



Improved Nutrient and Energy Management
through Anaerobic Digestion



WORKING PAPER 17

Comparison of different digestate processing systems concerning environmental efficiency

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ABSTRACT

On the one hand there are regions in Europe with high livestock density that means high quantities of manure with organic nutrients but insufficient areas to applicate this nutrient amounts. On the other hand there are large areas with a high nutrient demand for plant cultivation. There are several option to treat manure with the aim of saving emissions on the one way and to solve transport distance problems on the other. This assessment will make a contribution towards further optimization manure treatment systems with focus on climate change, eutrophication and acidification potential. The conducted life cycle assessment shows that manure treatment is not better than conventional manure handling in any case. From an overall ecological view treatment options that separate manure or digested manure with downstream composting can be an optimal way of manure treatment. Further positive aspects are the increase of transport distances in consequence of composting or drying processes.

Table of contents

Table of contents.....	2
List of figures	3
List of tables	3
1 Introduction.....	4
2 Research Questions.....	4
3 Methodology	4
4 Definition of scenarios.....	5
5 Results	10
6 Conclusion	16
7 References.....	19

List of figures

Figure 1:	Results of environmental impact assessment – climate change	11
Figure 2:	Results of environmental impact assessment of selected scenarios – climate change	12
Figure 3:	Results of environmental impact assessment – climate change — heat sensitivity.....	12
Figure 4:	Results of environmental impact assessment – eutrophication potential	13
Figure 5:	Results of environmental impact assessment – eutrophication potential— heat sensitivity	14
Figure 6:	Results of environmental impact assessment – acidification potential.....	14
Figure 7:	Results of environmental impact assessment – acidification potential — heat sensitivity	15
Figure 8:	Advantages and disadvantages of the treatment scenarios in comparison with the baseline scenario s00 and heat sensitivity — climate change.....	16
Figure 9:	Advantages and disadvantages of the treatment scenarios in comparison with the baseline scenario s00 — eutrophication potential.....	17
Figure 10:	Advantages and disadvantages of the treatment scenarios in comparison with the baseline scenario s00 — acidification potential — heat sensitivity	17
Figure 11:	Summary of advantages and disadvantages of selected impact assessment categories in the scenarios	18

List of tables

Table 1:	Characteristics of raw cattle manure [Albers, 2015].....	6
Table 2:	Nutrient content of digestate [Reinhold, 2014]	7
Table 3:	Nutrient allocation in separation process [Brauckmann, 2014]	7
Table 4:	Reference products of the products of manure treatment	9
Table 5:	Nutrient allocation in separation process [Baumgärtel and Benke, 2013], [LAD, 2011], [Source Effluent].....	9
Table 6:	Extraction of characterization factors for climate change by ReCiPe [Goedkoop et al., 2008]	10
Table 7:	Extraction of characterization factors for marine eutrophication by ReCiPe [Goedkoop et al., 2008]	10
Table 8:	Extraction of characterization factors for terrestrial acidification by ReCiPe [Goedkoop et al., 2008]	10

1 Introduction

In regions with intensified livestock production and high quantities of raw manure problems with nutrient surplus occur. On the other hand in crop cultivation organic fertilizer can substitute mineral fertilizer and contribute to the organic soil content and is therefore preferable. Problems for the effective use of manure are the high water content and uncertainties concerning the nutrient content. By the use of manure treatment systems the nutrient content can be reduced or more concentrated products can be generated. The aim is to come to a more effective and efficient nutrient management. Further advantages are that manure storage can be avoided and the products can be handled easier than raw manure. Manufactured manure products can be transported to areas with nutrient demand to substitute mineral fertilizers. Besides the efficient use of organic fertilizers conventional ways of manure treatment result in high emissions with effects on climate change, eutrophication and acidification. Manure treatment systems can help to reduce emissions enormously. Thus, in this approach several treatment opportunities are compared with conventional manure application regarding the environmental impacts on climate change, eutrophication and acidification potential.

2 Research Questions

In the described context the research questions of this working paper deal with the environmental impacts of manure application and several existing treatment systems. In detail there are following questions:

- How extensive are the impacts of conventional manure storage combined with direct manure application on environment?
- Which manure treatment technology is more efficient than direct manure application?
- Which treatment process has the least impacts on the environment?
- What are the significant key parameters in the treatment paths to handle manure economically?

3 Methodology

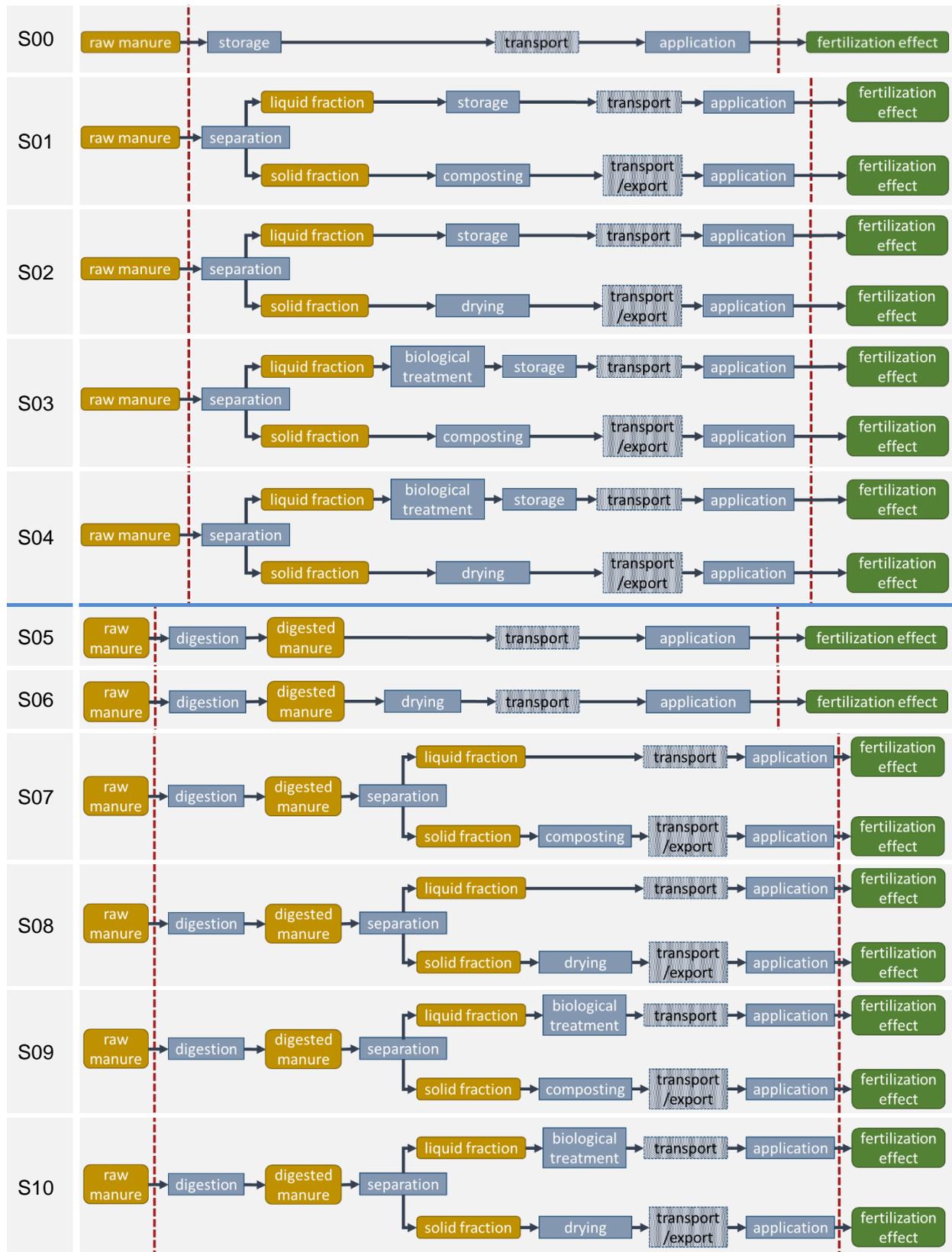
Analysing the environmental impact of different manure treatment technologies with the aim to identify treatment procedures with extraordinary environmental impacts the Life Cycle Assessment (LCA) tool was used. This approach was performed according to the Methodology described in the ILCD Handbook for LCA [EC JRC, 2010, 2010] and the [DIN EN ISO 14040/DIN EN ISO 14044].

The goal of this LCA approach has already been defined within the research question in chapter 2. Within the definition of the scenarios and the description of the treatment processes the scope of this analysis will be defined in chapter 4.

This Life Cycle Assessment focuses on the environmental impacts due to the treatment of *1 ton raw cattle manure (FU)*. The relevant impact assessment categories to answer the research questions are climate change, eutrophication and acidification. Although there are further interesting impact categories such as land occupation, human toxicity or fossil depletion, but on the one hand within the consideration of the focus of the *INEMAD* project this paper focussed on the nutrient relevant categories eutrophication and acidification plus the global topic climate change. On the other hand the data availability to cover completely all processes was not detailed enough to perform further categories. A comprehensive assessment can be part of further research question.

4 Definition of scenarios

To compare different manure treatment systems the following scenarios were selected (S00-S10).



In this list of the scenarios only processes are listed where emissions regarding the chosen impact categories are assumed. These 11 scenarios consist of the following single treatment processes:

- manure storage,
- digestion of manure,
- separation of manure or digestate in solid and liquid fraction,
- transport/export of manure or digestate,
- biological treatment of the liquid fraction of manure or digestate (to effluent),
- composting or drying of the solid fraction of manure or digestate and
- field application of manure (treatment) products.

The considered treatment processes are described separately below. For any treatment step there are different technologies available. In this analysis the technology with the highest market share or the best available data to evaluate ecological impacts was chosen. Before description of the several process steps the characteristics of the raw material has to be defined (Table 1).

Table 1: Characteristics of raw cattle manure [Albers, 2015]

	Quantity	Unit
Dry matter	9.58	%
total_N	4.70	kg/m ³
NH ₄ -N	1.90	kg/m ³
P ₂ O ₅	1.60	kg/m ³
K ₂ O	4.90	kg/m ³

There is a big range of data about dry matter and nutrient content of organic fertilizers depending on feeding material and water content. Thus, the values represent only reference values from Lower Saxony Chamber of Agriculture, German.

All single treatment processes will be described below.

Storage

In conventional manure treatment, Scenario *s00*, raw manure is stored before its field application. Field application is not allowed at any time of the year based on legal requirements. Thus, a manure storage is necessary and its emissions are assumed with 41 g NH₃/m³ untreated manure and 85 g CH₄/m³ untreated manure [Amon et al., 2004]. In scenario *s01* and *s02* storages for the liquid fraction after the separation of manure are necessary. A storage for the solid fraction is not considered because this fraction will be composted or dried and during the storing of composted or dried material no emissions occur. Emissions of 39 g NH₃/m³ liquid fraction and 36.3 g CH₄/m³ liquid fraction can be expected [Amon et al., 2004]. [Amon et al., 2004] also measured emissions from a storage of biological treated liquid fraction of 209 g NH₃/m³ and 36.5 g CH₄/m³ liquid fraction which are used in scenario *s03* and *s04*. Emissions from storing digested manure are not taken into account separately because they are considered with the biogas plant.

Digestion of manure

In the scenarios *s05 – s10* digestion is the first treatment process for raw manure. With a biogas yield of 25 Nm³/m³ raw cattle manure [FNR, 2013] and a methane content of 68 % [Naskeo, 2015] there is a methane yield of 17 Nm³/m³ raw cattle manure [see also KTBL, 2013] there can be produced 50,5 kWh electricity and 312.5 MJ heat per m³ raw manure input in a downstream combined heat and power unit (electrical efficiency of 32 % and thermal efficiency of 55 % [KTBL, 2013]). The nutrient content in digestate is presented in Table 2.

Table 2: Nutrient content of digestate [Reinhold, 2014]

	Nutrient content
Total N	0.41 %
NH ₄ -N	64 % of Total N
P ₂ O ₅	100 % of input
K ₂ O	100 % of input

The emissions of methane, carbon dioxide, hydrogen sulphide, ammonia and dinitrogen monoxide in digestion process are taken from the Ecoinvent database process for “treatment of manure by anaerobic digestion” [Weidema et al., 2013].

Separation of manure or digestate in solid and liquid fraction

Aim of this process is to separate the raw manure (Scenario *s01 – s04*)/ digestate (Scenario *s07 – s10*) into a liquid and a solid fraction. There are various technologies available on the market like centrifuge or screw press. Here a screw press separation is chosen. Due to data gaps it is assumed that the separation process itself does not produce any direct emission from manure or digestate. But there are indirect emissions due to the operation of the screw press. There is an electricity demand of 0.8 kWh/m³ input material assumed [Cielejewski, 2013]. Table 3 shows the allocation of nutrients into the liquid and the solid fraction after the separation process.

Table 3: Nutrient allocation in separation process [Brauckmann, 2014]

	solid fraction	liquid fraction
Dry matter	27,1 %	5,7 %
Total N	24 %	76 %
NH ₄ -N	14 %	86 %
P ₂ O ₅	22 %	78 %
K ₂ O	16 %	84 %

Biological treatment of the liquid fraction of manure or digestate (to effluent)

Biological treatment in scenarios *S03, S04 and S09* is a nitrification and denitrification process. The aim of the process is to eliminate organic material or the chemical (COD) or biological (BOD) oxygen demand¹. More interesting in this approach is the nutrient removal especially nitrogen. Due to nitrification and denitrification there are ammonia and dinitrogen monoxide emissions excepted. [Smet et al., 2003] measured that the total nitrogen losses (except N₂) go up to 0.5 % of amount of the nitrogen input. Whereas [Hersener et al., 2002] and [Schechtner, 1993] describe nitrogen losses up to 5 % of total N due to aeration of manure. Here an emission factors of up to 1 % of N that is lost as N₂O and 0.01 % as NH₃

¹ These two parameters describe the amount of organic matter in water that consumes oxygen while decomposition.

which can contribute to indirect N₂O emissions was chosen [source]. A share of 0.8 kg N per kg N input end up in the effluent (liquid end product) and a total decay rate of 25 % of organic matter were assumed. The electricity demand of the biological treatment is 17 kWh/m³ input material [Smet et al., 2003].

Composting of the solid fraction of manure or digestate

After separation manure or digestate one opportunity to treat the solid fraction is composting. Normally there is structure material necessary. [Martins and Dewes, 1992] mixed manure and straw with a mass content up to 10 % of straw. However to calculate the emissions from composting the co-product is not taken into account because it is also a by-product from plant production. Data to calculate the emissions are taken from [Hellebrand and Kalk, 2000]. An average share of 30.3 % CO₂-C and 2.5 % CH₄-C of carbon in dry matter and 4.9 % NH₃-N and 1.3 % N₂O-N of nitrogen in dry matter emits while composting. Further an average decay rate of 42 % was chosen [Berner, 2012].

Drying of the solid fraction of manure or digestate

An alternative to composting the solid fraction is drying the substance to reach higher dry matter content and hence higher nutrient concentration. Thus, with drying manure and digestate higher transport distances are possible. With a drying unit there is a dry matter content of up to 82 % realizable [Ferch, 2011]. It is 4.7 MJ is necessary to evaporate one litre water. The drying process causes ammonia emissions of 2.0 kg/m³ input material [Ferch, 2011]. Through purification of the exhaust air 91.7 % of ammonia can be removed. With sulphuric acid as additive approximately 3.8 kg ammonium sulphate per m³ exhaust air can be produced in the ammonium washer. Ammonium sulphate is used as mineral fertilizer.

Field application of manure treatment products

One aim of integration of manure treatment systems is the production of products that make the use of organic fertilizer more efficiency. The field application of these products results in emissions depending on their nutrient content and nutrient availability as well as the form² of nutrient application. Additionally indirect emissions arise from field work processes. Calculating emissions due to the application of the end products of manure treatment on field the calculation method according to [Nemecek and Kägi, 2007] and [Richner et al., 2014] with updated information of [Nemecek et al., 2012] was chosen.

Transport/export of manure or digestate

To use the products of manure treatment as organic fertilizer a transport process from treatment plant to field is included. The assumed transport distance depends on the water content of the products. For raw manure and liquid fraction (untreated and biological treated) a transport distance of 20 kilometres is taken. Compost, is transported 100 kilometres and dried solid fraction is transported 200 kilometres. The transport process is modelled by an Ecoinvent database process for a lorry with a capacity of 7.5-16 metric ton [Weidema et al., 2013].

Upstreaming processes

All upstreaming processes in the scenarios such as operation of storage or screw press, field work processes, etc. were performed with support of the Ecoinvent database [Weidema et al., 2013]. The Energy demand in the process chain was performed by the European electricity mix Entso-E. Heat is delivered by an European heating mix process taken from the Ecoinvent database. With regard to the high heat demand in drying process a sensitivity was calculate with heat delivered by wood chips burning.

² liquid, composted, dried or pelletized; water content
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Substitutes

The use of manure and products of manure treatment as organic fertilizer can avoid the use of conventional mineral fertilizer products. Due to this substitution emissions of the production and application of mineral fertilizer can be taken into account as benefits. Following list (Table 4) shows the products of the manure treatment and their reference products which can be replaced.

Table 4: Reference products of the products of manure treatment

Product of manure treatment	Reference product
Manure (Raw, liquid)*	Mineral fertilizer
Digestate*	Mineral fertilizer
Effluent*	Mineral fertilizer
Compost*	Mineral fertilizer
Dried solid fraction*	Mineral fertilizer
Ammonium sulphate	Mineral fertilizer
Electricity	Electricity, Entso-E
Heat	European heat mix

* Depending on nutrient content of the products

The benefits for the end- and by-products of manure treatment are calculated by their nutrient content. But not the whole nutrient share is available for crops. Organically bounded nutrients are less available for crops than mineral nutrients. Table 5 shows the products with their nutrient efficiency, that means the quantity of replaced mineral fertilizer the so called mineral fertilizer equivalent (MFE).

Table 5: Nutrient allocation in separation process [Baumgärtel and Benke, 2013], [LAD, 2011], [Source Effluent]

	N	P	K
Raw manure	60 %	90 %	90 %
Digestate	60 %	90 %	90 %
Effluent	100 %	100 %	100 %
Compost	30 %	90 %	90 %
Dried solid fraction	30 %	90 %	90 %
Ammonium sulphate	100 %	-	-

Due to the production of electricity and heat by the biogas plant there can also be avoided conventional produced electricity and heat based on fossil resources. In scenarios produced electricity by the biogas plant replaces the European electricity supply mix [ENTSO-E, 2014], the produced heat replaces an European average heat production mix [Weidema et al., 2013].

5 Results

The considered scenarios were calculated with the software umberto. To evaluate environmental impacts of manure treatment options in the scenarios the ReCiPe assessment method [Goedkoop et al., 2008] was chosen. With focus on the project alignment and the expected emissions due to manure treatment and application a pre selection of the impact assessment categories were taken. Thus, this analysis evaluates climate change, marine eutrophication and terrestrial acidification.

To calculate the environmental impacts based on the emissions resulting treatment and application of manure and manure products following characterization factors (extraction) for the category climate change (Table 6), for marine eutrophication (Table 7) and terrestrial acidification (Table 8) with time horizon of 100 years were applied.

Table 6: Extraction of characterization factors for climate change by ReCiPe [Goedkoop et al., 2008]

Emission	Characterization factor	Unit
Carbon dioxide, CO ₂	1	kg CO ₂ eq
Methane, CH ₄	25	kg CO ₂ eq
Dinitrogen monoxide, N ₂ O	298	kg CO ₂ eq

Table 7: Extraction of characterization factors for marine eutrophication by ReCiPe [Goedkoop et al., 2008]

Emission	Characterization factor	Unit
Nitrogen, total	1.429	kg Neq
Ammonia, NH ₃	1.177	kg Neq
Nitrogen oxides, NO ₂	0.039	kg Neq

Table 8: Extraction of characterization factors for terrestrial acidification by ReCiPe [Goedkoop et al., 2008]

Emission	Characterization factor	Unit
Nitrogen oxides, NO _x to air	0.56	kg SO ₂ eq
Ammonia, NH ₃ to air	2.45	kg SO ₂ eq
Sulfur dioxide, SO ₂ to air	1	kg SO ₂ eq

According to [Benini et al., 2014] the extraction here shows only the relevant emissions factors of the selected impact categories. However the calculation was performed including all category specific emissions and its characterization factors by using the assessment method ReCiPe [Goedkoop et al., 2008] which is implemented in the Ecoinvent database [Weidema et al., 2013].

The following figures show the results of the calculation of the environmental impacts in the 10 treatment scenarios and the baseline scenario. On the abscissas columns upwards (red) show the emissions of the different manure treatment processes, differentiated according to direct and indirect emissions, in contrast to that the columns downwards (green) show the emission benefits due to substitute conventional products. The net emissions are displayed as thin red column on each scenario column, depending on net emission debits the columns pointed upwards (net emissions occur) or the column pointed downwards (net emission savings).

Climate change

Figure 1 shows the results of the calculation regarding climate change. Only scenario S05 and S07 result in total emission benefits, so only these two treatment options can contribute to emission saving by manure treatment. Another aspect is a high negative effect of the drying process in scenario s06 that is instantly recognizable. Scenario s06 has the highest environmental impact on climate change of all scenarios especially due to the high energy demand (electricity and especially heat) for drying the digestate. The scenarios s02, s04, s08 and s10 have also included the drying processes but there is a separation process of liquid and solid fraction in front of the drying process, so not the whole water content of the digestate has to be evaporated in this scenarios. To have a better look on the other scenarios, the results are presented in Figure 2 again without the scenario s06.

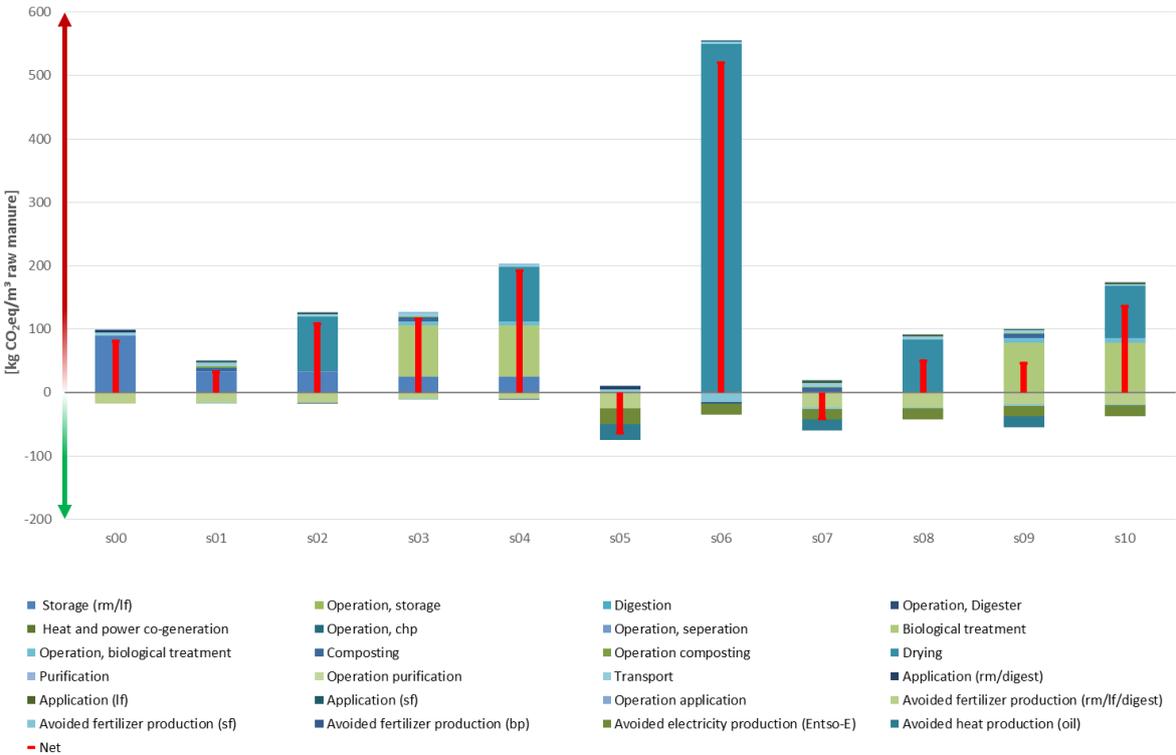


Figure 1: Results of environmental impact assessment – climate change³

Disregarding scenario s06 the other scenarios have high emissions from manure storage, biological treatment and the drying process, all other processes are nearly negligible. Scenarios without these high impact processes produce due to substitution of conventional products like mineral fertilizer, electricity or heat, net emission benefits (credits). Thus, Scenario s05 and s07 have the best performance. In all scenarios there are high emission benefits from avoided mineral fertilizer production. In the biogas scenarios additionally there are emission benefits due to energy supply. Normally GWP - emission benefits from energy production of biogas plants are higher, however, there is only manure as input material with a low biogas potential. Regarding climate change the best treatment option for manure is definitely the digestion of manure possibly in combination with separation of the digestate and composting of the solid fraction.

³ Abbreviations in the legend of the figure: rm: raw cattle manure; lf: liquid fraction; sf: solid fraction; digest: digestate; bp: by-product; Entso-E: European electricity supply mix
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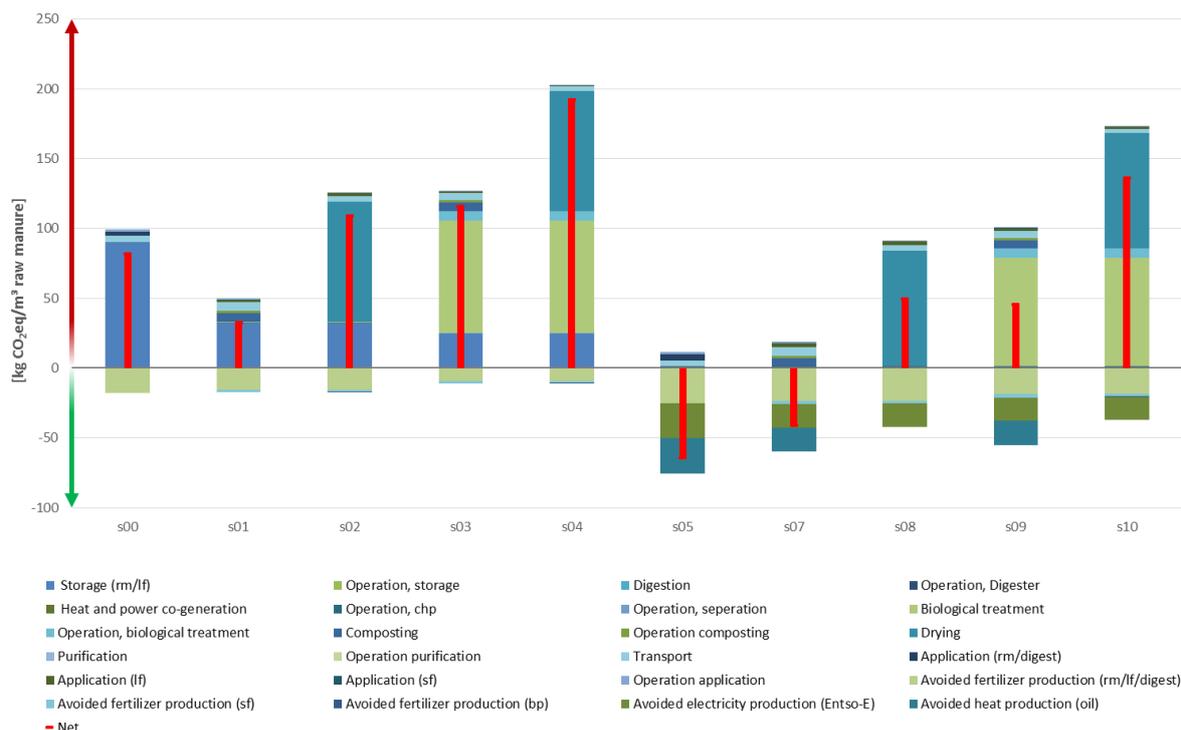


Figure 2: Results of environmental impact assessment of selected scenarios – climate change³

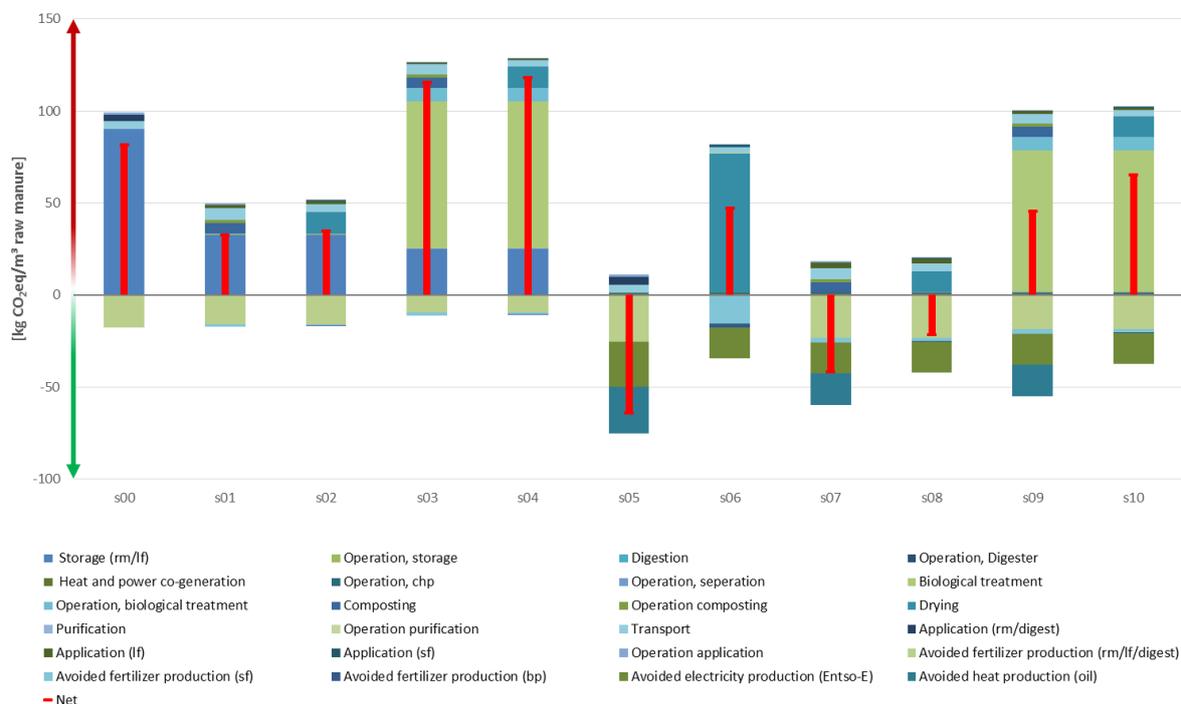


Figure 3: Results of environmental impact assessment – climate change – heat sensitivity³

As mentioned before there are high impact effects of the drying process in the scenario s02, s04, s06, s08 and s10. In the calculation this heat is produced conventional less the own produced heat by the biogas plant in s06, s08 and s10 and modelled by an European average heat mix, thus, these high emissions for heat supply arise. Alternatively this heat can be provided by renewable resources, such as wood

chips. This sensitivity is shown in Figure 3. The Scenarios mentioned above which dry solid fraction of manure, digestate or solid fraction of digestate are much better although the assumed transport distance of dried manure and digestate increases to 200 kilometres, so that s08 also contributes emissions savings.

Eutrophication potential

The results of the calculation of the environmental impact category eutrophication potential are described in Figure 4. This category focusses on the marine eutrophication. Marine eutrophication especially depends on nitrogen emission in contrast to freshwater eutrophication that especially depends on phosphorus emissions. But tracing phosphorus content in manure over all scenarios and treatment options no losses can be recognized because phosphorus is bounded organically and has to be mineralized after field application for crop uptake. Therefore the marine eutrophication was chosen to evaluate the environmental impacts.

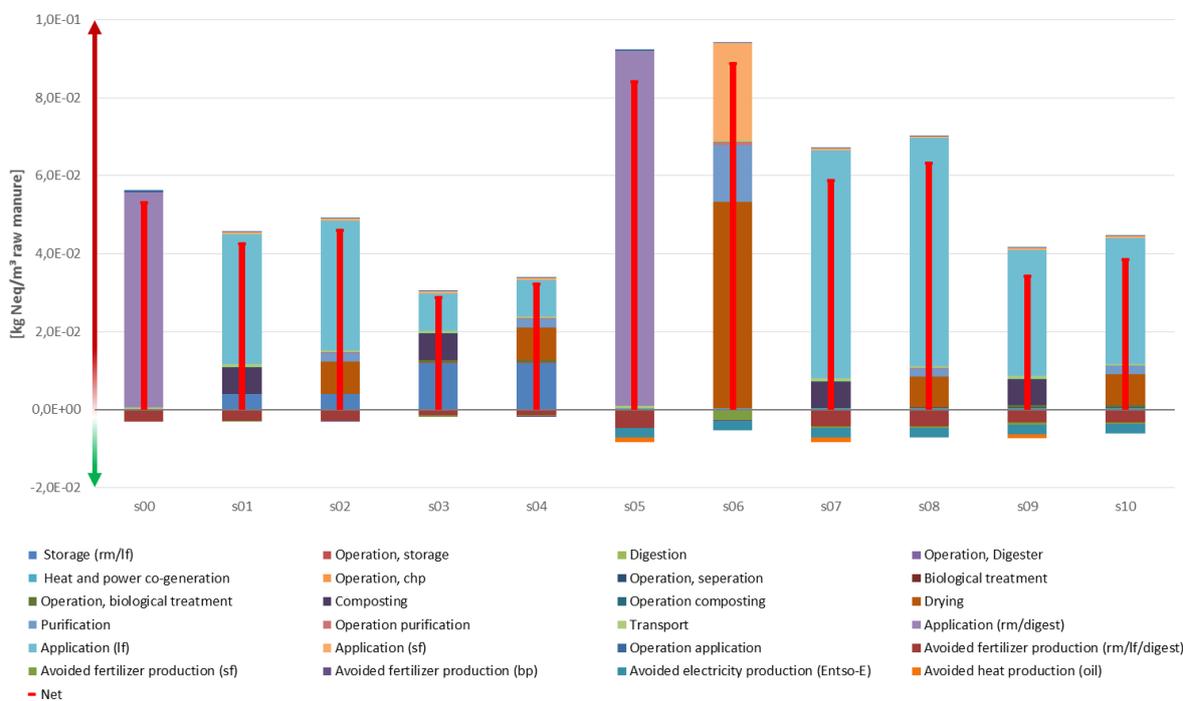


Figure 4: Results of environmental impact assessment – eutrophication potential³

Looking now at Figure 4, the main environmental impact is the result of nitrogen emissions by the field application of manure or digestate. Hereby the emissions due to the application of digestate are significant higher than the emissions due to manure application. Composting the solid fraction as well as drying with downstream purification of exhaust air produces further emissions, but the emissions in field application process can be reduced. By the biological treatment process nitrogen content in manure and digestate can be reduced which also leads to lower emissions in field application process. Thus, the biological treatment of manure with previous separation and composting the solid fraction (s03) is the best treatment option regarding the eutrophication potential. Substitution effects are also considered but in comparison with the impact category climate change the emission benefits are negligible and have no influence on the total results. As in the category climate change the influence of the type of heat delivery is also a key parameter to save emissions regarding eutrophication potential. So in Figure 5 the heat demand of the drying process is delivered based on renewable resources by wood chips instead of European average heat production mix. This alternative heat supply leads to lower emissions in drying process, but the effect is not as huge as the effect in the category climate change.

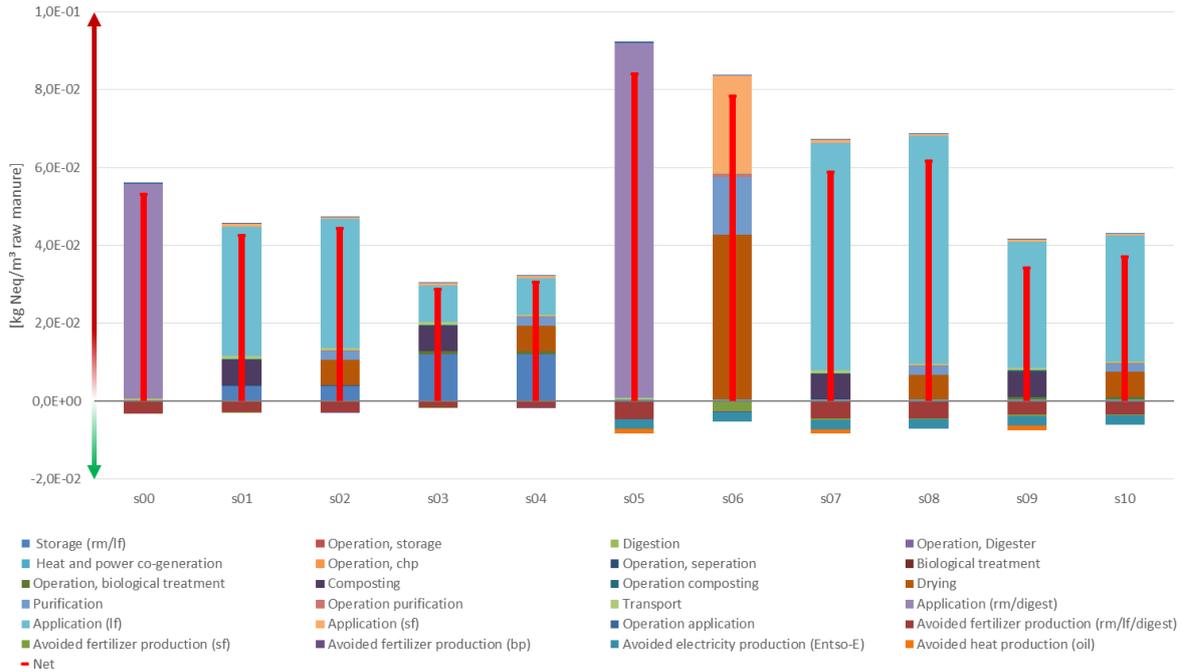


Figure 5: Results of environmental impact assessment – eutrophication potential— heat sensitivity³

Acidification potential

In Figure 6 the results of the calculation of the acidification potential are presented. Instantly recognizable are the emissions on the upwards columns which are relatively high in comparison with the emission benefits on the downwards columns.

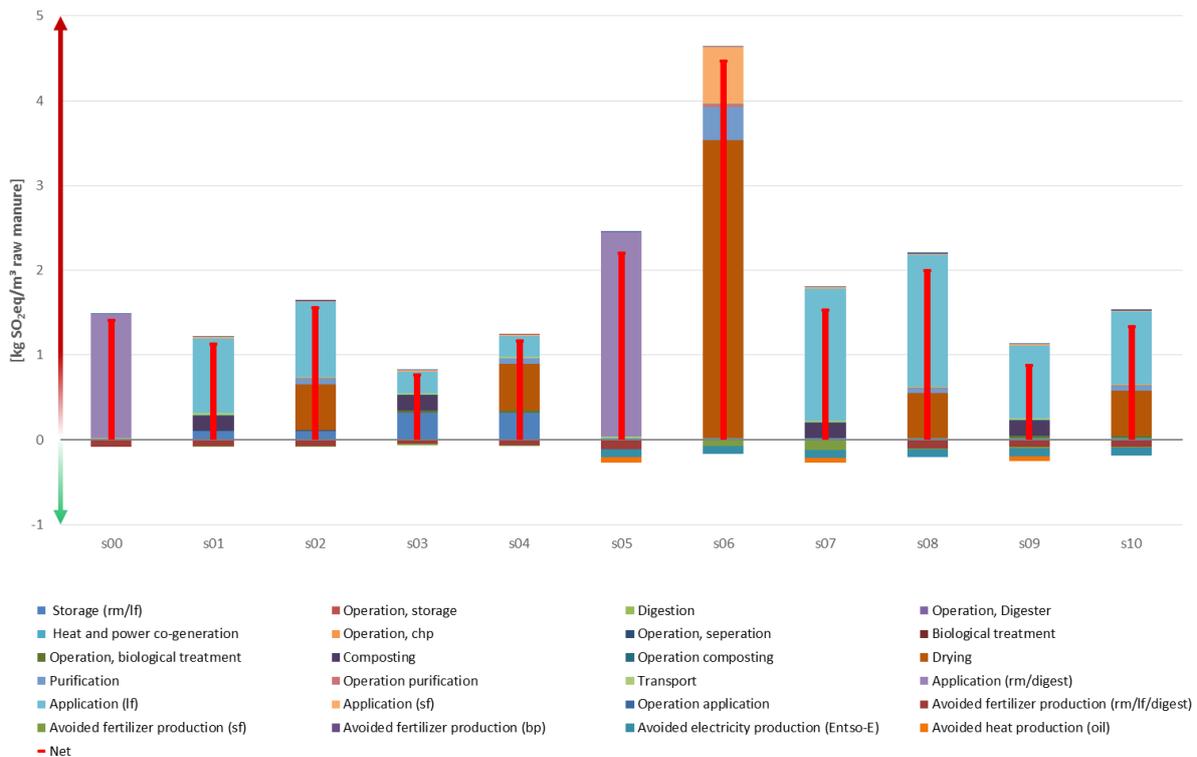


Figure 6: Results of environmental impact assessment – acidification potential³

The highest impacts in this category came from manure and digestate application and drying processes. Whereas more emissions occur through digestate application than through manure application. The benefits are negligible and have no influence on the total results. The best treatment scenario is the separation followed by biological treatment of the liquid fraction and composting the solid fraction (s03).

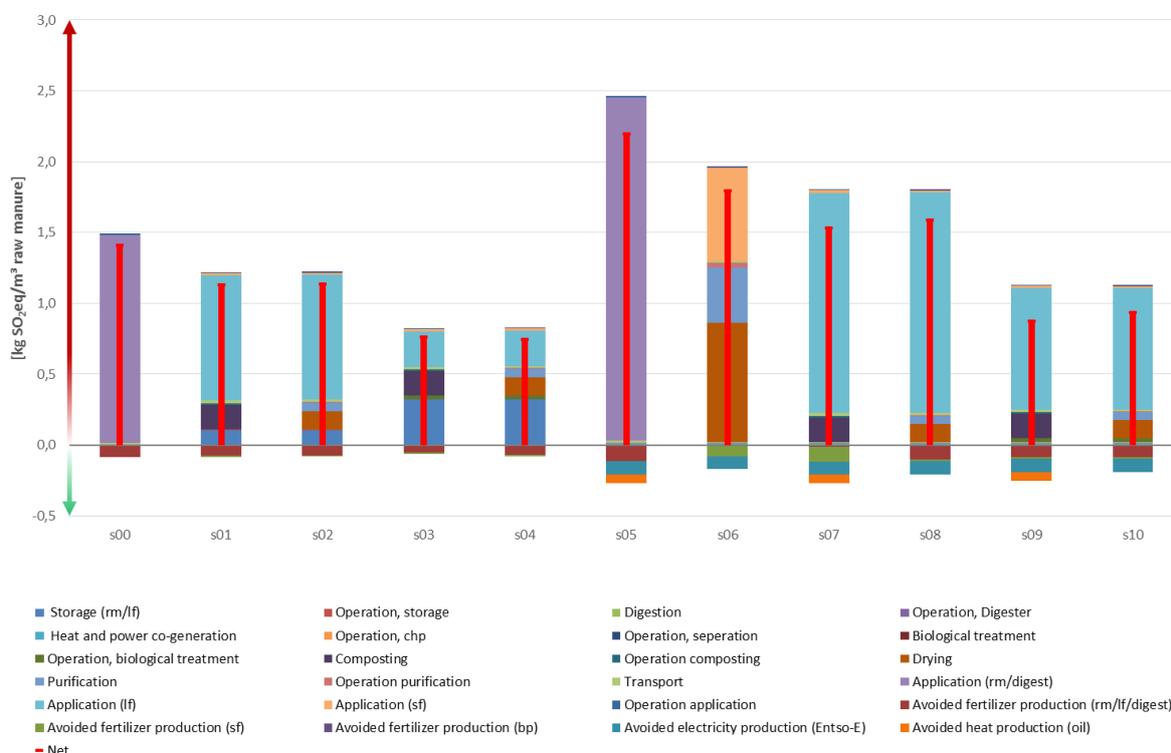


Figure 7: Results of environmental impact assessment – acidification potential – heat sensitivity³

The heat for the the drying process in Figure 6 is provide by conventional heat, thus Figure 7 shows the acidification potential of the scenarios with renewable heat delivery (wood chips) to dry manure and digestate. This option reduce the emissions of the drying process which also result in lower acidification potential. So s03 is still the best scenario, but due to lower emissions of the drying process scenario s04 is nearly as well as s03. Especially scenario s06 shows great emissions savings in comparison with Figure 6.

6 Conclusion

This analysis of manure treatment options shows interesting performance in terms of all three impact categories just considered. Following figures show emission saving potentials over all scenarios in the three considered impact categories in comparison with the baseline scenario.

Figure 8 highlights the advantages and disadvantages of the selected manure treatment processes in the scenarios in comparison with the baseline scenario s00 (the conventional manure application on field) for the category climate change.

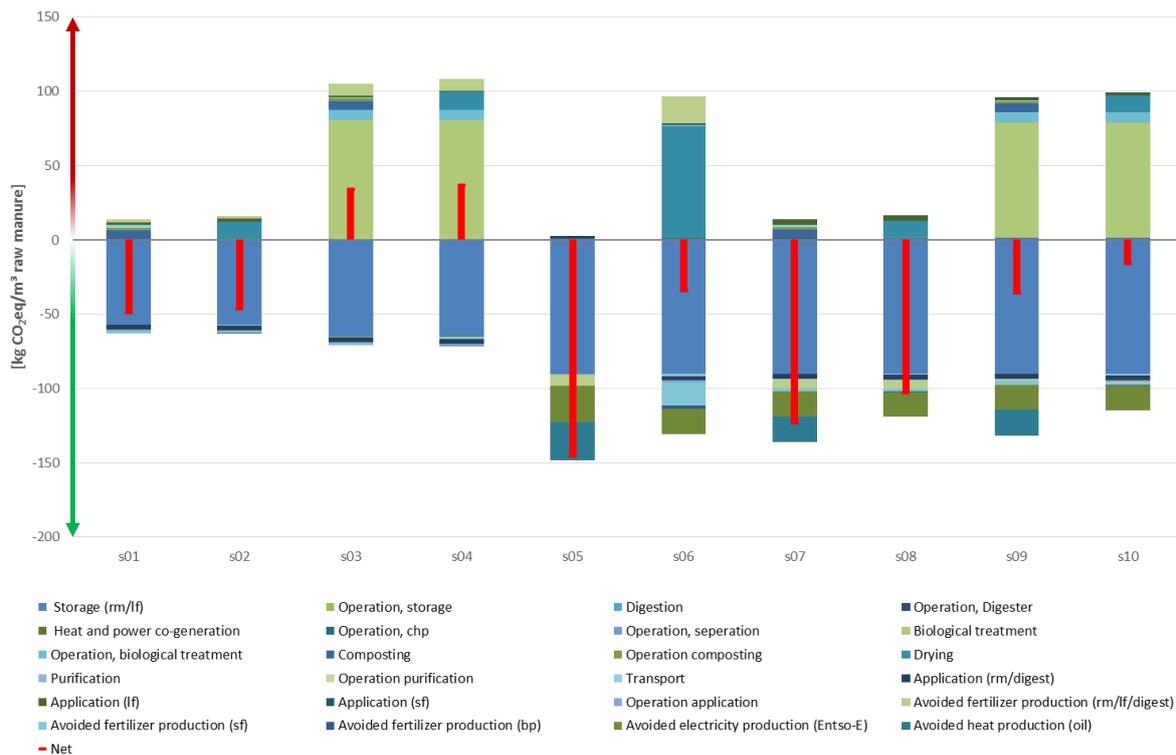


Figure 8: Advantages and disadvantages of the treatment scenarios in comparison with the baseline scenario s00 and heat sensitivity — climate change³

This chart (Figure 8) shows that manure treatment is definitely a way to save climate change emissions. Except for scenario s03 and scenario s04 all scenarios are better than the conventional manure application (related to scenarios with heat sensitivity). Especially the avoided storage emissions the emissions can be halved at least. Biological treatment of manure and digestate due to dinitrogen monoxide emissions of nitrification and denitrification process as well as heat demand to dry digestate result in high emissions. Only 1 % of nitrogen is lost in dinitrogen monoxide in the biological treatment but with a global warming potential of 298 kg CO₂eq per kg N₂O (see Table 6) the effects are enormous.

Figure 9 provides a comparison of all scenarios to baseline scenario s00, it shows emission saving potential for eutrophication potential of several treatment options. Especially the scenarios S05, S06, S07 and S08 with emission saving potential in the category climate change come off badly in the category eutrophication. This can be explained by the fact that digestion of manure generally leads to higher nitrogen emissions on field except of biological treated digestate. Otherwise the biological treatment produces dinitrogen monoxide which rises up global warming potential. The other scenarios (s01, s02, s03, s04, s09, s10) are better than the baseline scenario and can achieve emission savings. The effect of the exchange of the heat delivery from conventional heat to heat from wood chip burning in the scenarios with the drying process is more noticeable in climate change category than for eutrophication potential.

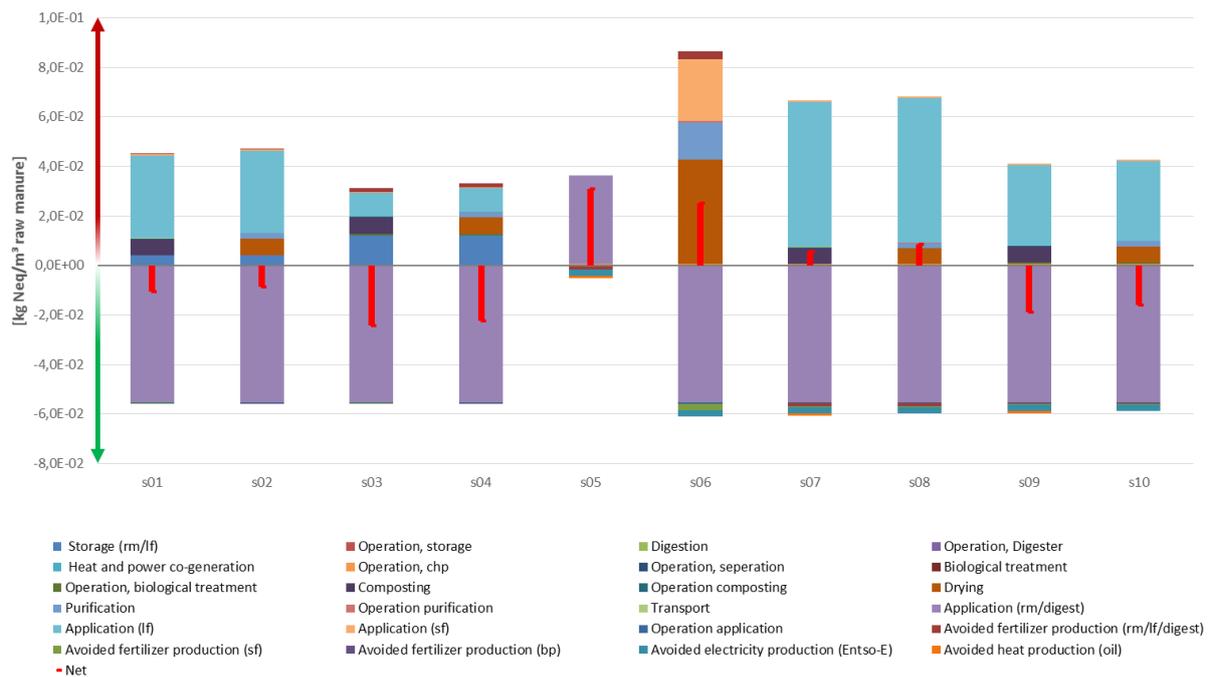


Figure 9: Advantages and disadvantages of the treatment scenarios in comparison with the baseline scenario s00 — eutrophication potential³

Figure 10 presents the results of the analysis in comparison of the baseline scenario s00 for the impact category acidification potential. So advantages and disadvantages to conventional manure handling and field application are noticeable which show as general tendency the same results than the eutrophication potential in Figure 9.

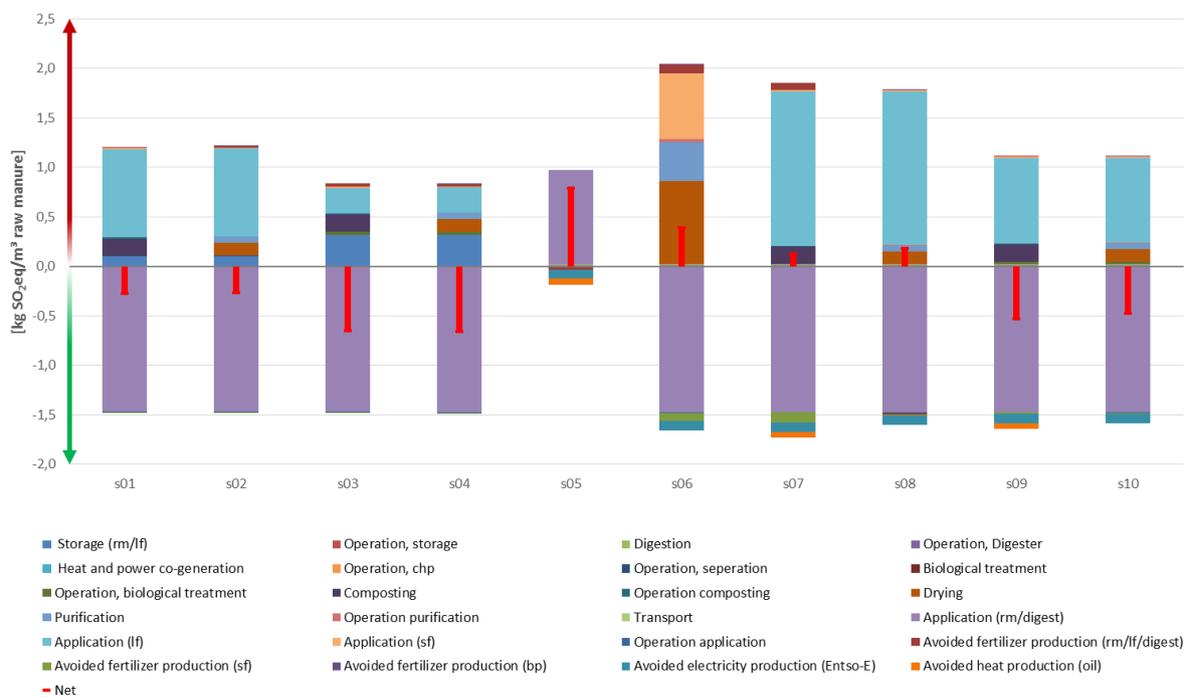


Figure 10: Advantages and disadvantages of the treatment scenarios in comparison with the baseline scenario s00 — acidification potential I— heat sensitivity³

The Figure 8 - Figure 10 show that treatment systems which save emissions related to impact category climate change show no advantages in the categories eutrophication and acidification potential. Not in any case manure treatment is the better option than simple manure storage and direct field application (baseline scenario). Thus, Figure 11 finally shows a summary of selected impact assessment categories over all scenarios always with heat sensitivity. Columns upwards represent scenarios which produce more emissions in their category than baseline scenario s00 whereas columns downwards show in which category scenarios save emissions in comparison with no any manure treatment.

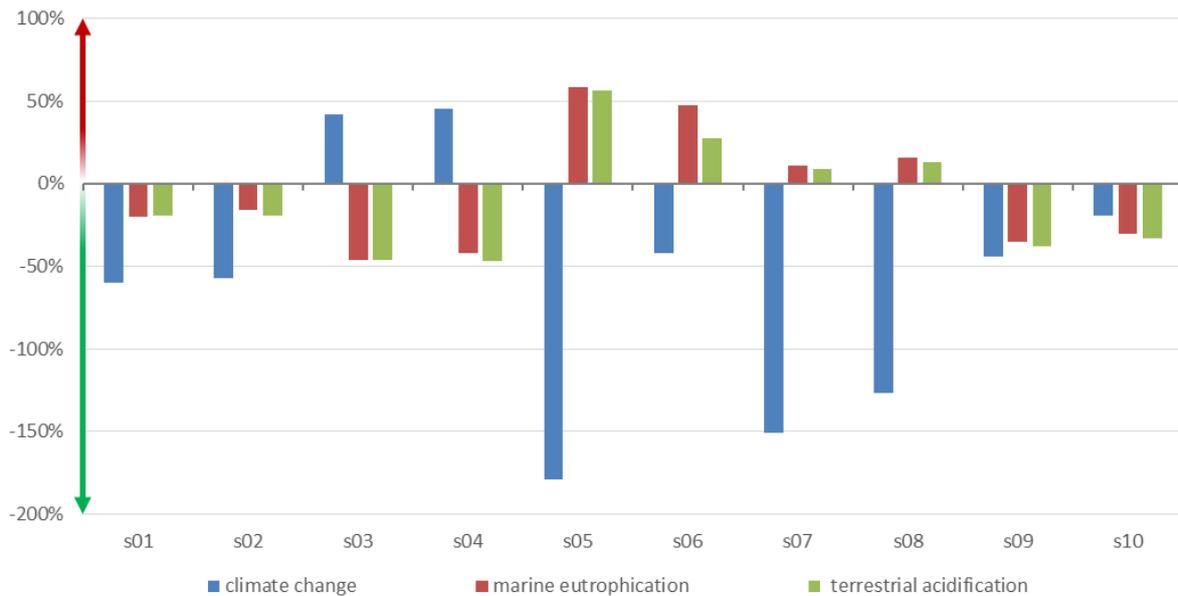


Figure 11: Summary of advantages and disadvantages of selected impact assessment categories in the scenarios with heat sensitivity

Only the scenarios s01, s02 and s09, S10 save emissions overall three impact assessment categories. Possibly other scenarios are more interesting depending on the environmental focus.

Generally the use of organic fertilizer is a good opportunity to close nutrient cycles as well as saving finite and fossil resources. Thus, processes with high nutrient losses respective nutrient destruction should be avoided. That means that the considered treatment options describe several opportunities to avoid emissions due to manure storing. Emissions as a consequence of the application of manure and digestate can be reduced by the use of application technologies that correspond to state of the art technologies. Further factors that have great influence on emissions due to field application are weather (wind speed, temperature and rainfall), slurry composition (dry matter content, pH- value), crops types (nutrient uptake) and soil conditions (soil type, nutrient content). If drying manure or digestate is an option for manure treatment, it is necessary that heat demand is delivered by renewable resource to handle emissions due to high energy production of the drying process. An interesting way to avoid nitrogen emission in field application process is biological treatment of manure or digestate otherwise through biological treatment there is a nutrient degradation with high nitrogen monoxide emissions and a loss of valuable resource. If there is a high quantity of manure that cannot be handled in conventional ways composting or drying as manure treatment can constitute a solution to store nutrients or increase transport distances. Further advantages of composting manure and digestate are the force of humus formation in soil and the bounding of nutrients in soil over longer periods.

7 References

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