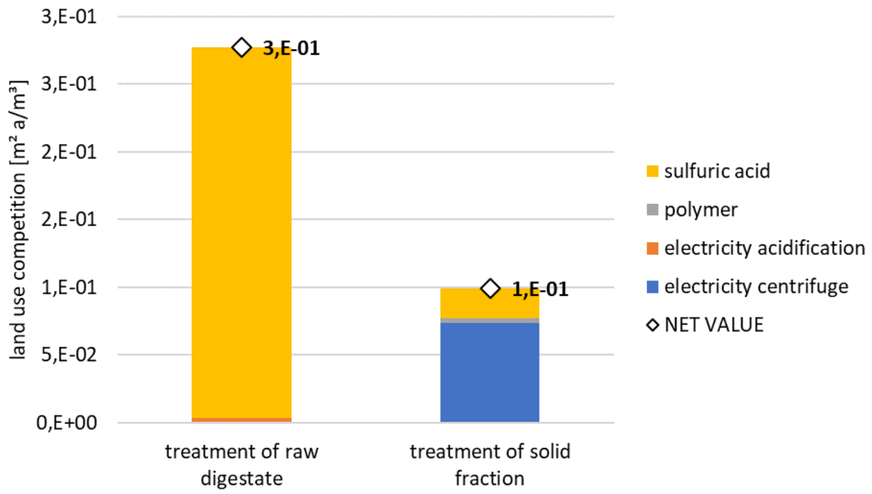

Figure 182. Land use competition for the different technical sub-systems involving acidification and solar drying of Experiment 4

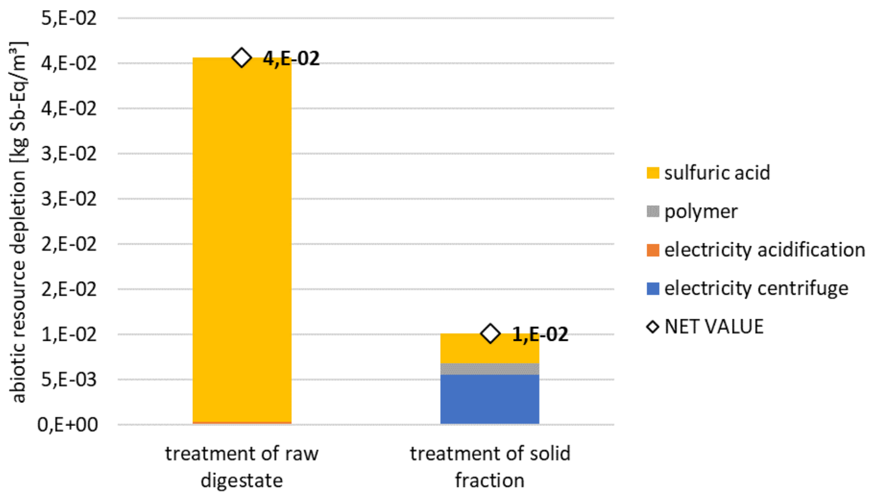

Figure 183. Abiotic resource depletion for the different technical sub-systems involving acidification and solar drying

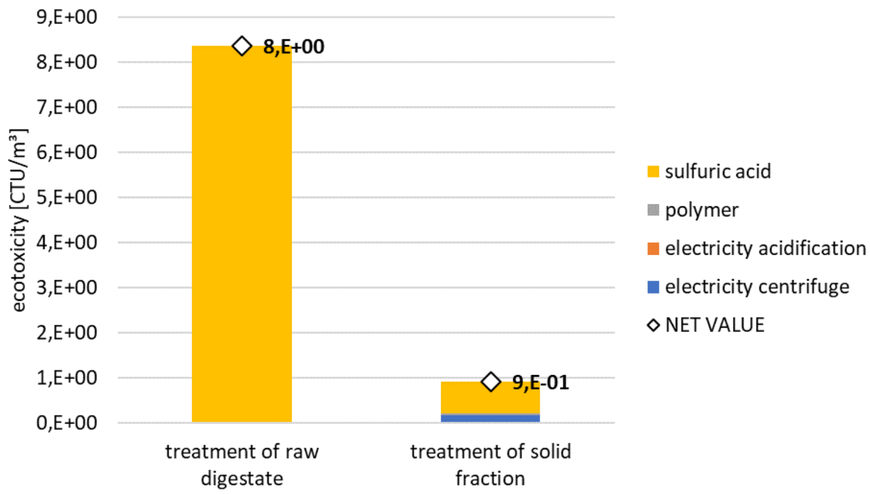

Figure 184. Ecotoxicity for the different technical sub-systems involving acidification and solar drying of Experiment 4

Experiment 5 - Digestate microfiltration/microsieving

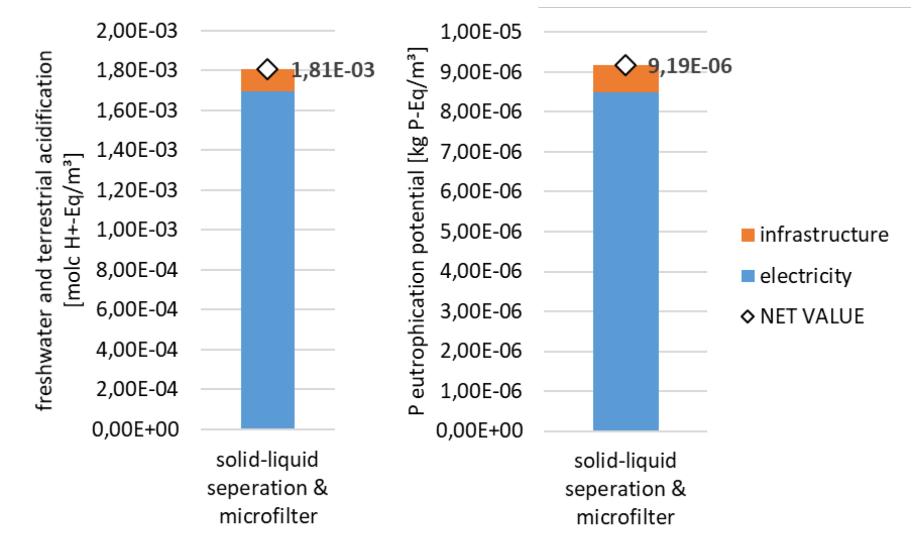

Figure 185. freshwater and terrestrial acidification and P eutrophication potential for the technical sub-system with microsieving of Experiment 5

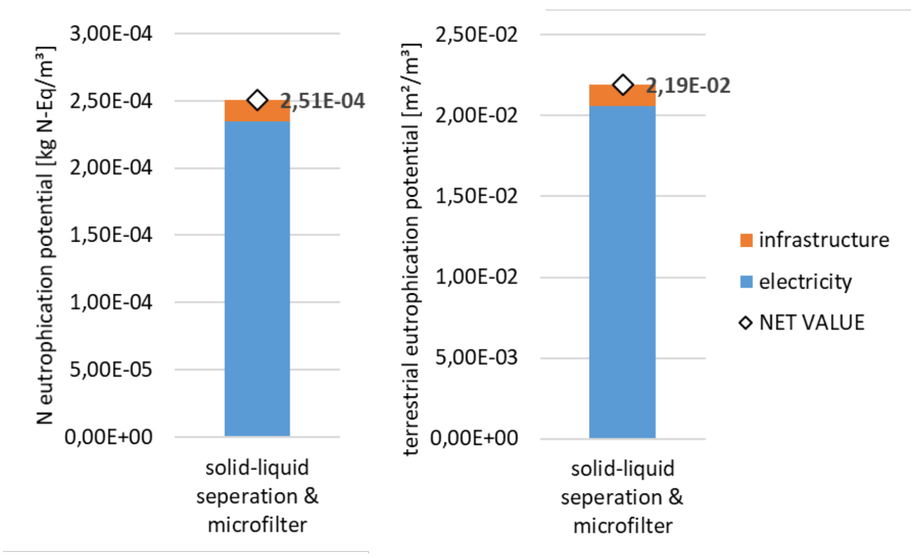

Figure 186. N eutrophication potential and terrestrial eutrophication potential for the technical sub-system with microsieving of Experiment 5

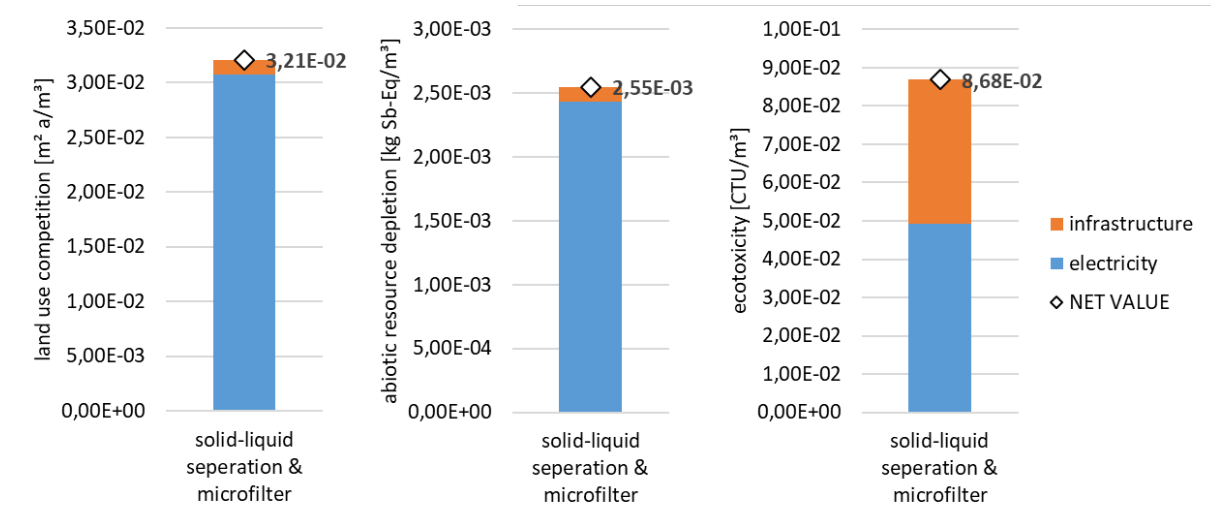

Figure 187. Land use competition, abiotic resource depletion, and ecotoxicity for the technical sub-system with microsieving of Experiment 5

Experiment 6 - Digestate vacuum degasification for nitrogen recovery

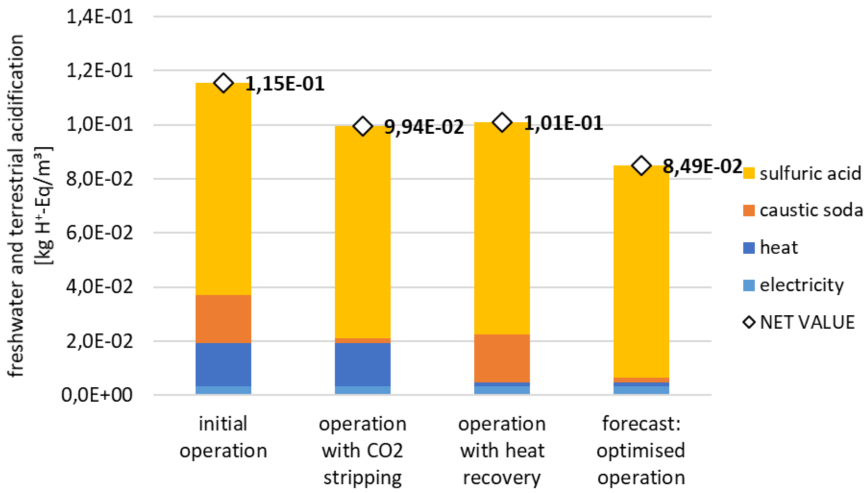

Figure 188. freshwater and terrestrial acidification for the technical sub-system with vacuum degasification for different operating modes of Experiment 6

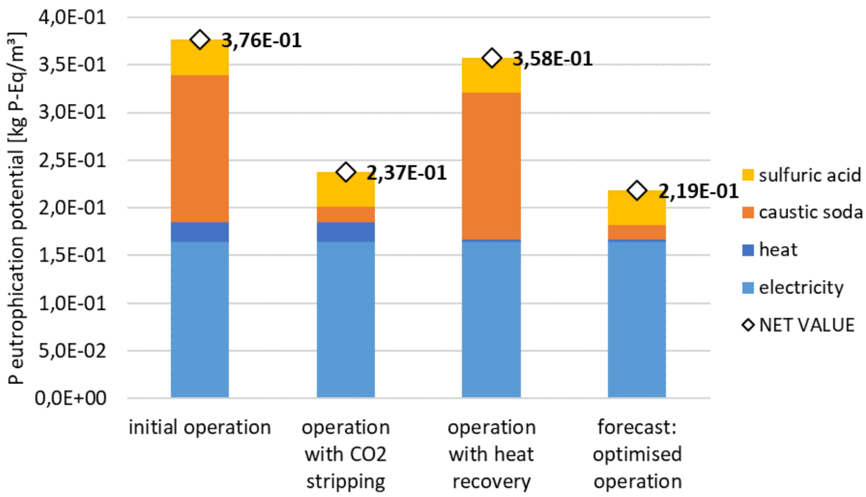

Figure 189. P eutrophication potential for the technical sub-system with vacuum degasification for different operating modes of Experiment 6

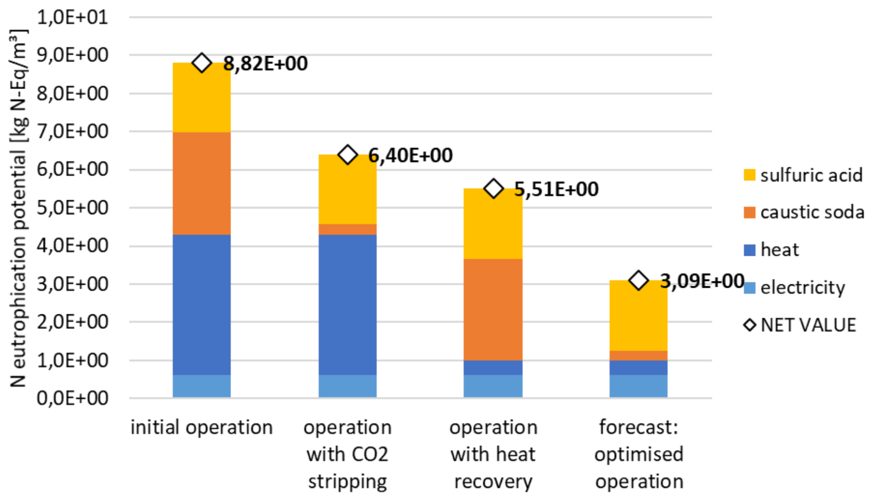

Figure 190. N eutrophication potential for the technical sub-system with vacuum degasification for different operating modes of Experiment 6

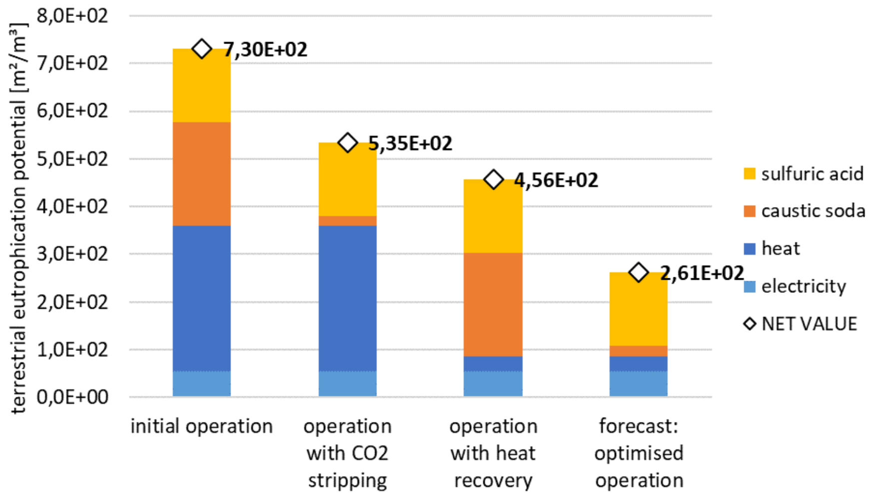

Figure 191. Terrestrial eutrophication potential for the technical sub-system with vacuum degasification for different operating modes of Experiment 6

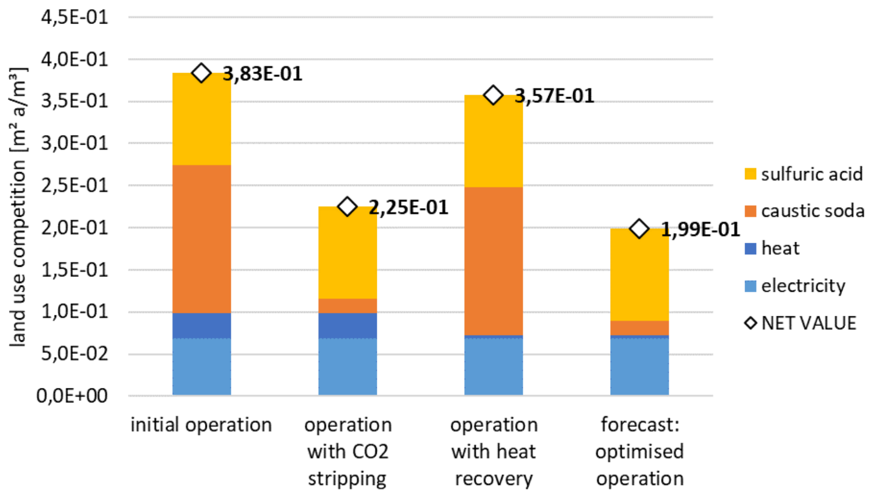

Figure 192. Land use competition for the technical sub-system with vacuum degasification for different operating modes of Experiment 6

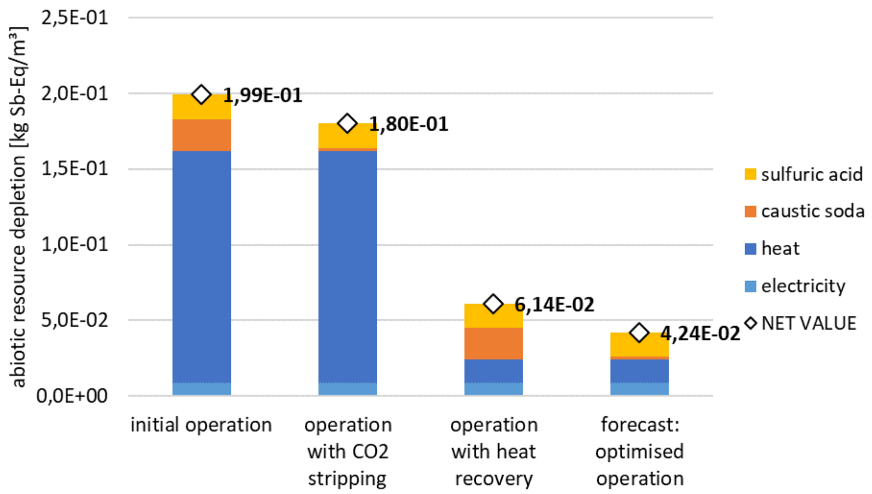

Figure 193. Abiotic resource depletion for the technical sub-system with vacuum degasification for different operating modes of Experiment 6

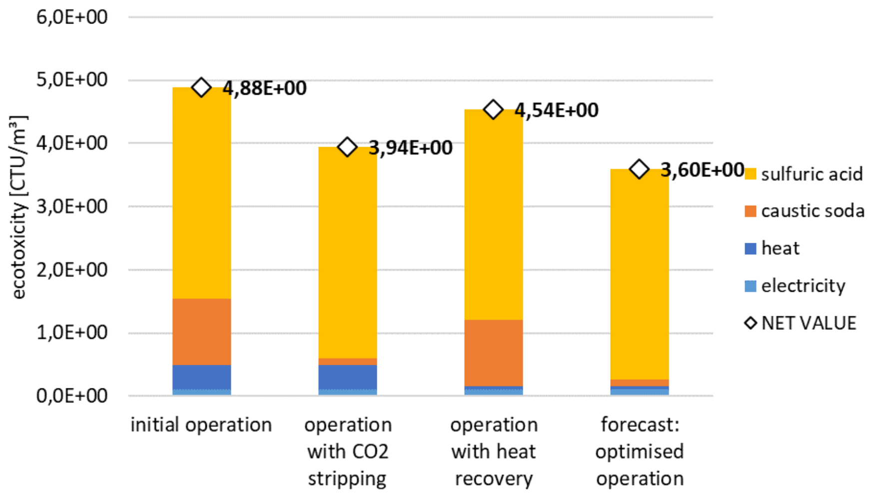

Figure 194. Ecotoxicity for the technical sub-system with vacuum degasification for different operating modes of Experiment 6

Experiment 7 - Phosphate recovery from soybean wastewater

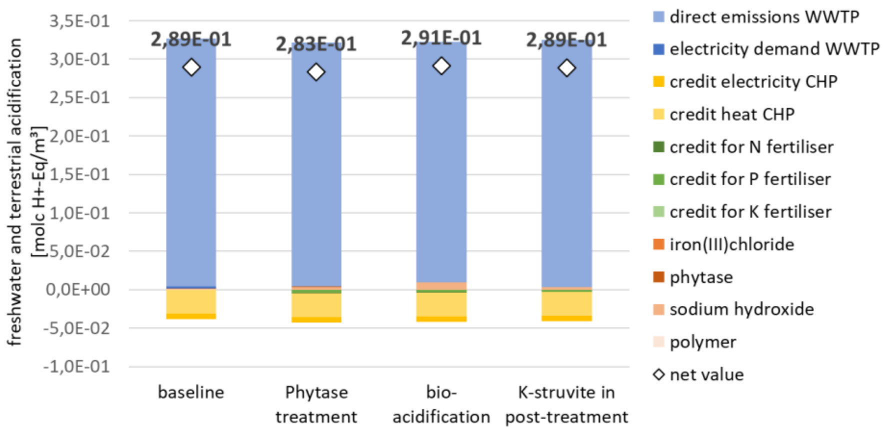

Figure 195. Freshwater and terrestrial acidification for the technical sub-system with phosphate recovery for different approaches/strategies of Experiment 7

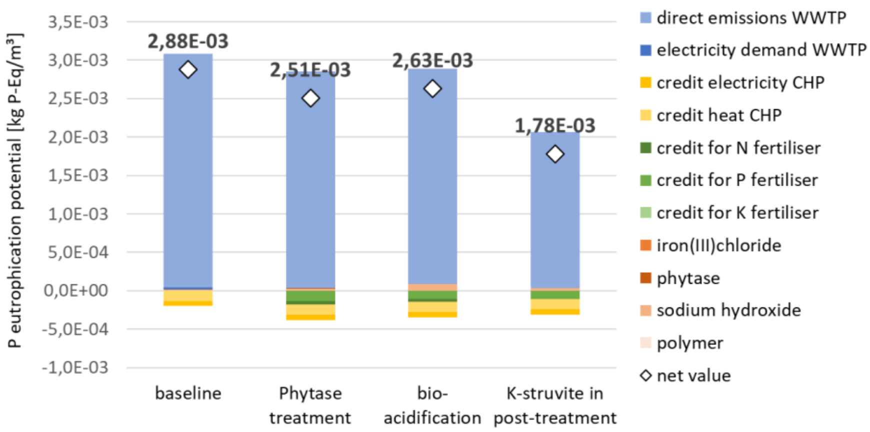

Figure 196. P eutrophication potential for the technical sub-system with phosphate recovery for different approaches/strategies of Experiment 7

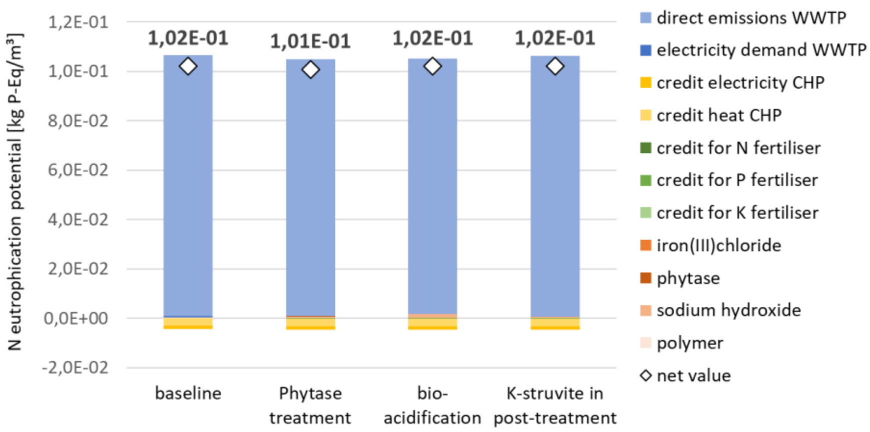

Figure 197. N eutrophication potential for the technical sub-system with phosphate recovery for different approaches/strategies of Experiment 7

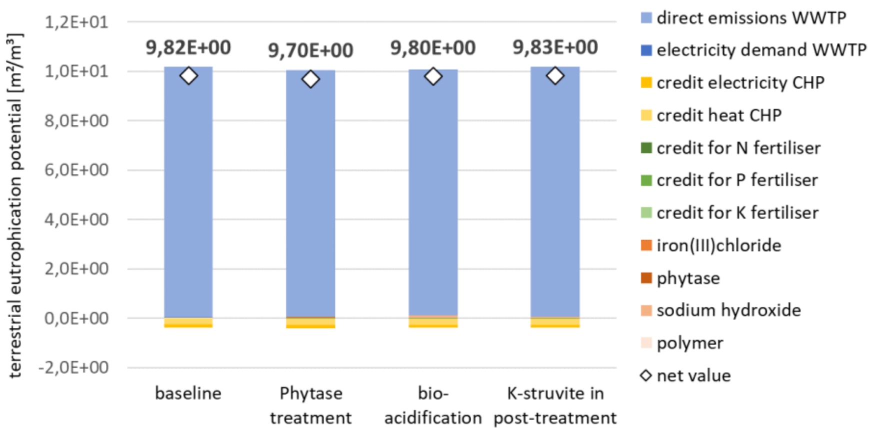

Figure 198. Terrestrial eutrophication potential for the technical sub-system with phosphate recovery for different approaches/strategies of Experiment 7

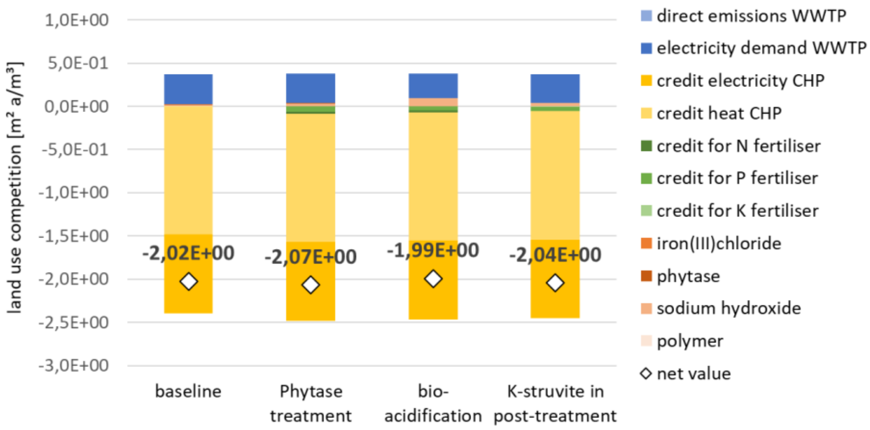

Figure 199. Land use competition for the technical sub-system with phosphate recovery for different approaches/strategies of Experiment 7

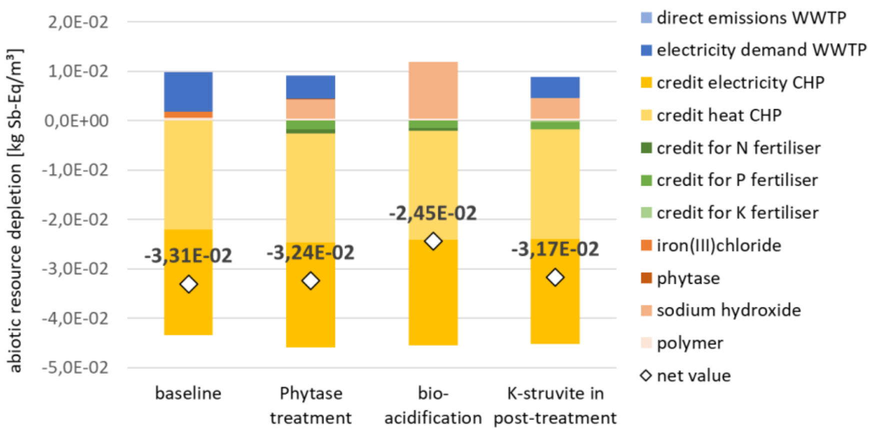

Figure 200. Abiotic resource depletion for the technical sub-system with phosphate recovery for different approaches/strategies of Experiment 7

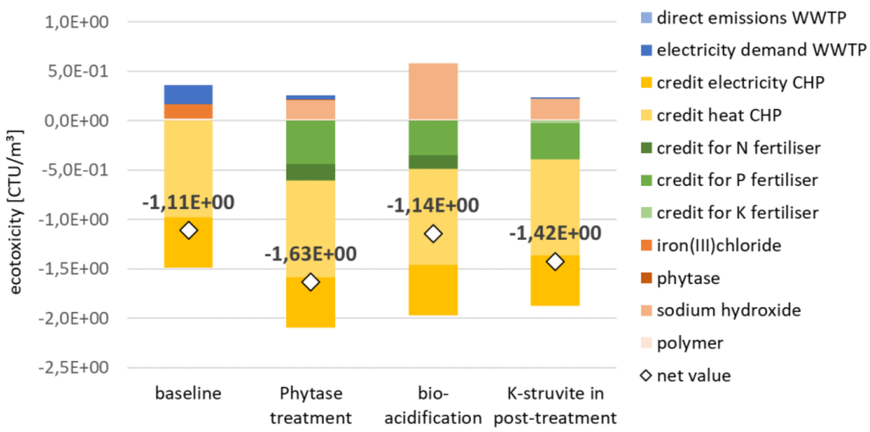

Figure 201. Ecotoxicity for the technical sub-system with phosphate recovery for different approaches/strategies of Experiment 7

Experiment 8 - Acid whey thickening with membrane treatment

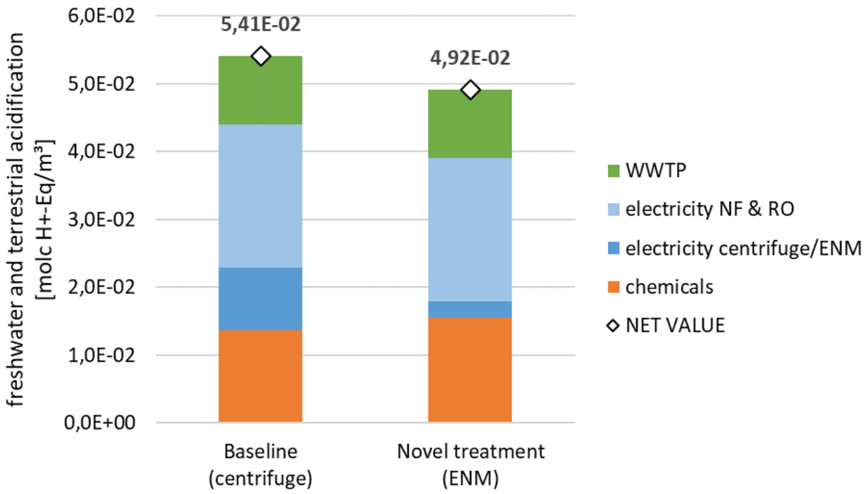

Figure 202. freshwater and terrestrial acidification for the technical sub-system using membranes for whey thickening of Experiment 8

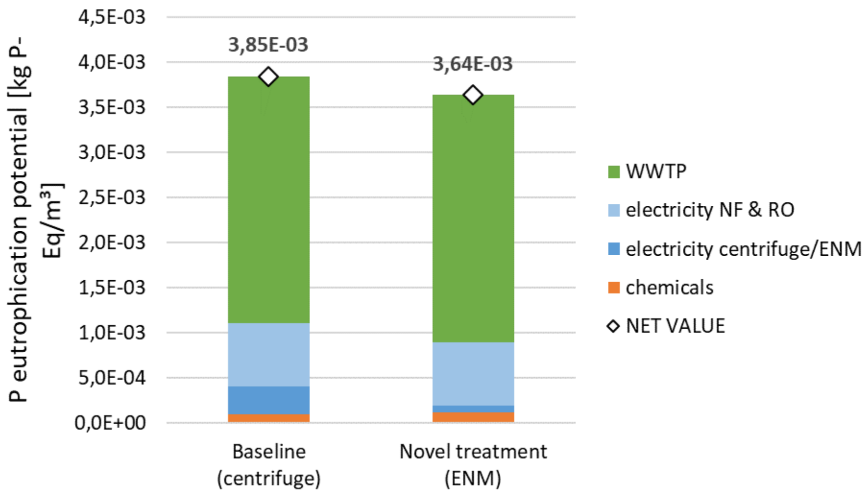

Figure 203. P eutrophication potential for the technical sub-system using membranes for whey thickening of Experiment 8

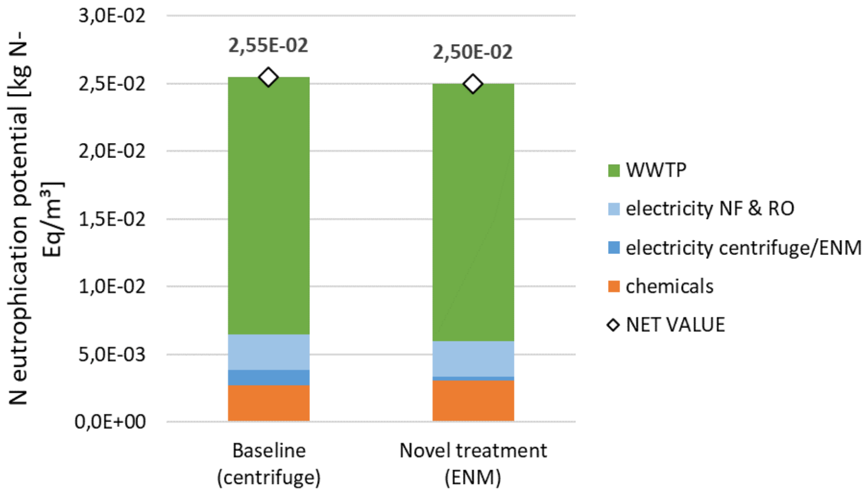

Figure 204. N eutrophication potential for the technical sub-system using membranes for whey thickening of Experiment 8

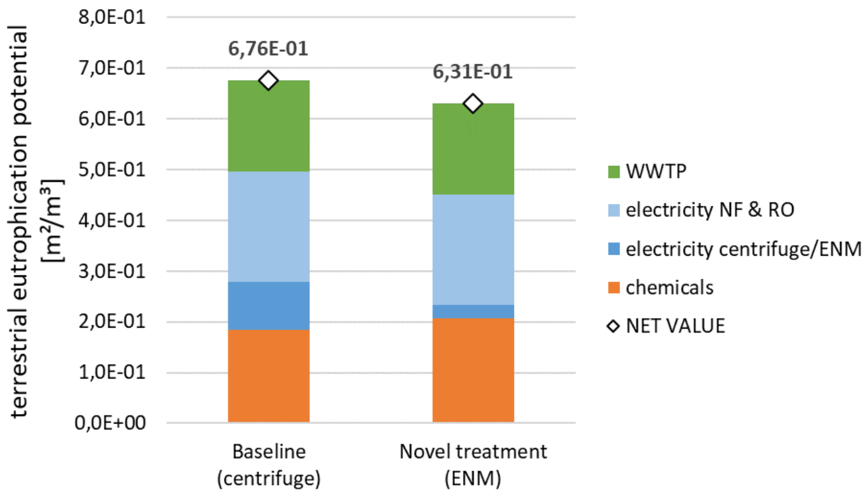

Figure 205. Terrestrial eutrophication potential for the technical sub-system using membranes for whey thickening of Experiment 8

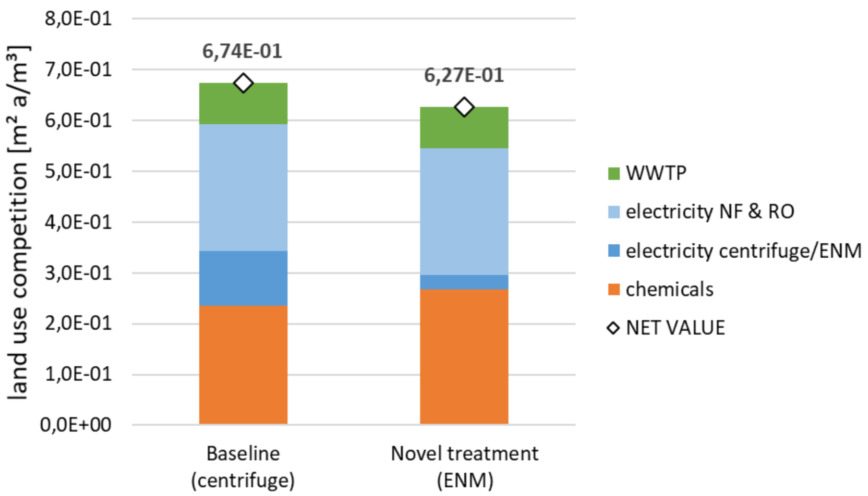

Figure 206. Land use competition of the technical sub-system using membranes for whey thickening of Experiment 8

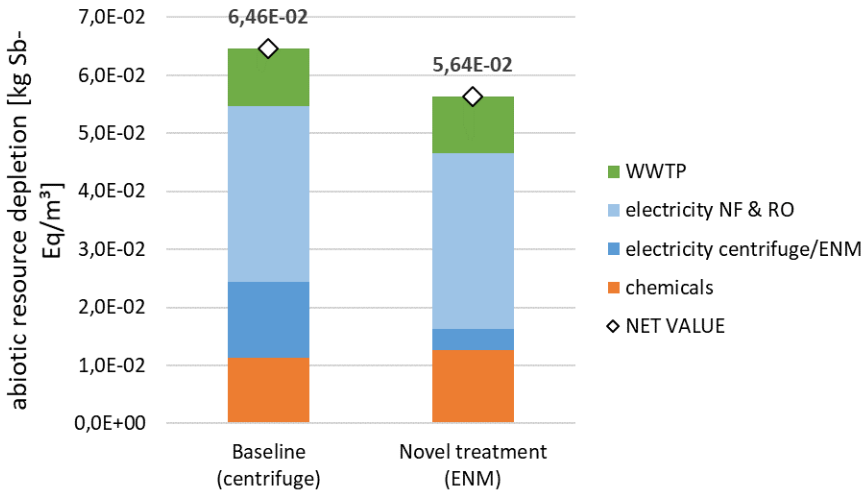

Figure 207. Abiotic resource depletion for the technical sub-system using membranes for whey thickening of Experiment 8

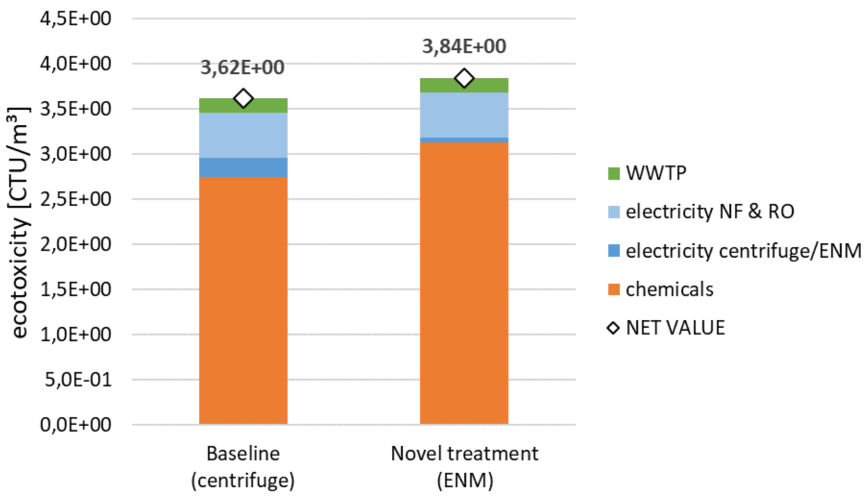

Figure 208. Ecotoxicity for the technical sub-system using membranes for whey thickening of Experiment 8

7.4 Results of combined LCA for Experiment 5

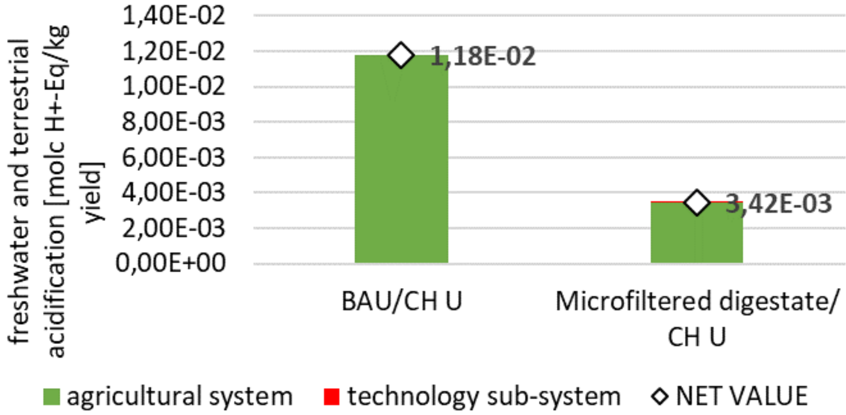

Figure 209. Freshwater and terrestrial eutrophication for the combined agricultural-technical system with microfiltration and fertigation of Experiment 5

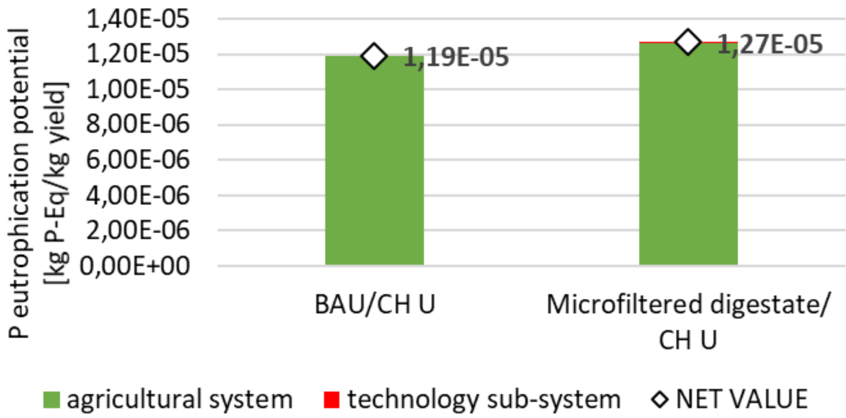

Figure 210. P eutrophication potential for the combined agricultural-technical system with microfiltration and fertigation of Experiment 5

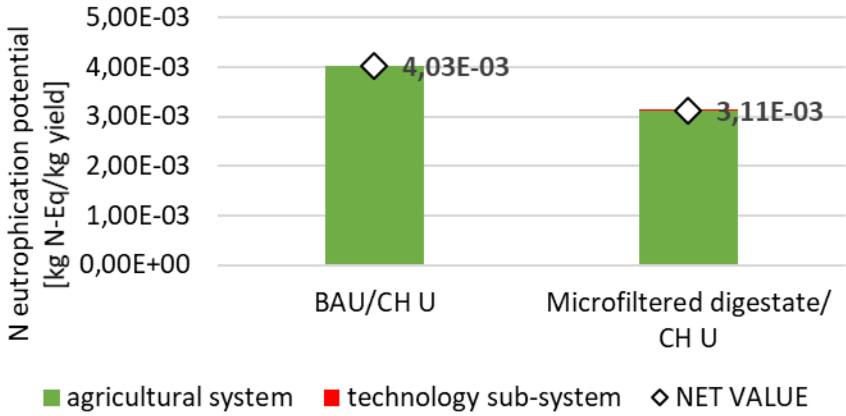

Figure 211. N eutrophication potential for the combined agricultural-technical system with microfiltration and fertigation of Experiment 5

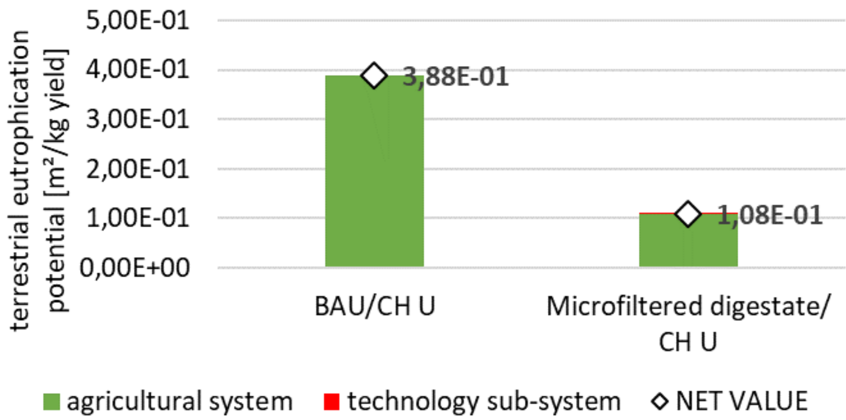

Figure 212. Terrestrial eutrophication potential for the combined agricultural-technical system with microfiltration and fertigation of Experiment 5

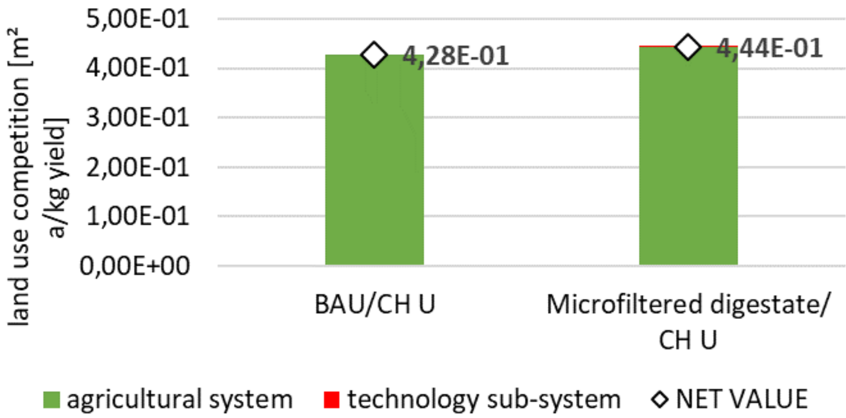

Figure 213. Land use competition for the combined agricultural-technical system with microfiltration and fertigation of Experiment 5