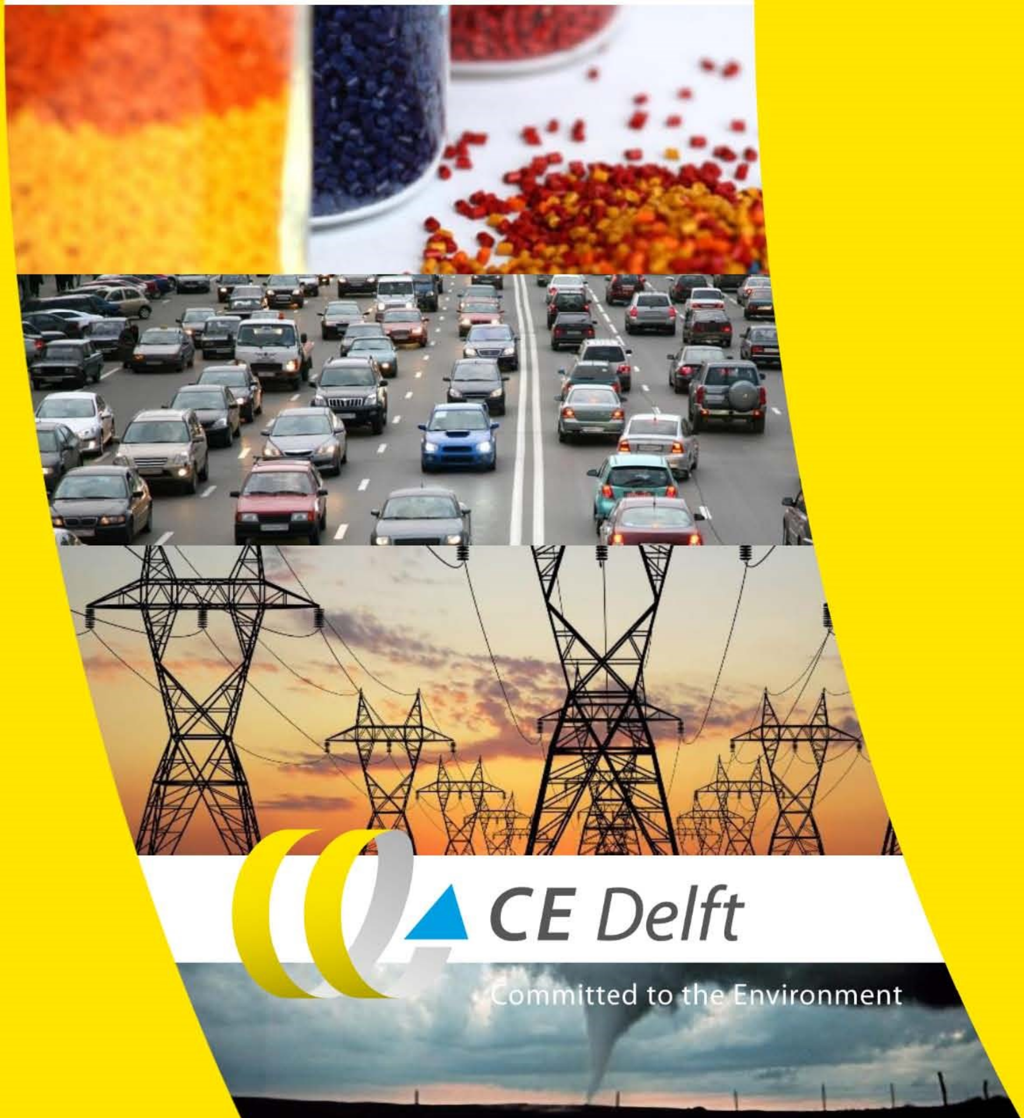
LCA of thermal conversion of poultry litter at BMC Moerdijk



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LCA of thermal conversion of poultry litter at BMC Moerdijk

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More information on this study can be obtained from the project leader Lonneke de Graaff.

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Contents

Summary

There are a range of options available for processing poultry litter. In the Netherlands over one-third is currently burned in the incinerator operated by BMC Moerdijk to generate electricity, with the ash being used as a fertilizer substitute. BMC Moerdijk commissioned CE Delft to assess the environmental impact of thermal conversion of the litter at their facility and compare it with that of eight alternative processing routes.

Methodology and scope

Core question

Does thermal conversion of poultry litter in the BMC facility have environmental benefits compared with eight other poultry litter processing routes?

Poultry litter composition

To ensure a fair comparison we assumed the same composition of litter feedstock in each of the routes; that of the mix currently processed at the BMC Moerdijk plant.

The functional unit adopted in the study is: processing of 1 metric ton of poultry litter as produced by Dutch poultry farmers consisting of 52% broiler chicken litter, 40% laying hen litter, 5% turkey litter and 3% manure-belt litter.

The routes

The following routes were assessed in this study:

Routes using poultry litter as an energy source and to produce a fertilizer substitute:

1. Thermal conversion at the **BMC** Moerdijk plant, generating electricity and marketing the ash as a fertilizer substitute *(reference route)*.
2. Thermal conversion on a **poultry farm**, generating electricity and marketing the ash as a fertilizer substitute.
3. **Co-digestion** at a digestion plant in Germany, generating electricity and marketing the digestate as a fertilizer substitute.

Route using poultry litter as an energy source:

4. Co-firing in a **wood-fired biomass power plant**, generating electricity but without marketing the ash as a fertilizer substitute.

Routes using poultry litter as a fertilizer:

5. **Direct application** of the raw litter in the **Netherlands**.
6. **Direct application** of the raw litter in **Germany**.
7. **Composting,** exporting the compost for use as a fertilizer substitute abroad.
8. Composting and **granulation,** exporting the granulate for use as a fertilizer substitute abroad.
9. Composting and application for **mushroom-growing**.

Because of the paucity of information on the mushroom-growing route, this was not included in the comparison. For an indication, though, a qualitative analysis of this route was performed.

Methodology
The study was broken down into two parts. The first, the nutrient balance, considers the presence of nutrients and organic matter before and after processing. The second part is a life cycle assessment (LCA) using the ReCiPe methodology in which 18 environmental impacts were analysed.

Data quality

Wherever possible, data on poultry litter processing was obtained directly from poultry litter processors (primary data). For the BMC Thermal conversion route only primary data was used. For the three routes Thermal conversion on a poultry farm, Composting and Granulation this was largely the case. For the routes Digestion, Co-firing in a power plant, Direct application in the Netherlands and in Germany a modelling approach was adopted. Though inferior to the analysis based (largely) on primary data, this latter approach provides a solid order-of-magnitude estimate.

Results of nutrient balance

In the biomass plant all organic matter and nutrients are lost
The nutrient balance shows that in a wood-fired biomass power plant all the useful resources – organic matter, nitrogen, phosphorus (as P_2O_5) and potassium (as K_2O) – are lost. This means no products are yielded that can be used as a fertilizer substitute. The wood-fired biomass plant therefore scores negatively in terms of nutrient balance.

For the routes Thermal conversion at BMC/Poultry farm, Digestion, Direct application, Composting and Granulation the results of the nutrient balance are summarized for each resource individually.

Organic matter
With thermal conversion of poultry litter at BMC or on a poultry farm, all organic matter is lost and converted to energy. Less (effective) organic matter is therefore returned to the soil than in the routes Digestion, Direct application, Composting and Granulation.

Nitrogen
In all routes at least some of the nitrogen is lost, for varying reasons. With thermal conversion at BMC Moerdijk or on a poultry farm the nitrogen is lost entirely. As far as this nutrient is concerned, the other processing routes are therefore better, viz.: Digestion, Direct application, Composting and Granulation.

Phosphorus (as P_2O_5)
The amount of P_2O_5 in the end-product (poultry litter ash, digestate, raw litter, compost, granulate) per tonne of processed litter is the same in every route. The difference between the ash and the other end-products lies in the efficacy of the P_2O_5. The efficacy of P_2O_5 in poultry litter ash varies from 37% to 100%, while in the other products it is around 70%. If the first year efficacy of P_2O_5 is less than 70%, then, less P_2O_5 becomes available within a year with thermal conversion of poultry litter than via the other routes.

Potassium (as K_2O)
The nutrient balance for potassium shows there is the same amount of K_2O in the end-product in every route.

Phosphorus and potassium are more important environmentally than organic matter and nitrogen
As phosphorus and potassium are finite resources, one may opt to attach greater weight to the results for these nutrients than to those for (effective) organic matter or nitrogen. Thermal processing of poultry litter at BMC scores just as well with respect to phosphorus and potassium as the other routes. The 1-year efficacy of phosphorus (as P_2O_5) can work out either better or worse, depending on the kind of arable regime in which the poultry litter ash is applied.

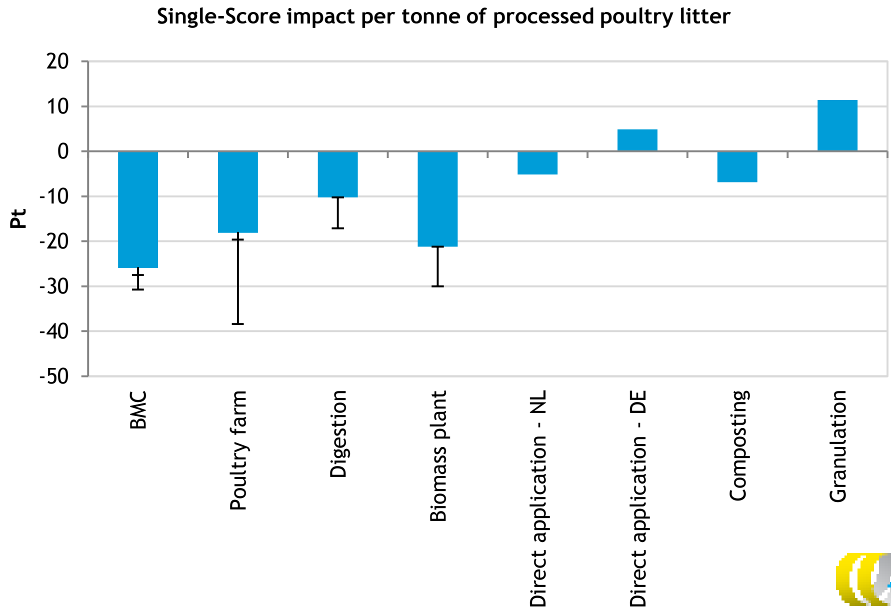
Results of LCA study

Figure 1 shows that all the routes with power generation have environmental benefits. These benefits are even greater if the heat output is also put to effective use (as indicated by the extended margin). If all the heat is used, thermal conversion on a poultry farm scores best, with the biomass plant and BMC Moerdijk sharing a second place in terms of environmental benefits.
If heat is effectively utilized, digestion ranks fourth.

If the heat cannot be used, thermal processing of poultry litter at the BMC plant is best for the environment, with the biomass plant ranking second, the poultry farm option third and digestion fourth.

All the routes generating no electricity or heat have an environmental impact or only minor environmental benefits.

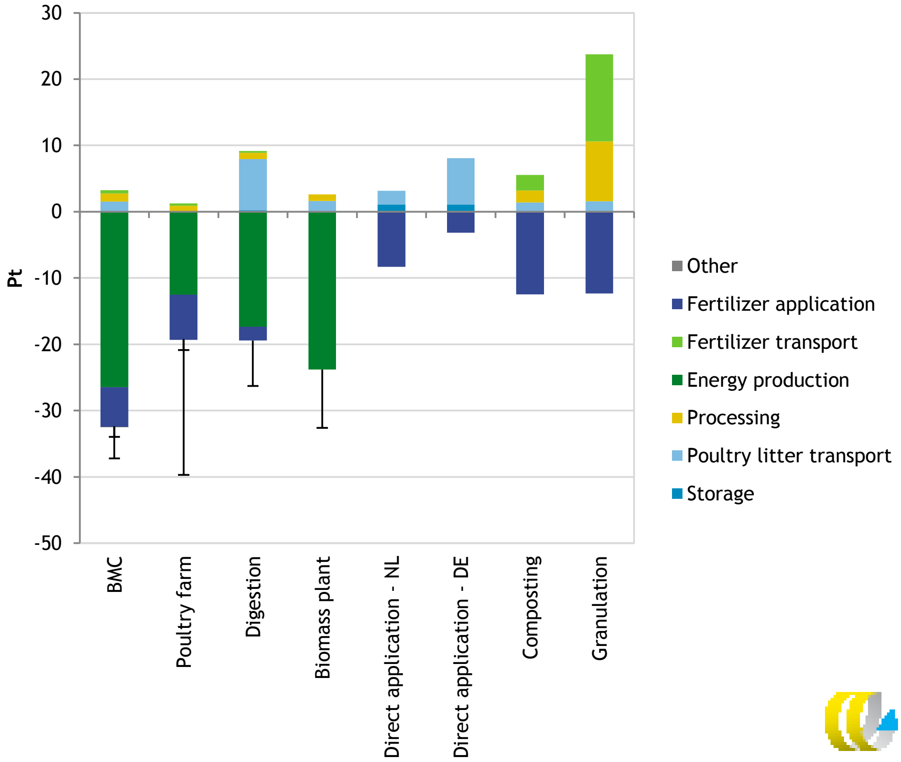
Figure 1 **Total environmental impact (Single-Score) per tonne of processed poultry litter**



The double margin represents partly the higher value of 1-year P_2O_5 efficacy in poultry litter ash (the upper part of the margin) and partly the marketing of heat. A negative score, below the x-axis, indicates there is no environmental burden but rather a positive environmental impact.

Results of contribution analysis
The eight routes differ in their positive and negative environmental impacts. These are summarized in Figure 2, which identifies the share of the individual processing steps in each route and thus the source of the differences in the Single-Score impact.

Figure 2 Contribution analysis of Single-Score impact per tonne of processed poultry litter



The double margin represents partly the higher value of 1-year P_2O_5 efficacy in the poultry litter ash (the upper section) and partly the marketing of heat.

The precise figures per category in the contribution analysis are reported in Table 1 and Table 2.

Table 1 Single-Score results, Routes 1-4

	BMC	Poultry farm	Digestion	Biomass plant
Storage emissions	N.a.	N.a.	0.21 Pt	N.a.
Poultry litter transport	1.54 Pt	0 Pt	7.71Pt	1.61 Pt
Process emissions	1.20 Pt	0.92 Pt	0.97 Pt	1.01 Pt
Direct emissions	0.57 Pt	0.56 Pt	0.97 Pt	0.54 Pt
Auxiliaries	0.62 Pt	0.36 Pt	0 Pt	0.38 Pt
Waste disposal	0 Pt	0 Pt	N.a.	0.09 Pt
Energy production	-23.25 to -26.49 Pt	-12.49 to -31.32 Pt	-17.33 - to -31.05	-23.82 to -32.63 Pt
Heat	0 to -3.24 Pt	0 to -18.83 Pt	0 to -6.86	0 to -8.81 Pt
Electricity	-23.25 Pt	12.49 Pt	-17.33	-23.82 Pt
Fertilizer transport	0.52 Pt	0.22 Pt	0.26 Pt	N.a.
Fertilizer application	-5.99 to -10.74 Pt	-6.68 Pt to -8.38 Pt	-2.08 Pt	N.a.
Direct emissions	0 Pt	0 Pt	13.40 Pt	N.a.
Fertilizer savings	-5.99 to -10.74 Pt	-6.68 Pt to -8.38 Pt	-13.57 Pt	N.a.

	BMC	Poultry farm	Digestion	Biomass plant
Carbon sequestration	N.a.	N.a.	-1.92 Pt	N.a.
Other	0 Pt	N.a.	N.a.	N.a.
TOTAL	**-25.98 to - 33.97 Pt**	**-18.10 to -38.45 Pt**	**-10.26 to -17.12 Pt**	**-21.19 to -30.00 Pt**

Table 2 Single-Score results, Routes 5-8

	Direct applic. - NL	Direct applic. - DE	Composting	Granulation
Storage emissions	1.06 Pt	1.06 Pt	0 Pt	0 Pt
Poultry litter transport	2.10 Pt	7.01 Pt	1.40 Pt	1.58 Pt
Process emissions	N.a.	N.a.	1.81 Pt	9.02 Pt
Direct emissions	N.a.	N.a.	1.75 Pt	2.48 Pt
Auxiliaries	N.a.	N.a.	0.06 Pt	6.54 Pt
Waste disposal	N.a.	N.a.	N.a.	N.a.
Energy production	N.a.	N.a.	N.a.	N.a.
Heat	N.a.	N.a.	N.a.	N.a.
Electricity	N.a.	N.a.	N.a.	N.a.
Fertilizer transport	N.a.	N.a.	2.35 Pt	13.13 Pt
Fertilizer application	-8.30 Pt	-3.18 Pt	-12.45 Pt	-12.32 Pt
Direct emissions	8.37 Pt	13.49 Pt	1.55 Pt	2.70 Pt
Fertilizer savings	-13.50 Pt	-13.50 Pt	-11.39 Pt	-12.77 Pt
Carbon sequestration	-3.16 Pt	-3.16 Pt	-2.61 Pt	-2.25 Pt
Other	N.a.	N.a.	N.a.	N.a.
TOTAL	**-5.14 Pt**	**4.89 Pt**	**-6.89 Pt**	**11.42 Pt**

The difference between the performance of the BMC facility and the wood-fired biomass plant derives mainly from use of the poultry litter ash as a fertilizer. The benefit of thermal processing at BMC over direct processing on a poultry farm and digestion is due to the higher electricity output.

The lower emissions during field application and a lower transport distance explain why direct application in the Netherlands scores better environmentally than application in Germany. Composting is environmentally better than granulation because the granulate must be transported further (to Asia in particular).

Results of analysis of environmental themes

The environmental themes contributing at least 10% to the total impact in one or more of the eight routes were examined further at midpoint level. These are: climate change, human toxicity, particulate emissions, depletion of mineral resources and depletion of fossil fuel. Thermal processing at BMC and on a poultry farm and co-firing in a wood-fired biomass plant are the only routes with environmental benefits on all these midpoints. The other routes have environmental drawbacks on one or more midpoints.

Results of sensitivity analysis

For each route a sensitivity analysis was carried out for themes contributing over 5% to the total environmental burden. For BMC this threshold was taken as 1% of the total burden. In this analysis we varied either the assumptions made or the year to which the data referred. The sensitivity analysis shows that despite the sensitivities the LCA results remain essentially unchanged.

Besides these sensitivity analyses we also performed a sensitivity analysis with respect to substituted electricity. The results show that the BMC Moerdijk route would score rather worse environmentally if the Netherlands' electricity system was 100% renewable. Both the BMC and poultry farm route still retain a slight environmental edge, but are then comparable with direct application of the litter in the Netherlands and composting.

Conclusion of LCA: BMC, poultry farm and biomass plant score best environmentally

The LCA shows that the processing routes with the least environmental impact are: thermal conversion at BMC Moerdijk, co-firing in a biomass plant and thermal conversion on a poultry farm. These have environmental benefits on all midpoints as well as in the Single Score. Litter digestion has benefits in the Single Score and on many midpoints, apart from the particulate emissions deriving from use of digestate as a farm fertilizer. The processing routes in which no electricity is generated have a (low) environmental impact either in the Single Score or on several midpoint categories.

In the basic model the greatest environmental benefits are associated with the BMC Moerdijk route, both on the Single Score and on most midpoints. This may pan out differently if the heat generated on a poultry farm or at the biomass plant can be effectively utilized. This is far from clear, though, as neither route is (yet) commonly used in the Netherlands. One recommendation for BMC Moerdijk is therefore to investigate whether the heat produced at the BMC facility can be marketed.

Results of the LCA study with system expansion

For more insight into the results, in addition to the basic LCA (using the substitution method) we also carried out an LCA with 'system expansion' in which all the routes were augmented to make the end-products comparable and a different functional unit was employed, as follows: "Processing of 1 metric ton of poultry litter and production of 597 kWh electricity, 14.4 kg 1-year available nitrogen, 14.8 kg 1-year available phosphorus (as P_2O_5), 21 kg 1-year available potassium (as K_2O) and 207 kg effective organic matter".

The LCA with system expansion shows that the BMC route has the least environmental burden, thus confirming the results of the basic LCA.

Final conclusion

The BMC and poultry farm routes score best environmentally

When the two parts of the study are combined – the nutrient balance and the LCA – thermal conversion at BMC and on a poultry farm both score positively in environmental terms.

In both routes organic matter and nitrogen are lost and converted to energy and various types of emission. Phosphorus and potassium are finite resources and therefore important from the perspective of a circular economy and resource conservation. For this reason it might be opted to attach greater weight to the results for these elements than to those for (effective) organic matter and nitrogen. In terms of conservation of phosphorus and potassium, thermal conversion of poultry litter at BMC scores just as well as the other routes.

The 1-year efficacy of phosphorus (as P_2O_5) can work out either better or worse, depending on the kind of arable regime in which the poultry litter ash is applied.

Organic matter and nitrogen are also important, though, because loss of soil organic matter and nitrogen can lower farmland productivity. These can both be replenished from other sources, however. The LCA study with system expansion indicates that the combination of thermal processing at BMC and replenishment of organic matter and nitrogen using artificial fertilizer or from other sources still yields a net environmental benefit.

Answer to the core question: BMC is environmentally beneficial
This study has shown that it is environmentally beneficial to process poultry litter in the BMC plant by means of thermal conversion when this is compared with eight other poultry litter processing routes. If thermal conversion on a poultry farm can be combined with effective use of most of the heat, this route scores best environmentally.

1 Introduction

The aim of this life-cycle assessment (LCA) study is to provide insight into the environmental impacts of thermal conversion of poultry litter at BMC Moerdijk to produce electricity and poultry litter ash that is used as a fertilizer substitute. The study explores both the nutrient balance and the full range of relevant environmental impacts by means of an LCA according to the ReCiPe methodology.

The central question addressed in the study is whether thermal conversion of poultry litter at the BMC Moerdijk plant has environmental benefits in comparison with eight other routes for processing poultry litter.

Chapter 2 describes the methodology and scope of the study. The process of data collection (inventory phase) for all nine routes is described in Chapter 3.

We explore the environmental impacts using three approaches:
1. A nutrient balance (Chapter 4).
2. An LCA (Chapters 5 and 6).
3. An LCA with system expansion (Chapter 7).

Finally, we report our conclusions and recommendations (Chapter 8).

About BMC

BMC Moerdijk is an initiative of over 600 poultry farmers and has been in operation since 2008. By thermal conversion of 430 kt poultry litter, BMC Moerdijk produces 285 GWh of renewable electricity and 60 kt poultry litter ash (PK fertilizer) annually. BMC Moerdijk processes 35% of all the poultry litter produced in the Netherlands.

BMC Moerdijk is owned by three shareholders:
- The DEP Cooperative (*Coöperatie DEP*), to which over 600 poultry farmers belong has been set up to handle and guarantee the supply of fuel – poultry litter – to the Moerdijk plant. Via DEP, the poultry farmers also participate financially in BMC Moerdijk.
- The Southern Agricultural and Horticultural Organization (*Zuidelijke Land- en Tuinbouworganisatie*), ZLTO, a branch organization serving the provinces of North Brabant, Zeeland and South Gelderland.
  The organization helps its members achieve a sustainable position in the market and society at large. Via *NCB Participaties*, ZLTO's investment company, this organization seeks to strengthen the global position of Dutch agricultural and horticultural enterprises.
- DELTA Energy, an energy company producing and supplying gas and electricity.

2 Methodology

2.1 Aim and intended readership

Aim

The aim of this study is to provide insight into the environmental impacts of thermal conversion of poultry litter at BMC Moerdijk to produce electricity and poultry litter ash for use as a fertilizer substitute. The study explores both the nutrient balance and the full range of relevant environmental impacts by means of an LCA according to the ReCiPe methodology.

The central question addressed in the study is whether thermal conversion of poultry litter at the BMC Moerdijk plant has environmental benefits in comparison with eight other routes for processing poultry litter.

Intended readership

By means of this study, BMC seeks to inform its stakeholders, including shareholders, regional and (inter)national government bodies, poultry farmers and non-governmental organizations on the environmental footprint of its operation.

2.2 ISO standard

In the LCA studies it conducts, CE Delft adheres to the rules for proper execution of LCAs laid down in ISO 14040/44, the ISO standard for LCA.

With the results of this study, BMC seeks in the first place to form a picture of the differences between the various routes and, secondly, to enter into dialogue with its stakeholders. An LCA report drawn up according to ISO 14040/44 is not essential for this purpose. For the stakeholder dialogue it is clearer to convert the environmental impacts into the resultant environmental damage and sum the various elements into a single score. This can be done according to the ReCiPe Single-Score method, which is also referred to as the endpoint level. ISO 14040/44 advises against working with a weighted Single Score in comparative studies. On this point we thus deviate from the ISO 14040/44 standard.

A comparative LCA according to ISO 14040/44 must be reviewed by a panel of at least three parties. With this study it was opted to have the review done by a single party: Blonk Consultants. On this point too, then, we deviate from the ISO 14040/44 standard.

The analysis was performed not only at the endpoint level but also at the midpoint level. This is in accordance with the ISO standard.

The LCA study was thus conducted according to the recommended ISO methodology in as far as this is in line with the aim of the study. In addition, the study provides additional insight by also weighting the various environmental impacts according to the frequently used ReCiPe method.

2.3 Function and functional unit

This LCA study is concerned with the following function: processing of the poultry litter produced by poultry farmers in the Netherlands[1]. The functional unit adopted in this study is processing of 1 metric ton of poultry litter with the composition shown in Box 1. This functional unit is based on the litter mix currently processed at the BMC Moerdijk plant.

Box 1 Functional unit

Processing of 1 tonne of poultry litter as produced by Dutch poultry farmers and consisting of 52% broiler chicken litter, 40% laying hen litter, 5% turkey litter and 3% manure-belt litter.

For fair comparison the same functional unit was used for all the routes analysed. The precise nutrient composition of the functional unit is reported in Table 3. The dry-matter content of this litter before further processing is 57%.

Table 3 Nutrient composition of the functional unit

	kg/t litter
Organic matter, OM	458
Effective Organic Matter, EOM	161
N	26
P_2O_5	21
K_2O	21

In day-to-day operations, various types of litter are processed via a variety of routes. Broiler chicken litter, for example, is generally composted or processed by BMC. Given the characteristics of this type of litter, granulation is an unlikely option. Post-dried laying-hen litter, on the other hand, is very suitable for granulation. In the future, each individual type of litter will in all likelihood be processed via a specific route (ZLTO, 2016).

In this study, though, we have taken as the functional unit for all routes 1 tonne of poultry litter with the composition reported in Box 1 and Table 3.

2.4 Routes

The routes examined in this study are routes in which poultry litter is used as an energy source, routes in which it is used directly as a fertilizer and routes combining energy and fertilizer production.

Routes using poultry litter as an energy source and a fertilizer:
1. Thermal conversion at the BMC Moerdijk plant, generating electricity and marketing the ash as a fertilizer substitute *(the reference route compared with the other routes below).*
   Referred to as “**BMC**”.

[1] This does not include the poultry litter produced on organic poultry farms.

2. Thermal conversion on a poultry farm, generating electricity and marketing the ash as a fertilizer substitute.
   Referred to as “**Poultry farm**”.
3. Co-digestion at a digestion plant in Germany, generating electricity and marketing the digestate as a fertilizer substitute.
   Referred to as “**Digestion**”.

Route using poultry litter as an energy source:

4. Co-firing in a wood-fired biomass plant, generating electricity without marketing the ash as a fertilizer substitute.
   Referred to as **“Biomass plant”.**

Routes using poultry litter as a fertilizer:

5. Direct application of the raw litter in the Netherlands.
   Referred to as **“Direct application - NL”.**
6. Direct application of the raw litter in Germany.
   Referred to as **“Direct application - DE”.**
7. Composting, exporting the compost for use as a fertilizer substitute abroad.
   Referred to as **“Composting”.**
8. Composting and granulation, exporting the granulate for use as a fertilizer substitute abroad.
   Referred to as “**Granulation**”.
9. Composting and application for mushroom-growing.
   Referred to as “**Mushroom-growing**”.

Reality of the routes

For the poultry litter processed at BMC Moerdijk, three of the above routes are reality. This obviously includes thermal conversion by BMC (Route 1), and in addition direct application of the raw litter in the Netherlands (Route 5) and in Germany (Route 6).

Four other processing routes are also operational. In the Netherlands poultry litter is composted (Routes 7 and 9) and granulated (Route 8). In Groningen, in the north of the country, there is a plant where broiler chicken litter is digested. In Germany digestion is more widespread. Dutch litter is then transported over the border. In this study we assume digestion in Germany (Route 3).

Two of the routes are not operational in the Netherlands. Poultry litter is not currently co-fired with wood in biomass power stations (Route 4). This is not yet economically viable, though it is technically feasible, which is why it has been included in the study. For co-firing of one tonne of poultry litter in a biomass plant, as examined in this study, we used the performance indicators of operational biomass plants.

Poultry litter is also not currently used in the Netherlands for thermal conversion on a poultry farm (Route 2). This processing route is in widespread use in Ireland and the United Kingdom, however. In the Netherlands there is one poultry farmer in the province of Drenthe who is working on setting up such a system (Dagblad van het Noorden, 2015), but at the time of writing this was not yet operational. Our modelling is based on BHSL technology, the thermal conversion system currently employed in Ireland and the UK.

2.5 System boundaries

The following sections describe the scope as it applies to all route. The precise system boundaries per route are given in Appendix A.

Substitution method

Production of electricity, heat and fertilizer means primary production of these commodities is avoided. In this study we make use of the 'substitution method', in which an equivalent amount of product is replaced as is produced.

In the case of electricity substitution, we proceed from the average Dutch electricity mix, based on the figures for 2013 (CE Delft, 2014), the most recent data available. Since 2013 the Dutch electricity mix has changed only slightly.

For substitution of artificial fertilizer, in the case of triple superphosphate and potassium sulphate we have used process cards from the Ecoinvent 3 database as a basis. For substitution of calcium ammonium nitrate (CAN) we worked with adjusted data for the CAN produced at OCI Nitrogen and reported in the Agri-footprint database (Blonk Agri-footprint B.V., 2015). This choice for CAN and the adjusted data are explained in Appendix B. For the substitution we assumed that the transport is the same as the market-average, as reported in the Ecoinvent 3 database.

Animal production system upstream of litter production

This study includes all relevant environmental impacts from the moment the litter is produced on a poultry farm. The animal production system from which the litter derives is not part of the study, since this production system is the same for all routes if the same poultry litter composition is assumed for each (i.e. the functional unit, with 52% broiler chicken litter, 40% laying hen litter, 5% turkey litter and 3% manure-belt litter).

Poultry litter storage at the poultry farm

The poultry litter is temporarily stored on the poultry farm. If it is for less than two weeks, this storage is ignored. Emissions from longer storage are therefore included.

Poultry litter drying

In this study the drying of the poultry litter on the poultry farm lies outside the system boundaries. Although litter quality (and thus drying) became an issue in the same period as start-up of the BMC plant, the latter was not the sole reason for poultry farmers to adopt (extra) drying. Since 2010 it is not only the poultry farmers supplying MBC that have taken measures to dry their litter, but also those using their litter directly or opting for a different route.

Poultry farmers invest in litter-drying for a variety of reasons:

1. Growing market demand for poultry litter:
   - a Litter is used as a renewable energy feedstock, with the poultry litter ash applied as a valuable fertilizer (BMC).
   - b Worldwide demand for organic nutrients is growing rapidly. Poultry litter, with over 80% dry matter, is now even a significant source of income for poultry farmers.
2. Transporting litter with copious water is expensive.
3. Drying reduces ammonia emissions.
4. Post-drying in a tunnel dryer or heat exchanger reduces particulate emissions.
5. Drying improves shed climate.

6. Drier litter improves the welfare of broiler chickens and turkeys in particular.

Farmers rearing broiler chickens and turkeys generally dry their sheds by means of ventilation. They also endeavour to lower litter moisture content by optimizing the feed as well as drinking-water systems. This generally leads to energy savings. Animal-welfare initiatives like the '*Beter Leven*' accreditation for keeping fewer animals per square metre also lead to improved litter quality and shed climate.

Many farmers with laying hens have invested in a post-drying unit that can increase litter dry-matter content to 90%. The incentive scheme introduced by DEP – a bonus/malus scheme that pays poultry farmers € 7.50 per tonne of higher-quality litter, has contributed minimally to use of such units.

Poultry farmers are now drying their litter more for two main reasons:
- Installing a litter dryer is one way to meet the ammonia emissions standards.
- A higher dry-matter content reduces transport costs, thus saving the farmer costs.

It can be concluded that (in)direct litter drying is applied across the poultry farming sector. Whether and to what extent this involves energy use depends above all on the type of litter. In this study we assumed a mix of 52% broiler chicken litter, 40% laying hen litter, 5% turkey litter and 3% manure-belt litter for all the routes considered. It may thus be assumed that the amount of energy used on average for drying is the same for all routes. This can therefore be left outside the system boundaries (Coöperatie Duurzame Energieproductie Pluimveehouderij (D.E.P), 2010); (BMC Moerdijk, 2016b); (ZLTO, 2016).

2.6 Environmental impact categories

This study consists of two parts. The first, the nutrient balance, is concerned with the presence of nutrients and organic matter before and after processing. The second part is a life-cycle assessment (LCA) in which 18 environmental impacts are analysed. In the following paragraphs we first list the 18 environmental impacts covered by the LCA, then explain why it is necessary to complement the LCA with a nutrient balance.

LCA environmental impact categories

The LCA is carried out according to the ReCiPe method (Goedkoop, et al., 2013), which is in widespread use in Europe. For more details on this methodology the reader is referred to Appendix C. In this study we use "ReCiPe Endpoint (H), Europe H/A" en "ReCiPe Midpoint (H), Europe", and the following (midpoint) environmental impact categories:
- climate change;
- ionising radiation;
- ozone depletion;
- terrestrial acidification;
- human toxicity;
- photochemical oxidant formation;
- particulate matter formation;
- eutrophication (marine and freshwater);
- ecotoxicity (terrestrial, freshwater, marine);
- land occupation (agricultural and urban);

– natural land transformation;
– water depletion;
– mineral resource depletion;
– fossil fuel depletion.

Losses of nutrients and organic matter
Although resource depletion is included in the LCA methodology under the headings of water, mineral resource depletion and fossil fuel depletion, the influence of that depletion on human and ecosystem health is not included. While depletion of substances of importance for soil fertility such as nutrients and organic matter are most certainly relevant for environmental damage in these categories. In other words, LCAs ignore the agricultural value of certain resources.

To make this value explicit, we drew up a nutrient balance that makes transparent the amounts of nutrients and organic matter lost in each route. This allows us to qualitatively assess the consequences of these losses for human and ecosystem health, now and in the future.

2.7 LCA method – further scope definition

Analysis method – attributional analysis
In this study we performed an 'attributional' LCA analysis. This means we consider all the interventions involved in processing 1 tonne of poultry litter of a given composition and that system changes do not form part of the analysis. BMC Moerdijk processes approximately 430 kt of litter a year. If we had opted for a 'consequential' analysis, we would have had to include the processing of this entire, huge volume and the consequences of a change in processing method for each route. We would then be looking at system changes and have had to make numerous assumptions. To make a transparent comparison, without uncertain assumptions about the consequences of processing huge quantities of litter, in this study we therefore opted for an attributional analysis.

As an example: with the biomass plant, in a consequential analysis we would have had to make due allowance for the fact that only 5-10% poultry litter can be co-fired. To process 430 kt litter would require additional capacity (more biomass plants). This issue would then have to be included in the study.

To summarize: in this analysis we do not consider what would happen if BMC Moerdijk's *entire* input stream of poultry litter were to be processed by the other routes. What we do consider, however, are the markets in which the respective products are sold: raw litter, poultry litter ash, compost, poultry litter granulate, digestate and drain water).

Allocation
The term 'allocation' refers to how the impacts of processes are assigned to the various products. If a process yields multiple end-products, its operation needs to be duly allocated across them. At BMC, for example, part of the operations could be allocated to energy production and part to the poultry manure ash.

In this study the issue of allocation is of only limited importance. If multiple streams are being processed in the same plant, process operation is allocated to the respective input streams. This is relevant for co-firing of poultry litter in a wood-fired biomass plant, for litter composting and for litter co-digestion. Here, allocation means *in concreto* that it is only the emissions associated with poultry litter processing that are explicitly considered in this study. The emissions due to wood incineration in the biomass plant and those due to the additional materials in composting or co-digestion are thus not included.

Allocation was implemented on the basis of physical relationships, with emissions and other outputs being calculated on the basis of the physical characteristics of the stream in question. This means that in calculations on electricity production, for example, we consider the calorific value of the individual streams and in determining the emissions we base ourselves on their physical composition (C, N, S, etc.).

Cut-off
In LCAs certain elements and issues are ignored because they are of only limited influence on the results. These are referred to as 'cut-offs'.

In our LCA the micronutrients and heavy metals contained in the end-products and ending up in agricultural soils were in principle ignored, because the quantities involved are similar for all the various end-products. For details see Appendix D. However, emissions (to air) of cadmium (Cd), mercury (Hg) and several other pollutants have been included in the analysis of the environmental impact of BMC Moerdijk and the other incineration routes.

Also not included in this LCA is the leaching of phosphate from the various end-products into agricultural soils. The amount of leaching is determined by a range of environmental factors like soil saturation and field slope rather than fertilizer type. Given the complexity of this issue, it was excluded from our analysis.

Finally, capital goods such as infrastructure and (use of) plant and machinery were also ignored in this study. This means power station construction was not included, for example. In LCAs capital goods are included within the system boundaries only when they make a significant contribution to the environmental footprint of the functional unit. In this study the amounts of capital goods used in the respective routes differ. We estimate that their contribution per tonne of poultry litter will be only minimal, however.

2.8 Nutrient balance method

To draw up a nutrient balance we identified the material products yielded by each of the poultry litter processing routes described in Sections 2.4 and 2.5. These products can be used as fertilizer substitutes. For each route with its products we assumed poultry litter of the composition defined by the functional unit in Section 2.2. In the routes involving direct application of raw litter the input stream is the same as the outgoing product.

The nutrient composition and efficacy of each product were determined using the methods described in (NMIa, 2016). Using these data, mass balances were drawn up for N, P, K and organic matter. The potential for fertilizer substitution was also determined.

2.9 Software and databases

For this study use was made of:
- LCA software SimaPro, version 8.1.0;
- Ecoinvent database 3.1, recycled content (Ecoinvent, 2014).

SimaPro is one of the most widely used software packages for performing LCAs and combines a variety of databases and methods.

LCA is a four-step process:
1. Defining the objective and scope.
2. Inventory.
3. Impact assessment.
4. Interpretation.

In Step 1 the goal and scope of the study are defined. In our case this is described in Chapter 2.

In Step 2, the inventory phase, the researcher determines what emissions, materials and energy are associated with the topic of the study (see Annex A): 'How much water is used in composting poultry litter?', for example.

Step 3, determining the environmental impacts, forms the core of the LCA. In doing so the researcher does not come up with his or her own estimates, but makes use of the existing databases and methods available in the SimaPro software package. One element of SimaPro is the Ecoinvent database, a Swiss database with information on thousands of materials and processes. In this study we used numerous processes contained in Ecoinvent. We selected the Ecoinvent process 'Tapwater'[2], for example, for which the associated environmental profile is automatically pulled up. The researcher thus lets the software calculate the environmental impact on the basis of standardized processes.

In the final step, interpretation, the results are explained in transparent terms to the intended readership. That is the aim of the present report.

2 More precisely: Tapwater (Europe without Switzerland).

3 Inventory and data quality

In this chapter for each route we explain the data employed in this study. The inventory for soil carbon fixation is described in Section 3.1, the inventory for fertilizer substitution in Section 3.2. Both hold universally across the various routes. In Section 3.3 we describe the specific inventory and data quality for each route. The full inventories and exact data used are given in Annex A.

3.1 Carbon fixation inventory

Some of the routes yield fertilizer materials containing organic matter (OM). If these are marketed for use by farmers, some of the carbon will be sequestered more or less permanently in agricultural soils. The carbon in the effective organic matter (EOM) remaining in soils for 100 years will be fixed there. We are concerned here specifically with the following fertilizer materials:

- raw litter (Direct application – NL or DE);
- poultry litter granulate (Granulation);
- compost (Composting);
- digestate (Digestion).

The amount of OM and EOM ending up in agricultural soils in the various routes per tonne of processed litter is reported in Chapter 4. A certain fraction of this total amount is assimilated by the soil each year. This fraction and the total amount of carbon fixed in each route are given in Table 4. The model used for calculating these figures is described in Annex E.

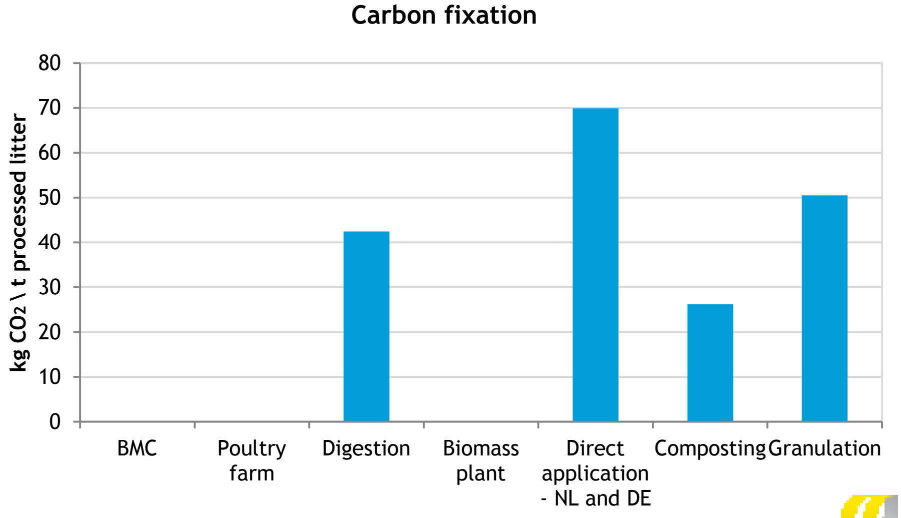
Table 4 Carbon fixtation per tonne of processed litter

	Carbon content (kg C/kg N in product)	Sequestered fraction (of total C in product)	Carbon fixation
BMC/Poultry farm	n.v.t.	n.v.t.	0 kg
Digestion	6 kg (LTZ, 2008)	7.3%	42.4 kg
Biomass plant	n.v.t.	n.v.t.	0 kg
Direct application - NL and DE	8.8 kg (BMC Moerdijk, 2015)	7.3%	69.9 kg
Granulation	9.0 kg	7.7%	50.5 kg
Composting	8.5 kg	7.7%	26.2 kg

Sequestered fraction calculated using the model described in Annex E, CO_2 fixation based on N-content of products and product volume per t processed litter, as reported in Annex E.

Total CO_2 fixation per tonne of processed litter is depicted in Figure 3.

Figure 3 Carbon fixation per tonne of processed poultry litter



3.2 Fertilizer substitution inventory

In all the routes except co-firing in a wood-fired biomass plant, nutrient-rich materials are produced that can serve as a fertilizer substitute, as follows:
- poultry litter ash (BMC/Poultry farm);
- raw litter (Direct application – NL or DE);
- poultry litter granulate (Granulation);
- compost (Composting);
- digestate (Digestion).

In 2015 BMC Moerdijk produced 62 kt poultry litter ash. This ash contains potassium (as K_2O) and phosphorus (as P_2O_5). All the nitrogen (N) is lost in incineration. The poultry litter fuel is thoroughly mixed at the BMC plant, giving it a constant composition and making the ash homogenous. We assume the same quantity of nutrients also end up in the ash after thermal conversion on a poultry farm if the farmer processes the same mix of litter. The fertilizer material produced in thermal conversion at BMC Moerdijk and on a poultry farm can therefore substitute the same amount of PK-fertilizer.

The untreated litter marketed in Germany or the Netherlands contains potassium (as K_2O), phosphorus (as P_2O_5) and nitrogen (N). This untreated poultry litter can therefore be used as a substitute for NPK fertilizer. This is also the case for the digestate, compost and poultry litter granulate.

The drain water arising during granulation and composting is marketed in the Netherlands as a nitrogenous fertilizer substitute (NMIa, 2016).

In calculating the amount of artificial fertilizer substituted, in this study we assumed 1-year fertilizer action. Table 5 reports the types and quantities of artificial fertilizers avoided per tonne of litter processed in the respective routes. The calculations determining the amounts of nutrients per tonne of litter available for use as a fertilizer substitute are given in Annex F.

Table 5 Fertilizer substitution per tonne of processed litter

	Calcium ammonium nitrate (as N)	Triple superphosphate (as P_2O_5)	Potassium sulphate (as K_2O)
BMC/Poultry farm	n.a.	7.8-21.0 kg	21.0 kg
Direct application - NL and DE	14.3 kg	14.7 kg	21.0 kg
Granulation	9.1 kg	14.7 kg	21.0 kg
Composting	8.9 kg	14.7 kg	21.0 kg
Digestion	14.4 kg	14.8 kg	21.0 kg
Biomass plant	0 kg	0 kg	0 kg

In all the routes, compliance with the fertilizer standards in force in the country concerned has been assumed for application of the various fertilizer substitutes.

3.3 Inventory and data quality per route

For specific data on the various poultry litter processing routes, wherever possible we used primary data from the processors themselves. For those routes for which such data were unavailable, a modelling approach was adopted using empirical data. In the following subsections we comment briefly on the inventory and data quality for each route.

3.3.1 Thermal conversion at BMC Moerdijk

For the central BMC route use was made of the process data, monitoring data, studies and environmental annual report provided by BMC Moerdijk. These data, for the year 2015, are robust, recent and high-quality.

3.3.2 Thermal conversion on a poultry farm

At the moment there is scarcely any thermal conversion of poultry litter on Dutch farms. This processing method is in widespread use in Ireland and the UK, however. The modelling data are from BSHL, who apply the process on Irish farms. These data are for 2015 and are robust, recent and high-quality.

The data on gross electrical and thermal efficiency are also from BHSL. Net efficiency data were calculated by CE Delft based on the difference between gross and net efficiency at the biomass plant.

In line with European legislation a distinction has been made between large-scale processing plant such as BMC (as per the EU Activities Directive) and small-scale plant on poultry farming premises (as per EU Regulation 592/2014). The former are classified as waste processing plants, for which there are more, and stricter, emission standards in force. In addition, these large-scale plants must monitor their emissions continuously. This means that in the LCA we only included those emissions that must by law be monitored and are indeed measured and that fewer emissions were included for incineration on a poultry farm than for BMC Moerdijk.

Thanks to the direct contact with BHSL, the data are robust, recent and high-quality, with the exception of net efficiency. This parameter is based on assumptions and is therefore of lower quality than for the BMC route.

3.3.3 Co-digestion at a digestion plant in Germany

In the north of the Netherlands, in Groningen, is a digestion plant processing broiler chicken litter. In Germany, where manure digestion is far more common, Dutch poultry litter is also processed. In this study we based our calculations on digestion in Germany. The co-digestion process used there yields both biogas and digestate.

As primary data from a German poultry litter digester could not be obtained, a modelling approach was adopted.

Practical information on litter digestion and storage in Germany were taken from (Commissie Deskundigen Meststoffenwet, 2015). Theoretical data on plant operation, biogas production and cogeneration plant operation are based on (Zwart, et al., 2006) and (Reinhold, 2005).

As no primary data on this route were available, several assumptions were made for modelling. Data quality for this route is therefore lower than for the BMC route. The analysis does provide an order-of-magnitude estimate of the impacts of the various links in the chain, however, giving a fairly good idea of the potential environmental benefits and drawbacks of processing poultry litter in a German co-digestion plant.

3.3.4 Co-firing in a wood-fired biomass plant

As poultry litter is not currently co-fired in Dutch biomass plants, no primary data are available and a modelling approach was therefore adopted.

For this route it was assumed that the biomass plant functions the same as a Dutch waste incineration plant, as described in the Environmental Impact Statement for the National Waste Management Plan, MER-LAP (AOO, 2002), but making due allowance for the specifications of the material being burned. For example, auxiliary materials consumption has been adjusted for the presence of sulphur, chloride, fluoride and mercury. Emissions have also been adjusted for the presence of contaminants in the poultry litter (incl. heavy metals). Waste production is assumed to be proportional to production of dry matter and ash content. Processing of this waste was assumed to be in accordance with Dutch legislation for the materials concerned.

In our model, plant efficiency (electrical and thermal) has been taken equal to that of Europe’s most efficient biomass plant to ensure the biomass route is not underestimated compared with thermal conversion at BMC.

As this route is not yet operational, our model is based on assumptions.
The data quality for this is consequently lower than for the BMC route.
Our analysis does give an order-of-magnitude estimate of the impacts of the various links in the chain, however.

3.3.5 Direct application in the Netherlands or Germany

For these two routes, for the emissions occurring during storage and application use was made of data reported by the IPCC (IPCC, 2006) and, when available, data from specifically Dutch sources (Van der Hoek & van Schijndel, 2006); (CDM, 2013); (Rietberg, et al., 2013).

For litter transport, assumptions were based on the poultry farmers and manure brokers currently active in the Netherlands.

The data used are the best available. The data quality for this route is lower than for the BMC route, because primary data were not used. Our analysis does give an order-of-magnitude estimate of the impacts of the various links in the chain, however.

3.3.6 Composting

For the Composting route, use was made of data reported on a technical datasheet and provided in a telephone interview with a Dutch composting firm (Composteerbedrijf, 2016). Data on processing, emissions, energy consumption and feedstock composition are based on the telephone interview, those on composition of the outgoing product are from the datasheet.

Poultry litter is composted at various locations in the Netherlands. In this study we based ourselves on the technology used at an operational Dutch composting plant (Composteerbedrijf, 2016), where poultry litter is largely processed in two composting tunnels. 80% of the litter is composted naturally and 20% forced.

As there was direct contact with the composting firm, these data are robust and recent.

For feedstock composition, the composting firm gave the following estimate: 30% broiler chicken litter, 45% manure-belt litter (laying hens), 20% compost and 5% pig manure. In this study we assumed the same composition as at BMC, which thus deviates from this estimate. The data quality of this route is therefore lower than for the BMC route. Our analysis does give an order-of-magnitude estimate of the impacts of the various links in the chain, however.

3.3.7 Composting and granulation

For this route we used data from a technical datasheet and information from Ferm O Feed. The data on composition of the output product are from the datasheet. Data on processing, emissions, energy consumption and feedstock composition have been retrieved from Ferm O Feed. As there was direct contact with Ferm O Feed, these data are robust and recent.

For feedstock composition, Ferm O Feed gave the following estimate: 50% broiler chicken litter and 50% manure-belt litter (laying hens). Although this differs in composition from that used in this study (i.e. the BMC feedstock), its dry-matter content is similar. The data quality for this route is consequently lower than for the BMC route, but higher than for the composting route because it only involves poultry litter. The analysis for composting and granulation gives an order-of-magnitude estimate of the impacts of the various links in the chain (Ferm O Feed, 2016).

3.3.8 Composting and application for mushroom-growing

For data on this route we contacted producers and sought publically available information. None of the Dutch producers of mushroom substrate was willing to cooperate, however, and so we were unable to use primary data. Nor is there sufficient public data available to adopt a modelling approach. On the following issues data is lacking:

– How much phase-3 compost and champost can be produced from 1 tonne of poultry litter?
– What fraction of the OM, EOM, N, P_2O_5 and K_2O in the champost can be allocated to 1 tonne of poultry litter?
– What is the mushroom yield per tonne of litter?
– What can serve as a substitute for mushroom substrate?
– How much energy and auxiliaries are required for the production process?

– What are the quantitative process emissions? Are air scrubbers used and how effective are they?
– Over what distances are the (sub)products transported?

Because of the major uncertainties surrounding this route it was decided not to model a separate route for composting and application in mushroom-growing. This route is therefore not covered in the nutrient balance or LCA.

What we have done, though, is used the publically available data to indicate, in qualitative terms, how the transport, auxiliaries, emissions and avoided product of the mushroom-growing route compare with those of the composting route. Based on this qualitative analysis (see Annex A.9) it can be assumed that the environmental impact of the mushroom-growing route is at least comparable with and probably greater than that of the composting route.
Our analysis provides a first-pass indication.

4 Nutrient balance

This chapter reports the nutrient balance of the various routes.

In terms of the nutrients involved there is no difference between thermal conversion at BMC Moerdijk and on a poultry farm. These two routes are therefore depicted in a single results bar. Neither is there any difference in this respect between direct application of raw litter in the Netherlands and in Germany. Again, these two routes are reported in a single bar.

Because of the limited amount of information available on the mushroom-growing route, no nutrient balance was drawn up for this route.

This nutrient balance was therefore carried out for six routes:
- thermal conversion at BMC Moerdijk or on a poultry farm (BMC/Poultry farm);
- co-digestion in a digestion plant (Digestion);
- co-firing in a wood-fired biomass power plant (Biomass plant);
- direct application of raw litter in the Netherlands or in Germany (Direct application – NL or DE);
- composting (Composting);
- composting and granulation (Granulation).

For each route we established the volume and composition (OM, N, P_2O_5 and K_2O) of the end-product. For each of the substances we then assessed efficacy on the basis of nutrient value.

> The nutrient value of organic matter is characterised by its stability: the effective organic matter (EOM), that is, the fraction of the organic matter that is still present after one year.
>
> For N, P and K the nutrient value can be expressed as the efficacy coefficient indicating the fraction that can actually be taken up by the crop during the growing season. The efficacy coefficient is expressed relative to the efficacy of a reference fertilizer. For nitrogen CAN is generally taken as a reference, for phosphorus (triple) superphosphate, since these fertilizers are in widespread use. For organic fertilizers a coefficient of 100% is generally assumed for potassium oxide, as this is present in the liquid phase in readily available form.

The precise calculations and data used for the nutrient balance are reported in Annex F.

The nutrient balance associated with each poultry-litter processing route is reported in Figure 4 to Figure 9, which give the fraction of the incoming feedstock lost, the amount remaining in the end-product and the efficacy of the latter. In the next section we describe the balances for organic matter (OM), nitrogen (N), phosphorus (as P_2O_5) and potassium (as K_2O).

4.1 Nutrient balances for the various substances

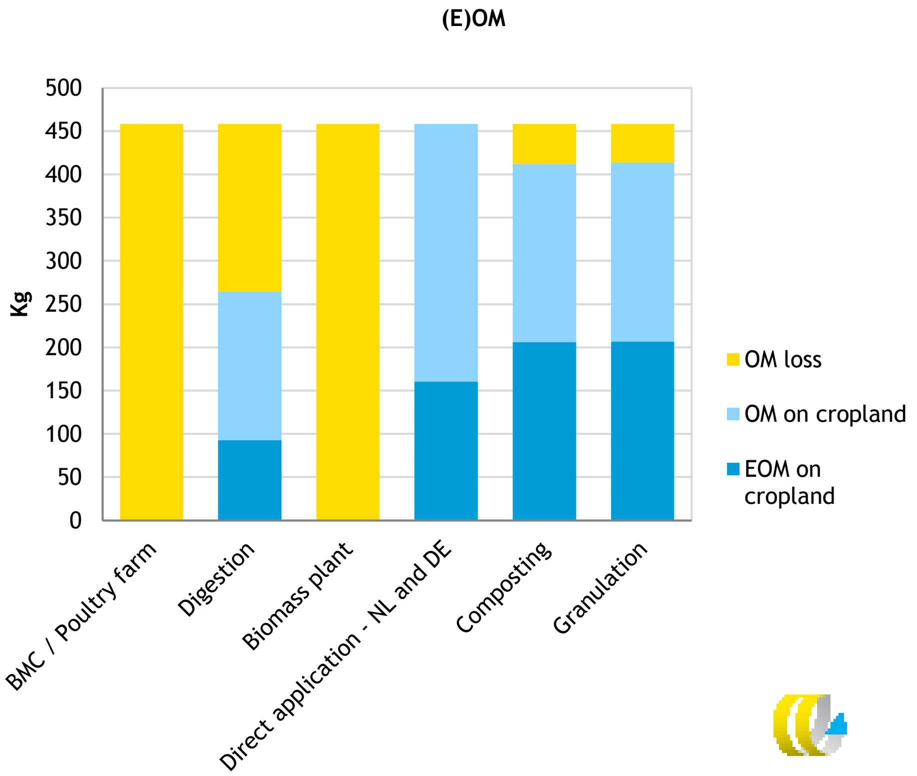
4.1.1 (Effective) organic matter

To maintain proper soil air and water balances and retain nutrients, arable soils need a certain amount of effective organic matter (EOM). When fertilizer substitutes are applied, the organic matter they contain supplements the EOM already there if it is still available after one year. The remainder is bound in the soil for less than a year and does not therefore enrich the EOM content.

Figure 4 shows that organic matter loss varies between 0 and 100%.

- In the BMC and Poultry farm routes, all organic matter is lost during thermal conversion.
- With Direct application (NL and DE), no organic matter is lost and 30% EOM remains.
- In the Granulation and Composting routes, organic matter is lost through emissions of biogenic CO_2. In both these routes, readily degradable organic matter is converted to more stable humus, which means more EOM is transferred to the cropland than with Direct application.
- In the Digestion route, organic matter is lost in the gas generated. The poultry litter digestate thus contains less organic matter than in the case of Direct application and consequently less EOM, too.

Figure 4 **Nutrient balance for organic matter (OM) and effective organic matter (EOM) per tonne of poultry litter**



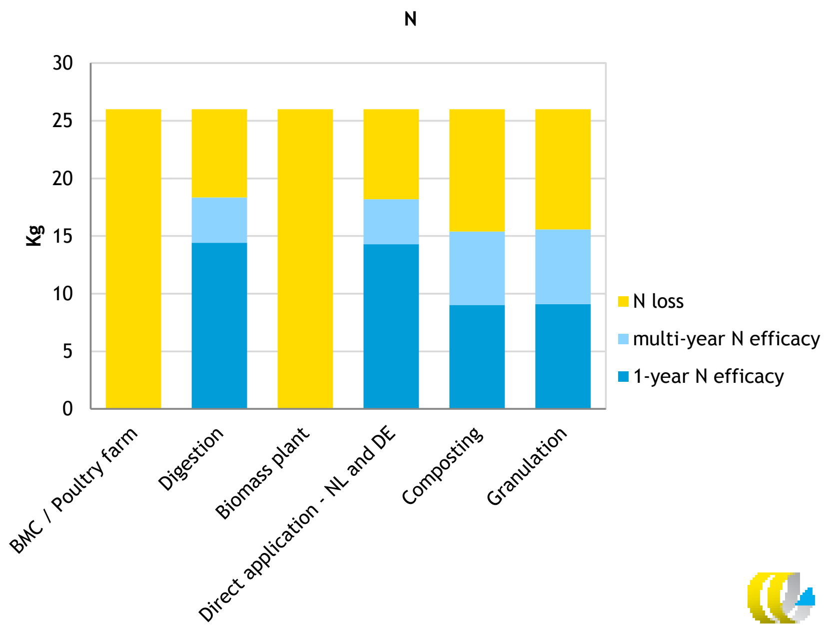
4.1.2 Nitrogen

Based on the calculations in Annex F it appears that a considerable amount of nitrogen is lost in the Granulation route. If we look at the mass balance, however, the only nitrogen that should be 'lost' is that evaporating during the composting and granulation process and the nitrogen fraction unavailable to crops during application relative to CAN fertilizer. The (overly) substantial loss in the calculation in Annex F might be explained by, on the one hand, the use of various other kinds of manure in the composting process and, on the other, the different dry-matter content of the poultry litter feedstock used in the Granulation and BMC routes. Figure 5 is therefore based on the theoretical 'loss' during composting and granulation, comprising the direct ammonia emissions during processing and the low nitrogen efficacy of the compost/granulate.

Figure 5 shows that nitrogen is lost in all the routes, but to a varying extent.
- In the BMC, Poultry farm and Biomass plant routes all the nitrogen is lost.
- In Direct application (NL and DE) 30% of the nitrogen is not available to the crop compared with CAN fertilizer.
- In the Digestion route, this percentage is just as high.
- In the Granulation and Composting routes the losses are greater, for two reasons. First, a greater fraction of the nitrogen evaporates than in Direct application; some of this is retained by air scrubbers and ends up in the drain water[3]. Second, the nitrogen in the compost and granulate has a lower efficacy than in fresh poultry litter.

For Granulation and Composting, Figure 5 also includes the nitrogen retained in the air scrubbers and ending up in the drain water. For Digestion, the balance shown is for the nitrogen in the digestate that can be allocated to the poultry litter.

Figure 5 Nutrient balance for nitrogen (N) per tonne of poultry litter



[3] The nitrogen ending up in the drain water is not taken as a loss because the drain water is also marketed.

4.1.3 Phosphorus (as P_2O_5)

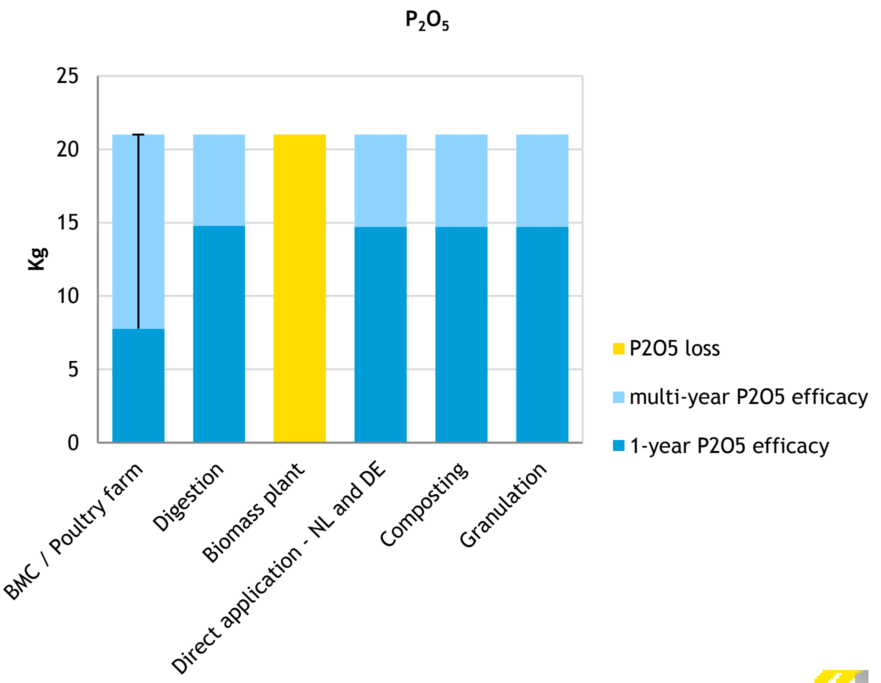
Based on the calculations in Annex F, P_2O_5 would appear to be lost in the two thermal conversion routes (BMC and Poultry farm) as well as in Composting and Granulation. In theory, though, no such losses can occur in these processes, because P_2O_5 is not volatile. Given the law of conservation of mass, all the P_2O_5 must therefore end up in the products. The calculated 'loss' for Composting and Granulation can be explained by the different composition of the poultry litter composted/granulated and that processed at BMC Moerdijk; see Sections 2.3 and 3.3.6. The calculated 'loss' for the poultry litter ash is due to the use of different measurement methods (see Annex F.1).

In this study it was assumed that the measurements on the litter itself are robust, because the profiles are in good accordance with (RVO, 2016). Because P_2O_5 is not volatile, in Figure 6 we have therefore corrected the result for these four routes, reflecting the fact that no P_2O_5 is lost. In the case of BMC/Poultry farmer 0.4% of the ash is lost as off-spec ash, which means the phosphorus is also lost. This is such a small quantity, though, that it is not visible in Figure 6.

Figure 6 shows that there are no P_2O_5 losses in any route except for the Biomass plant. In the case of BMC/Poultry farm, the efficacy differs from that in the other four routes where P_2O_5 ends up in the produced product. The efficacy of the P_2O_5 in Granulation and Composting is similar to that in Direct application.

In the BMC and Poultry farm routes, different measurements yield different results for the one-year efficacy of phosphorus relative to triple super-phosphate, varying from 37% (Alterra Wageningen UR, 2015a) to 100% (Alterra Wageningen UR, 2015b). In Figure 6 this variation is indicated by the margin.

Figure 6 Nutrient balance for phosphorus (as P_2O_5) per tonne of poultry litter



4.1.4 Potassium (as K_2O)

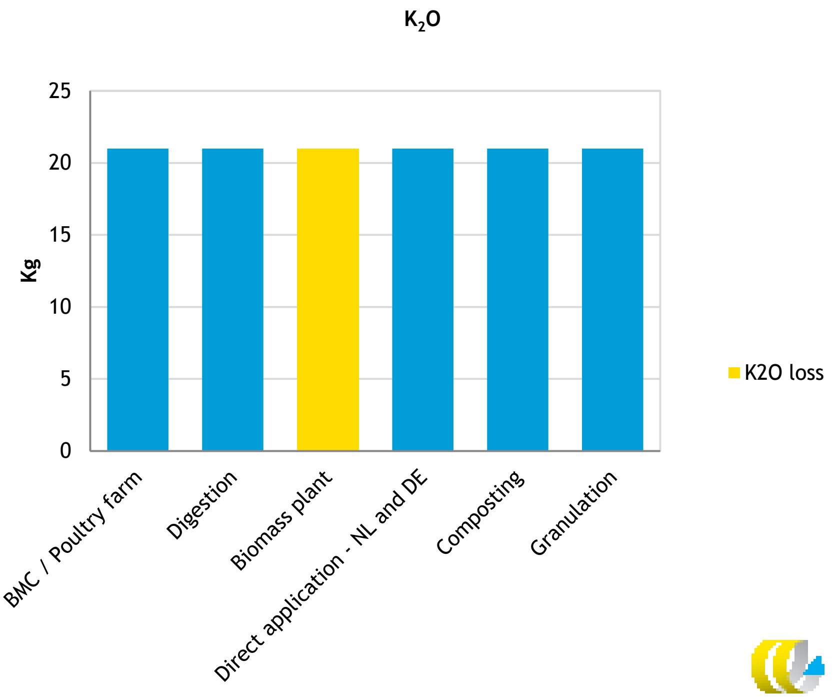
In both Direct application and Digestion, no potassium is lost. Although the calculations in Annex F appear to show a loss during thermal conversion, composting and granulation, in principle no potassium can be lost during these processes because it is not volatile. Conservation of mass therefore dictates that all the potassium ends up in the products.

The calculated 'loss' for Composting and Granulation can be explained by the different composition of the poultry litter granulated/composted and that processed at BMC; see Sections 2.3 and 3.3.6. The calculated 'loss' for the BMC/Poultry routes is due to differences in measurement methods (see Annex F).

In this study it was assumed that the measurements on the litter are robust, because the profiles are in good accordance with (RVO, 2016). Because potassium is not volatile, in Figure 7 we have therefore corrected the result for these four routes, reflecting the fact that there are no potassium losses.

Figure 7 shows there are no potassium losses in any of the routes. In all the products yielded by the various routes the potassium has a similar efficacy. We may therefore conclude that the nutrient balance for potassium is the same in every route.

Figure 7 Nutrient balance for potassium oxide (K_2O) per tonne of poultry litter



4.2 Conclusion on nutrient balance

In a biomass plant all organic matter and nutrients are lost

Co-firing poultry litter in a wood-fired biomass plant yields no product that can be used as a fertilizer substitute. In this route, then, all the valuable constituents - organic matter, nitrogen, phosphorus (as P_2O_5) and potassium (as K_2O) – are lost.

In the next few paragraphs we summarize the results of the nutrient balance for each constituent for each route, viz. BMC/Poultry farm, Digestion, Direct application, Composting and Granulation.

Organic matter

With thermal conversion of poultry litter at BMC or on a poultry farm, all the organic matter is lost. This means less (effective) organic matter will be added to soils than in the Digestion, Direct application, Composting and Granulation routes.

Nitrogen

In all the routes some of the nitrogen is lost, while in thermal conversion at BMC and on a poultry farm it is all lost. For this nutrient, then, all the other processing routes perform better, viz. Digestion, Direct application, Composting and Granulation.

Phosphorus (as P_2O_5)

The end-products of all the routes (i.e. poultry litter ash, digestate, litter, compost and granulate) contain the same amount of P_2O_5 per tonne of processed litter. The difference between the poultry litter ash and the other products lies in the efficacy of the P_2O_5. In poultry litter ash the 1-year efficacy of the P_2O_5 is between 37% (Alterra Wageningen UR, 2015a) and 100% (Alterra Wageningen UR, 2015b), while for the other products it is around 70%. If the 1-year efficacy of P_2O_5 is less than 70%, less P_2O_5 become available within one year with thermal conversion of poultry litter than with the other routes.

It should be noted that in this study the leaching of phosphate from agricultural soils was not included for any of the end-products. The extent of phosphate leaching is governed more by environmental factors like soil saturation and field slope than by fertilizer type. Given the complexity of the issue, it was not included in this study.

Potassium

The nutrient balance for potassium (as K_2O) shows the end-product of all the routes contains the same amount of potassium oxide.

P and K are more important environmentally than OM and N

As phosphorus and potassium are finite resources, greater weight might be attached to the results for these two elements than for (effective) organic matter and nitrogen. Thermal conversion of poultry litter at BMC scores equal to the other routes with respect to conservation of potassium and phosphorus. The 1-year efficacy of phosphorus (as P_2O_5) may work out either better or worse, depending on the arable regime where the litter ash is used.

5 LCA results

This chapter describes the results of the Life-Cycle Assessment comparing the route of thermal conversion at BMC with seven other routes[4]. The results are summarized in Figure 8. The exact data are provided in Annex G.

5.1 Single-Score environmental impact

Figure 8 summarizes the results of the LCA for all the routes expressed as a ReCiPe Single Score. This score is explained in Annex C. Use was made of the standard weighting procedure for the ReCiPe method, with health impacts contributing 40% of the score, ecosystem impacts 40% and impacts on resource depletion 20%.

Basic route and margin

For four routes the impacts were assessed for the basic route with and without an additional margin, as summarized in Table 6. For the basic route the most conservative choice was made.

Table 6 Definition of basic route and margin for four routes

	Basic route	Margin
BMC	Lowest measured 1-year P_2O_5 efficacy of poultry litter ash.	Heat marketed and highest measured 1-year P_2O_5 efficacy in poultry litter ash.
Biomass plant	No marketing of heat.	Heat marketed.
Poultry farm	No marketing of heat and lowest measured 1-year P_2O_5 efficacy in poultry litter ash.	Heat marketed and highest measured 1-year P_2O_5 efficacy in poultry litter ash.
Digestion	No marketing of heat.	Heat marketed.

Power production has environmental benefits, heat-marketing even more

As Figure 8 shows, all the routes with power generation have environmental benefits, which is even greater if the heat produced is also marketed (as indicated by the margin).

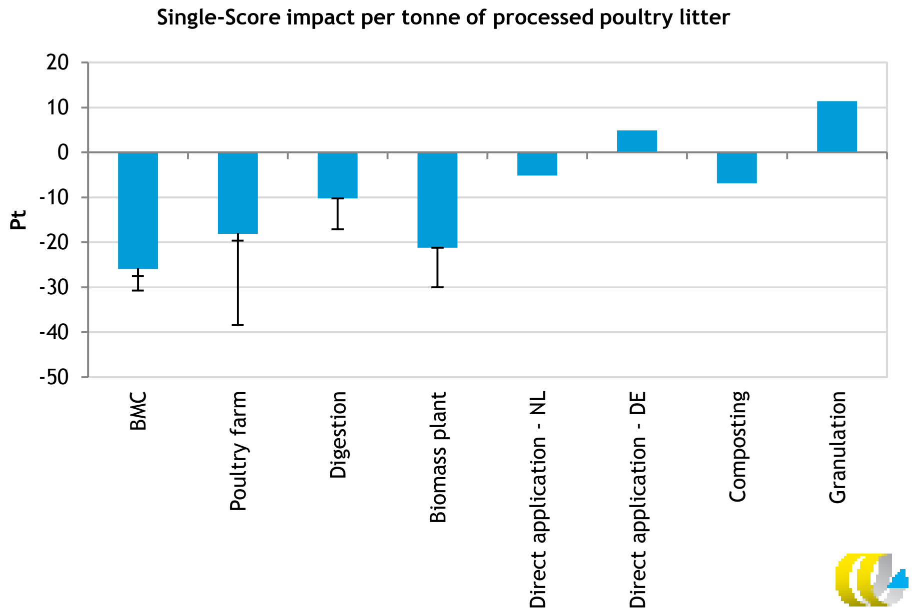
If all the heat from the poultry farm plant is used as a substitute for heat generated using the average Dutch gas mix, thermal conversion on a poultry farm scores best. If the waste heat is marketed, co-firing of poultry litter in a wood-fired biomass plant and thermal conversion at BMC Moerdijk have a similar environmental profile, and together rank second/third. Digestion with the heat marketed comes fourth.

4 Because there was insufficient information available on composting and subsequent use in mushroom-growing, for this route no LCA was performed (see further Annex A.9).

If the heat cannot be marketed, the BMC route scores best environmentally, followed second by the Biomass plant. The Poultry farm and Digestion routes both score less well environmentally, ranking third and fourth respectively if the heat is not marketed.

All the routes without power or heat generation have a net environmental burden or only a slight environmental benefit.

Figure 8 **Single-Score impact per tonne of processed poultry litter**



The double margin indicates partly (the upper part) a higher 1-year P_2O_5 efficacy of the poultry litter ash and partly the marketing of heat. A negative score, below the x-axis, indicates there is no environmental impact but rather a net environmental benefit.

Contribution analysis: energy production contributes most to environmental benefits

The eight routes each have different positive and negative environmental impacts. Figure 9 provides a summary, showing for each route the contribution of the individual links in the chain and thus where the main differences in the Single-Score impact arise.

Ash marketing explains advantage of BMC over Biomass plant

The difference between the BMC plant and the wood-fired biomass plant derives from the poultry litter ash being marketed as a fertilizer. The biomass plant yields no fertilizer material that can be sold for farmland use.

More power output explains advantage of BMC over Poultry farm

Thermal conversion on a poultry farm has less environmental benefits than thermal conversion at BMC Moerdijk because less electricity is generated. This is because the far smaller local plant has a lower electrical efficiency than BMC Moerdijk: 13.5 vs. 29% net efficiency. If the poultry farmer can make effective use of the power he generates and thus save on his gas consumption (average Dutch mix), the Poultry farm route scores better environmentally.
If the BMC plant can also market its waste heat, both forms of thermal conversion score roughly the same.

More power output and less transport explains advantage of BMC over Digestion

Less electrical power is generated with Digestion than at the BMC plant. The environmental benefits are furthermore partly offset by the transport of the poultry litter to Germany or within the Netherlands.

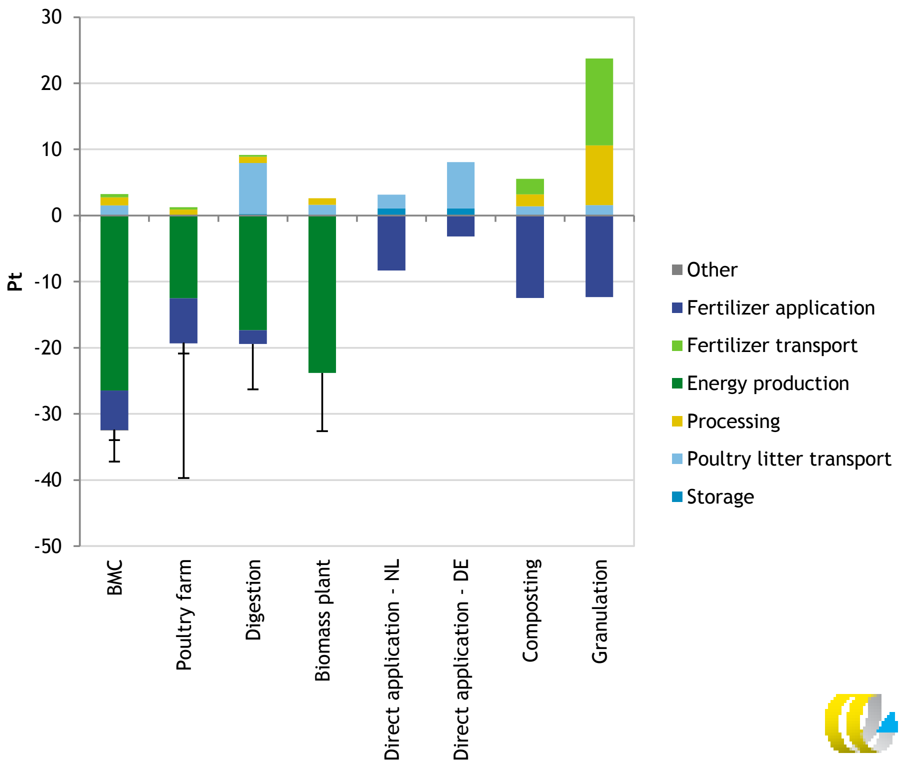
Lower emissions in application and less transport explain advantage of Direct application in NL over Direct application in DE

Direct application of raw poultry litter in Germany gives rise to a net environmental burden. Although its use there means artificial fertilizer is substituted, litter-spreading is associated with higher nitrogen emissions than in the Netherlands, owing to the less stringent German legislation on this point. In addition, there is transport from the Netherlands to Germany. If the litter is marketed in the Netherlands, emissions are lower because of the stricter legislation, so this route has a slight environmental benefit.

Less transport explains advantage of Composting over Granulation

That Granulation has a net environmental impact and Composting a net environmental benefit is explained by the difference in litter transport after processing. In the case of Granulation, much of the granulate is marketed in Asia. If the transport distance of these routes were lower, they would both be environmentally neutral, of might even score slightly positive. In terms of transport distance there is thus a tipping point where marketing organic matter and nutrients switches from being environmentally neutral to having an environmental impact.

Figure 9 **Contribution analysis, Single-Score impact per tonne of processed poultry litter**



The double margin indicates partly (the upper part) a higher 1-year P_2O_5 efficacy of the poultry litter ash and partly the marketing of heat.

The precise figures per category in the contribution analysis are reported in Table 7 and Table 8.

Table 7 Single-Score results, Routes 1-4

	BMC	Poultry farmer	Digestion	Biomass plant
Storage emissions	n.a.	n.a.	0.21 Pt	n.a.
Litter transport	1.54 Pt	0 Pt	7.71Pt	1.61 Pt
Process emissions	1.20 Pt	0.92 Pt	0.97 Pt	1.01 Pt
Direct emissions	0.57 Pt	0.56 Pt	0.97 Pt	0.54 Pt
Auxiliaries	0.62 Pt	0.36 Pt	0 Pt	0.38 Pt
Waste disposal	0 Pt	0 Pt	n.a.	0.09 Pt
Energy production	-23.25 to -26.49 Pt	-12.49 to -31.32 Pt	-17.33 - to -31.05	-23.82 to -32.63 Pt
Heat	0 to -3.24 Pt	0 to -18.83 Pt	0 to -6.86	0 to -8.81 Pt
Electricity	-23.25 Pt	12.49 Pt	-17.33	-23.82 Pt
Fertilizer transport	0.52 Pt	0.22 Pt	0.26 Pt	n.a.
Fertilizer application	-5.99 to -10.74 Pt	-6.68 Pt to -8.38 Pt	-2.08 Pt	n.a.
Direct emissions	0 Pt	0 Pt	13.40 Pt	n.a.
Fertilizer savings	-5.99 to -10.74 Pt	-6.68 Pt to -8.38 Pt	-13.57 Pt	n.a.
Carbon fixation	n.a.	n.a.	-1.92 Pt	n.a.
Other	0 Pt	n.a.	n.a.	n.a.
TOTAL	**-25.98 to - 33.97 Pt**	**-18.10 to -38.45 Pt**	**-10.26 to -17.12 Pt**	**-21.19 to -30.00 Pt**

Table 8 Single-Score results, Routes 5-8

	Direct applic. - NL	Direct applic. - DE	Composting	Granulation
Storage emissions	1.06 Pt	1.06 Pt	0 Pt	0 Pt
Litter transport	2.10 Pt	7.01 Pt	1.40 Pt	1.58 Pt
Process emissions	n.a.	n.a.	1.81 Pt	9.02 Pt
Direct emissions	n.a.	n.a.	1.75 Pt	2.48 Pt
Auxiliaries	n.a.	n.a.	0.06 Pt	6.54 Pt
Waste disposal	n.a.	n.a.	n.a.	n.a.
Energy production	n.a.	n.a.	n.a.	n.a.
Heat	n.a.	n.a.	n.a.	n.a.
Electricity	n.a.	n.a.	n.a.	n.a.
Fertilizer transport	n.a.	n.a.	2.35 Pt	13.13 Pt
Fertilizer application	-8.30 Pt	-3.18 Pt	-12.45 Pt	-12.32 Pt
Direct emissions	8.37 Pt	13.49 Pt	1.55 Pt	2.70 Pt
Fertilizer savings	-13.50 Pt	-13.50 Pt	-11.39 Pt	-12.77 Pt
Carbon fixation	-3.16 Pt	-3.16 Pt	-2.61 Pt	-2.25 Pt
Other	n.a.	n.a.	n.a.	n.a.
TOTAL	**-5.14 Pt**	**4.89 Pt**	**-6.89 Pt**	**11.42 Pt**

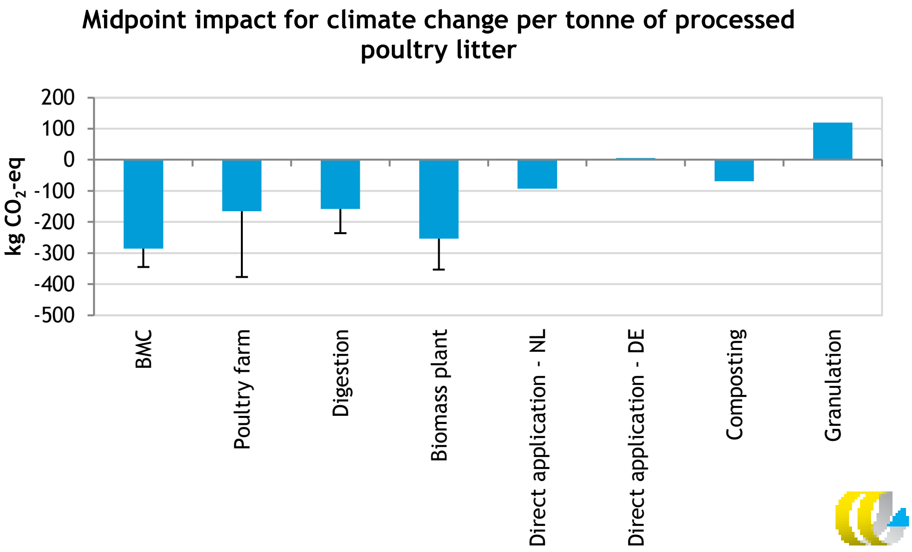
The full contribution analysis for thermal conversion at BMC is given in Annex H.1. Annex I provides a more extended contribution analysis for all the other routes.

5.2 Analysis results for individual environmental themes

In this section we report the LCA results on individual environmental themes for the midpoint categories climate change, human toxicity, particulate emissions, mineral resource depletion and depletion of fossil fuels. These are the categories that contribute at least 10% to the Single Score in one or more of the eight routes. The reasoning behind the choice of these midpoints is given in Annex G.3.

As Figure 10 shows, all the routes except for Direct application in Germany and Granulation have environmental benefits in terms of climate change impact. In other words, most of the routes contribute less to climate change than use of electricity from the regular power grid and use of artificial fertilizer. If the waste heat is marketed, the Poultry farm and Biomass plant routes have a slight environmental edge over the BMC route. If the heat is not sold, thermal conversion at BMC scores best with respect to climate change.

Figure 10 Results for climate change



The impact category 'human toxicity' is a measure of the damage to human health due to toxic emissions. As Figure 11 shows, all the routes have benefits on this score, i.e. there is less impact due to toxic emissions than there would be with use of electricity from the regular grid and use of artificial fertilizer. Thermal conversion at BMC scores best, but Digestion also has major environmental benefits.

Figure 11 Results for human toxicity

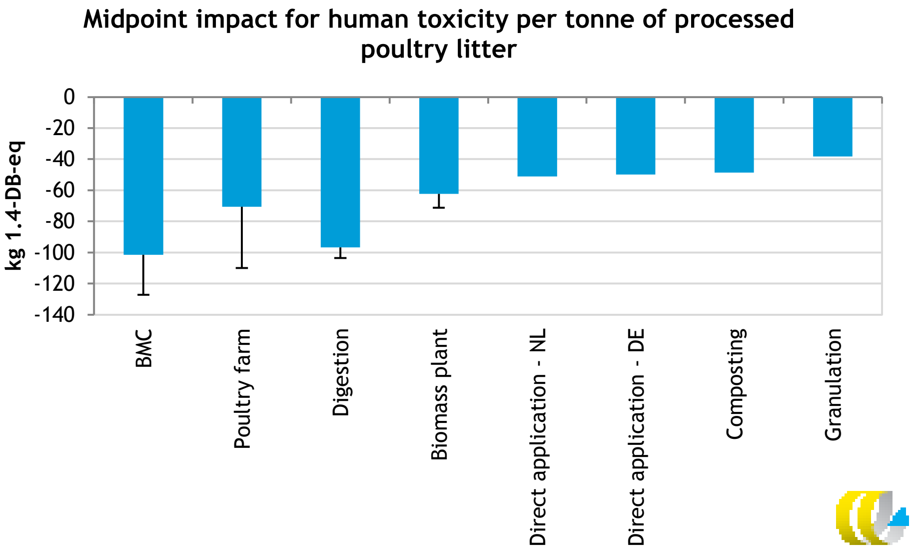


Figure 12 shows that the routes in which no nitrogen-containing products are marketed to farmers have environmental benefits. The high impact of Direct application and Digestion are due to the ammonia emissions associated with agricultural application of raw litter and digestate. Particulate matter formation during transport also contribute, particularly with the Granulation route. Thermal conversion at BMC scores best on this impact. If the waste heat is also marketed, the Poultry farm route may score slightly better than BMC.

Figure 12 Results for particulate matter formation

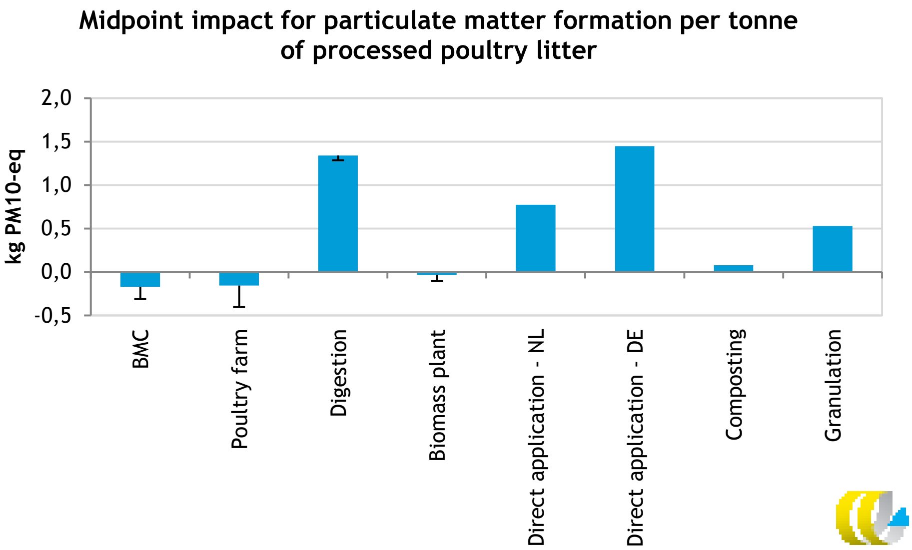


Figure 13 shows that all the routes except for co-firing in a biomass plant score similarly on mineral resource depletion. This is the only route in which no phosphorus (as P_2O_5) or potassium (as K_2O) is marketed to farmers. If P_2O_5 proves to have an efficacy of 100% rather than 37%, thermal conversion at both

BMC and poultry farmers scores even better. If the P_2O_5 efficacy is 37%, Digestion scores best on this impact.

Figure 13 **Results for mineral resource depletion**

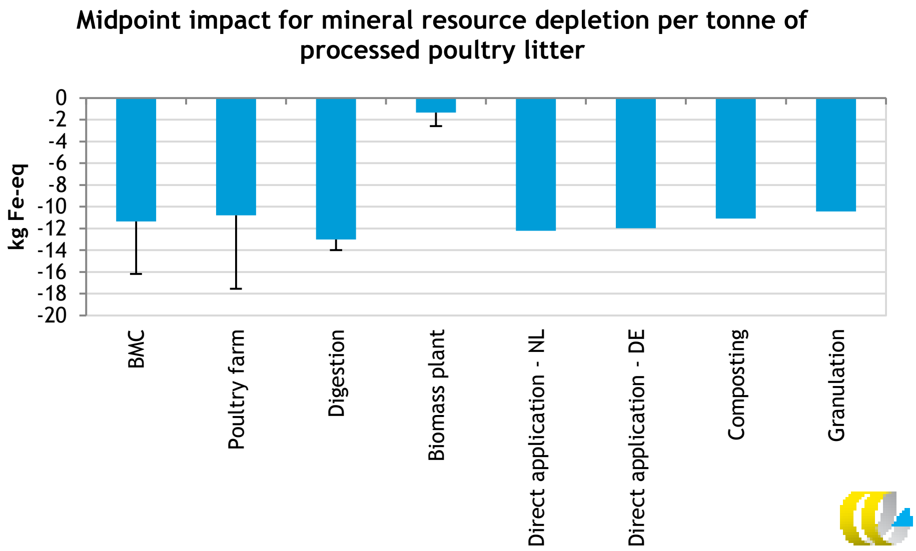
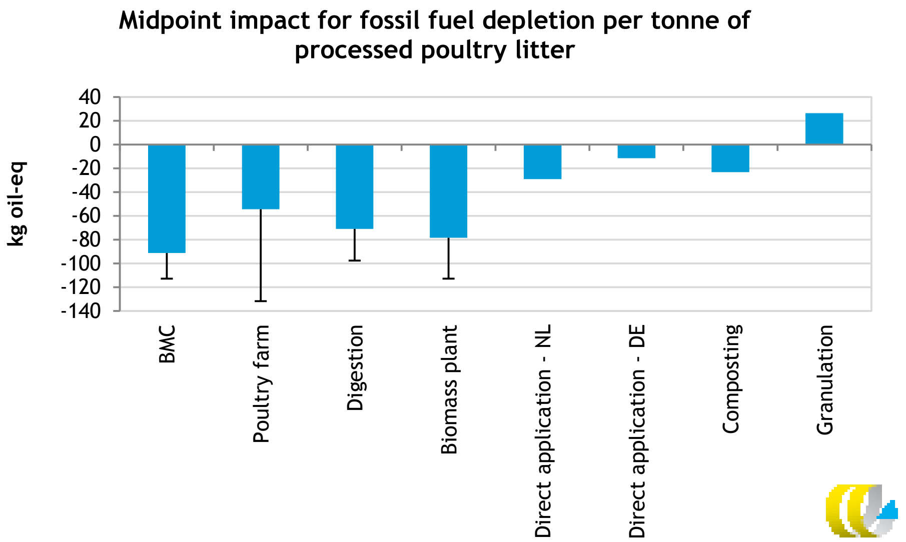


Figure 14 shows that all the routes except Granulation have benefits in terms of depletion of fossil fuels, due mainly to savings on nitrogenous fertilizer and electricity. Thermal conversion at BMC Moerdijk scores best. If the waste heat is also marketed, the Poultry farm and Biomass plant and Digestion routes could have a greater net environmental benefit than thermal conversion at BMC if no heat were marketed in that route.

Figure 14 **Results for fossil fuel depletion**



5.3 Conclusions of LCA

BMC, Poultry farm and Biomass plant score best environmentally

The processing routes with the greatest environmental benefits are thermal conversion at BMC Moerdijk, co-firing in a wood-fired biomass plant and thermal conversion on a poultry farm. These have a net environmental benefit on all the midpoints as well in the Single Score. Digestion of poultry litter scores well on most environmental impacts, except for the midpoint 'particulate emissions', occurring when the digestate is applied as a fertilizer.

In the basic model, thermal conversion at BMC Moerdijk has the greatest environmental benefits on most midpoints and in the Single Score. This picture would differ if the heat from the Poultry farm or Biomass plant routes were put to effective use. There are many uncertainties involved here, however, because neither route is (yet) used much in the Netherlands. It is therefore recommended that BMC Moerdijk investigate whether the heat produced at their plant can be marketed.

It can be concluded that all the processing routes generating no electricity have a (small) environmental impact, either on the Single Score or on several midpoint categories.

Methodological limitations

The LCA methodology employed has a number of limitations:

- Nitrate emissions to water are not expressed in the ReCiPe Single Score.
- In normalization and weighting of the toxic emissions, these contribute only very little to the ReCiPe Single Score compared with the other midpoints, which means they are scarcely reflected in that score.

The overall conclusions are not changed by these limitations. Nitrate emissions occur only with Direct application, Composting, Granulation and Digestion. These would therefore have a slightly greater environmental impact or slightly less environmental benefits if the nitrate emissions were included.

The heavy metals that are not included (as indicated in Appendix D) contribute very little to the ReCiPe Single Score. This is not surprising, because toxic emissions are scarcely carried over to the ReCiPe Single Score after normalization. However, because the amount of virtually all the heavy metals in poultry litter ash is lower than or comparable with that in untreated litter, this will leave the basic conclusions unchanged.

Limitations of leaving the drying process outside the system boundaries

When defining the system boundaries it was decided to exclude the drying of poultry litter. Based on RVO data, the situation is as follows: To dry poultry litter to the dry-matter content of 1 tonne of poultry litter incinerated at BMC (viz. 57%) requires around 1.5 times as much energy as is generated per tonne at BMC by thermal conversion of the litter[5].

[5] Drying from 30% dry matter to the 57% dry matter used at BMC means that for each tonne of litter processed at BMC (57/30) * 570-300 = 513 kg water must be removed from the litter. If a tunnel dryer or belt dryer is used, energy consumption is max. 6 MJ/kg water (RVO, 2015). This translates to approx. 3,000 MJ per tonne of litter dried. At BMC around 2,100 MJ electricity is produced per tonne of litter processed.

The fraction of this energy that would be within the system boundaries and the fraction saved is unknown, for two reasons.

The first relates to allocation. As indicated in Section 2.5, there are a number of reasons for drying the litter, including reasons that have nothing to do with its processing. The energy consumed must therefore be allocated accordingly. To the input flow used in this study, only that fraction of the energy must therefore be allocated that is required for the supply of litter to BMC.

The second reason relates to the heat source used for drying the litter.
One option is to use the waste heat from the poultry sheds, particularly in the summer, in which case no extra energy needs to be produced. Nonetheless, this still means that not modelling the drying process is a limitation of our study that may well influence the results.

6 Sensitivity analysis

Based on the contribution analyses reported in Annex I it was decided which sensitivity analyses would be most useful. For thermal processing at BMC we looked into processes contributing more than 1% of the aggregate environmental burden, for the other routes those contributing over 5%.

In these sensitivity analyses we varied the input for either the assumptions made or for the year to which the data relate, taking the average for 2010 to 2015 rather than 2015.

A synopsis of the sensitivity analyses is provided in Table 9 and Table 10. The sensitivity analysis for the BMC route is discussed in Annex H.2, the analyses for the other routes in Annex J.

Table 9 Sensitivity analyses for all routes

Sensitivity analysis	Description
Fossil carbon in poultry feed	Poultry feed may contain about 10% w/w calcium of fossil origin. $CaCO_3$ contains 12% w/w carbon, while the other 90% of the feed contains about 40% carbon. Poultry feed therefore contains approx. (10%*12%)/((10%*12%)+(90%*40%))=3.2% fossil carbon. We assumed this ratio also holds for the poultry litter, so 3% of the litter carbon is fossil.

Table 10 Synopsis of sensitivity analyses per route

Route	Sensitivity analysis topic	Variation 2010-2015/Description
BMC	Diesel fuel consumption	446,875 - 824,713 litre/a Variation determined by number of start-ups and shut-downs (BMC Moerdijk, 2016a).
	Natural gas consumption	246,945 to 1,682,936 $m^{3/}$a Through structural process changes BMC has reduced gas consumption by 85% (BMC Moerdijk, 2016a).
	Electrical power to grid	0.54 to 0.58 MWh / t litter (BMC Moerdijk, 2016a)
	K_20 efficacy	80 to 100%.
	P_2O_5 content, poultry litter ash	18 to 21 kg/t litter Given the discrepancy between the P_2O_5 measured in the litter feedstock and in the resultant ash, it was opted to use variation based on the level actually measured in the ash.
	K_2O content, poultry litter ash	17 to 21 kg/t litter Given the discrepancy between the K_2O measured in the litter feedstock and in the resultant ash, it was opted to use variation based on the level actually measured in the ash.
	Transport distance, poultry litter	50 to 150 km

Route	Sensitivity analysis topic	Variation 2010-2015/Description
Biomass plant	Calorific value, poultry litter	7.15 to 7.38 GJ/t litter (BMC Moerdijk, 2016a)
	Electrical efficiency	From lowest electrical efficiency in Europe for cogeneration plant >20 MW (BASIS, 2015) with 16% gross, 15.4% net, to 29.4% net
	Transport distance, poultry litter	50 to 150 km
Thermal conversion on poultry farm	Calorific value, poultry litter	7.15 to 7.38 GJ/t litter (BMC Moerdijk, 2016a)
	Net electrical efficiency	15 to 10%
	P_2O_5 content of poultry litter ash	18 to 21 kg/t litter, same as thermal conversion at BMC
	K_2O content of poultry litter ash	17 to 21 kg/t litter, same as thermal conversion at BMC
Direct litter application - NL	Ammonia and nitrous oxide emissions, litter application	-20 to +20%
	No fertilizer substitution value	The Netherlands has a manure surplus and poultry farmers must therefore pay to get rid of their raw litter. For useful application of raw poultry litter on certain Dutch crops, substantial amounts of nitrogen and potassium fertilizers need to be added (NMIa, 2016). Poultry litter delivers far less nitrogen to crops than pig slurry, which is therefore preferred if and when there is a surplus. Substitution of artificial fertilizer was not included.
	Carbon fixation	-20 to +20%
	Transport distance, poultry litter	50 to 150 km
Direct litter application - DE	Transport distance to Germany	150 to 500 km
	Ammonia emission, litter application	Minimum emissions, as in the Netherlands. Max. +30% ammonia emission factor (N/N_{org}) and ureic acid concentration in litter 0.7 kg/kg N_{org}. Uncertainty in ammonia emission factor as reported by (Dämmgen, 2009) and ureic acid level by (NMI, 2016b).
	Nitrous oxide emission, litter application	Emission in the Netherlands to +100%. Uncertainty as reported by (Dämmgen, 2009).
	Carbon fixation	-20 to +20%
Composting	N content of compost	-20 to +20%
	P_2O_5 content, compost	12.6 to 14.7 kg/t litter processed Given the discrepancy between the theoretical and calculated P_2O_5 level of the compost, it was opted to use variation based on the calculated figure.
	K_2O content, compost	18 to 21 kg/t litter processed Given the discrepancy between the theoretical and calculated K_2O level of the compost, it was opted to use variation based on the calculated figure.
	Carbon fixation	-20 to +20%
	Transport distance, compost	To Germany (150 km) instead of France (300 km)
	Ammonia emission, processing	-20 to +20%
	Nitrous oxide emission, application	-20 to +20%
Composting and granulation	N content of granulate	-20 to +20%
	K_2O content, granulate	15 to 21 kg/t litter processed Given the discrepancy between the theoretical and calculated K_2O level of the granulate, it was opted to use variation based on the calculated value.
	P_2O_5 content, granulate	9.4 to 14.7 kg/t litter processed Given the discrepancy between the theoretical and

Route	Sensitivity analysis topic	Variation 2010-2015/Description
		calculated P_2O_5 level of the granulate, it was opted to use variation based on the calculated value.
	Carbon fixation	-20 to +20%
	Transport distance, fertilizer	100% marketed in Spain rather than partly in Asia
	Natural gas consumption	-20 to +20%
	Ammonia emission, application	-20 to +20%
	Nitrous oxide emission, application	-20 to +20%
Co-digestion in plant in DE	Biogas production	-20%
	Electrical efficiency	-10 to +10%
	P_2O_5 content, digestate	-20%
	K_2O content, digestate	-20%
	N content, digestate	-20 to +20%
	Nitrous oxide emission, application	-20 to +20%
	Ammonia emission, application	-20 to +20%

6.1 Conclusions of sensitivity analyses

Figure 15 summarizes the results of the sensitivity analyses performed for the LCAs of the basic routes. The figure shows that despite the sensitivities of the basic analysis the results are broadly comparable. We discuss the sensitivities of each route.

Thermal processing and Biomass plant

With thermal conversion at BMC and on a poultry farm as well as processing in a wood-fired biomass plant, the greatest uncertainty is due to the electrical efficiency of the plant. Processing at BMC Moerdijk and on a poultry farm may score slightly better environmentally if the efficacy of the phosphorus in the litter ash proves to be over 37%. These routes will not score much higher, though, unless waste heat can be marketed, as already discussed in Chapter 5.

Digestion

Poultry litter digestion most probably has environmental benefits, but their magnitude is fairly uncertain because this processing method is not yet applied in the Netherlands. This uncertainty derives mainly from the electrical efficiency of the cogeneration plant used to generate power from the biogas and the amount of gas produced.

Direct application in the Netherlands

The greatest uncertainty associated with application of raw litter in the Netherlands is whether the litter can indeed be marketed in this country, with its manure surplus. If the litter can be marketed, its application in the Netherlands has slight environmental benefits

Direct application in Germany

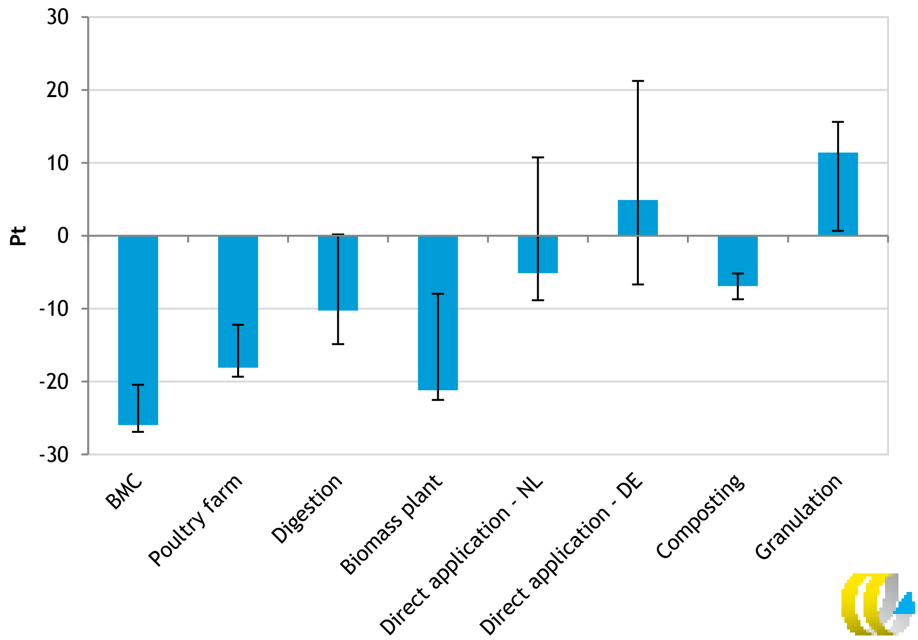
The uncertainties associated with direct application of raw litter in Germany stem mainly from the direct emissions occurring during farmland application. Application in Germany may score either better or worse than application in the Netherlands. The most positive assumptions for application in Germany give it a slight environmental edge.

Composting

While composting poultry litter most probably has environmental benefits, it will not come close to routes in which energy is generated, all the more so if the latter can market their heat.

Granulation
Poultry litter granulation will score considerably better environmentally if the granulate transport distance is reduced, but even then will probably not have environmental benefits.

Figure 15 Comparison based on sensitivity analyses, without earlier uncertainties



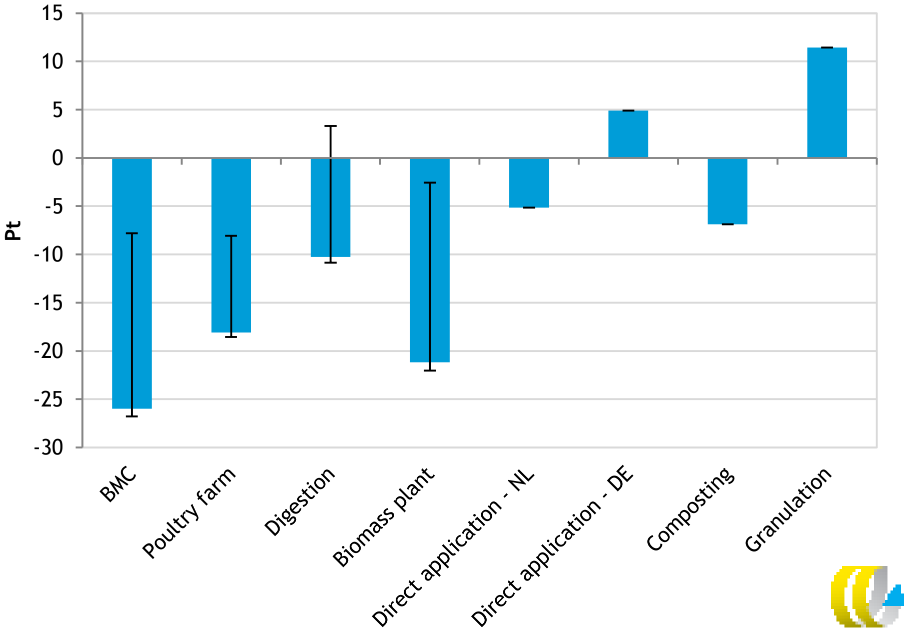
The detailed sensitivity analysis for each route is given in Annex J, except that for the BMC route, which is in Annex G.

Sensitivity analysis for different electricity mix
Besides the sensitivity analyses just described, the results depend also on the average electricity mix in the Netherlands. In our analysis we assumed that the power generated in various routes replaces the average Dutch electricity mix, which consists at present largely of grey, i.e. fossil, electricity.

If more green electricity is used in the future, this will knock on in all the results. In Figure 16 this is represented by the margin bar going upwards, towards environmental impacts. The small margin going downwards, towards environmental benefits, represents en ever greyer electricity mix than is currently the case.

If the Dutch electricity mix were to become 100% green, Digestion would in all likelihood cease to be a viable option. The BMC, Biomass plant and Poultry farm routes might still have environmental benefits. Thermal conversion would then have a similar environmental advantage to Direct application in the Netherlands and Composting.

Figure 16 Sensitivity analysis for different electricity mix



Replacement of grey electricity mix based on current grey supply to Dutch grid, green mix on current green supply to Dutch grid, as reported in (CE Delft, 2014).

7 LCA with system expansion

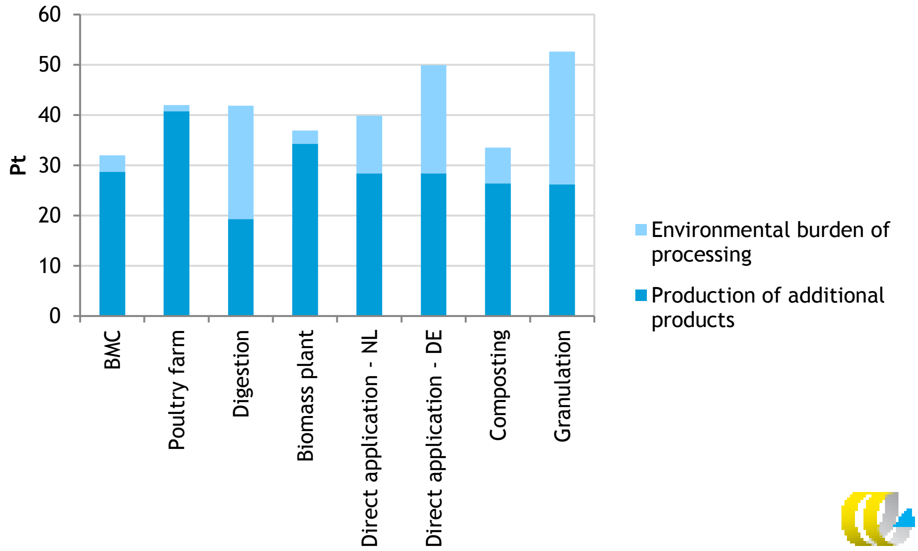
Annex K reports the results of an LCA carried out on the basis of system expansion instead of allocation based on physical relationships, as in the basic LCA. This chapter describes the main conclusions of the LCA with system expansion.

In an LCA with system expansion all the routes are extended in such a way as to make the end-products comparable. This means a different functional unit is also used, in our case: “Processing 1 tonne of poultry litter and production of 597 kWh electricity, 14.4 kg 1-year-active nitrogen, 14.8 kg 1-year-active phosphorus (as P_2O_5), 21 kg 1-year active potassium (as K_2O) and 207 kg effective organic matter”.

This functional unit combines the maximum output of electricity, nutrients and effective organic matter from the various routes. To be clear: the routes are not therefore extended to match the maximum amount of nutrients, say, in the poultry litter, but to match the maximum 1-year active nutrient level in the end-product of one of the routes. In the case of the BMC route this therefore means that not all the lost nitrogen needs to be compensated, only that retained in the Digestion route, the route in which most nitrogen is conserved.

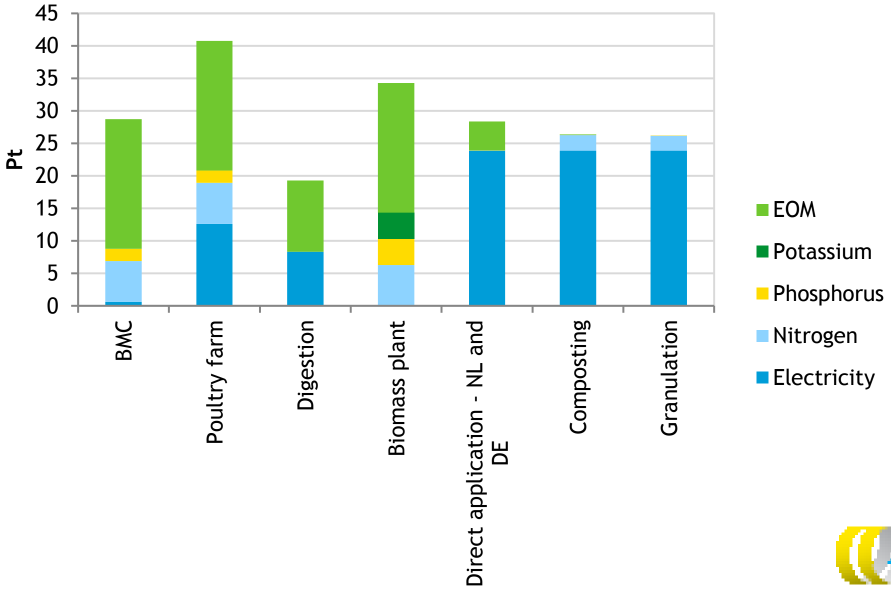
Figure 17 (the same as Figure 55) shows the total environmental impact of each route after system expansion, indicating what fraction of the impact is due to processing of 1 tonne poultry litter (in light blue) and what fraction to production of the additional products (in dark blue) required to arrive at the functional unit.

Figure 17 Comparison of environmental impact after system expansion



The environmental burden associated with processing (light blue in Figure 17) is the same as the burden depicted above the x-axis in Figure 9. In this system expansion, the environmental benefit shown in Figure 9 below the x-axis does not feature as a benefit but as a disadvantage of the other routes (dark blue in Figure 17). To illustrate: at BMC, electricity production is shown in Figure 9 below the x-axis as an environmental benefit, while in the LCA with system expansion it features in Direct application and other routes without power generation as an environmental burden of the additional product 'electricity'.

Figure 18 Environmental impact of the additional products for each route



7.1 Conclusions of LCA with system expansion

From the LCA with system expansion it can be concluded that the BMC route has the smallest environmental footprint. This route thus performs best environmentally, as in the basic LCA. Composting poultry litter performs almost just as well, while in the basic LCA it had a lower score.

Comparing Figure 17 with Figure 8, we see that Composting moves from fifth to second place. Direct litter application in the Netherlands moves from sixth to fourth place.

This change is surprising; in principle, the absolute differences between the various routes should be the same in the substitution method as in system expansion. In other words, system expansion should not alter the relative ranking of the routes relative to the basic LCA: the route with the greatest burden should retain this position, as should that with the least burden.

The change is due to the fact that in the basic LCA model the EOM added to agricultural soils is not deemed to be a product that can be substituted, because in the real world the EOM is not supplemented by farmers. Instead, in the basic LCA carbon fixation was assumed. Because the EOM is supplemented in system expansion, there is a shift in ranking.

As an illustration: in the case of additional electricity we assume in the basic LCA a substitution (thus an environmental benefit), while in the LCA with system expansion extra electricity must be produced (thus an environmental burden). In this case the environmental benefit of the Biomass plant in the basic LCA and the environmental disadvantage of Direct application are exactly the same. Because the environmental benefit of the EOM in the basic LCA is different (viz. carbon fixation) from the disadvantage of the EOM in the LCA with system expansion (addition of EOM), this results in a shift in ranking.

In the LCA with system expansion, thermal conversion at BMC has the lowest environmental impact, which is in line with the result of the basic LCA.
The greatest environmental impact is associated with Granulation and Direct application in Germany, the two routes also scoring worst in the basic LCA.

8 Conclusions and recommendations

In Section 8.1 we present the final conclusions of this study, based on the conclusions on the individual elements described in the following sections:

Nutrient balance	Section 4.2
Basic LCA	Section 5.3
Sensitivity analysis	Section 6.1
LCA with system expansion	Section 7.1

8.1 Final conclusions

Nutrient balance: In the Biomass plant all the nutrients are lost, with thermal conversion phosphorus and potassium are conserved
The nutrient balance shows that when poultry litter is co-fired in a wood-fired biomass plant all the nutrients of agricultural relevance are lost. With thermal conversion, organic matter and nitrogen are lost, but phosphorus (as P_2O_5) and potassium (as K_2O) are conserved. In the other routes all four are conserved.

LCA: Routes with power generation have an environmental benefit
The LCA shows that all the routes in which electricity is generated score best environmentally, viz. thermal conversion at BMC and on a poultry farm, co-firing in a biomass plant and digestion. These routes have a positive score for both total environmental burden and each individual impact, except for digestion, which scores negatively on particulate emissions. All these routes score even better if the waste heat can be marketed, which may thus determine the difference between these power-generating routes.

Overall picture from LCA and nutrient balance: BMC en Poultry farm score best environmentally
Combining the two parts of this study, the nutrient balance and the LCA, thermal conversion at both BMC and on a poultry farm score positively. In neither route are organic matter and nitrogen lost. Phosphorus and potassium are finite resources and therefore important from the perspective of a circular economy and resource conservation. It may consequently be opted to attach greater weight to the results for these elements than to those for (effective) organic matter or nitrogen. Thermal conversion of poultry litter at BMC scores just as well as the other routes in terms of conservation of potassium or phosphorus. The 1-year action of phosphorus (as P_2O_5) can work out either better or worse (depending on the type of crop on which the poultry litter is applied).

Organic matter and nitrogen are also important, however, because declining soil levels can lower farmland productivity. These can both be supplemented from other sources. As shown in Annex K, thermal processing at BMC combined with organic matter and nitrogen supplements from another source such as artificial fertilizer still yields an environmental benefit.

Even with 100% green electricity BMC Moerdijk has environmental benefits

If the Dutch electricity mix were 100% green, thermal conversion of poultry litter would have rather less environmental benefits. Thermal conversion both on a poultry farm and at BMC Moerdijk would then still have a small environmental advantage and score roughly the same as direct litter application in the Netherlands and composting.

Biomass plant scores positively in LCA but negatively in nutrient balance

Co-firing in a biomass plant comes out positively in the LCA, but the nutrient balance shows that in this route all the nutrients of agricultural relevance are lost. Overall, then, this route does not score positively.

Digestion scores moderately in both LCA and nutrient balance

No unambiguous conclusion can be drawn when it comes to poultry litter digestion because of the high sensitivities in the analysis. The environmental benefits will probably be lower than for thermal conversion. The nutrient balance shows that Digestion scores similarly to the other routes with respect to phosphorus (as P_2O_5) and potassium (as K_2O), better for nitrogen, and worse for organic matter.

Direct application, composting and granulation score low in LCA and positively in nutrient balance

Direct application of raw litter in Germany and Granulation have a (small) environmental impact in the LCA, while Direct application in the Netherlands and Composting have a small environmental benefit. The nutrient balance shows that in all these routes, which produce no electricity or heat, organic matter and nitrogen are conserved, as well as phosphorus (as P_2O_5) and potassium (as K_2O).

Answer to the core question: BMC is an environmentally appealing route

This study has demonstrated that thermal conversion of poultry litter in the BMC plant is environmentally appealing in comparison with eight other processing routes. If the waste heat generated can be marketed, thermal conversion on a poultry farm scores best environmentally, however.

8.2 Recommendations to BMC

BMC Moerdijk can further increase the environmental benefits achieved by thermal conversion of poultry litter at its plant by marketing the waste heat produced. It is therefore recommended to investigate whether this is feasible.

The factors contributing most to the environmental burden associated with operation of the BMC plant are the CO_2 and NO_x emissions arising during transport of the poultry litter to the plant and transport of the resultant ash. It is therefore recommended to investigate whether it is feasible to reduce these emissions through efficiency and conservation measures in these two transport phases.

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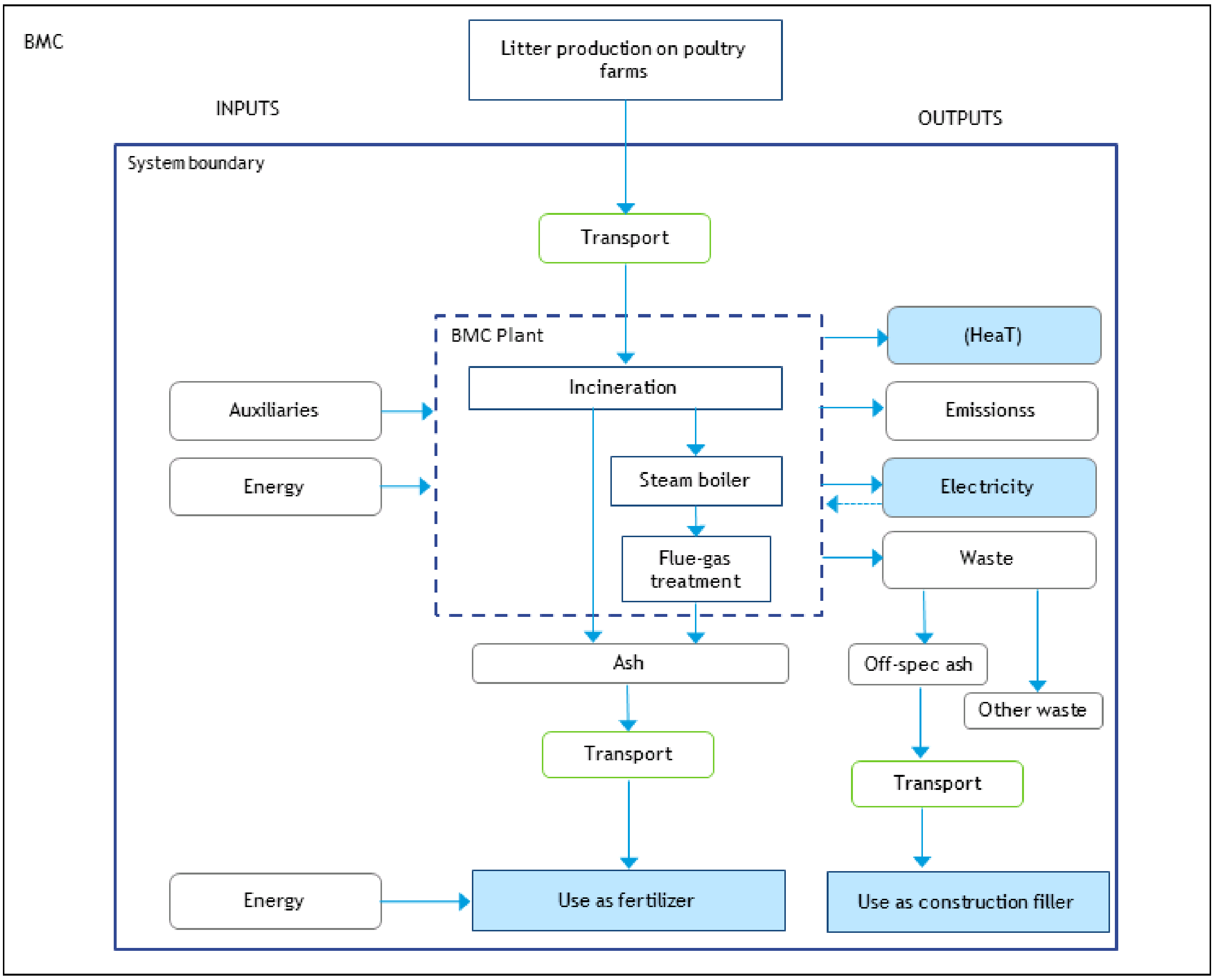
Annex A Inventory

This annex gives all the data used as input for the LCA. For each route the system boundaries are first indicated and the data then presented.

A.1 Thermal conversion at BMC Moerdijk

In 2015 BMC Moerdijk processed 438 kt poultry litter, one-third of the total quantity produced annually in the Netherlands.

A.1.1 System boundary



The energy consumption and emissions associated with green 'Transport' boxes are included in the LCA. A blue box denotes an avoided product.

A.1.2 Inventory description

Poultry litter transport

The poultry litter is transported from a poultry farm to the BMC Moerdijk plant. This transport distance is 124 km on average, with 30% of the litter being transported in a container truck and 70% in a 'walking floor' truck. These trucks are full on the incoming trip and empty on the way back. Both transport legs are allocated to BMC Moerdijk. The environmental impact of this truck transport was modelled using the database on the environmental impacts of transport, STREAM (Study on Transport Emissions of All Modes) (CE Delft, 2011)[6].

Auxiliaries

In the BMC plant a number of auxiliary materials are used, as specified in Table 11. In 2015 BMC Moerdijk processed 1 kt of wood chips to boost the calorific value of the poultry litter during the winter period. These chips consist of 30% untreated Class A wood and 70% prunings. They were modelled as 100% wood pellets.

Energy consumption and power production

The BMC plant generates 285 GWh of electrical power annually, part of which is for own use. The remaining 254 GWh is fed into the national grid, enough to supply 70,000 households. This translates to a net efficiency of 29%.

At the moment BMC does not market the waste heat produced, though this is feasible. This would be a total of 60,000 MWh per annum.

Process emissions

The direct emissions reported by BMC are shown in Table 11. Besides these emissions are also caused by burning natural gas and diesel fuel, these were calculated using RVO indices for energy content and CO_2 emissions per GJ (Vreuls & Zijlema, 2012).

Waste processing

Wastewater from BMC Moerdijk is discharged to the sewer and is consequently processed at a regular wastewater treatment plant. There is no pre-treatment. The other waste streams are processed by Sita and Wubben.

Ash marketed as fertilizer

BMC Moerdijk markets its poultry litter ash abroad, in France and Belgium. In many cases the ash is used as it is, but it is also mixed with other fertilizer materials to produce a specific mix. The ash used as a fertilizer is transported 5 km to storage facilities, from which 40% is transported to the Walloon part of Belgium and 60% to northern France. Transport to Wallonia is 160 km by truck, that to France 500 km by canal barge. In France the ash is transported by truck from the port to the farmers, for which a distance of 100 km was assumed. The environmental impact of truck and barge transport were modelled based on STREAM (CE Delft, 2011)[7]. The diesel consumption associated with field application of the ash is based on the figure reported in an Ecoinvent report (Nemecek & Kägi, 2007).

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6 This assumes truck trailers with heavy cargo, a load factor of 1 and a load-kilometre factor and share of containers loaded of 0.5.

7 This assumes a >20 t truck with heavy cargo and a Rhine Herne Canal Ship on a CEMT VI-canal with heavy bulk and general cargo.

Ash marketed as construction filler

Around 0.4% of the poultry litter ash produced at BMC cannot be marketed as a fertilizer, but is sold to a firm that processes it to construction filler. We assumed that this filler substitutes chalk and that its transport is equivalent to that of normal chalk.

Table 11 provides a full synopsis of the LCA inventory for thermal conversion at BMC Moerdijk, based on data provided by BMC for the year 2015 unless otherwise stated.

Table 11 LCA inventory for BMC Moerdijk per tonne of processed poultry litter, 2015

Item	Description	Quantity	Comments
Poultry litter transport	Truck transport	124 km	Full out, empty return
Auxiliaries	Natural gas	0.564 m^3/t litter	
	Diesel	1.02 litre/t litter	
	Wood chips	2.32 kg/t litter	70% prunings, 30% Class A wood
	Ammonia	0.08 kg/t litter	
	Chalk	1.98 kg/t litter	
	Lubricating oil	2.74 g/t litter	
	Sodium hypochlorite	0.04 kg/t litter	
	P3-Incidin 05	0.09 g/t litter	
	Performax 1085	0.01 kg/t litter	
	Sand	14.06 kg/t litter	
	Sulphuric acid	0.48 kg/t litter	
	Cooling water	0.990 m^3/t litter	
	Drinking water	0.003 m^3/t litter	
	Industrial water	0.129 m^3/t litter	
Direct atmospheric emissions	Biogenic CO_2	810,460 kg/t litter	
	Fossil CO_2	3.794 kg/t litter	
	CO	0.026 kg/t litter	
	NO_x	0.329 kg/t litter	
	TOC	0.003 kg/t litter	
	SO_2	0.006 kg/t litter	
	HCl	0.003 kg/t litter	
	Particulates	0.001 kg/t litter	
	NH_3	0.003 kg/t litter	
	HF	0.626 g/t litter	
	Mercury	0.001 g/t litter	
	SO_3	0.039 g/t litter	
	Cadmium	0.004 g/t litter	
Waste processing	Waste water	0.012 m^3/t litter	
	Commercial waste	0.059 kg/t litter	
	Waste oil	0.006 kg/t litter	
Energy production	Electricity	581.96 kWh/t litter	Supplied to grid in 2015
	Heat	137.12 kWh/t litter	Can be potentially marketed
Ash marketed as fertilizer	Poultry litter ash	141.26 kg/t litter	
	Truck transport	5 km	One-way, ash to storage
	Truck transport	160 km	One-way, ash to customers in Wallonia
	Barge transport	500 km	One-way, ash to port in France
	Truck transport	100 km	From port in France to customers in France
	Field application	0.0531 kg/t litter ash	Tractor diesel consumption (Nemecek & Kägi, 2007)
Ash marketed as construction filler	Poultry litter ash	0.62 kg/t litter	
	Truck transport	3 km	One-way, ash to processor
Avoided products	Triple superphosphate (as P_2O_5)	7.8 kg/t litter	Based on 37% 1-year efficacy
	Potassium sulphate (as K_2O)	21.0 kg/t litter	Based on 100% 1-year efficacy

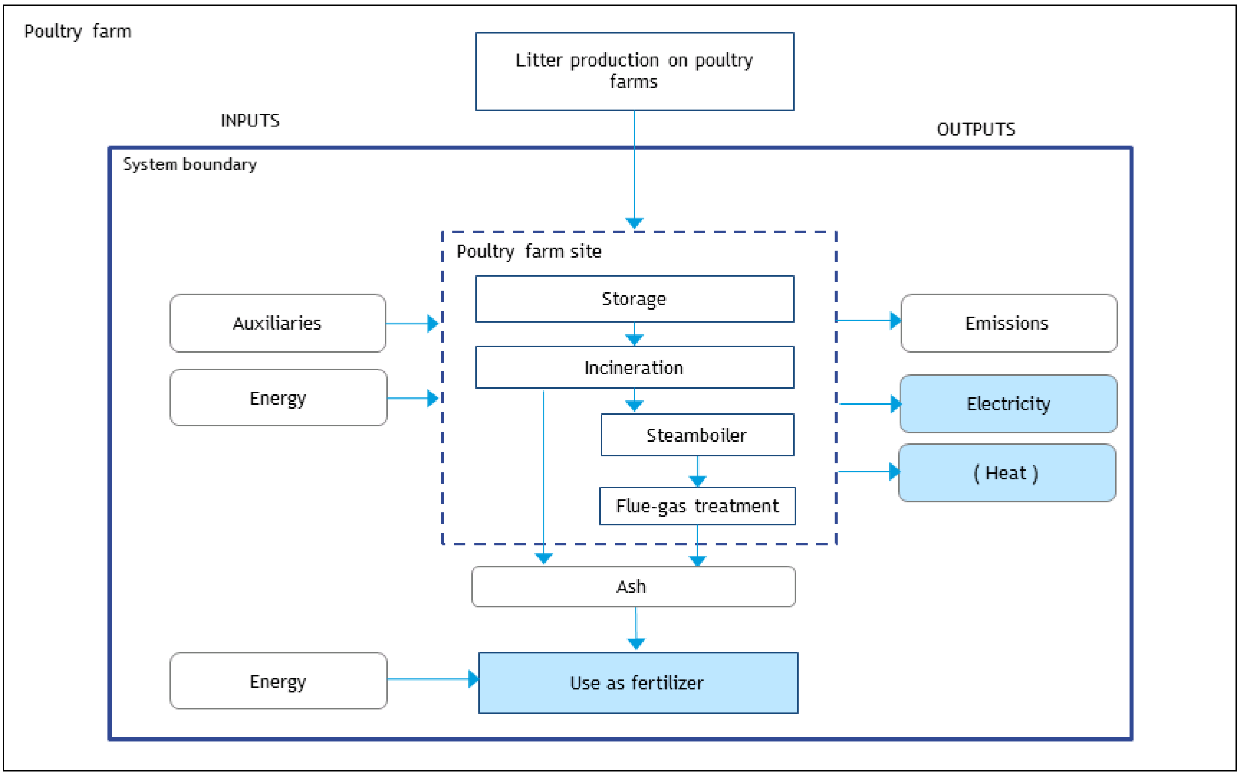
A.2 Thermal conversion on poultry farm

Poultry litter can be processed locally by thermal conversion on a poultry farm. While this does not yet occur in the Netherlands, there is an operational example of this route in Ireland at BHSL (BHSL, 2016a). This route allows the poultry farmer to recover energy in the form of electricity and heat.

Although the poultry litter processed by BHSL has a different composition from that processed by BMC, its dry-matter content is the same. We assumed that BHSL could equally well process poultry litter with the BMC composition.

BHSL processes approximately 10 t poultry litter a day (BHSL, 2016c), compared with over 1,250 t/d at BMC.

A.2.1 System boundary



A blue box denotes an avoided product.

A.2.2 Inventory description

Storage emissions
While total litter storage time may be up to six weeks, all the treated air from the storage facility is sent to the incineration furnace (BHSL, 2016c). There are therefore zero emissions. We assumed this would also be the case if the process were applied in the Netherlands.

Poultry litter transport
Because processing takes place on the poultry farm, there is no need for transport to processors.

Auxiliaries
Because BHSL uses fluidized-bed combustion to incinerate the poultry litter, sand is used. No quantitative data is available, however, so we assumed the same amount as at BMC: 14.06 kg/t processed poultry litter[8].

To get incineration started, 10 litres of diesel is used (BHSL, 2016c). This occurs every six weeks (BHSL, 2016c). This translates to approx. 0.24 l diesel a day, or 0.024 l/t poultry litter.

A maximum of 5 litres of water is used weekly (BHSL, 2016c). We assumed 250 l/a.

Finally, chalk is used. Because no data is available on the amount used at BHSL, we assumed the same quantity as used at BMC: 1.98 kg/t processed poultry litter.

Energy production
Thermal conversion on a poultry farm yields both warm water and electricity, at respective gross efficiencies of 15 and 85% according to BHSL (BHSL, 2016b). In practice, these figures are unachievable because there are always losses in energy conversion. We therefore assumed the same gross efficiency as for the biomass plant: 53%, which means 38% gross efficiency for the heat. Because the net efficiency is unclear, we assumed it was 8% lower, the same figure as for co-firing in a biomass plant. This means we assumed a net efficiency of 13.8% for electricity and 35.0% for heat.

At the moment the heat is only used locally, on the poultry farm itself. It is unclear whether the heat could be marketed in the Dutch situation. In this basic model we therefore assumed this is not the case.

The efficiency achieved was calculated using a calorific value of 7.3 MJ/kg poultry litter, the average of the material processed at BMC Moerdijk.

Process emissions
BHSL has had the emissions from its thermal conversion plant analysed twice, with differing results. We therefore worked with the average: particulates 1.37 g/h, SO_2 0.038 g/h and NO_2 108 g/h. We assumed a continuous process operated 24 hours a day.

Under European legislation a distinction is made between large processing installations like BMC (Activities Directive) and small installations on poultry farms (EU Regulation 592/2014). Large installations are classified as waste-processing plants and therefore subject to stricter emission standards and must also monitor their emissions continuously. In the LCA we consequently only included those emissions to which this obligation applies and which are indeed measured. This means fewer emissions were included with processing on a poultry farm than with processing at BMC Moerdijk.

Waste processing
As all the ash is marketed as fertilizer (BHSL, 2016c) this process has no waste.

[8] According to BHSL this figure is about right (BHSL, 2016c).

Ash marketed as fertilizer

Because of the minor quantities involved, it is highly unlikely the ash from Dutch poultry farms could be marketed domestically. While in theory feasible, it would probably have to be marketed abroad. The latter option was therefore assumed.

The ash produced at BHSL has higher nutrients concentrations than that from BMC Moerdijk, because less ash is generated. This has consequences for the quantity of ash to be transported. At BHSL 1 t ash is generated for every 10 t litter processed. It was assumed the ash is transported the same distance as for the BMC plant.

The diesel consumption associated with field application of the ash is based on the figure reported in an Ecoinvent report (Nemecek & Kägi, 2007).

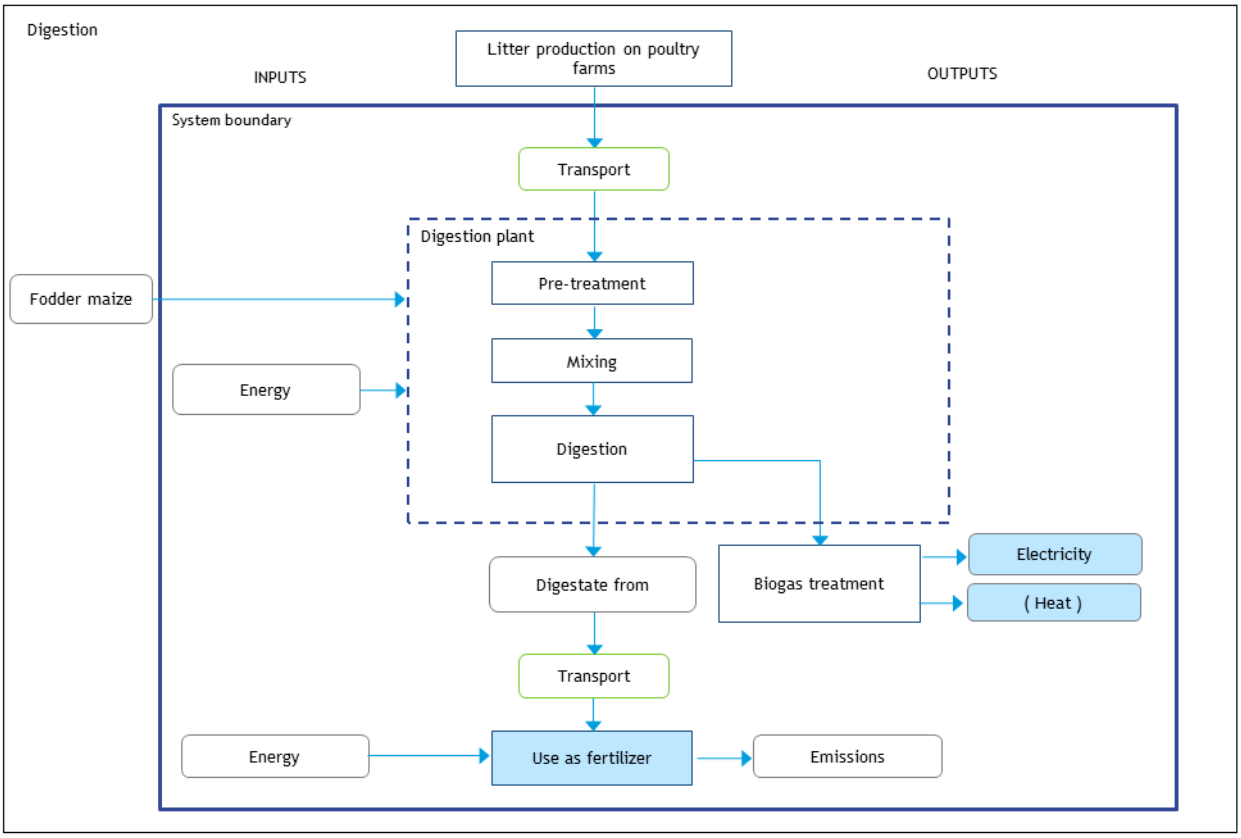
Table 12 LCA inventory for local thermal conversion on a poultry farm per tonne of processed poultry litter

Item	Description	Quantity	Comments
Net efficiency	Electrical efficiency Heat efficiency	13.8% of calorific value 35.0% of calorific value	Gross efficiency is 15% for electricity, 38% for heat; 8% reduction for net efficiency
Calorific value		7.3 GJ/t litter	Average value for litter processed at BMC
Emissions	SO_2 Particulates CO_2 NO_2	0.0812 g/t litter 3.29 g/t litter 2.72 kg/t litter 259 g/t litter	0038 g/h, 24 h/d operation, 10 t/d processed 1.37 g/h, 24 h/d operation, 10 t/d processed Emissions from burning diesel 108 g/h, 24 h/d operation, 10 t/d processed
Auxiliaries	Sand Diesel Water	14 kg/t litter 0.024 l/t litter 0.07 l/t litter	
Ash marketed as fertilizer	Poultry litter ash Truck transport Truck transport Barge transport Truck transport Field application	0.1 t/t litter 5 km 160 km 500 km 10 km 0.0531 kg/t litter ash	For 2015 One-way, ash to storage One-way, ash to customers in Wallonia One-way, ash to customers in France Port in France to customers in France Tractor diesel consumption (Nemecek & Kägi, 2007)
Avoided product	Triple superphosphate (as P_2O_5) Potassium sulphate (as K_2O)	7.8 kg/t litter 21.0 kg/t litter	Based on 37% 1-year efficacy Based on 100% 1-year efficacy

A.3 Co-digestion in German plant

Poultry litter can be co-digested in a plant in Germany to produce biogas and digestate. Using the biogas for power generation is not economically viable without a subsidy and without useful application of the waste heat and digestate (Commissie Deskundigen Meststoffenwet, 2015). We therefore assumed the digestate is marketed as a fertilizer and the biogas burned directly in a cogeneration plant.

A.3.1 System boundary



The energy consumption and emissions associated with green 'Transport' boxes are included in the LCA. A blue box denotes an avoided product.

A.3.2 Inventory description

Co-digestion

Poultry litter is rarely digested on its own. By mixing it with energy crops higher yields can be obtained and quality guaranteed. German co-digestion plants use a mix of 49% energy crops and 43% manure as feedstock (Commissie Deskundigen Meststoffenwet, 2015). The energy crops are almost entirely fodder maize (Commissie Deskundigen Meststoffenwet, 2015).

The manure may be a mix of different types, with various mixes being used in different types of digestion plant; see for example (UTS Biogastechnik, 2014). Our model assumed a mix of 50% fodder maize and 50% poultry litter.

For this co-digestion process, operation was allocated to the respective input flows, on the basis of physical properties.

Emissions during storage

As fresh litter digests better, the poultry litter is processed as soon as possible. Given transport to Germany, a storage time of over 2 weeks was assumed. Short storage means limited emissions (Commissie Deskundigen Meststoffenwet, 2015). According to Zwart et al. (2006) emissions of CH_4, N_2O and NH_3 are 5% of those associated with standard storage. We here assumed 5% of the emissions explained under Direct application.

Poultry litter transport
As with Direct application in the Netherlands, the manure broker was assumed to be in the same province as the poultry farmer, with 50 km transport distance.

In Germany there are 7,800 co-digestion plants that can handle manure (Commissie Deskundigen Meststoffenwet, 2015). As the Dutch poultry litter can be processed in western Germany a transport distance of 200 km was assumed.

Auxiliaries
As poultry litter and fodder maize are relatively dry, water needs to be added to help the process along. Enzymes and bacteria are also required. On these no data are available, however, so they were not included. Generally speaking, water consumption and enzyme use contribute little to the overall environmental impact.

Energy production
According to Reinhold (2005) 500 litre biogas can be produced from dry chicken litter per kilogram dry organic matter. This also holds for broiler chicken litter (StMELF, 2016). We assumed the same yield is also valid for the poultry litter mix processed at BMC Moerdijk. A dry organic matter content of 458 kg/t poultry litter therefore yields 229 m^3 biogas. This biogas has a methane content of 65% (Reinhold, 2005).

This means that poultry-litter processing in a co-digestion plant yields 229 m^3 biogas per tonne of processed litter. Based on the mass balance of CO_2 and methane, the biogas then has a methane content of 55%.

The produced biogas can be burned in a cogeneration plant to generate heat and power. Biogas with 55% methane has an energy content of 22 MJ/m^3 (Zwart, et al., 2006).

A cogeneration plant using biogas has a net electrical efficiency of 31% and a net heat efficiency of 36.4%[9] (Organic Waste Systems, 2013).

Process emissions
During co-digestion of poultry litter 1% of the methane yield is lost as leakage (Zwart, et al., 2006). There may also be ammonia leakage losses. The precise amount is unclear but is probably minor and has therefore been ignored.

Since water is added to the digestion mix, wastewater will also be produced. Again, though, the amount is unclear. As wastewater with only organic constituents generally has little environmental impact, this was also ignored.

Digestate marketed as fertilizer
The digestate transported to arable farmers for use as a fertilizer was assumed to be transported 50 km, using a truck modelled with data from STREAM (CE Delft, 2011)[10].

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9 40% of the energy content in the gas is converted to useful heat, 9% of which is needed to maintain the temperature of the digestion reactor (Organic Waste Systems, 2013).

10 Assuming a >20 t truck with heavy cargo.

Emissions during application

Ammonia emissions and nitrate leaching during field application of the digestate are roughly equal to those due to application of raw litter (Commissie Deskundigen Meststoffenwet, 2015). The N_2O emissions may differ slightly (Commissie Deskundigen Meststoffenwet, 2015) and we assumed 5% less than for Direct application in Germany.

Diesel fuel consumption for digestate application is based on the figure reported for application of fertilizer in an Ecoinvent report (Nemecek & Kägi, 2007).

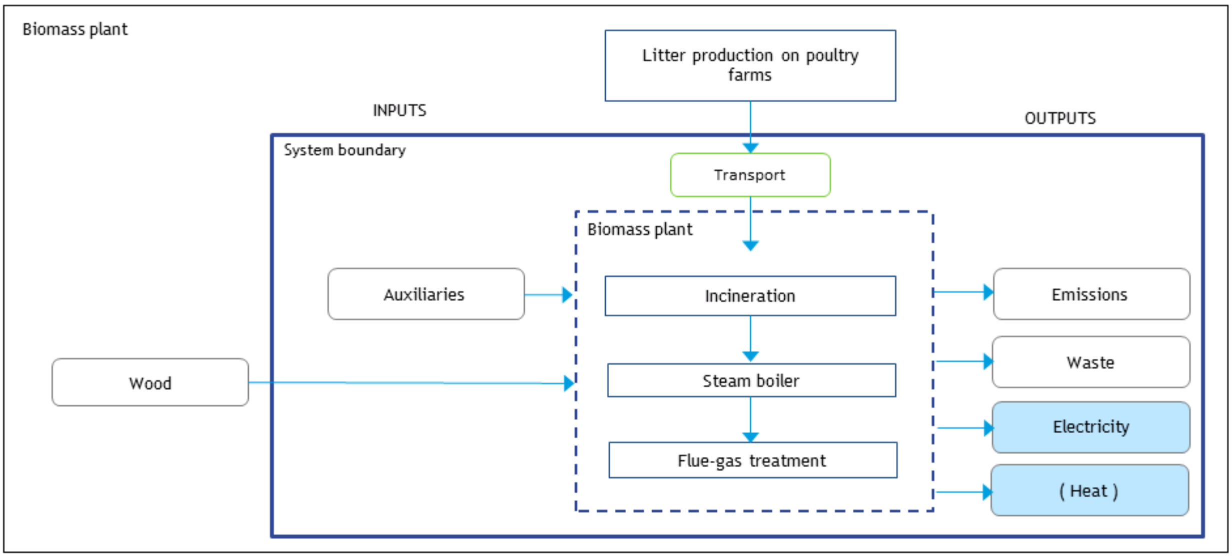
Table 13 LCA inventory for co-digestion in German digestion plant per tonne of processed poultry litter

Item	Description	Quantity	Comments
Storage emissions	CH_4 N_2O NH_3	0136 kg/t litter 0.00196 kg/t litter 0029 kg/t litter	5% of emissions of direct application of raw litter
Transport	Truck transport Truck transport Truck transport	50 km 200 km 50 km	From poultry farmer to manure broker From manure broker to German digestion plant From digestion plant to farm digestate user
Process emissions	CH_4	0.86 kg/t litter	1% of methane production
Biogas production	Biogas	229 m^3/t litter	
Energy content of biogas		22 MJ/m^3 biogas	55% methane content
Cogeneration efficiency	Net electrical efficiency Net heat efficiency	31% 36.4%	
Field application	Diesel consumption	0.0531 kg/t digestate	Tractor diesel consumption (Nemecek & Kägi, 2007)
Post-application emissions	N_2O NH_3 NO_3	0.41 kg/t litter 4.69 kg/t litter 18.7 kg/t litter	Same % as for direct application of raw litter, but 5% less for N_2O
CO_2 fixation	Organic matter stored in soil	42.4 kg/t litter	
Avoided product	Calcium ammonium nitrate (N) Triple superphosphate (as P_2O_5) Potassium sulphate (as K_2O)	79 kg/t litter 10.4 kg/t litter 21.0 kg/t litter	Based on 55% 1-year efficacy Based on 70% 1-year efficacy Based on 100% 1-year efficacy

A.4 Co-firing in a wood-fired biomass plant

In the Netherlands poultry litter is not currently co-fired in biomass plants. Given the material's composition it is unlikely to be an attractive option, as plant operation would be suboptimal. In this route it was therefore assumed that the biomass plant is optimized for co-burning poultry litter, just like the BMC Moerdijk plant. We assumed co-firing of max. 15% poultry litter in the biomass plant.

A.4.1 System boundary



The energy consumption and emissions associated with green 'Transport' boxes are included in the LCA. A blue box denotes an avoided product.

A.4.1 Inventory description

Poultry litter transport

To keep the routes comparable, we assumed the transport distance from poultry farmer to biomass plant is the same as from poultry farmer to BMC Moerdijk. Here too, the litter is therefore transported 124 km in a full truck that returns empty.

Auxiliaries

The required auxiliaries were estimated on the basis of the auxiliaries used in a waste incinerator, as reported in the Environmental Impact Statement for National Waste Management Plan, MER-LAP (AOO, 2002), which gives the relationship between feedstock chemical composition and auxiliaries requirements. For firing up the biomass plant we assumed the same amount of diesel needed for firing up the BMC plant.

Energy production

We assumed the efficiency of the biomass plant is equal to that of the average biomass plant burning only wood

The gross efficiency of these plants is between 30% and 35% (RWE, 2016). At the newest Dutch plant, the Bio Golden Raand, is it even 37% (Eneco, 2016). This new unit is not yet used to produce heat, too, though. When that is the case, the electrical efficiency will be slightly lower (RVO, 2015).

In this study we proceeded from the data for the EON Blackburn Meadows plant, a cogeneration plant that came on stream in 2014[11]. It has a gross electrical efficiency of 32% and a gross heat efficiency of 20% (BASIS, 2015). For a biomass plant the net efficiency is 8% lower (Liu, et al., 2014). We therefore assumed a net electrical efficiency of 29.4% and a net heat efficiency of 18.4%.

The efficiency achieved was used with a calorific value of 7.3 MJ/kg poultry litter, the average for the material processed at BMC. This means 29.5% of the calorific value of 7.3 MJ/kg litter is converted to electricity and 18.5% to heat.

Process emissions

The bulk of the feedstock is wood, supplemented by the poultry litter. In this study we allocated only those emissions due to litter incineration to the poultry litter and ignored those deriving from incineration of the wood.
For these emissions (as well as the required auxiliaries and waste streams) we based ourselves on the MER-LAP (AOO, 2002), which gives the relationship between feedstock chemical composition and emissions for a waste incinerator. We assumed this to be similar for a biomass plant.

Also following the MER-LAP (AOO, 2002), the biomass plant was assumed to have effluent-free flue-gas treatment. No wastewater was therefore included.

Waste processing

In contrast to the BMC plant, the ash remaining after the poultry litter and wood have been incinerated in the biomass plant is not used as a fertilizer substitute, as wood ash may not be used for this purpose in the Netherlands. Bottom ash and fly ash from biomass plants are processed as industrial waste.

As with auxiliaries and emissions, waste processing was based on the MER-LAP (AOO, 2002) and is in line with Dutch practice.

Table 14 LCA inventory for co-firing of poultry litter in a wood-fired biomass plant per tonne of processed poultry litter

Item	Description	Quantity	Comments
Transport	Truck transport	124 km	Full out, empty return
Efficiency	Electrical efficiency Heat efficiency	29.5% of calorific value 18.5% of calorific value	
Calorific value		7.3 GJ/t litter	Average value for litter processed at BMC Moerdijk
Direct atmospheric emissions	NO_x NH_3 CO Hydrocarbons Dioxins Particulates As Cd Co Cr Cu Hg	263 g/t litter 13.1 g/t litter 87.6 g/t litter 21.9 g/t litter 0.000219 mg/t litter 13.1 g/t litter 1.19 mg/t litter 0.767 mg/t litter 1.99 mg/t litter 4.41 mg/t litter 37.1 mg/t litter 0.852 mg/t litter	Based on MER-LAP (AOO, 2002), with addition of fossil emissions of natural gas fuel (MER-LAP: Environmental Impact Statement for National Waste Management Plan)

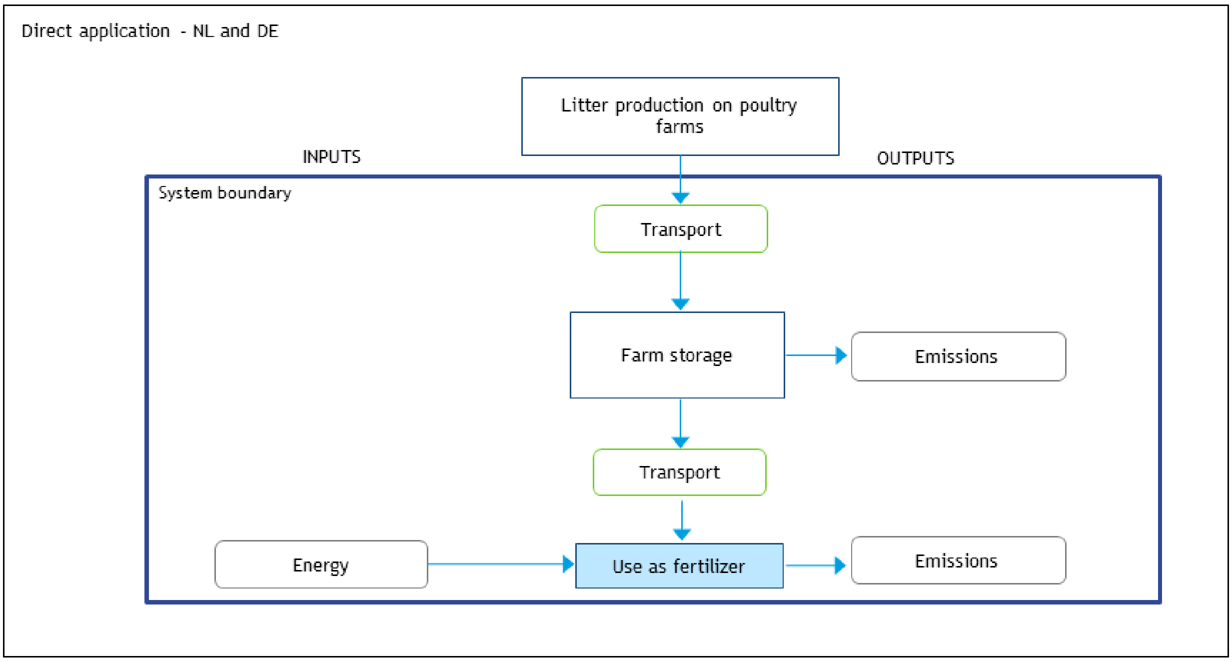
11 This UK biomass plant is the most efficient in Europe; it is optimized for power production.

Item	Description	Quantity	Comments
	Mn	208 mg/t litter	
	Mo	1.59 mg/t litter	
	Ni	2.78 mg/t litter	
	Pb	1.99 mg/t litter	
	Se	1.99 mg/t litter	
	Sn	0.0199 mg/t litter	
	V	0.398 mg/t litter	
	Zn	180 mg/t litter	
	Cl	5.68 g/t litter	
	F	2.84 g/t litter	
	S	2.4 g/t litter	
	Biogenic CO_2	827 kg/t litter	
	Fossil CO_2	2.8 kg/t litter	
Direct emissions to soil	As	0.96 mg/t litter	Based on MER-LAP (AOO, 2002)
	Cd	0.107 mg/t litter	
	Co	1.99 mg/t litter	
	Cr	3.56 mg/t litter	
	Cu	29.9 mg/t litter	
	Hg	0.00142 mg/t litter	
	Mn	168 mg/t litter	
	Mo	68 mg/t litter	
	Ni	2.25 mg/t litter	
	Pb	1.6 mg/t litter	
	Se	4.33 mg/t litter	
	Sn	0.016 mg/t litter	
	V	0.476 mg/t litter	
	Zn	145 mg/t litter	
	Cl	97.6 g/t litter	
	F	93.7 mg/t litter	
	SO_4	53.3 g/t litter	
Auxiliaries	NaOH	2.39 kg/t litter	Based on MER-LAP (AOO, 2002) with addition of natural gas
	Chalk	2.1 kg/t litter	
	Ammonia water	113 g/t litter	
	Active carbon	21.8 g/t litter	
	Diesel	1.02 l/t litter	
Waste processing	Flue-gas-treatment residues	5.32 kg/t litter	Based on MER-LAP (AOO, 2002)
	Slag	103 kg/t litter	
	Fly ash	8.24 kg/t litter	

A.5 Direct application of raw poultry litter in the Netherlands

In this route the raw litter is applied as a fertilizer on Dutch farmland.

A.5.1 System boundary



The energy consumption and emissions associated with green 'Transport' boxes are included in the LCA. A blue box denotes an avoided product.

A.5.2 Inventory description

Storage emissions

The poultry farmer stores the litter. The arable farmer applying it may also store it temporarily, as it may not be applied year-round. During this storage there will be emissions. In this route the poultry litter is assumed to be stored for more than two weeks in the 4 months from October to January.

One kg organic matter in poultry litter generates 0.34 m^3 methane gas (Van der Hoek & van Schijndel, 2006). Under proper litter management 1.5% of this is emitted during storage (IPCC, 2006).
Emissions of N_2O during storage are 0.1% of the N present in the litter (IPCC, 2006). In the Netherlands NH_3 emissions are on average 0.019% of the N in the litter [12].

All emissions were calculated based on litter composition.

12 Calculated based on total storage NH_3 emissions expressed as N as a percentage of total N emission from litter. From data in Table 4 (Velthof, et al., 2012).

Poultry litter transport
The litter is transported from the poultry farmer to the arable farmer.

Most of the chickens reared in the Netherlands are kept in the provinces of North Brabant (33%), Gelderland (19%), Overijssel (12%) and Limburg (11%) (CBS, 2016). In terms of hectares farmed, arable farming is concentrated in Groningen (15%), North Brabant (14%), Zeeland (14%), Drenthe (10%) and Flevoland (10%) (CBS, 2016). This means the poultry litter will generally need to be transported 1 or 2 provinces further. We therefore assumed 150 km transport distance.

Emissions during application
During field application volatile components will be lost. In average Dutch agricultural practice 0.65% of the N is lost as N_2O (CDM, 2013). In addition, 9% of the N is lost as NH_3, while 10% of the N leaches out as NO_3 (CDM, 2013).

Emissions were calculated based on the composition of the poultry litter mix used as feedstock at BMC, as reported in the first column of Figure 2 in Annex F (Nutrient balance calculations).

Diesel fuel consumption for field application of the litter is based on the figure reported for manure application in an Ecoinvent report (Nemecek & Kägi, 2007).

Table 15 LCA inventory for direct application in the Netherlands per tonne of processed poultry litter

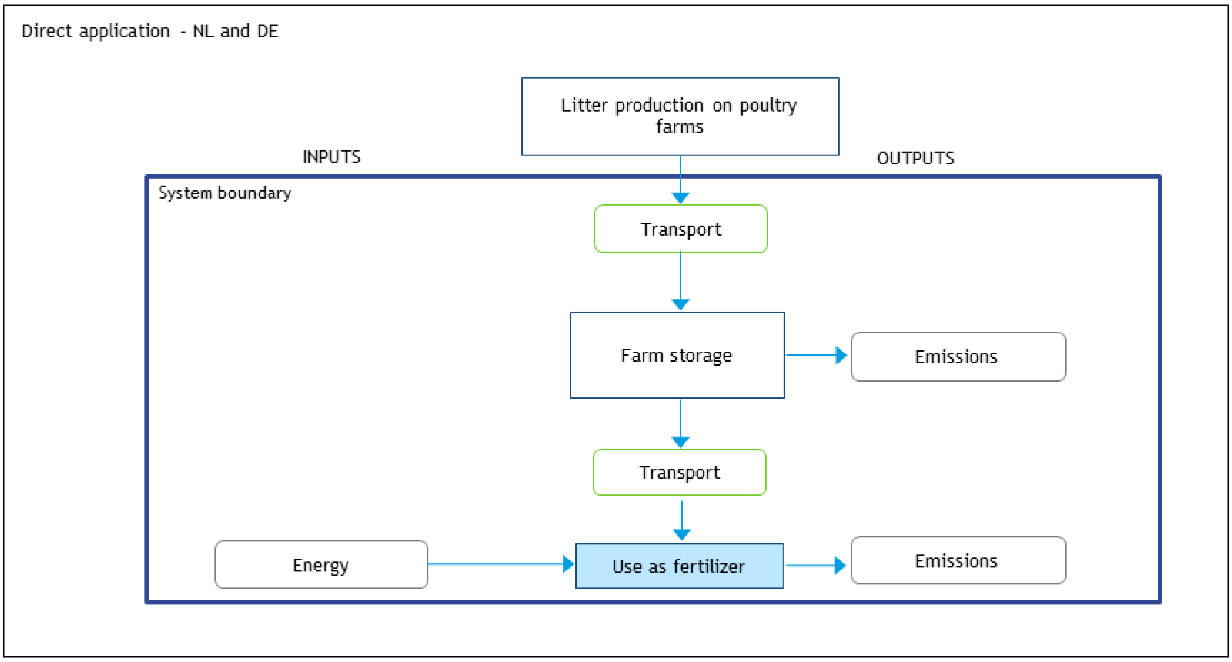
Item	Description	Quantity	Comments
Storage emissions	CH_4 N_2O NH_3	0.68 kg/t litter 0.01 kg/t litter 0.15 kg/t litter	Potential CH_4 emissions with 34% organic matter content (Van der Hoek & van Schijndel, 2006), of which 1.5% released during storage (IPCC, 2006) for ¼ of year N_2O: 0.1% of N (IPCC, 2006) for ¼ of year NH_3: 0.019% of N for ¼ of year
Transport	Truck transport	150 km	From poultry farmer to Dutch arable farmer
Field application	Diesel consumption	0.0531 kg/t litter	Tractor diesel consumption (Nemecek & Kägi, 2007)
Post-application emissions	N_2O NH_3 NO_3	0.266 kg/t litter 2.84 kg/t litter 11.5 kg/t litter	N_2O: 0.65% of N (CDM, 2013) NH_3: 9% of N (CDM, 2013) NO_3: 10% of N (CDM, 2013)
CO_2 fixation	Organic matter stored in soil	69.9 kg/t litter	
Avoided product	Calcium ammonium nitrate (N) Triple superphosphate (as P_2O_5) Potassium sulphate (as K_2O)	14.3 kg/t litter 14.7 kg/t litter 21.0 kg /t litter	Based on 55% 1-year efficacy Based on 70% 1-year efficacy Based on 100% 1-year efficacy

A.6 Direct application of raw poultry litter in Germany

There is scarcely any difference between application of the raw litter as a fertilizer in the Netherlands and in Germany. In both cases it is spread on arable farmland, the only difference being that in the latter case it is transported to a farm in Germany.

Below we describe only those aspects that differ between the two countries. For the others the inventory given in Section A.5 applies.

A.6.1 System boundary



The energy consumption and emissions associated with green 'Transport' boxes are included in the LCA. A blue box denotes an avoided product.

A.6.2 Inventory description

Poultry litter transport

Dutch poultry litter is exported mainly to Germany and France. In the former case it may be exported in untreated form, but this is not so for France. Cost considerations mean that solid litter can be transported no further than 400 to 600 km (NMI, 2014); beyond that it becomes unprofitable. We assumed an average distance of 500 km for transport from poultry farm to arable farmer in Germany.

Emissions during application

The emissions occurring in field application are different in the Netherlands than in Germany, because of different legislation. In Germany farmers are still allowed to spread manure directly on soil surfaces (Pellikaan, 2014), which results in higher emissions than when it is injected, as in the Netherlands. Of the N present as ureic acid poultry litter, 45% evaporates as NH_3 in Germany (Dämmgen, 2009). Ureic acid levels in poultry litter vary widely, from 10% to 70% of organic N (CBAV, 2016b). We assumed 40%. This means 18% of the organic N evaporates as NH_3 when the litter is applied on German farms, 1.6 times the figure for the Netherlands. We assumed the N_2O and NO_3 emissions are also 1.6 higher, thus 1% en 16% of the N present in the poultry litter, respectively.

Emissions were calculated based on the composition of the poultry litter mix used as feedstock at BMC, as reported in the first column of Figure 22 in Annex F.

Table 16 LCA inventory for direct application in Germany per tonne of processed poultry litter

Items	Description	Quantity	Comments
Storage emissions	CH_4 N_2O NH_3	0.68 kg/t litter 0.01 kg/t litter 0.15 kg/t litter	Potential CH_4 emissions with 34% organic matter content (Van der Hoek & van Schijndel, 2006), of which 1.5% released during storage (IPCC, 2006) for ¼ of year N_2O: 0.1% of N (IPCC, 2006) for ¼ of year NH_3: 0.019% of N for ¼ of year
Transport	Truck transport	500 km	From poultry farmer to German arable farmer
Field application	Diesel consumption	0.0531 kg/t litter	Tractor diesel consumption (Nemecek & Kägi, 2007).
Post-application emissions	N_2O NH_3 NO_3	0.425 kg/t litter 4.61 kg/t litter 18.4 kg/t litter	N_2O: 1.6x emission of direct application in the Netherlands, 1% of N NH_3: 45% of ureic acid (Dämmgen, 2009), 18% of N NO_3: 1.6x emission of direct application in the Netherlands, 16% of N
CO_2 fixation	Organic matter stored in soil	69.9 kg/t litter	
Avoided product	Calcium ammonium nitrate (N) Triple superphosphate (as P_2O_5) Potassium sulphate (as K_2O)	14.3 kg/t litter 14.7 kg/t litter 21.0 kg/t litter	Based on 55% 1-year efficacy Based on 70% 1-year efficacy Based on 100% 1-year efficacy

A.7 Composting

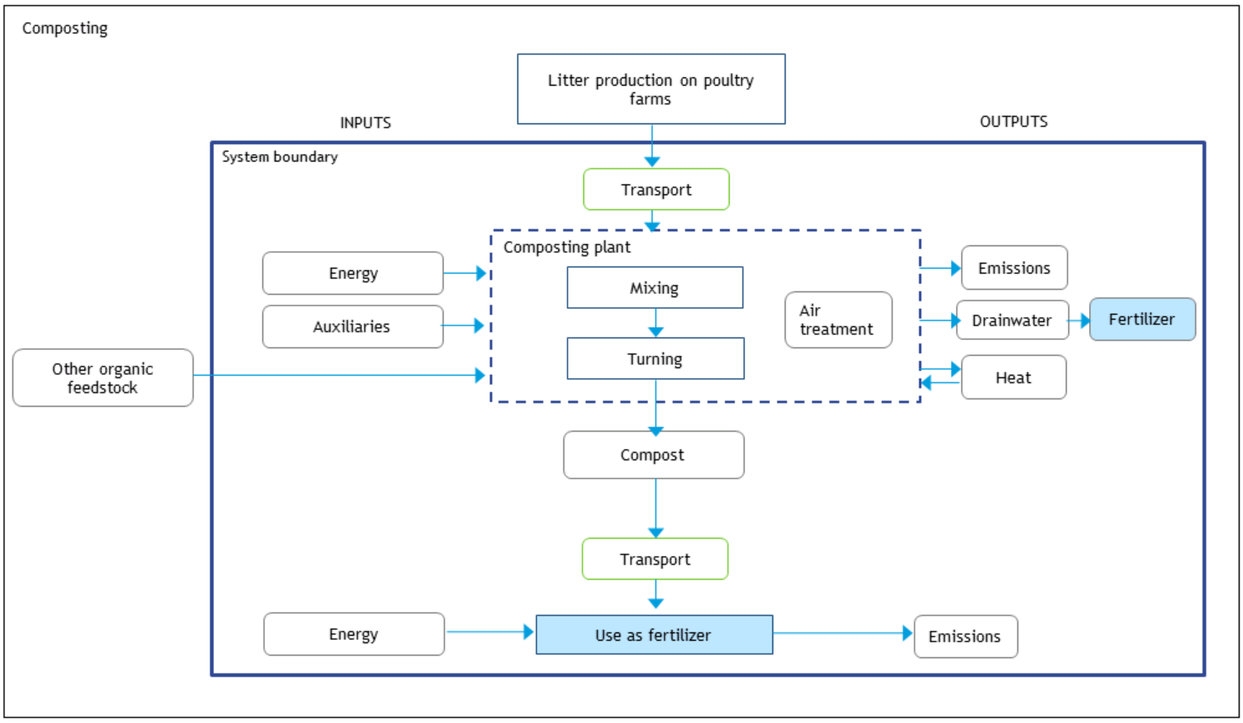
Poultry litter is composted at various sites in the Netherlands and for this study we based ourselves on the technology used at one of these (Composteerbedrijf, 2016)[13]. Most of the feedstock, consisting mainly of poultry litter, is processed in two composting tunnels; 80% is composted naturally and 20% forced.

The feedstock contains broiler chicken litter and manure-belt litter. Here, though, we took the same mix as processed at BMC, i.e. 52% broiler chicken litter, 40% laying hen litter, 5% turkey litter and 3% manure-belt litter, assuming that this only affects compost composition and not processing.

Of the 55,000 t material processed annually at this composting plant, 75% is poultry litter and 25% other types of manure and organic waste (greenwaste). Annual output is 50,000 t compost, with the difference in weight due to moisture evaporation.

13 All the data in the following text are based on the information obtained in a personal contact with the owner of this composting firm.

A.7.1 System boundary



The energy consumption and emissions associated with green 'Transport' boxes are included in the LCA. A blue box denotes an avoided product.

A.7.1 Inventory description

Poultry litter transport

The composting plant receives poultry litter both directly from a poultry farm and from a manure broker. We assumed a maximum transport distance of 100 km.

Auxiliaries

Composting requires no additional heat, as this is produced in the composting process. Electrical power is needed for the air-scrubbing unit, though, which uses about 36.5 kWh/d for pumping and 39.9 kWh/d for the fans (DLG, 2010). We assumed 28,000 kWh/a. In natural composting, tractor are used to turn the compost. These use around 250 l diesel per week, so we took a figure of 13,000 l/a.

During forced composting the material is aerated with normal air. Energy requirements are unknown, but low according to the plant operator. We took them to be zero.

The air scrubber uses several cubic metres of water a week. We took a figure of 10 m^3/week, or 520 m^3/a.

Finally, phosphorus and/or potassium are sometimes mixed in with the compost to maintain a uniform NPK ratio. As this is only done rarely it has been ignored.

Energy production

Heat is produced in the composting process. This is not marketed at the moment, but used partly for the process.

Process emissions

All the emissions occurring during the composting process are treated in an air scrubber. Besides the NH_3 emission, which is within legal standards, no emissions are measured.

The scrubber treats 100,000 m^3 air per hour, keeping the NH_3 emission below the statutory limit of 5 mg/m^3 (Rijkswaterstraat, 2016). In the model we assumed a continuous process with an emission of 5 mg/m^3.

Marketed fertilizer materials

We assumed the same volume of water used in the air scrubber leaves the plant as drain water. This is used in the Netherlands as a fertilizer.

The compost is marketed mainly in France (90%), with the remainder going to Germany. We assumed it all goes to the north of France, for use as a fertilizer, with a transport distance of 300 km and with the truck returning with a full load of raw materials for the fodder industry. The truck was modelled on the basis of STREAM with a full load (CE Delft, 2011)[14].

Diesel fuel consumption for field application of the compost is based on the figure reported for manure application in an Ecoinvent report (Nemecek & Kägi, 2007).

Emissions during application

No data were found on emissions during spreading of compost from poultry litter. There are generally no NH_3 emissions when manure-based compost is spread (Plant Research International B.V., 2007). Field emissions of N_2O are 0.4% of the N in the compost (Bruggen, et al., 2015). No data on NO_3 leaching emissions from compost were found and we therefore took the same percentage as for direct application of poultry litter in the Netherlands per tonne of product applied.

Table 17 LCA inventory for composting and export to France per tonne of processed poultry litter

Item	Description	Quantity	Comments
Transport	Truck transport Truck transport	100 km 300 km	From poultry farmer to composting plant From composting plant to farmer in N. France
Process emissions	NH_3 CO_2	0.597 kg/t litter 16.5 kg/t litter	Continuous air-scrubber process, 100,000 m^3/h, NH_3 concentration in treated air 5 mg/m^3 Emissions from diesel consumption
Auxiliaries	Electricity Diesel Water	0.509 kWh/t litter 0.202 kg/t litter 9.45 litre/t litter	For air scrubbers For air scrubbers
Compost application	Diesel consumption	0.0531 kg/t compost	Tractor diesel consumption (Nemecek & Kägi, 2007).
Post-application emissions	N_2O NO_3	0.113 kg/t litter 7.97 kg/t litter	N_2O: 0.4% of N in compost (Bruggen, et al., 2015). NO_3: 10% of N in compost (CDM, 2013).
CO_2 fixation	Organic matter stored in soil	26.2 kg/t litter	
Avoided product	Calcium ammonium nitrate (N)	8.9 kg/t litter	Based on 35% 1-year efficacy

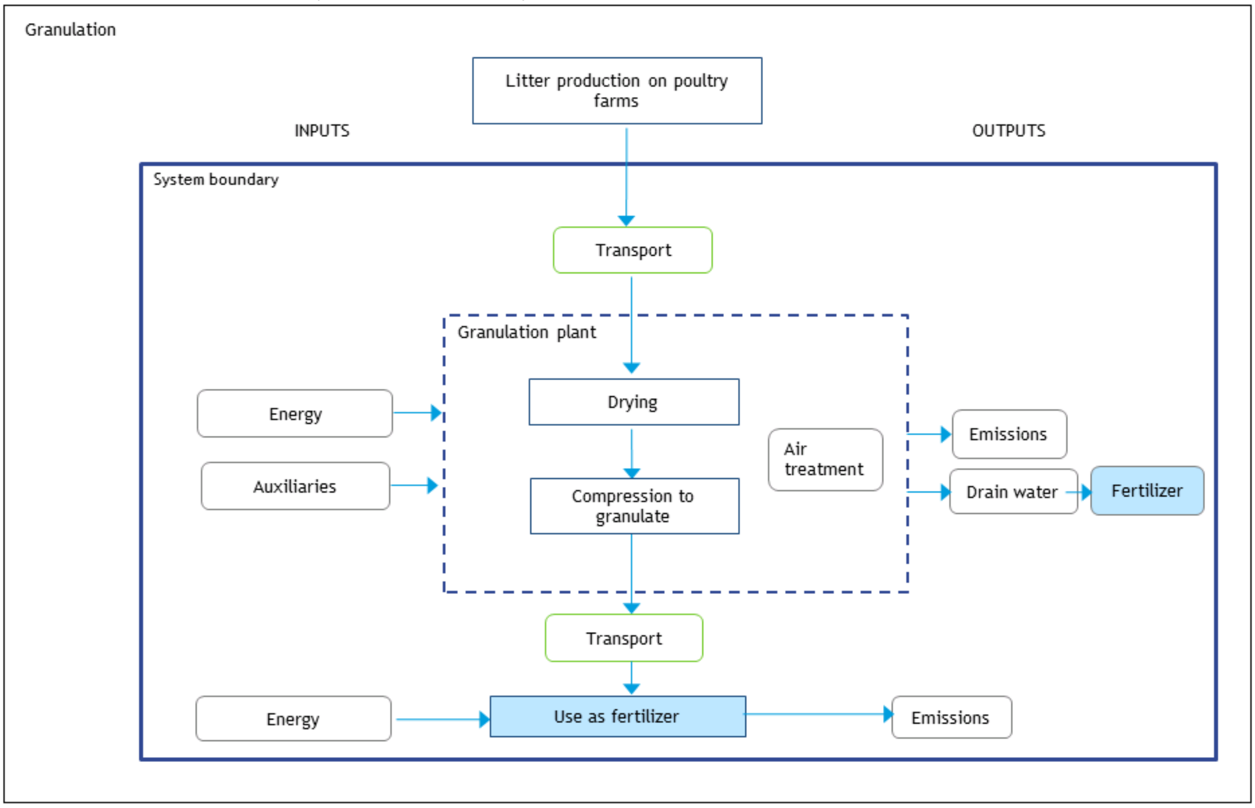
[14] We assumed a >20 t truck with heavy cargo with a full load on both trips.

Item	Description	Quantity	Comments
	Triple superphosphate (as P_2O_5) Potassium sulphate (as K_2O)	14.7 kg/t litter 21 kg/t litter	Based on 70% 1-year efficacy Based on 100% 1-year efficacy

A.8 Composting and granulation

Composting and granulation is operational at a number of plants in the Netherlands. Our model is based largely on the process used as Ferm O Feed, where in 2015 45,000 t poultry litter granulate was produced from 57,500 t poultry litter using a fluid-bed dryer.

A.8.1 System boundary



The energy consumption and emissions associated with green ‘Transport’ boxes are included in the LCA. A blue box denotes an avoided product.

A.8.1 Inventory description

Poultry litter transport

The Ferm O Feed poultry litter granulation plant is in North Brabant. As most Dutch poultry farmers are located in North Brabant, Gelderland, Overijssel and Limburg (CBS, 2016); (RVO, 2016) we took a maximum transport distance of 100 km.

Auxiliaries

Electrical power and natural gas consumption for the granulation process are about 65 kWh and 25 m^3 per tonne of processed poultry litter.

Little water is used in the granulation process: about 3.5 l/t litter.
Around 100 m^3 of sulphuric acid is used annually.

Process emissions
Per tonne of processed litter approx. 0.07 kg NH_3 and 0.19 kg NO_x are emitted.

Application of fertilizer substitutes
Besides the poultry litter granulate, Ferm O Feed markets around 250 m^3 drain water (nitrogen precipitated as ammonium sulphate) annually to Dutch farmers for use as a fertilizer.

The poultry litter granulate is marketed domestically and abroad: 3% in the Netherlands, 40% in southern Europe, 40% in Asia and 17% in the rest of the world. For transport, we assumed 50% is marketed in China and 50% in Spain. The granulate has an NPK ratio of 4-3-3.

The granulate marketed in Spain is transported 1,300 km to northern Spain. We assumed the truck also returns with a full load. Truck transport was modelled on the basis of STREAM with average load (CE Delft, 2011)[15].
The granulate for China is transported max. 100 km by truck to the nearest seaport, then 10,000 km by ship to China, where a further 500 km by truck is assumed. Both trucks are modelled on the basis of STREAM with average load (CE Delft, 2011)[16] with the same also holding for the ship (CE Delft, 2011)[17]. Neither return with a full load.

Diesel fuel consumption for field application of the granulate is based on the figure reported for manure application in an Ecoinvent report (Nemecek & Kägi, 2007).

Emissions during application
No data were found on emissions occurring during field application of poultry litter granulate. We therefore assumed the same evaporation and leaching percentages as for compost application.

Table 18 LCA inventory for composting, granulation and application abroad per tonne of processed poultry litter

Item	Description	Quantity	Comments
Transport	Truck transport Truck transport Truck transport Ship Truck transport	100 km 1,300 km 100 km 10,000 km 500 km	From poultry farmer to composting plant From granulation plant to farmer in N. Spain From poultry farmer to seaport From Dutch seaport to Chinese seaport From Chinese seaport to arable farmer
Process emissions	NH_3 NO_x CO_2	0.07 kg/t litter 0.19 kg/t litter 44.7 kg/t litter	Emissions from natural gas consumption
Auxiliaries	Electricity Natural gas Water Sulphuric acid	65 kWh/t litter 25 m^3/t litter 3.5 l/t litter 3.18 kg/t litter	
Granulate application	Diesel consumption	0.0531 kg/t granulate	Tractor diesel consumption (Nemecek & Kägi, 2007)
Post-application emissions	N_2O NO_3	0.203 kg/t litter 8.81 kg/t litter	N_2O: 0.65% of N in litter granulate NO_3: 10% of N in litter granulate

15 A >20 ton truck with heavy cargo was assumed.

16 A >20 ton truck with heavy cargo was assumed.

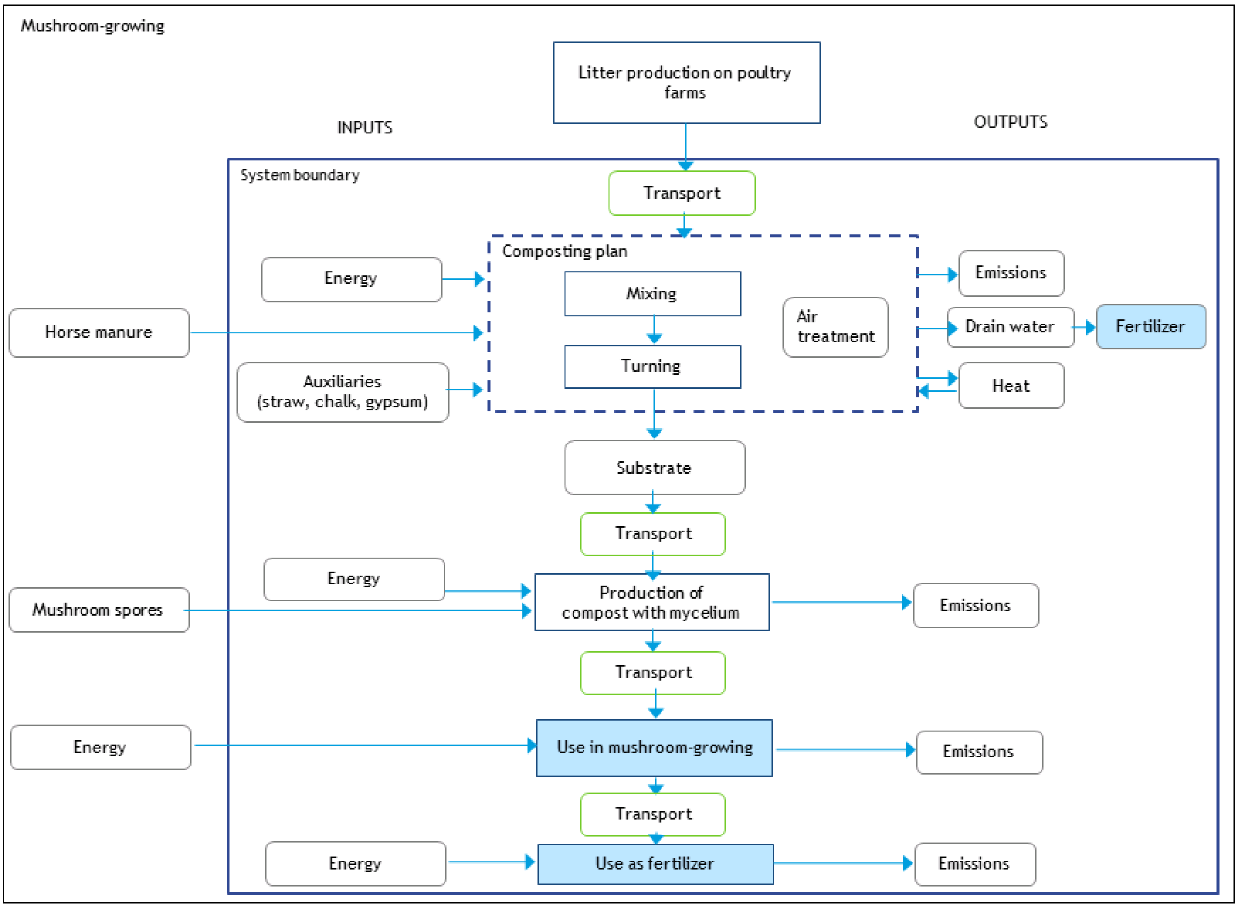
17 General Cargo 2-5 dwkt was assumed.

Item	Description	Quantity	Comments
CO_2 fixation	Organic matter stored in soil	50.5 kg/t litter	
Avoided product	Calcium ammonium nitrate (N) Triple superphosphate (as P_2O_5) Potassium sulphate (as K_2O)	9.1 kg/t litter 14.7 kg/t litter 21 kg/t litter	Based on 35% 1-year efficacy Based on 70% 1-year efficacy Based on 100% 1-year efficacy

A.9 Composting and application in mushroom-growing

Mushroom substrate is produced from poultry litter and horse manure at several sites in the Netherlands.

A.9.1 System boundary



The energy consumption and emissions associated with green 'Transport' boxes are included in the LCA. A blue box denotes an avoided product.

A.9.2 Inventory desciption

This route comprises the following steps:

1. Production of mushroom substrate.
2. Ammonia expulsion.
3. Addition of mushroom mycelium.
4. Mushroom-growing.
5. Marketing of compost.

On this route there is too little publicly available information to draw up a nutrient balance or perform an LCA. Our requests for information from mushroom-substrate producers went unheeded, while data on Step 3 was obtained from a single mushroom-processor. We have used public data. The collected was not sufficient to base a nutrient balance and LCA study on.

Below we set out what little we know about this route, state the open questions and make a qualitative comparison with the Composting route to give a sense of the status of the Mushroom-growing route among the others.

Known information

The information we managed to obtain on the constituent steps of this route is summarized below.

1. **Production of mushroom substrate**
   Besides poultry litter and horse manure, mushroom substrate production also requires straw, gypsum and water. Process water is also added, including the drain water (Walkro, 2016). Wheat straw is generally used. Mushroom substrate has a moisture content of 72% (Champignonverwerkend bedrijf, 2016).

2. **Ammonia expulsion and addition of mushroom mycelium**
   To process the substrate into the compost used for mushroom-growing, the ammonia is expelled using ammonia scrubbers and a wood-bark bed. This process takes about 5 days. The compost is then inoculated with the mushroom mycelium, which takes 16 days. In this latter process a nutrient supplement is also added (Walkro, 2016).

   During the second and third phase there is a 43% reduction in weight: 26.3% moisture and 16% organic matter (Champignonverwerkend bedrijf, 2016). The resultant compost has a moisture content of 63%. The nitrogen content of the dry-matter fraction is 2.5%, or 0.945% of the compost (Champignonverwerkend bedrijf, 2016).

3. **Mushroom-growing**
   Before mushrooms can be grown on the inoculated compost, one-third of the compost by weight is mixed with topsoil (NMIa, 2016). This topsoil consists of peat and filter-press residue. About 25% of the organic matter in the compost is used by the mushrooms, or 17% of the dry matter (Plant Research International, 2013).

   In the Netherlands inoculated compost as described above is always used. This mixture, which also contains poultry litter, proves to be a good nitrogen source. Although artificial fertilizer could in theory be used instead of poultry litter, this is not the case in practice (Champignonverwerkend bedrijf, 2016).

4. **Champost marketing**
   After harvesting of the mushrooms the remaining compost combined with the topsoil can be marketed as ‘champost’, though it must first be sterilized. It is sold as a soil improver; it is very stable and has a high organic matter content.

Missing information

No information is available on the following aspects:

- How much Phase 3 compost and champost is produced from 1 tonne of poultry litter?
- What fraction of the OM, EOM, N, P_2O_5 and K_2O in the champost can be allocated to 1 tonne of litter?
- What is the mushroom yield per tonne of litter?
- What could serve as a substitute for mushroom substrate?
- What are the energy and auxiliary requirements of the production process?
- What are the process emissions? If air scrubbers are used, how effective are they?
- What are the transport distances of the various (sub)products?

Given these open questions, it is impossible to draw up a nutrient balance or LCA for this route. Instead, we provide a qualitative comparison with the Composting route.

Qualitative comparison with composting route

Table 19 gives a qualitative idea of how this route compares with the Composting route plus application abroad in terms of transport, auxiliaries, emissions and avoided product.

Table 19 Comparison of LCA inventory for Composting (compost) and Composting for use in mushroom-growing (champost)

Item	Description	Comparison of compost & champost
Transport	From poultry farmer to processing to product From processing to product to product application	=, Transport similar +, Transport from substrate producer to mushroom-grower *and* from mushroom-grower to farmer
Process emissions	NH_3 CO_2	=, Ammonia lost in both, assuming air scrubbers equally effective +, Emissions from energy used for spreading at mushroom-grower
Auxiliaries	Electricity Diesel Water Other auxiliaries	+, More production steps +, More production steps +, More production steps +, Extra auxiliaries: wheat straw, chalk, topsoil (peat + filter-press residues) & nutrient supplement
Field application	Diesel consumption for agricultural application	=, Field application equivalent
Post-application emissions	N_2O NH_3 NO_3	-, Less nitrogen in champost than in compost
CO_2 fixation	Sequestration of organic matter in soil/mushrooms	?, Organic matter taken up partly by mushrooms, transferred partly to farmland in champost; insufficient data for weighting these

Item	Description	Comparison of compost & champost
Avoided product	Calcium ammonium nitrate (N) Triple superphosphate (as P_2O_5) Potassium sulphate (as K_2O)	?, No data on substitutes if poultry litter not used for mushroom-growing

Note: '=' means the two routes are comparable, '-' that composting and use in mushroom-growing has less environmental impact for the step concerned, '+' that this route has a greater environmental impact for the step concerned; '?' situation unclear.

As can be seen in Table 19, champost production involves more transport, more process emissions and more auxiliaries than normal compost production. On the other hand, post-application emissions are lower.

The greatest uncertainty relates to avoided product and CO_2 fixation.
The compost used for mushroom-growing can be used twice: first as mushroom substrate, then as champost by arable farmers. This means uncertainty on the following issues:
- Champost has a lower nutrient content than compost, as some of the nutrients have been taken up by the mushrooms. To determine the difference, we need data on the amount of champost produced from 1 tonne of poultry litter and on the nutrient fraction that can be allocated to the litter. In both cases such data was unavailable.
- Because mushrooms are only grown on materials categorized as waste, no 'avoided product' can be set for the mushroom substrate.
- The mushroom yield per tonne of poultry litter is also unknown.

Conclusion
Based on the qualitative analysis, the overall environmental burden of the Mushroom-growing route can be assumed to be at least similar to that of the Composting route and, given the numerous 'plusses', will probably exceed it.

As no energy is produced in the Mushroom-growing route, its environmental performance will be nowhere near that of the routes that do generate energy.

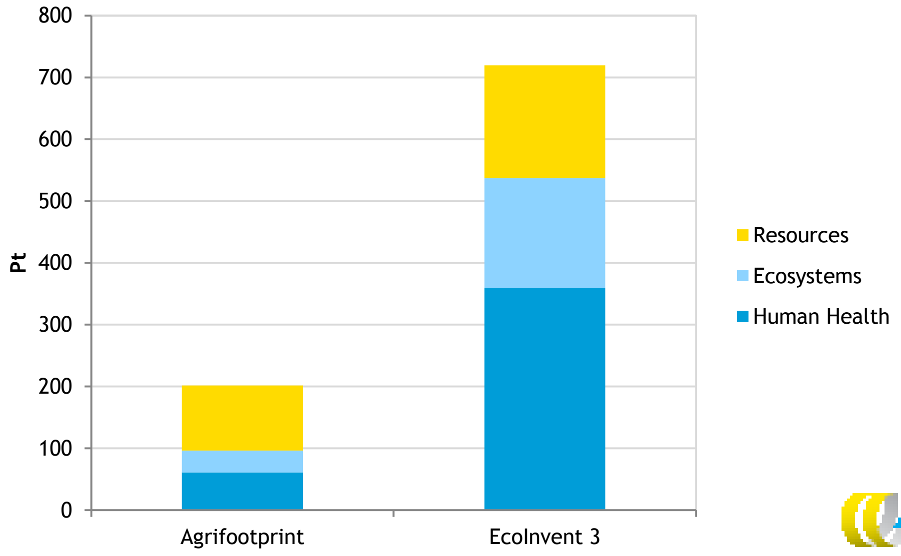
The environmental footprint of this route will depend above all on transport requirements and the amount of energy needed for the production process. No quantitative information is available on either, however.

Annex B Explanation of artificial fertilizer substitution

This appendix explains the choices made on type of fertilizer substituted.

For the nitrogen in the products, it was opted to use fertilizer substitution based on the calcium ammonium nitrate (CAN) as modelled in the Agrifootprint database (OCI Nitrogen variant).

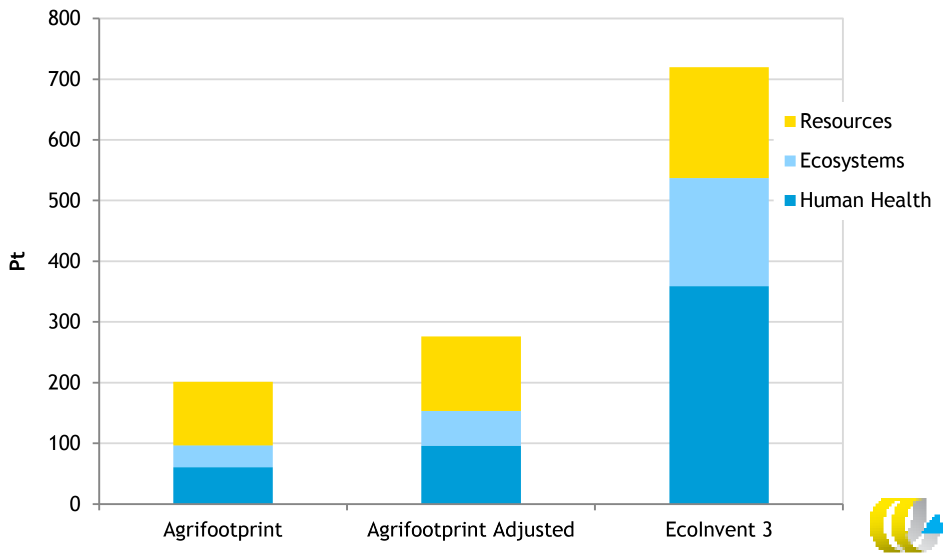
Figure 19 Comparison of CAN in Agrifootprint and Ecoinvent 3 database, per kg N



As shown in Figure 19, according to the Ecoinvent database CAN production has a 3.5 times greater environmental footprint than CAN production at OCI Nitrogen as cited in the Agrifootprint database. The main difference is in the N_2O emissions during nitric acid and ammonia production and the CO_2 emissions of energy consumption. These lower emissions can be explained by advances in CAN fertilizer production technology since 1998, the year on which the Ecoinvent 3 data are based.

What the Agrifootprint database does factor in is some of the CO_2 and heat output used by other firms on industrial estates. Because this is not always possible, however, as a variant we excluded this from the process. This gives the comparison shown in Figure 20.

Figure 20 Comparison of CAN in adjusted version of Agri-footprint and Ecoinvent 3 database, per kg N



Annex C Explanation of ReCiPe methodology

This appendix explains the ReCiPe methodology used for the Life-Cycle Assessment (LCA) in this study.

The ReCiPe LCA methodology was developed on a commission from the Dutch government and is widely used in the Netherlands for LCA studies. The ReCiPe methodology converts the long list of primary results into a set of indicators that are easier to interpret.

In this method, environmental impacts are reported at three levels:
- midpoints: problem-oriented environmental impacts such as global warming and acidification. The ReCiPe method has 17 midpoints;
- endpoints: damage-oriented impacts: on nature, humans and resources. The ReCiPe method translates the damage of the 17 midpoints into 3 endpoints;
- Single-Score: the weighted environmental-impact score of the 3 endpoints.

Midpoint level
The midpoint level, or environmental-impact level, is a direct translation from pollutant/emission to environmental impact. The midpoint level provides insight into the individual impacts and is characterized by a high level of transparency. The consequences of this score, the actual environmental damage, is not apparent, though. For this purpose the three endpoints (level 2) are more suitable.

Endpoint level
With the endpoint level, the environmental impacts are normalised and translated into damage. In the normalization step the impact is related to the impact of a European citizen in a year.

A certain score on ecotoxicity, for example, has an impact on biodiversity (a reduction), causing 'damage to ecosystems'. In the ReCiPe method environmental damage is grouped under three headings:
1. Damage to human health.
2. Damage to ecosystems.
3. Damage to resource availability.

Single-Score
The result of an LCA expressed as a Single Score is the sum total of the environmental damage at endpoint level, with each damage category weighted. The Single-Score result is thus a weighted final score of all the environmental damage combined.

Table 20 lists the environmental impacts reported quantitatively in this study's LCA.

Table 20 **Environmental impact categories, units and weighting according to ReCiPe**

Midpoints	Endpoints	Standard weighting for Single Score
Climate change, Human health (kg CO_2-eq.)	Human health (DALY)	40%
Ionising radiation (kBq U235-eq.)		
Ozone depletion (kg CFC-11-eq.)		
Terrestrial acidification (kg SO_2-eq.)		
Human toxicity (kg 1,4-DB-eq.)		
Photochemical oxidant formation (kg NMVOC)		
Particulate matter formation (kg PM_{10}-eq.)		
Marine eutrophication (kg P-eq.)	Ecosystems (species.year)	40%
Freshwater eutrophication (kg P-eq.)		
Climate change, Ecosystems (kg CO_2-eq.)		
Terrestrial ecotoxicity (kg 1,4-DB-eq.)		
Freshwater ecotoxicity (kg 1,4-DB-eq.)		
Marine ecotoxicity (kg 1,4-DB-eq.)		
Agricultural land occupation (m^2a)		
Urban land occupation (m^2a)		
Natural land transformation (m^2)		
Water depletion (m^3)		
Mineral resource depletion (kg Fe-eq.)	Resources ($)	20%
Fossil fuel depletion (kg oil-eq.)		

Source: (Goedkoop, et al., 2013).

Annex D Heavy metals, micronutrients

In our analyses, the heavy metals and micronutrients present in the end-products and ending up in the soil when the fertilizer materials are spread on farmland have been ignored. If these emissions had been included, their total impact for the BMC route would have been less than 0.1% of the overall environmental impact (Single-Score) and less than 1.5% for direct application of poultry litter in the Netherlands. In this appendix we discuss the issue.

In the routes involving incineration (1, 2, 4) some of these pollutants will be retained in flue-gas treatment units, with the remainder being emitted to the atmosphere. Based on our functional unit of 1 tonne of poultry litter, less of these pollutants will therefore end up on farmland and in soils. On the other hand, for proper comparison of the impact of farmland application of these pollutants it is better to compare what actually ends up on the land (surface) per hectare. In the Netherlands there are statutory limits in force (though not for animal manure) which lay down that a fertilizer material may not be applied at a level leading to application of over 80 kg phosphorus, 100 kg nitrogen, 150 kg potassium, 400 kg neutralising value or 3,000 kg organic matter per hectare, whichever is reached first. For poultry litter this is phosphorus.

Table 21 indicates the amounts of heavy metals and micronutrients in litter and ash, expressed in mg/kg P_2O_5. As can be seen, in the BMC ash these values are higher for some constituents and lower for others. Given the law of conservation of mass and the fact that BMC uses no auxiliaries that can affect ash composition, the differences cannot be significant. Because of differences in analysis methods and sample preparation, for example (see also the explanation in Annex F.1) the mass balance cannot be fully balanced, however.

The maximum permitted heavy-metal values are given in the last column of Table 21. Under these standards poultry litter ash may not be applied as a fertilizer in the Netherlands, because the copper and zinc concentrations per kg P_2O_5 are too high. It may be added, though, that these levels are almost identical to those in untreated poultry litter, for which no such ban is in force.

Given the above it was decided to ignore the heavy metals and micronutrients in our analysis.

Table 21 **Heavy-metal and micronutrient content of raw poultry litter and ash, mg/kg P_2O_5**

	mg/kg P_2O_5		BMC ash lower or higher?	Fertilizer Act (max. permitted value in mg/P_2O_5)[a]
	Raw litter	BMC ash		
As	<81	<22	↓	**375**
Cd	5.7	6.1	↑	**31.3**
Cr	271	95	↓	**1,875**
Cu	2,497	2,472	↓	**1,875**
Hg	<1	<0.5	↓	**18.8**
Ni	174	141	↓	**750**
Pb	<136	39	↓	**2,500**
Zn	12,214	12,726	↑	**7,500**

[a] Source: Fertilizer Act Implementation Decree, Annex II, Table 1 (Rijksoverheid, 2005).

Other emissions to the soil and (atmospheric) emissions of cadmium (Cd), mercury (Hg) have been included in the environmental impact analysis, as have all other emissions.

Annex E Carbon fixation

Because carbon-containing material (litter, compost, poultry litter granulate, digestate) is sold to and applied by farmers, some fraction of the carbon will be sequestered in arable soils for a longer period of time. The carbon in the effective organic matter (EOM) that remains in the soil for 100 years is said to be ‘fixed’ there.

The amount of EOM carbon fixed in 100 years was calculated using a rough approximation of organic matter decomposition and formation and decomposition of soil organic matter, using the Roth-C model.

In the Roth-C model biomass is taken to be a combination of readily decomposable organic material (DPM) and material that is less so (RPM). Both types of plant material are broken down into CO_2, microbial biomass (BIO) and humified organic matter (HUM). In Roth-C the ratio of HUM to BIO is set at 46:54%. In turn, both these decomposition products (BIO and HUM) are converted to a mixture of CO_2, BIO and HUM.

Decomposition proceeds according to the relationship (Coleman & Jenkinson, 1999):

$$C_t = C_{t=0} \cdot e^{a \cdot b \cdot c \cdot k \cdot t}$$

where:
- a, b, c are factors describing the influence of temperature, soil moisture content and vegetation cover;
- k is a fixed decomposition rate for each type of organic material: 10 for DPM, 0.3 for RPM, 0.66 for BIO and 0.02 for HUM;
- t is the time (in years) since the start of the decomposition process.

In this study the factors a, b and c were not used, so that no allowance was made for differences in:
- the moisture regime in the soils where the fertilizer materials are applied;
- the soil temperatures in the areas concerned;
- the nitrogen and phosphorus available for formation of soil organic matter;
- the aging of the organic matter involved in the decomposition process.

The ratio between CO_2, BIO and HUM is determined by soil clay content and given by the following relationship (Krull, et al., 2001):

$$\frac{CO_2}{(BIO+HUM)} = 1.67 \cdot (1.85 + 1.60 \cdot e^{-(0.0786 \cdot \%clay)})$$

In this study a clay content of 35% was assumed.

Annex F Nutrient balance calculations

Table 22 gives the composition of the BMC feedstock mix, the ash and the litter when this is spread on soils untreated. The quantities of ash, compost, litter granulate and digestate shown in the table refer to the amounts produced per tonne of BMC feedstock mix.

Table 22 Composition of products that can be used as a fertilize substitute

Litter-processing method	Direct application	BMC & poultry farmer	Composting	Granulation	Digestion
Product description	BMC feedstock mix	Poultry litter ash	Compost and drain water	Litter granulate and drain water	Digestate
Quantity (kg/t litter)	1,000	141[18]	1,212 compost and 10 drain water[19]	636 granulate and 5 drain water[20]	1,570[21] of which 810 from poultry litter[22]
Organic matter, OM (kg/t litter)	458[23]	0	408[24]	414[25]	327[26], of which 266 from poultry litter [27]
Effective Organic Matter,	161[28]	0	206	207	93[29]

18 In 2015 BMC produced 62 kt poultry-litter ash that was marketed as a fertilizer, with a total of 438 kt litter being processed. 62/438 = 141 kg (rounded).

19 Based on information obtained in personal contact with the owner of a Dutch composting firm. There is around 10% moisture loss in the composting process. The feedstock consists of 75% poultry litter (broiler chicken litter and manure-belt litter). In combination with the 25% other manure that is added, 1.2 t compost can therefore be produced from 1 t poultry litter. Around 520 m^3 drain water is produced annually, i.e. 0.01 m^3/t compost produced. 0.01 * 1.212 * 1.1 t/m^3 drain water = 0.0139 t, of which we allocate 75% to the poultry litter: 0.75 * 0.0139 = 10 kg drain water.

20 Based on information from Ferm O Feed, which uses a feedstock consisting solely of poultry litter, 78% of which ends up in the granulate. The feedstock has a dry-matter content 23% higher than that of the BMC feedstock mix. This means 19% (=1-(100/123)) less granulate can be produced from the BMC mix. 78% * 81% * 1 t = 640 kg (rounded). Around 250 m^3 drain water is produced annually: 0.004 m^3 per tonne of feedstock. 0.004 m^3 * 1.1 t/m^3 drain water = 5 kg drain water.

21 From 1 tonne of feedstock (50% fodder maize silage, 50% poultry litter) 785 kg digestate is produced. For 1 tonne of litter this is therefore 2 * 785 kg = 1,570 t.

22 The reduction in mass of the poultry litter fraction of the digestate is 19%, so for every tonne of litter 810 kg ends up in the digestate.

23 Median composition of BMC feedstock mix (BMC Moerdijk, 2015).

24 The values for most of the compost produced at the Dutch composting firm are 340 kg OM, 20 kg N, 20 kg P_2O_5 and 20 kg K_20 per tonne of compost. The feedstock is 75% poultry litter, so from 1 t litter around 1.2 t compost is produced. The OM, N, P_2O_5 and K_20 values were therefore multiplied by 1.2, with 75% allocated to the poultry litter. The compost has a humification coefficient of 50% (NMIa, 2016), giving 206 kg EOM.

25 Based on information from Ferm O Feed. The OM content of the granulate is 65%. This was multiplied by the amount of granulate produced from 1 tonne of poultry litter. The granulate has a humification coefficient of 50% (NMIa, 2016), giving 207 kg EOM.

26 From 500 kg poultry litter and 500 kg maize silage a digestate is produced with 208 kg OM. From 1 tonne of poultry litter digestate can therefore be produced containing 208 * 1,570 = 327 kg OM.

27 The poultry litter has 46% OM. The reduction in mass of the poultry litter fraction of the digestate is 19%, so for every tonne of litter around 810 kg ends up in the digestate. If this entire loss is allocated to the OM fraction, this means that the amount of OM remaining is 1 - ((1000*46%)-(1000*19%) / (1000*46%)) = 42%. Processing 1 t poultry litter then gives 458 * (1-42%) = 266 kg OM in the digestate.

Litter-processing method	Direct application	BMC & poultry farmer	Composting	Granulation	Digestion
EOM (kg/t litter)					
N (kg/t litter)	26	0	18.2 compost, 0.1 drain water[30]	19.9 granulate, <0.05 drain water[31]	26.4[32]
P_2O_5 (kg/t litter)	21	17.7[33]	18.2	13.4[34]	14.8[35]
K_2O (kg/t litter)	21	16.7	18.2	15.0[36]	21[37]

Table 23 Nutrient efficacy of products that can be used as a fertilizer substitute

Litter-processing method	Direct application	BMC & poultry farmer	Composting	Granulation	Digestion
Product description	BMC feedstock mix	Poultry litter ash	Compost and drain water	Litter granulate	Digestate
Efficacy coefficient, N, 1-year	55% [b]	N.a.	35% compost, 100% drain water[b]	35% granulate, 100% drain water[b]	55% [b]
Efficacy coefficient, N, long-term	70% [b]	N.a.	60% [b]	60% [b]	70% [b]

28 The EOM of the BMC feedstock mix is 35% of the OM, the average for the EOM of poultry-bedding and broiler-chicken litter (CBAV, 2016a). 35% * 458 kg = 160 kg.

29 The humification coefficient of the digestate is 35% (NMIa, 2016), giving 266 * 35% = 93 kg EOM.

30 One tonne of composting drain water contains 80 kg nitrogen (INAGRO, 2015). This was multiplied by the amount of drain water per tonne of poultry litter composted.

31 The N-content of the feedstock used for granulation by Ferm O Feed is 35% higher than at BMC. It was assumed that the amount of N ending up in the granulate is proportional to the feedstock N-content. The N-content of the granulate is 4.2%. 42 * (100/135) = 31. This value was multiplied by the amount of granulate produced from 1 tonne of poultry litter. One tonne of composting drain water contains 80 kg N (INAGRO, 2015), which was multiplied by the amount of drain water per tonne of litter granulated.

32 One tonne of digestate from poultry litter contains 19.3 kg N (NMIa, 2016), of which 87% is from the litter. So for each tonne of litter processed, 19.3 * 87% * 1.57 = 26.4 kg N ends up in the digestate.

33 The BMC poultry litter ash contains 12.5% P_2O5 and 11.8% K_2O. This was multiplied by the amount of ash produced per tonne of litter processed.

34 The Ferm O Feed granulation feedstock has a 43% higher P_2O_5-content than the BMC feedstock mix. We assumed the amount of P_2O_5 ending up in the granulate is proportional to the P_2O_5-content of the feedstock. The P_2O_5-content of the granulate is 3%. 30 * (100/143) = 21. This value was multiplied by the amount of granulate produced per tonne of poultry litter processed.

35 One tonne of digestate from poultry litter contains 14.4 kg P_2O_5 (NMIa, 2016), of which 94% derives from the litter. This was multiplied by the amount of digestate produced from 1 t litter. Per tonne of litter processed this gives 14.4 * 1.57 * 0.9% = 14.8 kg P_2O_5.

36 The feedstock used by Ferm O Feed for granulation has a 19% higher K_2O-content than the BMC feedstock. We assumed the amount of K_2O ending up in the granulate is proportional to the K_2O-content of the feedstock. The K_2O-content of the granulate is 2.8%. 28 * (100/119) = 23.5. This value was multiplied by the amount of granulate produced per tonne of poultry litter processed.

37 One tonne of digestate from poultry litter contains 16.6 kg K_2O (NMIa, 2016), of which 83% derives from the litter. This was multiplied by the amount of digestate produced from 1 t litter. Per tonne of litter processed this gives 16.6 * 1.57 * 0.83 = 21.6 kg K_2O available to crops. As this is more than the incoming maximum of 21 kg per t litter, this was rounded down to 21 kg.

Litter-processing method	Direct application	BMC & poultry farmer	Composting	Granulation	Digestion
Efficacy coefficient, P_2O_5, relative to triple superphosphate, 1-year	70% a	37 c - 100% [d]	70% [b]	70 [b]	70% [b]
Efficacy coefficient, P_2O_5, relative to triple superphosphate, long-term	100% [a]	100%[38]	100% [b]	100% [b]	100% [b]
Efficacy coefficient, K_2O	100% [b]	100% [e]	100% [b]	100% [b]	100% [b]

[a] (CBAV, 2016b), b: (NMIa, 2016), c: (Alterra Wageningen UR, 2015a), d: (Alterra Wageningen UR, 2015b), e: (Alterra Wageningen UR, 2015c).

Combining Table 22, we obtain the active nutrient data shown in Table 24.

Table 24 Active nutrients in products that can be used as a fertilizer substitute

Litter-processing method	Direct application	BMC & poultry farmer	Composting	Granulation	Digestion
Product description	BMC feedstock mix	Poultry litter ash	Compost	Litter granulate	Digestate
Active N, 1-year (kg/t litter)	14.3	0	6.4 compost, 0.1 drain water	6.9 granulate, <0.05 drain water	14.4
Active N, long-term (kg/t litter)	18.2	0	10.9 compost, 0.1 drain water	11.9 granulate, <0.05 drain water	18.3
Active P_2O_5, 1-year (kg/t litter)	14.7	6.5-17.7	12.7	9.3	14.8
Active P_2O_5, long-term (kg/t litter)	21.0	17.7	18.2	13.3	21.0
Active K_2O (kg/t litter)	21.0	16.7	18.2	15.0	21.0

F.1 Measurements of phosphorus and potassium in the BMC Moerdijk ash

Phosphorus (expressed as P_2O_5) and potassium (expressed as K_2O) are valuable constituents of both poultry litter and poultry litter ash and BMC analyses the levels in both feedstock and ash. It transpires that the figures for the incoming and outgoing streams do not match, though: there is structurally more P and K in the poultry litter than in the ash. In this section we provide a possible explanation.

Phosphorus and potassium cannot disappear

All the phosphorus and potassium coming into the BMC plant must also leave it. The various constituents of the poultry litter feedstock end up in the ash and flue gases and, to a very minor extent, in the off-spec ash (271 t) and the residues removed when the plant is cleaned during maintenance (521 t in 2015). Potassium and phosphorus are not released with the flue gases (they do not form gases condensing above 135°C) and so must end up in the ash and residues collected during maintenance (which are analysed and found to be present in insufficient quantities to explain the discrepancy). In other words, the law of conservation of mass dictates that virtually all the P and K ends up in the ash.

[38] Long-term P_2O_5 efficacy of poultry litter ash: oral information from Phillip Ehlert (Alterra).

Laboratory data

The analyses from several laboratories may provide a possible explanation for this discrepancy, involving the following issues:

- Use of different spectroscopic methods (ICP-MS and ICP-AES) may yield different results.
- The discrepancy may be associated with sample preparation, which entails dilution, acid digesting, extraction, slurry sampling and analysis of the direct samples. The main errors that are likely to occur are sample contamination, degradation and matrix outages.
- Owing to the intense heating and the oxidation reaction that occurs, some elements may be lost because they do not remain oxygen-bound.
- The high temperature of ICP can ionize much of the potassium. If the samples have a high Na-level (or even Rb-level), this could reduce the K ionization relative to the K in the standards, possibly leading to incorrect K-readings.

Data validation

The phosphorus content of the poultry litter (as P_2O_5) is well in line with the values used by the Netherlands Enterprise Agency, RVO (RVO, 2015b). However, if one compares the P-content of litter from Belgian and Dutch broiler chickens, for example, the figure used in Belgium is 14.1 kg P_2O_5 per tonne of litter, which is 2.5 kg/t or 15% less (Vlaamse Land Maatschappij, 2016). It is unclear whether these figures can be compared, though. With respect to the ash, the results from three different labs are lower than to be expected based on the analyses of a single lab.

As the values measured in the litter are in agreement with (RVO, 2015b) we can assume these figures are correct. In that case, one possible explanation for the structurally lower ash analyses is that P and K are captured on the grains of sand in the fluid bed as extremely hard layers of calcium phosphate and potassium silicate. When the grains are ground for analysis, it may be the case that not all P and K is freed up (BMC Moerdijk, 2016b).

Assumption in this study

In this study CE Delft assumed that the P- and K-contents measured in the litter are correct, as these measurements are in line with (RVO, 2015b). These contents were therefore used for both the litter and the ash.

Annex G LCA results

This annex reports the quantitative results of the LCA.

G.1 Single-Score results

Table 25 Single-Score results, Routes 1 to 4

	BMC	Poultry farmer	Digestion	Biomass plant
Storage emissions	n.a.	n.a.	0.21 Pt	n.a.
Poultry litter transport	1.54 Pt	0 Pt	7.71Pt	1.61 Pt
Process emissions	1.20 Pt	0.92 Pt	0.97 Pt	1.01 Pt
Direct emissions	0.57 Pt	0.56 Pt	0.97 Pt	0.54 Pt
Auxiliaries	0.62 Pt	0.36 Pt	0 Pt	0.38 Pt
Waste processing	0 Pt	0 Pt	n.a.	0.09 Pt
Energy production	-23.25 to -26.49 Pt	-12.49 to -31.32 Pt	-17.33 - to -31.05	-23.82 to -32.63 Pt
Heat	0 to -3.24 Pt	0 to -18.83 Pt	0 to -6.86	0 to -8.81 Pt
Electricity	-23.25 Pt	12.49 Pt	-17.33	-23.82 Pt
Fertilizer transport	0.52 Pt	0.22 Pt	0.26 Pt	n.a.
Fertilizer application	-5.99 to -10.74 Pt	-6.68 Pt to -8.38 Pt	-2.08 Pt	n.a.
Direct emissions	0 Pt	0 Pt	13.40 Pt	n.a.
Fertilizer savings	-5.99 to -10.74 Pt	-6.68 Pt to -8.38 Pt	-13.57 Pt	n.a.
CO_2 fixation	n.a.	n.a.	-1.92 Pt	n.a.
Other	0 Pt	n.a.	n.a.	n.a.
TOTAL	**-25.98 tot - 33.97 Pt**	**-18.10 tot -38.45 Pt**	**-10.26 tot -17.12 Pt**	**-21.19 tot -30.00 Pt**

Table 26 Single-Score results, Routes 5 to 8

	Direct application - NL	Direct application - DE	Composting	Granulation
Storage emissions	1.06 Pt	1.06 Pt	0 Pt	0 Pt
Poultry litter transport	2.10 Pt	7.01 Pt	1.40 Pt	1.58 Pt
Process emissions	n.a.	n.a.	1.81 Pt	9.02 Pt
Direct emissions	n.a.	n.a.	1.75 Pt	2.48 Pt
Auxiliaries	n.a.	n.a.	0.06 Pt	6.54 Pt
Waste processing	n.a.	n.a.	n.a.	n.a.
Energy production	n.a.	n.a.	n.a.	n.a.
Heat	n.a.	n.a.	n.a.	n.a.
Electricity	n.a.	n.a.	n.a.	n.a.
Fertilizer transport	n.a.	n.a.	2.35 Pt	13.13 Pt
Fertilizer application	-8.30 Pt	-3.18 Pt	-12.45 Pt	-12.32 Pt
Direct emissions	8.37 Pt	13.49 Pt	1.55 Pt	2.70 Pt
Fertilizer savings	-13.50 Pt	-13.50 Pt	-11.39 Pt	-12.77 Pt
CO_2 fixation	-3.16 Pt	-3.16 Pt	-2.61 Pt	-2.25 Pt
Other	n.a.	n.a.	n.a.	n.a.
TOTAL	**-5.14 Pt**	**4.89 Pt**	**-6.89 Pt**	**11.42 Pt**

G.2 Midpoint results

Table 27 Midpoint results

	Climate change (kg CO_2-eq)	Human toxicity (kg 1,4-DB-eq)	Mineral resource depletion (kg Fe-eq)	Particulate matter formation (kg PM_{10}-eq)	Fossil fuel depletion (kg oil-eq)
BMC	-2.91E+02	-1.02E+02	-1.14E+01	-1.87E-01	-9.29E+01
Poultry farmer	-1.70E+02	-4.89E+01	-6.42E+00	-5.35E-02	-6.89E+01
Digestion	-1.17E+02	-8.95E+01	-1.16E+01	1.37E+00	-6.27E+01
Biomass plant	-2.54E+02	-6.23E+01	-1.34E+00	-3.44E-02	-7.84E+01
Direct application – NL	-1.00E+02	-5.12E+01	-1.22E+01	7.56E-01	-3.15E+01
Direct application - DE	-1.59E+00	-4.99E+01	-1.20E+01	1.43E+00	-1.38E+01
Composting	-7.63E+01	-4.86E+01	-1.11E+01	6.06E-02	-2.54E+01
Granulation	1.13E+02	-3.83E+01	-1.04E+01	5.11E-01	2.41E+01

G.3 Relative share of midpoints in Single Score

Table 28 Relative contribution of midpoints to Single-Score

	BMC	Poultry farmer	Digestion	Biomass plant	Direct application - NL	Direct application - DE	Composting	Granulation
Climate change, Human health	-30%	-30%	-38%	-33%	-48%	-1%	-28%	35%
Ozone depletion	0%	0%	0%	0%	0%	0%	0%	0%
Human toxicity	-5%	-4%	-8%	-3%	-12%	-16%	-9%	-6%
Photochemical oxidant formation	0%	0%	0%	0%	0%	0%	0%	0%
Particulate matter formation	-4%	-5%	37%	-2%	68%	172%	4%	29%
Ionizing radiation	0%	0%	0%	0%	0%	0%	0%	0%
Climate change, Ecosystems	-19%	-19%	-24%	-21%	-31%	-1%	-18%	22%
Terrestrial acidification	0%	0%	1%	0%	1%	3%	0%	0%
Freshwater eutrophication	0%	0%	0%	0%	0%	0%	0%	0%
Terrestrial ecotoxicity	0%	0%	0%	0%	0%	1%	0%	0%
Freshwater ecotoxicity	0%	0%	0%	0%	0%	0%	0%	0%
Marine ecotoxicity	0%	0%	0%	0%	0%	0%	0%	0%
Agricultural land occupation	0%	-1%	-1%	0%	-3%	-4%	-2%	-2%
Urban land occupation	-1%	-1%	-2%	0%	-6%	-8%	-4%	-4%
Natural land transformation	0%	0%	0%	0%	0%	2%	0%	1%
Mineral resource depletion	-2%	-2%	-4%	0%	-10%	-13%	-7%	-5%
Fossil fuel depletion	-38%	-39%	-60%	-40%	-58%	-34%	-36%	29%

In green, midpoint categories contributing over 10% to the Single Score.

G.4 Midpoint share, BMC

Table 29 Midpoint share, BMC

Midpoint	Unit	Total	Other	Poultry litter transport	Direct process emissions	Auxiliaries	Electricity production	Fertilizer transport	Fertilizer savings
Climate change	kg CO_2-eq.	-2.91E+02	-1.53E-02	1.61E+01	3.78E+00	3.36E+00	5.10E-02	-2.71E+02	5.67E+00
Ozone depletion	kg CFC-11-eq.	-9.73E-06	-4.34E-09	2.92E-06	0.00E+00	9.89E-07	8.05E-10	-8.51E-06	7.99E-07
Terrestrial acidification	kg SO_2-eq.	-6.26E-01	-1.61E-04	8.52E-02	1.98E-01	1.74E-02	5.74E-05	-4.57E-01	3.89E-02
Freshwater eutrophication	kg P-eq.	-1.34E-01	-6.39E-06	2.57E-04	0.00E+00	4.05E-04	1.47E-05	-9.85E-02	7.17E-05
Marine eutrophication	kg N-eq.	-3.04E-02	-2.36E-05	4.91E-03	1.31E-02	4.69E-04	3.75E-04	-3.85E-02	2.34E-03
Human toxicity	kg 1,4-DB-eq.	-1.02E+02	-8.38E-03	4.05E-01	9.15E-01	6.42E-01	2.87E-02	-6.30E+01	1.10E-01
Photochemical oxidant formation	kg NMVOC	-1.57E-01	-2.04E-04	1.27E-01	3.34E-01	1.22E-02	5.26E-05	-4.43E-01	6.03E-02
Particulate matter formation	kg PM_{10}-eq.	-1.87E-01	-2.18E-04	3.49E-02	7.53E-02	5.74E-03	2.16E-05	-1.49E-01	1.64E-02
Terrestrial ecotoxicity	kg 1,4-DB-eq.	1.72E-02	-1.69E-06	2.20E-02	1.64E-04	4.18E-04	3.77E-06	-1.65E-03	6.04E-03
Freshwater ecotoxicity	kg 1,4-DB-eq.	-2.94E+00	-3.72E-04	3.01E-02	5.71E-06	2.15E-02	1.14E-02	-1.56E+00	8.26E-03
Marine ecotoxicity	kg 1,4-DB-eq.	-2.80E+00	-3.46E-04	8.82E-02	8.06E-04	2.27E-02	1.01E-02	-1.58E+00	2.41E-02
Ionizing radiation	kBq U235-eq.	-5.34E+01	-2.81E-02	1.13E+00	0.00E+00	4.03E-01	2.21E-03	-4.83E+01	3.09E-01
Agricultural land occupation	m^2a	-3.93E+00	-1.53E-02	3.01E-02	0.00E+00	6.26E+00	2.70E-04	-4.11E+00	8.11E-03
Urban land occupation	m^2a	-5.72E+00	-4.54E-04	2.69E-02	0.00E+00	9.65E-02	3.17E-04	-1.18E+00	7.05E-03
Natural land transformation	m^2	-4.45E-02	-3.70E-06	5.70E-03	0.00E+00	2.34E-03	-1.53E-06	-4.66E-02	1.56E-03
Water depletion	m^3	-6.80E+00	-2.67E-03	2.65E-02	0.00E+00	1.04E+00	-1.05E-02	-6.22E+00	7.26E-03
Mineral resource depletion	kg Fe-eq.	-1.14E+01	-3.78E-03	7.52E-02	0.00E+00	1.15E-01	1.71E-03	-1.41E+00	2.05E-02
Fossil fuel depletion	kg oil-eq.	-9.29E+01	-4.49E-03	5.48E+00	0.00E+00	2.30E+00	1.77E-03	-8.39E+01	1.50E+00

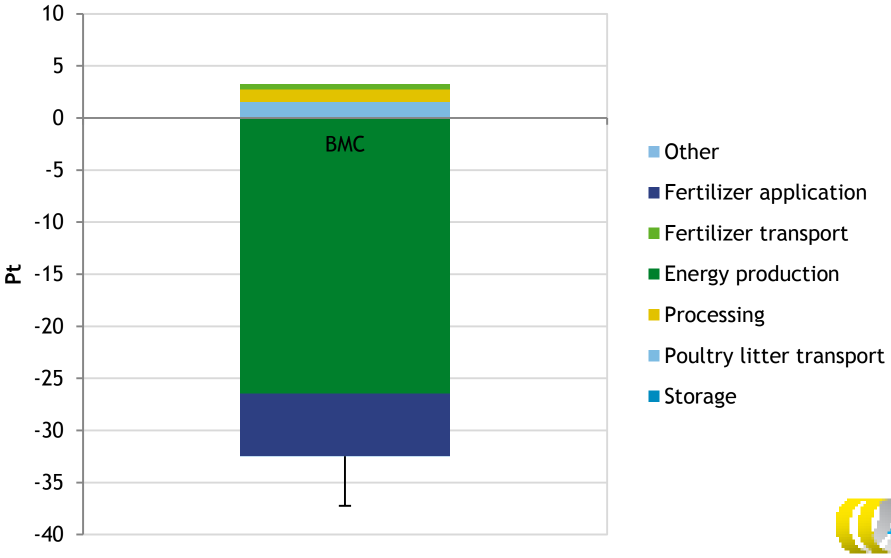
Annex H Results for BMC Moerdijk

In this appendix we consider the Single-Score results for BMC Moerdijk in more detail and describe the results at midpoint level. The terms 'Single Score' and 'midpoint level' are explained in Annex C. We also compare the results presented in this report with those of an earlier study carried out in 2001.

H.1 Single-Score results and contribution analysis

Figure 21 shows the results for thermal conversion of poultry litter at BMC Moerdijk. As is immediately clear, the environmental benefits (the negative score) far outweigh the environmental burden (the positive score).

Figure 21 Single-Score results for BMC Moerdijk



From Figure 22, on the following page, it can be seen that the environmental benefit (90% of the total environmental impact) derives largely from electric power generation, with fertilizer savings also making a sizable contribution.

Figure 22 Positive contribution of BMC Moerdijk (90%)

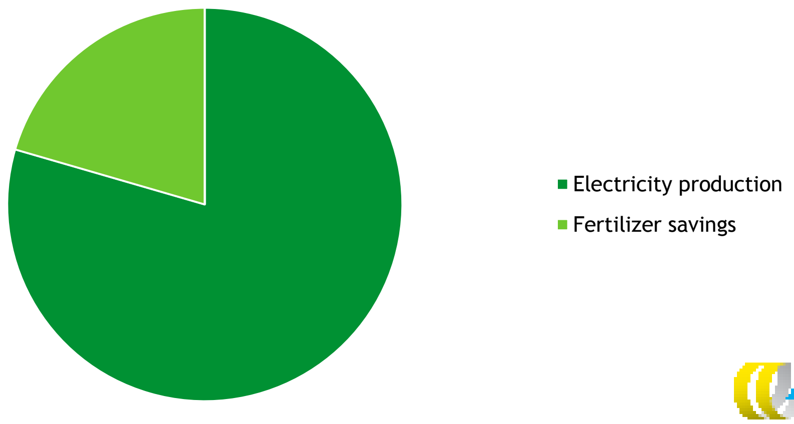
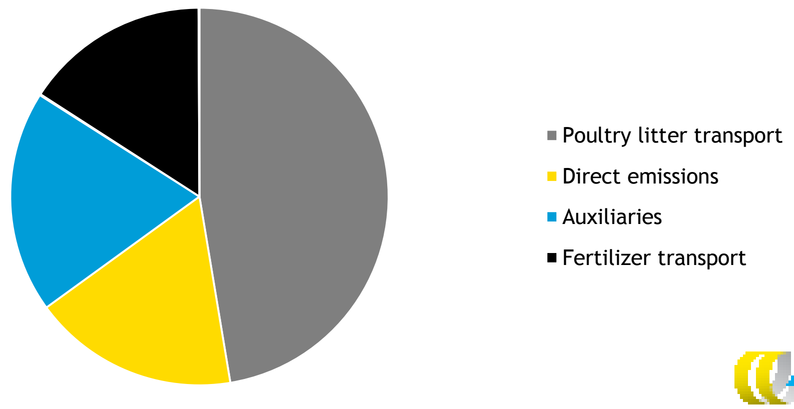


Figure 23 shows the environmental burden (10% of the total environmental impact). Most of this burden is due to the CO_2 and NO_x emissions associated with transporting the poultry litter and poultry litter ash and the use of fossil fuels to do so. The rest of the environmental burden derives from the direct CO_2 and NO_x emissions during thermal conversion of the litter and production of the various raw materials and auxiliaries. The direct CO_2 emissions during thermal conversion depend on consumption of diesel fuel or natural gas.

Figure 23 Negative contribution of BMC Moerdijk (10%)



The items 'Auxiliaries' and 'Direct emissions' are detailed further in Figure 24 and Figure 27.

Figure 24 shows the share of the various auxiliaries used by BMC in the overall environmental burden of the process. As auxiliaries together contribute only about 2% to the overall burden, each is responsible for only a very minor share, with none contributing more than 1%. There are differences, though, with diesel fuel and wood chips contributing most: around 0.5% each.

Figure 24 Share of auxiliaries production in overall burden of BMC Moerdijk (approx. 2%)

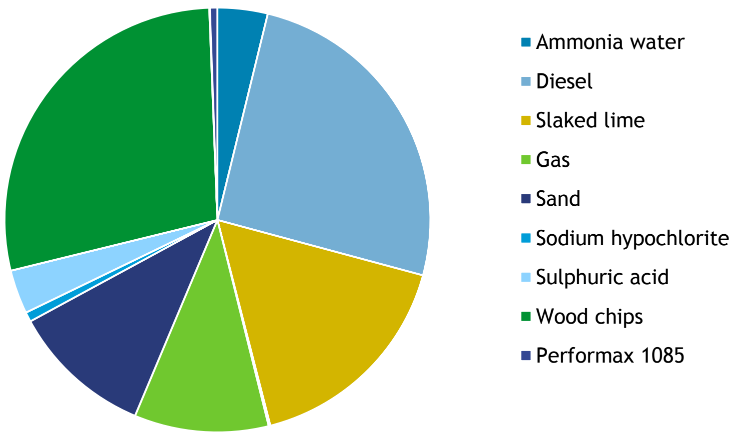
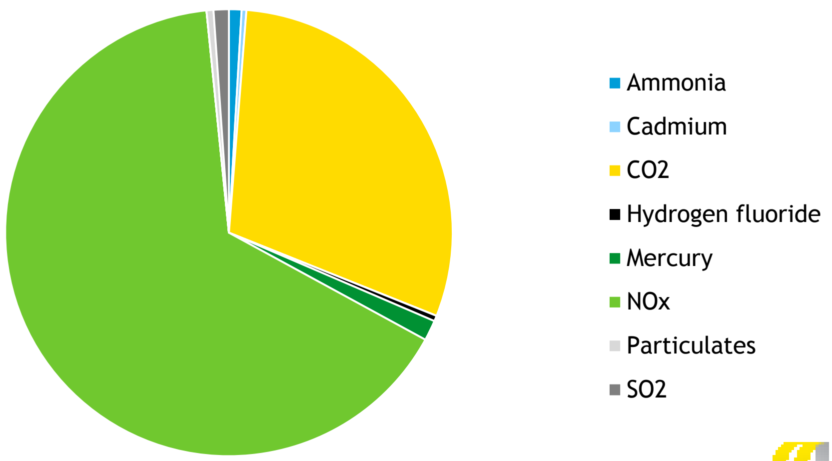


Figure 25 shows the contribution of direct emissions at BMC Moerdijk to the overall environmental burden. It can be seen that NO_x contributes most, at around 1.3%, followed by CO_2, at around 0.6%. The share of the other direct emissions is negligible.

Figure 25 Share of direct emissions in overall burden of BMC Moerdijk (approx. 2%)



H.2 Sensitivity analysis for thermal conversion at BMC Moerdijk

The results of the contribution analysis were used to decide what sensitivity analyses should be performed. For the BMC-route we examined those processes contributing more than 1% of the aggregate environmental burden.

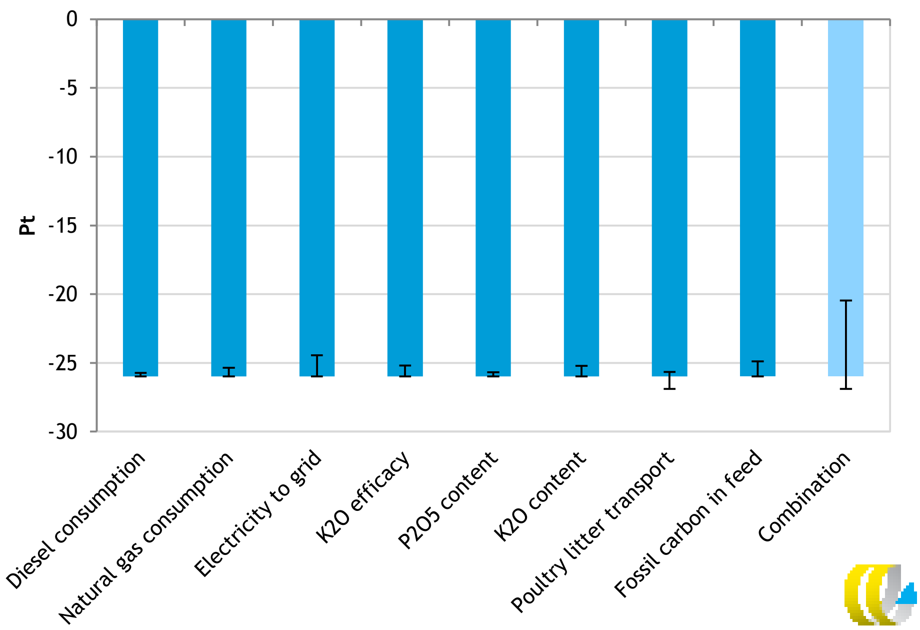
Table 30 Synopsis of sensitivity analyses for BMC

Sensitivity analysis	Description
Diesel fuel consumption	Varying from 446,875 to 824,713 l/a between 2010 and 2015 (BMC Moerdijk, 2016a).
Natural gas consumption	Varying from 246,945 to 1,682,936 m^3/a between 2010 and 2015 (BMC Moerdijk, 2016a).
Electrical power to grid	Varying from 0.54 to 0.58 MWh/t processed litter between 2010 and 2015 (BMC Moerdijk, 2016a).
K_20 efficacy	80 to 100%.
P_2O_5 content of poultry litter ash	18 to 21 kg/t litter. Given the discrepancy between the quantity of P_2O_5 measured in the litter and litter ash, we based ourselves on the content actually measured in the latter.
K_2O content of poultry litter ash	17 to 21 kg/t litter. Given the discrepancy between the quantity of K_2O measured in the litter and litter ash, we based ourselves on the content actually measured in the latter.
Poultry litter transport distance	Varying from 50 to 150 km.

Table 30 shows that the initial conclusions on thermal processing of poultry litter at BMC are fairly robust. In combination, the various sensitivity analyses indicate that the environmental benefits of the BMC process may be 16% lower. This is due mainly to the variation in the amount of electricity supplied to the grid. Between 2010 and 2014 this was less than in 2015. The variation in diesel and natural gas consumption from 2010 to 2015 makes little difference to the overall environmental benefits. The same holds for the P_2O_5 content, K_2O content and K_2O efficacy of the poultry litter ash.

The environmental benefits can be further increased by 2% by acquiring litter from poultry farmers close to Moerdijk, to decrease the transport distance.

Figure 26 Sensitivity analysis for thermal conversion at BMC Moerdijk



H.3 Midpoint results

Table 31 shows the relative contribution of the LCA results at midpoint level, or environmental-impact level, for thermal conversion at BMC Moerdijk. The results at this level provide insight into the impacts of the main links in the overall chain.

The results are reported here as a percentage of the total burden per environmental category. The impacts cannot be mutually compared, because the damage they give rise to cannot be seen in these figures. A positive relative contribution means an environmental burden, a negative score an environmental benefit.

The percentages marked blue in the table indicate that the direct emissions of litter processing at BMC Moerdijk and the transport of the litter and litter ash give rise to a significant burden for four environmental impact categories compared with the others: terrestrial acidification, marine eutrophication, photochemical oxidant formation and particulate matter formation.

The percentages marked red in the table indicate that the fertilizer savings due to use of the litter ash contributes significantly to the environmental benefits in the impact categories urban land occupation and metals depletion relative to the others.

The percentage marked green indicates that auxiliaries production contributes significantly in the impact category agricultural land occupation. This is due to the inclusion of wood chips in the BMC feedstock.

The percentages marked orange indicate that the direct emissions of litter transport contribute significantly in the impact category terrestrial ecotoxicity.

With all the other environmental impact categories it can be seen (in purple) that the savings on power production contribute most to the environmental benefits of the BMC route.

Table 31 **Relative share of midpoint results for BMC Moerdijk**

	Poultry litter transport	Direct process emissions	Auxiliaries	Electricity production	Fertilizer transport	Fertilizer savings
Terrestrial acidification	7%	15%	1%	-36%	3%	-39%
Marine eutrophication	7%	18%	1%	-53%	3%	-18%
Photochemical oxidant formation	10%	27%	1%	-36%	5%	-27%
Particulate matter formation	8%	17%	1%	-33%	4%	-38%
Terrestrial ecotoxicity	55%	0%	1%	-4%	15%	-25%
Urban land occupation	0%	0%	2%	-20%	0%	-78%
Mineral resource depletion	1%	0%	1%	-12%	0%	-86%
Agricultural land occupation	0%	0%	38%	-25%	0%	-37%
Climate change	5%	1%	1%	-78%	2%	-14%
Ozone depletion	15%	0%	5%	-44%	4%	-31%
Freshwater eutrophication	0%	0%	0%	-73%	0%	-27%
Human toxicity	0%	1%	1%	-60%	0%	-38%
Freshwater ecotoxicity	1%	0%	1%	-50%	0%	-47%
Marine ecotoxicity	3%	0%	1%	-51%	1%	-44%
Ionizing radiation	2%	0%	1%	-85%	1%	-12%
Natural land transformation	9%	0%	4%	-73%	2%	-12%
Water depletion	0%	0%	12%	-70%	0%	-18%
Fossil fuel depletion	5%	0%	2%	-75%	1%	-16%

H.4 Comparison with results from 2001

In 2001 CE Delft carried out a study entitled ‘De netto CO_2-emissie van hergebruik en energieproductie uit afval vergeleken’ (A comparison of the net CO_2 emissions of waste recycling and use for energy production), in which thermal conversion of poultry litter was also assessed. This section explains the differences between the 2001 study and the present study from 2016 (referred to as ‘the new study’).

Functional unit

The 2001 study was based on a feedstock of litter from laying hens (25%) and broiler chickens (75%). The dry-matter content of this unprocessed feedstock (raw litter, including any sawdust from the sheds) is approximately 22%.

The new study is based on a mixture of 52% broiler chicken litter, 40% laying hen litter, 5% turkey litter and 3% manure-belt litter (= laying hen litter). The dry-matter content of this unprocessed feedstock is 57%.

Routes

In the 2001 study the following routes were assessed:
- co-firing poultry litter in a coal-fired power station;
- power generation in a plant burning poultry litter;
- heat and power generation in a cogeneration plant burning poultry litter;
- direct application of raw poultry litter in parts of the Netherlands with a nutrient deficit;

– direct application of shed-dried poultry litter in the Netherlands;
– direct application of raw poultry litter abroad;
– direct application of shed-dried poultry litter abroad;
– composting of poultry litter and application abroad;
– thermal drying of poultry litter and application abroad.

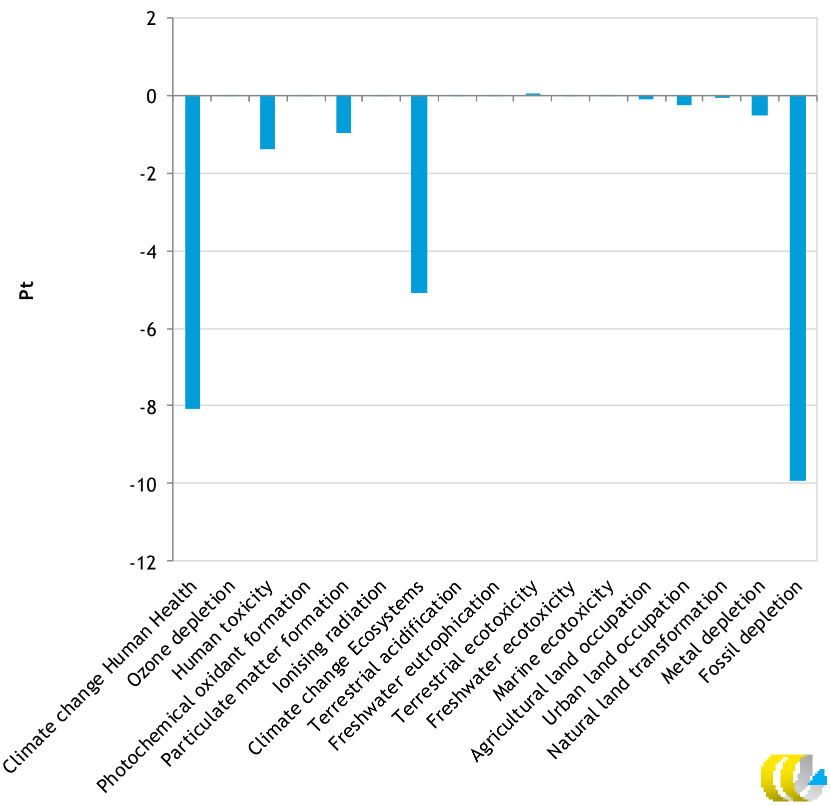
Of these routes, the new study only considers power generation in a plant burning poultry litter, direct application of raw poultry litter in the Netherlands and abroad, and composting of poultry litter and application abroad. The new study also assesses co-firing in a biomass plant, thermal conversion on a poultry farm, composting with granulation, and processing in a digestion plant. In addition, in a number of routes the effect of additional generation of useful heat was also considered.

Environmental impacts

In the 2001 study the only environmental impact considered was climate change, i.e. CO_2 emissions. The new study considers all the environmental impacts covered by ReCiPe LCA methodology.

Figure 27 summarizes which environmental impacts contribute most to the overall environmental benefits of the basic route: thermal conversion at BMC Moerdijk. As the figure shows, the impact 'climate change' contributes 49% to the total benefits, a combination of Climate Change, Human Health (30%) and Climate Change, Ecosystems (19%). An additional 39% comes from (avoided) 'fossil fuel depletion'. The remaining 12% is due to other (avoided) environmental impacts such as Human toxicity (5%), Particulate matter formation (3%) and Metals depletion (2%).

Figure 27 Relative share of environmental impacts in Single Score for BMC Moerdijk



Energy consumption for litter-drying

The 2001 study took a dry-matter content of 22% for the raw litter from the poultry shed and assumed it needed to be further dried to 60% prior to thermal conversion. For direct application of the raw litter no further drying was assumed.

The new study works with the actual poultry litter feedstock mix used at BMC Moerdijk. The dry-matter content of this mix is 57% and so requires no further drying. The dry-matter content of the broiler chicken and laying-hen litter used directly for field application is over 60% and so requires no additional drying either (CBAV, 2016a). This litter comes straight from the shed and is now considerably dryer than was the case in 2001 thanks to the use of air-conditioned sheds. This air conditioning is for meat and/or egg production and so does not need to be allocated to the litter.

Since drying the litter from 22% to 60% dry-matter content went a long way to determining the CO_2 emissions in the 2001 study, the inventory and modelling, and consequently the results, of the two studies cannot be compared.

CO_2 emissions versus CO_2 fixation

The 2001 study reported that the total CO_2 emissions of applying poultry litter as a fertilizer are the same as those of incinerating it. In the new study it was assumed that when raw litter is applied as a fertilizer, some of the carbon is fixed in the soil through addition of organic matter, with the remainder released as short-cycle CO_2.

Results

In the 2001 study it was concluded that thermal conversion of poultry litter is better for the environment than direct application of the raw litter (whether in the Netherlands or abroad) and thermal drying. Thermal conversion scored worse than composting with field application abroad, though.

In the new study, too, it is concluded that thermal conversion of poultry litter at BMC Moerdijk is better than direct application of the raw litter. However, it has now been shown that thermal conversion is in fact better than composting with application abroad, owing to the major environmental benefits of energy production. Because the new study uses a different functional unit, the extra drying step allocated to thermal conversion in the 2001 study is unnecessary. This means more electricity production, which affects the results.

Conclusion

The new study cannot be properly compared with the 2001 study because a different functional unit was used, with a different dry-matter content.
The new study works with the actual feedstock mix used in 2015 at BMC Moerdijk. As this mix has a 57% dry-matter content, no additional drying is required.

Another difference is that the 2001 study considered only the CO_2 emissions, while the new study takes on board all the environmental impacts in the ReCiPe LCA methodology, leading to entirely different results. Finally, the 2001 study did not factor in soil carbon fixation, which is included in the present study.

Together, these issues lead to a different outcome: in the new study, thermal conversion scores better than composting with application abroad, in contrast to what was concluded in the 2001 study, where composting scored better.

In both studies, however, thermal conversion of poultry litter scores better than direct application of the raw litter, both domestically and abroad.

Annex I Contribution analyses

The contribution analysis was elaborated for each of the other routes, focusing on those processes contributing over 5% to the total environmental burden. For a better understanding of the respective contributions of the various links in the chain we consider both the positive and negative impacts.

I.1 Thermal conversion on a poultry farm

Figure 28 shows that for thermal conversion on a poultry farm 2/3 of the positive contribution (94% of the total environmental impact) derives from electricity production and 1/3 from fertilizer savings from use of the poultry litter ash by farmers.

Figure 28 Positive contribution, thermal conversion on a poultry farm (94%)

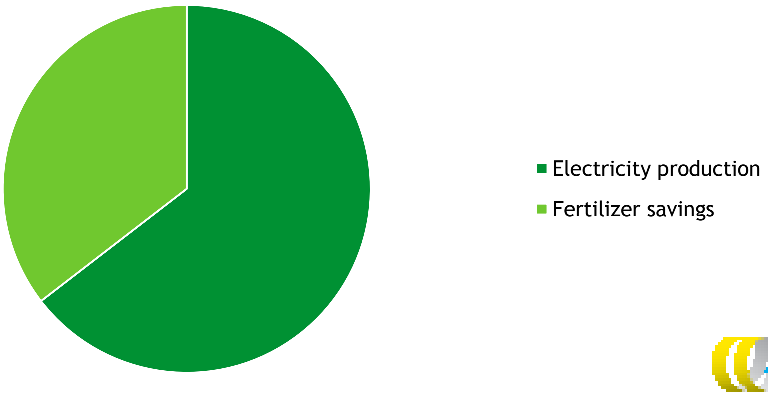
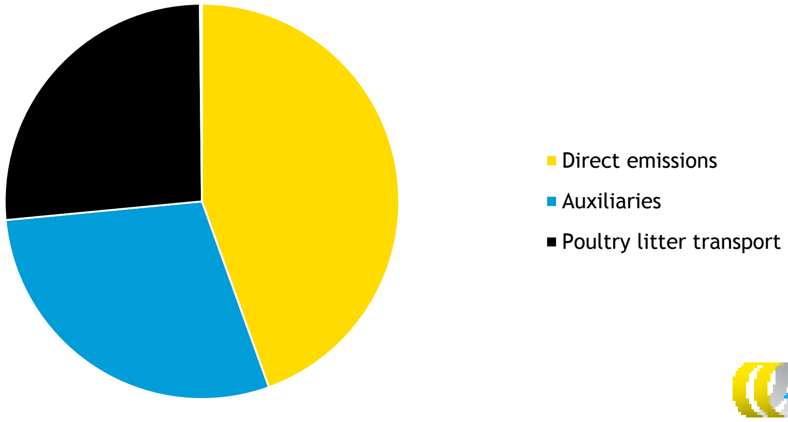


Figure 29 shows that the negative contribution for thermal conversion on a poultry farm (6% of the total environmental impact) derives mainly from direct process emissions, although auxiliaries and litter transport also contribute.

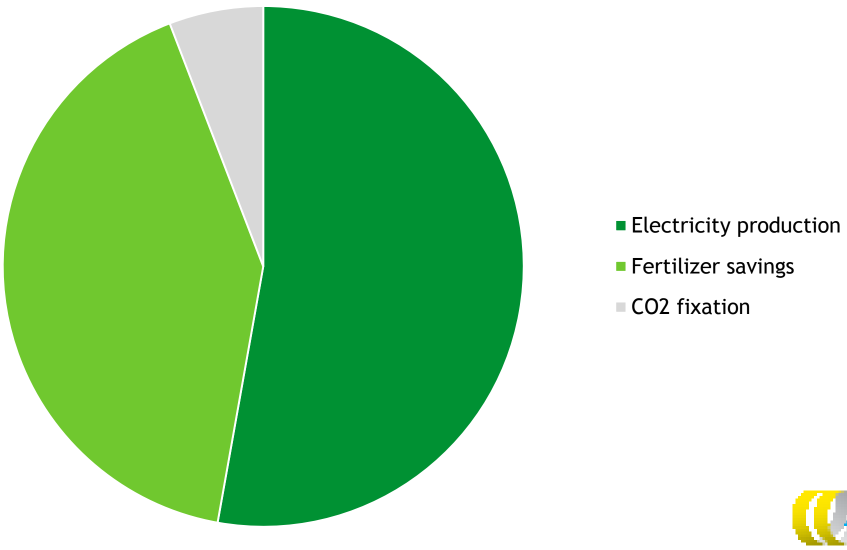
Figure 29 **Negative contribution, thermal conversion on a poultry farm (6%)**



I.2 Co-digestion in German digestion plant

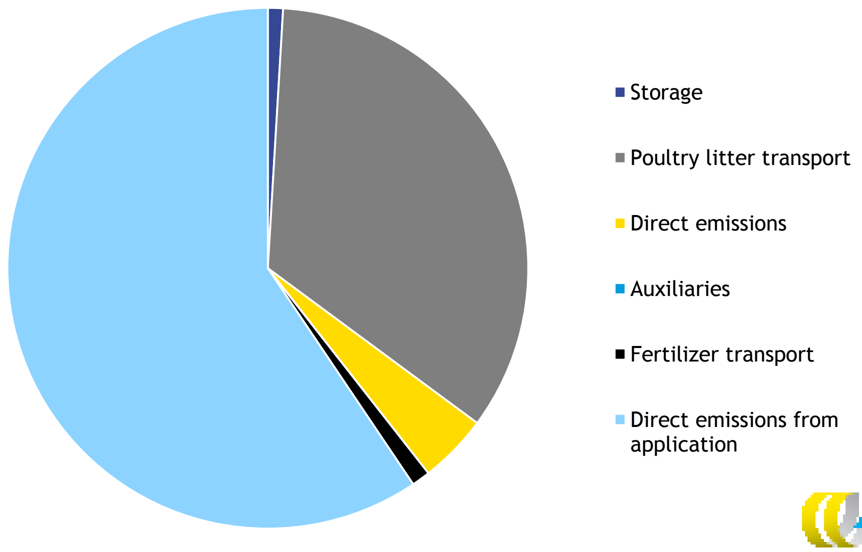
In the poultry litter digestion route, around half the positive contribution (60% of the total environmental impact) derives from electricity production. Fertilizer savings from farmland use of the digestate contributes about 20%, while CO_2 fixation in soils also has a positive effect, as Figure 30 shows.

Figure 30 **Positive contribution, co-digestion in German digestion plant (60%)**



The negative contribution (40% of the total environmental impact) is shown in Figure 31. Half derives from fertilizer application, particularly through evaporative NH_3 and N_2O emissions. Poultry litter transport also accounts for a substantial share.

Figure 31 **Negative contribution, co-digestion in German digestion plant (40%)**



I.3 Co-firing in a biomass plant

With co-firing poultry litter in a biomass plant, the positive contribution (90% of the total environmental impact) derives entirely from energy production, as seen in Figure 32.

Figure 32 **Positive contribution, biomass plant (90%)**

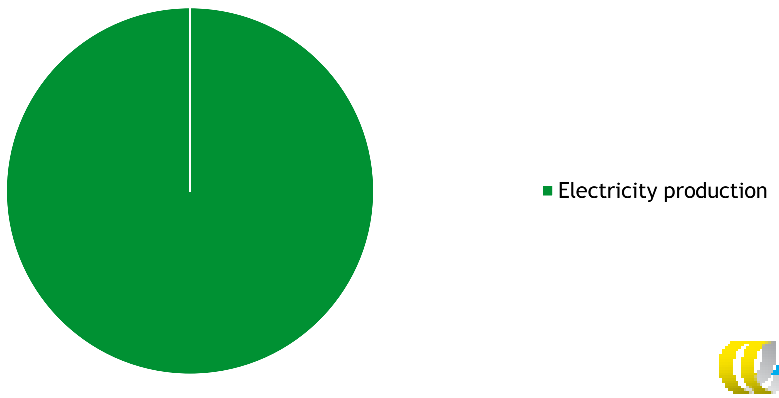
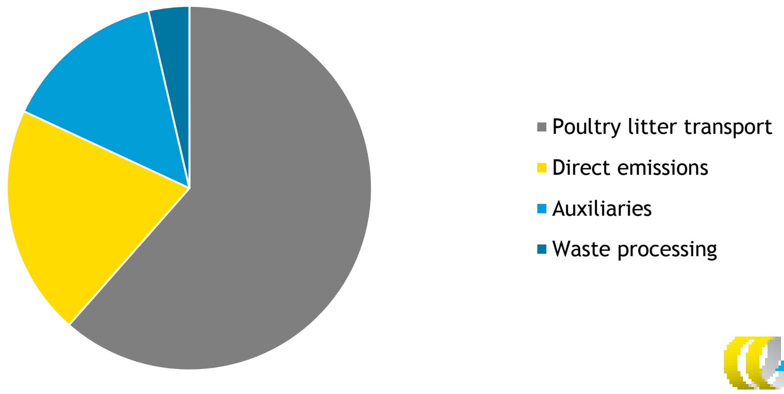


Figure 33 shows the negative contribution for biomass-plant processing (10% of the total environmental impact). The bulk is due to the CO_2 and NO_x emissions during litter transport and the direct NO_x, particulate and ammonia emissions from the biomass plant. The other factors, including the individual auxiliaries, contribute less than 1% to the total environmental impact.

Figure 33 Negative contribution, biomass plant (10%)



I.4 Direct application of raw litter in the Netherlands

With direct application of raw litter in the Netherlands, the positive contribution (60% of the total environmental impact), shown in Figure 34, derives mainly from fertilizer savings, with a smaller contribution from soil CO_2 fixation.

Figure 34 Positive contribution, direct litter application - NL (60%)

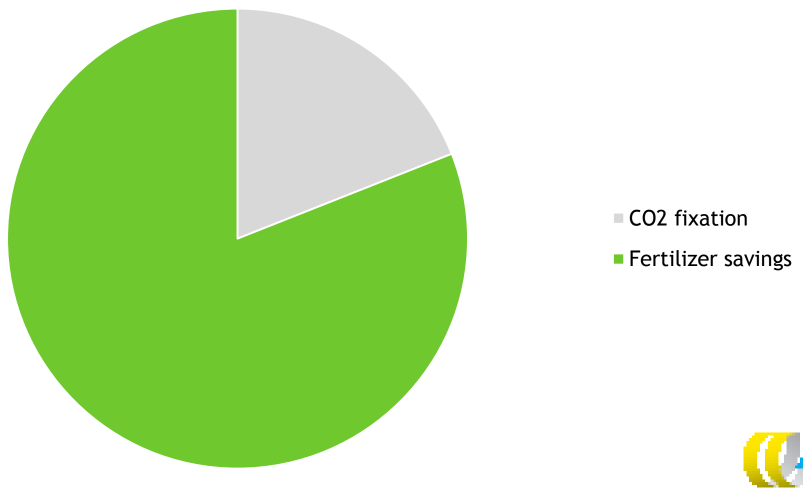
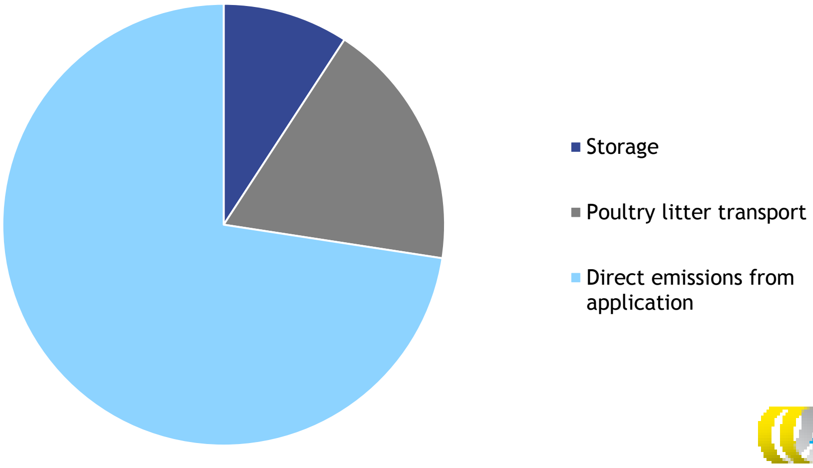


Figure 35 shows the negative contribution for direct application of raw litter in the Netherlands (40% of the total environmental impact). Most derives from direct evaporative NH_3, N_2O and CH_4 emissions. Most important under the heading 'litter transport' is the transport from the broker to the farmer.

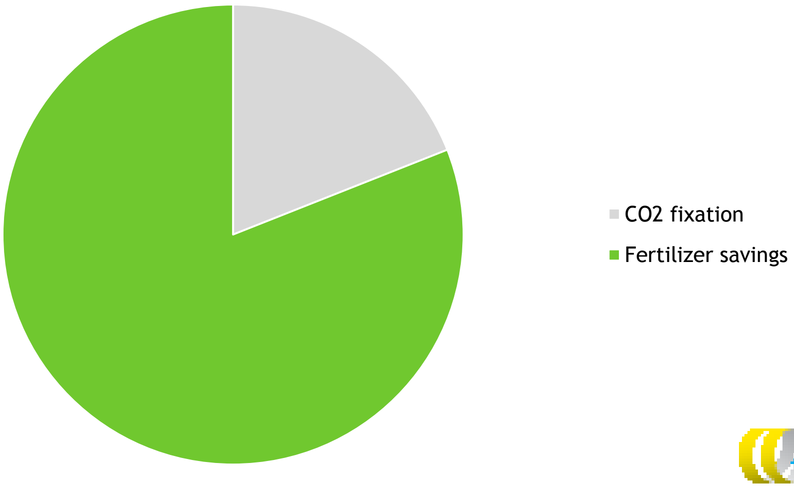
Figure 35 Negative contribution, direct litter application - NL (40%)



I.5 Direct application of raw litter in Germany

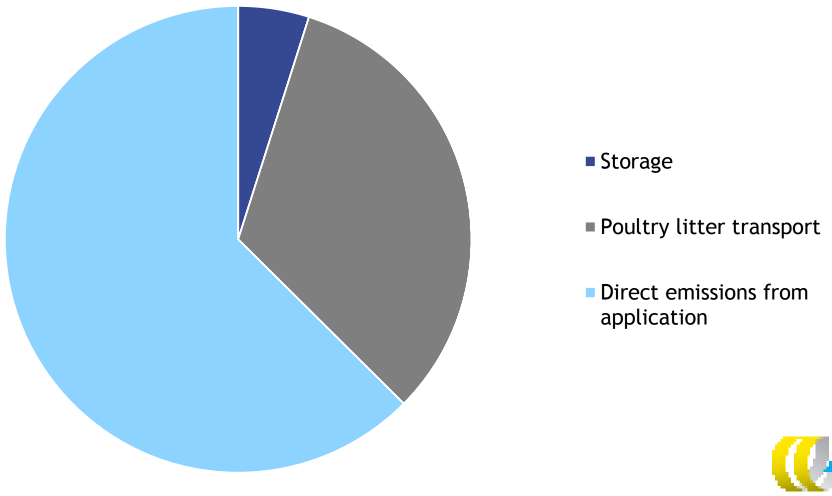
Figure 36 shows the positive contribution for direct application of raw litter in Germany (45% of the total environmental impact). The bulk is due to fertilizer savings, with the rest due to soil CO_2 fixation.

Figure 36 Positive contribution, direct litter application - DE (45%)



The negative contribution (55% of the total environmental impact) is shown in Figure 37. The contribution of ‘storage’ is due to NH_3, N_2O and CH_4 emissions. Most important under the heading ‘litter transport’ is the transport from the broker to the receiving farms in Germany. During field application the main emissions are NH_3 and N_2O due to evaporation from the litter.

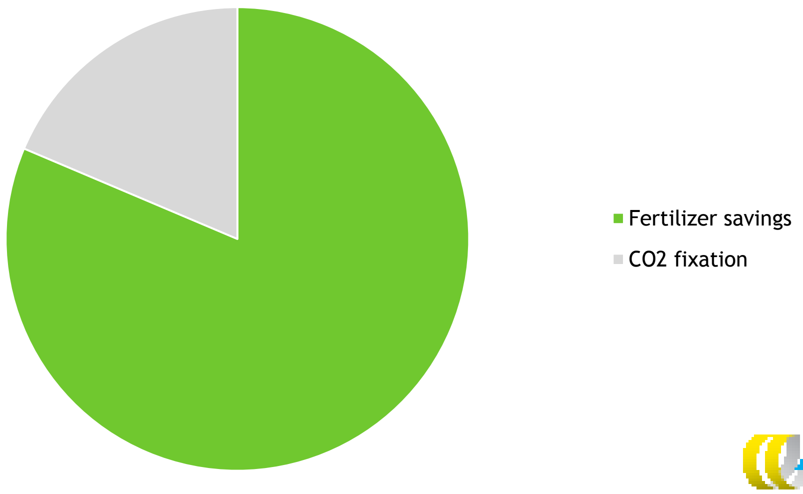
Figure 37 Negative contribution, direct litter application - DE (55%)



I.6 Composting with application abroad

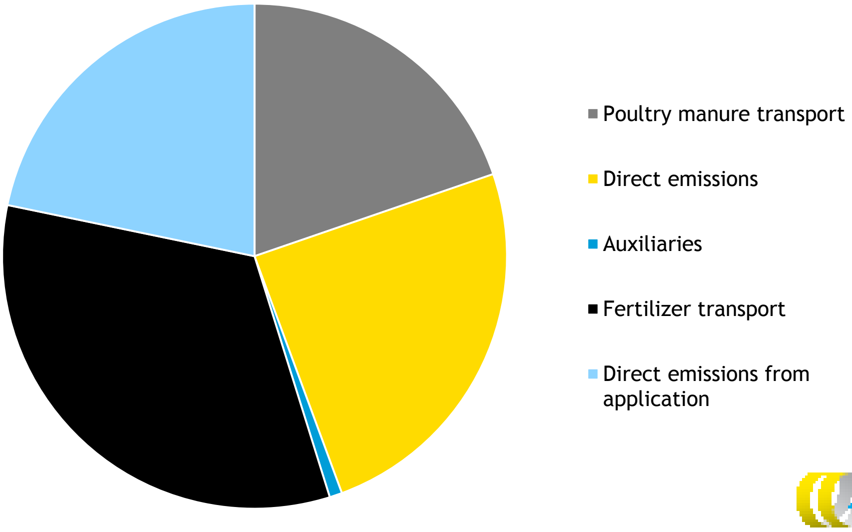
With poultry-litter composting and application in France, the positive contribution (67% of the total environmental impact) derives mainly from fertilizer savings, with a smaller contribution from soil CO_2 fixation, as Figure 38 shows.

Figure 38 Positive contribution, composting with use abroad (67%)



The negative contribution (33% of the total environmental impact) is shown in Figure 39. The main emission in field application is N_2O. As the compost is sent to France, transport accounts for a relatively large share. Direct process emissions also make a significant contribution: half of these are ammonia emissions and half CO_2 emissions from diesel use.

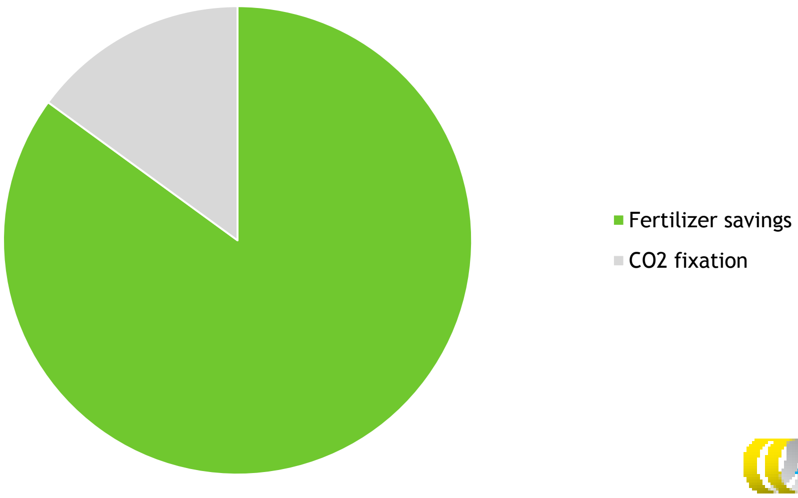
Figure 39 Negative contribution, composting with use abroad (33%)



I.7 Composting, granlation and use abroad

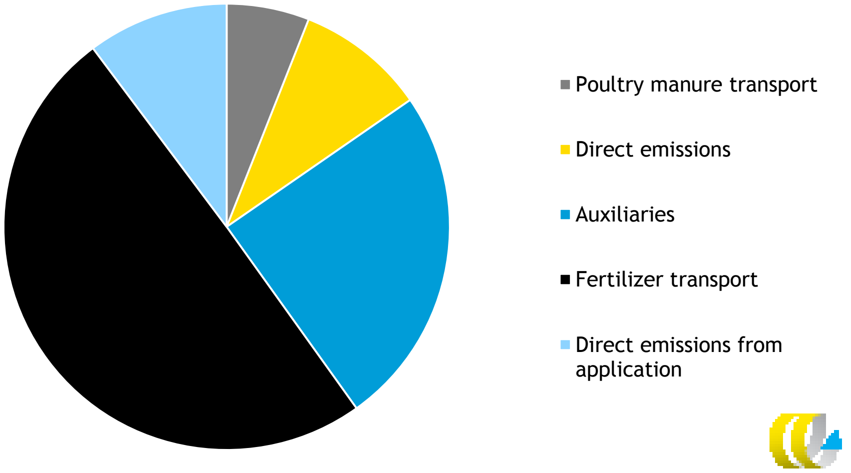
The positive contribution for composting, granulation and use abroad (37% of the total environmental impact) derives mainly from fertilizer savings, with a smaller contribution from soil CO_2 fixation, as shown in Figure 40.

Figure 40 Positive contribution, composting, granulation and use abroad (37%)



The negative contribution (63% of the total environmental impact) is shown in Figure 41. Most of this derives from transport of the granulate, which is marketed in Asia, with a considerable transport distance. 91% of the transport impact is due to transport to Asia and 9% to transport to Spain. Auxiliaries with a negative impact are gas and electricity consumption.

Figure 41 Negative contribution, composting, granulation and use abroad (63%)

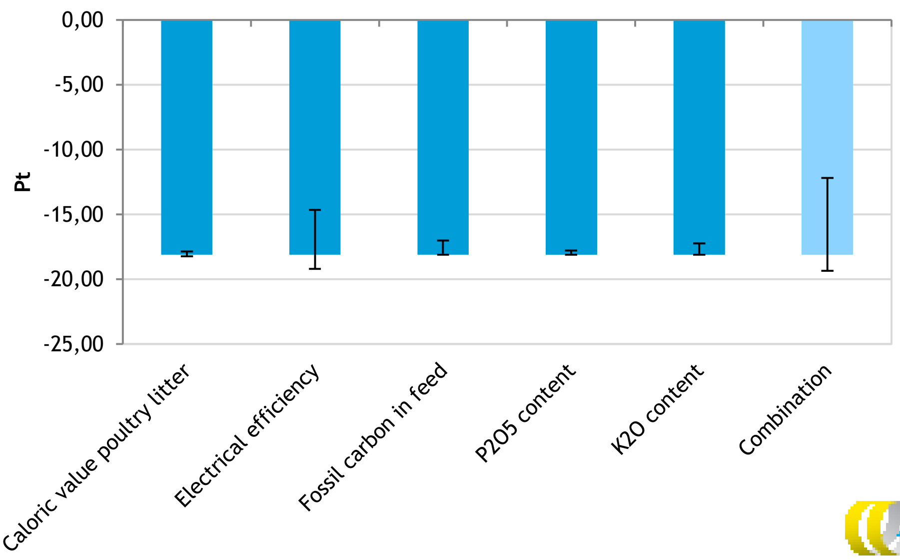


Annex J Sensitivity analyses

J.1 Sensitivity analysis, thermal conversion on poultry farm

Figure 42 shows that the electrical efficiency of thermal conversion on a poultry farm is of major influence on the environmental benefits of this processing route. The variation in calorific value measured by BMC Moerdijk from 2010 to 2015 translates into only a very small margin. The same holds for the fossil-carbon content of the poultry fodder and the P_2O_5 and K_2O content of the poultry litter ash.

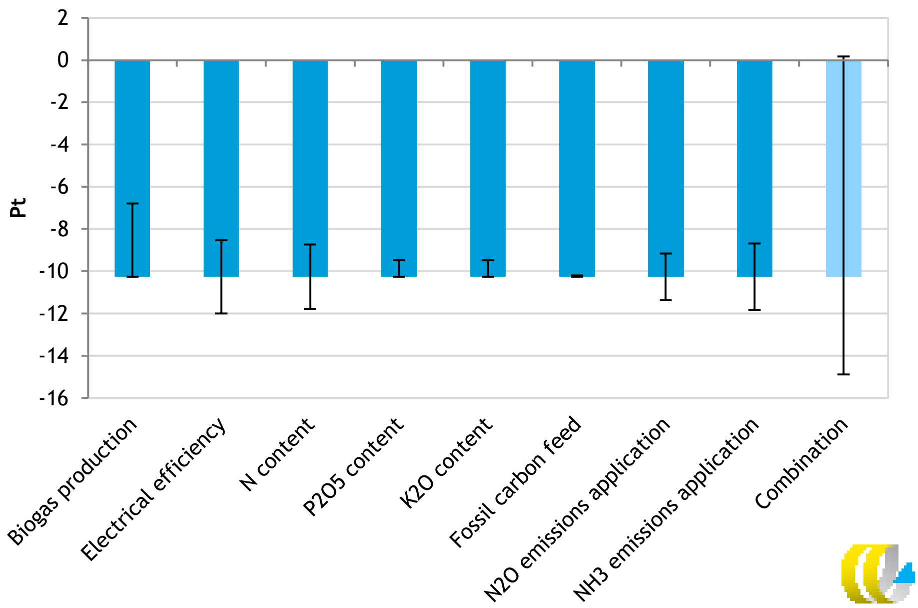
Figure 42 Sensitivity analysis, thermal conversion on poultry farm



J.2 Sensitivity analysis, co-digestion in German digestion plant

Co-digestion of poultry litter with fodder maize silage can perform either better or worse environmentally. This route is unlikely to create a net environmental burden, but particularly because of the uncertainty about biogas yields and the electrical efficiency of the biogas power plant the environmental benefits may turn out to be rather lower. The nitrogen content of the digestate and the emissions from it during application may also mean a decrease in net environmental benefits.

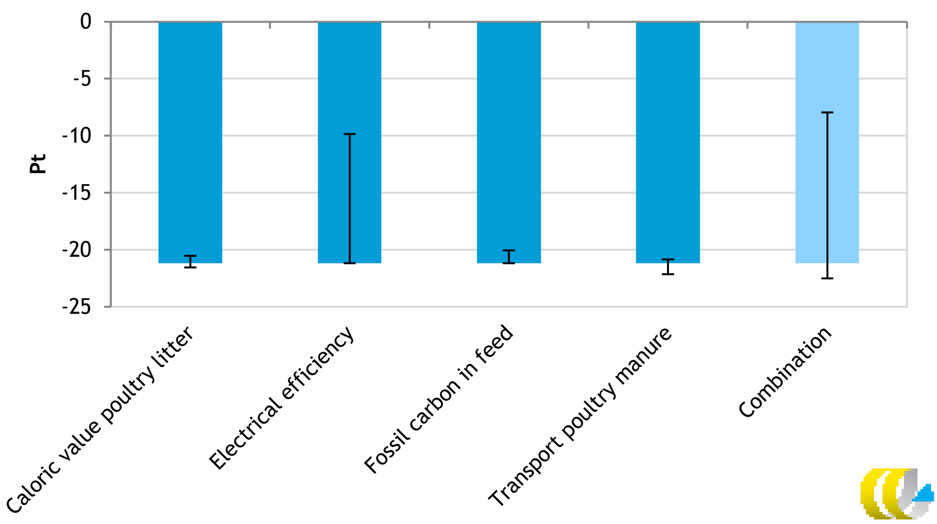
Figure 43 Sensitivity analysis, co-digestion in German digestion plant



J.3 Sensitivity analysis, cofiring in biomass plant

Figure 44 shows that the electrical efficiency of the wood-fired biomass plant is of major influence on the environmental benefits of poultry-litter processing by this route. The variation in calorific value measured by BMC Moerdijk from 2010 to 2015 translates into only a very small margin. The same holds for the fossil-carbon content of the poultry feed and litter transport.

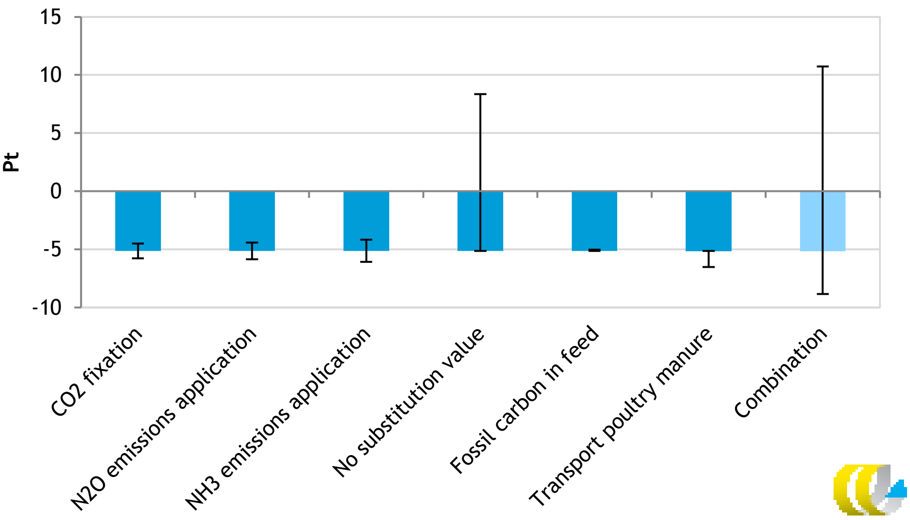
Figure 44 Sensitivity analysis, co-firing in biomass plant



J.4 Sensitivity analysis, direct application of raw litter, Netherlands

With this route it is above all the variation in emissions during field application of the litter that has a significant influence on the environmental profile, as can be seen in Figure 45. Overall, processing poultry litter by direct application in the Netherlands may work out either positively or negatively for the environment.

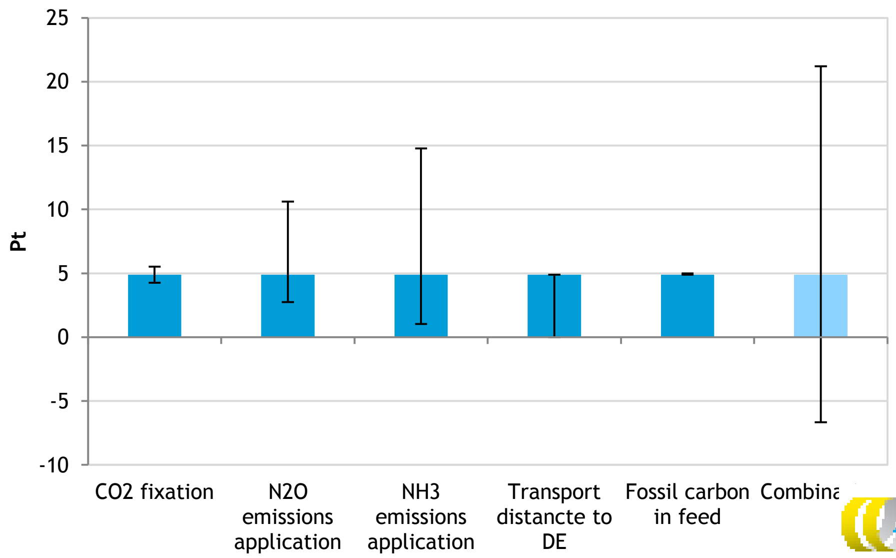
Figure 45 Sensitivity analysis, direct application of raw litter, Netherlands



J.5 Sensitivity analysis, direct application of raw litter, Germany

Because there was insufficient data available, there are major uncertainties in this study when it comes to the emissions occurring during direct application of raw litter in Germany. This route may therefore have a substantially greater environmental impact, as N_2O and NH_3 emissions during farmland application knock on enormously. Emissions during storage have far less influence. With respect to transport, the sensitivity analysis shows that a difference between 150 km and 500 km also has a major impact. If minimum emissions and minimum transport are assumed, though, the environmental performance of application of raw litter in Germany may work out positive.

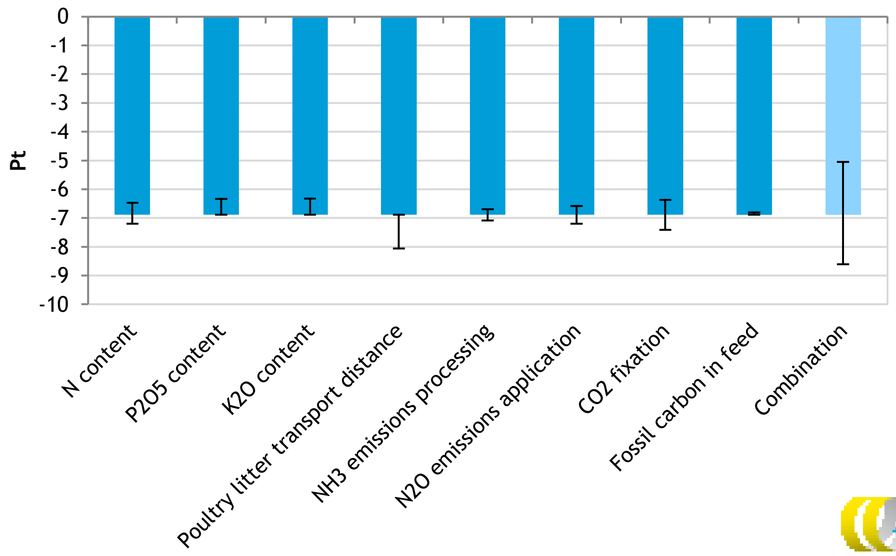
Figure 46 Sensitivity analysis, direct application of raw litter, Germany



J.6 Sensitivity analysis, composting with application abroad

Compared with the environmental impact of composting in the basic analysis, the sensitivity of this route is considerable; the transport distance, particularly, may be of major influence. The analysis shows that composting poultry litter can have environmental benefits.

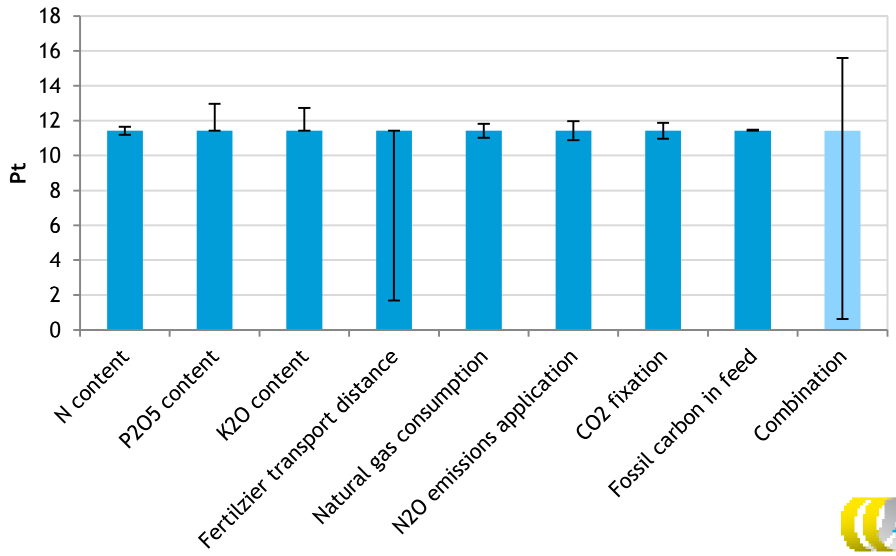
Figure 47 Sensitivity analysis, composting with application abroad



J.7 Sensitivity analysis, composting, granulation and application abroad

The poultry-litter granulation route would have a substantially better environmental profile if the granulate were transported less far. At the moment approximately half the Ferm O Feed granulate is marketed in Asia. This transport has an enormous environmental footprint. In the sensitivity analysis, marketing in southern Europe (Spain) instead of Asia was considered. All in all, it seems clear that granulation of poultry litter in all probability has no environmental benefits.

Figure 48 Sensitivity analysis, composting, granulation and application abroad



Annex K System expansion

In this appendix an alternative LCA is carried out, based on 'system expansion' rather than the substitution method, using a different functional unit from that used in the basic LCA.

LCA according to the substitution method (the basic LCA)

De LCA analysis in the main report (the basic LCA) provides insight into the net environmental impact of processing 1 tonne of poultry litter of a certain composition. This analysis was based on 'substitution', which means, for example, that the electricity generated at the BMC plant is taken to substitute the average electricity mix that would otherwise have been consumed. Because this is now produced by BMC, there are environmental gains.

In this way the various routes therefore yield a variety of useful products. Besides electricity, BMC produces ash containing phosphorus (as P_2O_5) and potassium (as K_2O), for instance. With direct application of the litter, nutrients are produced that contain not only P_2O_5 and K_2O but also organic matter and nitrogen.

LCA with system expansion (the study in this appendix)

An alternative way to compare the various routes is by means of so-called system expansion. In this approach all the routes are 'expanded' to make the end-products comparable. In the BMC route, for example, the expansion is for sequestration of soil organic matter and nitrogen, while in the direct application routes it is for electricity production.

In the study with system expansion the following functional unit was taken: "Processing of 1 tonne of poultry litter and production of 597 kWh electricity, 14.4 kg nitrogen, 14.8 kg phosphorus (expressed as P_2O_5), 21 kg potassium (expressed as K_2O) and 207 kg effective organic matter".

If a route does not involve the required amount defined in this functional unit, it is supplemented by the product cited in Table 32.

Table 32 **Products for system expansion**

Product	Quantity	Comments
Electricity	597 kWh/t litter	Maximum electricity production, as with co-firing in wood-fired biomass plant
Calcium ammonium nitrate (as N)	14.4 kg/t litter	Maximum N efficacy, as with co-digestion
Triple superphosphate (as P_2O_5)	14,8 kg/t litter	Maximum P_2O_5 efficacy, as with co-digestion
Potassium sulphate (as K_2O)	21.0 kg/t litter	Maximum K_2O efficacy, as in all routes except for co-firing in wood-fired biomass plant
EOM	207 kg EOM/t litter	Maximum EOM addition, as with granulation

Heat was not considered to be a product in the basic model and is therefore not included in the analysis with system expansion.

K.1 Additional power production

Question 1: What is the environmental burden (expressed in Single-Score mPt) of producing the same amount of electricity as yielded by co-firing 1 tonne of poultry litter in a wood-fired biomass plant?

To answer this question, in this analysis the environmental impact of power production is considered. In doing so it is assumed that the power is generated using the average Dutch mix of energy sources. This average is based on the mix for 2013 (CE Delft, 2014).

The routes were supplemented with varying amounts of electricity to arrive at 597 kWh/t litter, the amount produced by co-firing 1 tonne of poultry litter in a biomass plant. The respective figures for the various routes are shown in Table 15.

Table 1 Additional power production up to 597 kWh/t litter

Route	Quantity produced	Addition
BMC	582 kWh/t litter	15 kWh
Poultry farm	281 kWh/t litter	316 kWh
Digestion	389 kWh/t litter	208 kWh
Biomass plant	**597 kWh/t litter**	**0 kWh**
Direct application, NL and DE	0 kWh/t litter	597 kWh
Composting	0 kWh/t litter	597 kWh
Granulation	0 kWh/t litter	597 kWh

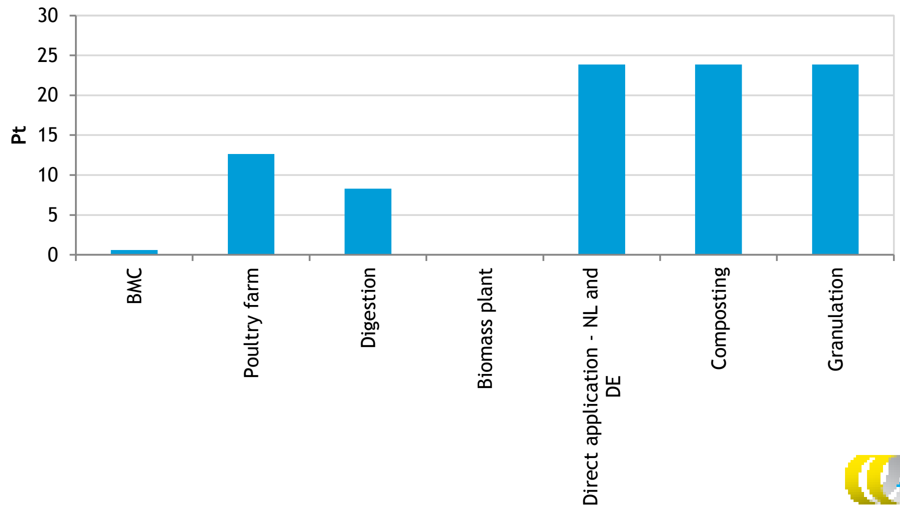
Per kWh electricity this leads to an additional 39.9 mPt environmental burden. Table 33 shows the respective contributions of the various factors.

Table 33 Contributions for generating 1 kWh electricity

	mPt	Source
CO_2	20.2	Power-plant emissions
Natural gas	8.4	Use of natural gas stocks
Coal	6.3	Use of coal stocks
Manganese	1.2	Use of manganese stocks
NO_x	0.8	Power-plant emissions
Methane	0.5	Use of methane
Petroleum	0.6	Use of petroleum stocks
Other	2.0	
Total	**39.9**	

The extra environmental burden due to additional power production is shown for each route in Figure 49.

Figure 49 **Additional power production up to 597 kWh/t litter**



K.2 Additional nitrogen

Question 2: What is the environmental burden (expressed in Single-Score mPt) of adding the same amount of active nitrogen to the soil as via direct application of 1 tonne of poultry litter?

To answer this question, in this analysis we considered the main contours of the environmental impact of nitrogen addition to the soil in the form of CAN fertilizer. We also included the emissions during field application. For ammonia emissions we took an emission factor of 1.8% of the N (Chapter 9.3.9 of (Quantis, 2014)). Because the specific emissions of N_2O and nitrate are unknown, we assumed the same emissions as from litter, although they will in reality be lower for artificial fertilizer.

The routes were supplemented with varying amounts of CAN fertilizer to arrive at 14.4 kg N/t litter, the amount added to soils by direct application of 1 tonne of poultry litter. The respective figures for the various routes are shown in Table 34.

Table 34 **Additional active nitrogen up to 14.4 kg N/t litter**

Route	Quantity produced	Addition
BMC	0 kg/t litter	14.4 kg
Poultry farm	0 kg/t litter	14.4 kg
Digestion	**14.4/t litter**	**0 kg**
Biomass plant	0 kg/t litter	14.4 kg
Direct application, NL and DE	14.3/t litter	0.1 kg
Composting	8.9/t litter	5.5 kg
Granulation	9.1/t litter	5.3 kg

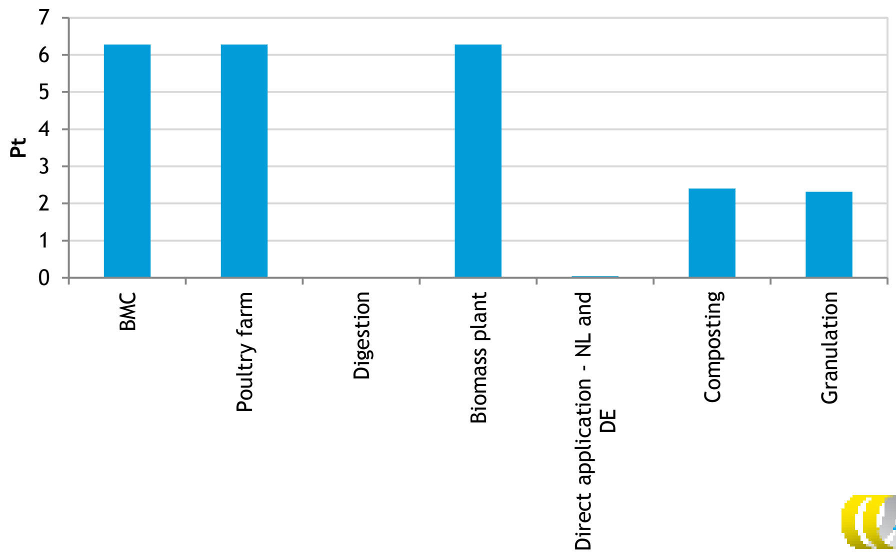
Per kg nitrogen this leads to an additional 436 mPt environmental burden. Table 35 shows the respective contributions of the various factors.

Table 35 Contributions for sequestration of 1 kg N

	mPt	Source
CO_2	140.3	Emissions, fertilizer production
N_2O	143.9	Emissions, fertilizer application
NO_x	11.8	Energy use, fertilizer application
Energy from natural gas	117.8	Fertilizer production
Other	34.3	
Total	**436**	

The extra environmental burden due to additional active nitrogen is shown for each route in Figure 50.

Figure 50 Additional effective nitrogen up to 14.4 kg N/t litter



K.3 Additional phosphorus

Question 3: What is the environmental burden (expressed in Single-Score mPt) of adding the same amount of active P_2O_5 to the soil as via direct application of 1 tonne of poultry litter?

To answer this question, in this analysis we considered the main contours of the environmental impact of adding phosphorus to the soil in the form of triple superphosphate fertilizer.

The routes were supplemented with varying amounts of triple superphosphate to arrive at 14.8 kg P_2O_5/t litter, the amount added to soils by direct application of 1 tonne of poultry litter. The respective figures for the various routes are shown in Table 36.

Table 36 **Additional active phosphorus up to 14.8 kg P_2O_5/t litter**

Route	Quantity produced	Addition
BMC	7.8 kg P_2O_5/t litter	7.0 kg
Poultry farm	7.8 kg P_2O_5/t litter	7.0 kg
Digestion	14.8 kg P_2O_5/t litter	0 kg
Biomass plant	0 kg P_2O_5/t litter	14.8 kg
Direct application, NL and DE	14.7 kg P_2O_5/t litter	0.1 kg
Composting	14.7 kg P_2O_5/t litter	0.1 kg
Granulation	14.7 kg P_2O_5/t litter	0.1 kg

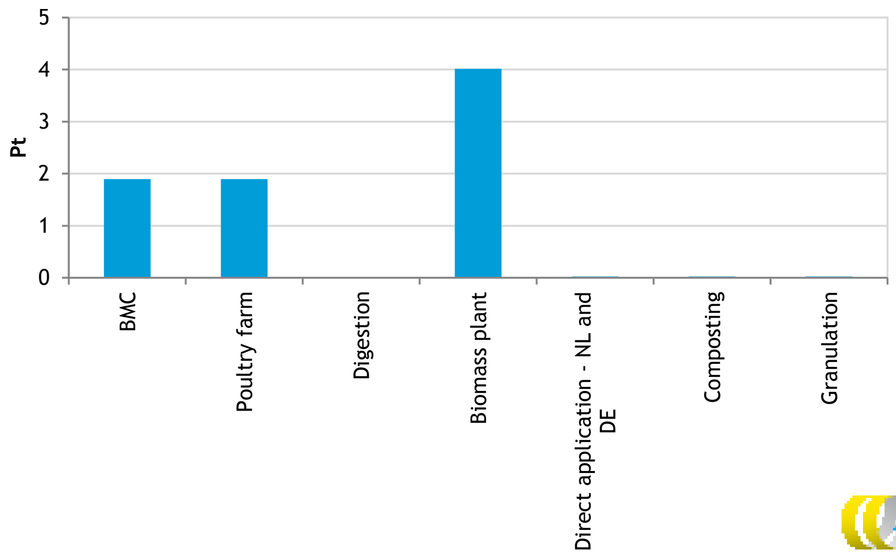
Per kg P_2O_5 this leads to an additional 271 mPt environmental burden. Table 37 shows the respective contributions of the various factors.

Table 37 **Contributions for sequestration of 1 kg P_2O_5**

	mPt	Source
CO_2	73.2	Emissions, fertilizer production
Petroleum	35.6	Use of petroleum stocks, fertilizer production
Natural gas	24.2	Use of natural gas stocks, fertilizer production
Land occupation, buildings	19.4	Land occupation, fertilizer production
SO_2	19.0	Emissions, fertilizer production
Particulate matter	18.7	Emissions, fertilizer production
Coal	13.9	Use of coal stocks, fertilizer production
Manganese	12.3	Emissions, fertilizer production
NO_x	72	Emissions, fertilizer production
Copper	5.3	Use of copper stocks, fertilizer production
Other	47.4	
Total	**271**	

The extra environmental burden due to additional active phosphorus is shown for each route in Figure 51.

Figure 51 **Additional active phosphorus up to 14.8 kg P_2O_5/t litter**



K.4 Additional potassium

Question 4: What is the environmental burden (expressed in Single-Score mPt) of adding the same amount of active K_2O to the soil as via direct application of 1 tonne of poultry litter?

To answer this question, in this analysis we considered the main contours of the environmental impact of adding potassium in the form of potassium sulphate fertilizer.

For all routes except the biomass plant route, 21 kg K_20/t litter is added to the soil. For that route we therefore added potassium sulphate fertilizer to arrive at the same figure. The figures for each route are shown in Table 38.

Table 38 Additional active potassium up to 21.0 kg K_2O/t litter

Route	Quantity produced	Addition
BMC	21.0 kg/t litter	0 kg
Biomass plant	0 kg/t litter	21 kg
Poultry farm	21.0 kg/t litter	0 kg
Direct application, NL and DE	21.0 kg/t litter	0 kg
Composting	21.0 kg/t litter	0 kg
Granulation	21.0 kg/t litter	0 kg
Digestion	21.0 kg/t litter	0 kg

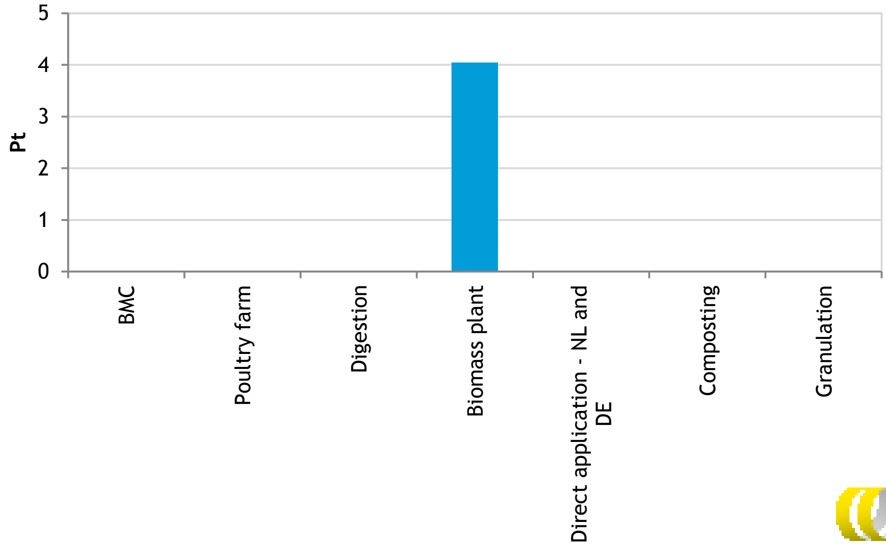
Per kg K_2O this leads to an additional 192 mPt environmental burden. Table 39 shows the respective contributions of the various factors.

Table 39 Contributions for sequestration of 1 kg K_2O

	mPt	Source
CO_2	60.9	Emissions, fertilizer production
Petroleum	25.0	Use of petroleum stocks, fertilizer production
Natural gas	17.1	Use of petroleum stocks, fertilizer production
Coal	14.6	Use of petroleum stocks, fertilizer production
SO_2	13.1	Emissions, fertilizer production
Manganese	10.4	Emissions, fertilizer production
NO_x	5.2	Emissions, fertilizer production and application
Land occupation	6.3	Land occupation, fertilizer production
Copper	5.3	Use of copper stocks, fertilizer production
Methane	4.5	Emissions, fertilizer production
Other	12.3	
Total	**192**	

The extra environmental burden due to additional potassium (as K_2O) is shown for each route in Figure 52.

Figure 52 Additional active potassium (as K_2O) up to 21 kg/t litter



K.5 Additional organic matter

Question 5: What is the environmental burden (expressed in Single-Score mPt) of adding the same amount of organic matter to the soil as via application of 1 tonne of granulated poultry litter?

(Effective) organic matter (EOM) can be added to soils via green manure crops or crop residues, for example. To answer this question, in this analysis we considered the environmental impact of using winter rye as a green manure crop, under the following assumptions:

- Cultivation (yields, etc.) of winter rye in the Netherlands is comparable with that of rye in France (listed in the Agri-footprint database (Blonk Agri-footprint B.V., 2015), with one exception: only nitrogenous fertilizer is used (Kennisakker.nl, 2004).
- For every hectare of rye, 840 kg EOM is sequestered in the soil and the EOM has a humification coefficient of 0.26 (Kennisakker.nl, 2013); this means 7.2% of the carbon is retained (for further explanation see Annex E).
- For every hectare, 3.81 t of carbon is added (Departement Leefmilieu, Natuur en Energie, 2009).
- The green manure crop, in this case winter rye, is included in the cropping scheme, with no additional land use or shift of crops to another area.

The routes were supplemented with varying amounts of green manure crop to arrive at 207 kg EOM/t litter, the amount added to soils via granulation of 1 tonne of poultry litter. The figures for the various routes are shown in Table 40.

Table 40 **Additional EOM up to 207 kg/t litter**

Route	Quantity produced	Addition
BMC	0 kg/t litter	207 kg
Biomass plant	0 kg/t litter	207 kg
Poultry farm	0 kg/t litter	207 kg
Direct application, NL and DE	161 kg/t litter	46 kg
Composting	206 kg/t litter	1 kg
Granulation	**207 kg/t litter**	**0 kg**
Digestion	93 kg/t litter	114 kg

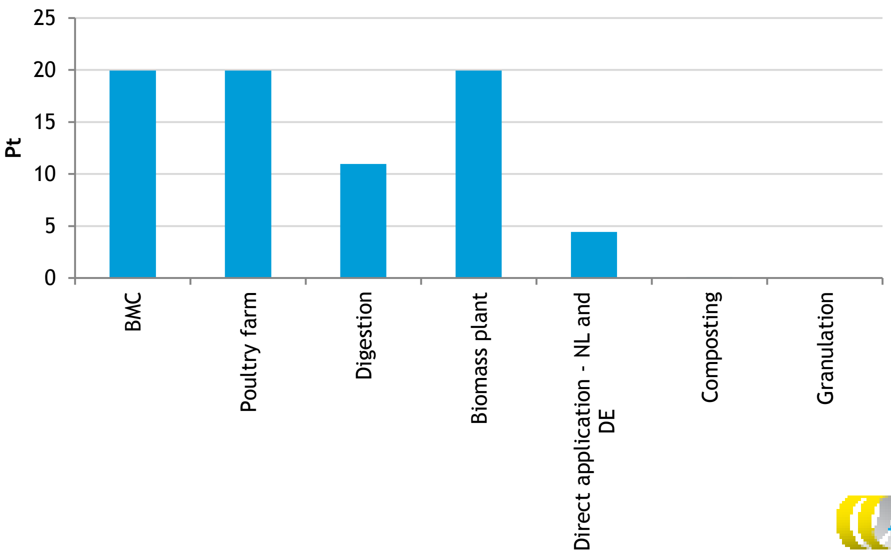
Per kg EOM added via a green manure crop this leads to an additional 96.3 mPt environmental burden. This is mainly due to pesticide use, which is probably lower than for a food crop. Table 41 shows the respective contributions of the various factors.

Table 41 **Contributions for sequestration of 1 kg EOM**

	mPt	Source
N_2O	49.6	Emissions, use of fertilizer and crop residues
NH_3	24.3	Emissions, use of fertilizer and crop residues
CO_2	37.2	Fertilizer production and emissions from diesel use, farmland machinery
Energy (oil)	19.4	Diesel
Energy (gas)	10.2	Fertilizer production
NO_x	6.0	Emissions, use of fertilizer and crop residues
CO_2	-54.2	Sequestration of organic matter
Other	4.0	
Total	**96.3**	

The extra environmental burden due to additional effective organic matter is shown for each route in Figure 53.

Figure 53 **Additional EOM to 206 kg/t litter**



K.6 Result: Comparison of routes based on system expansion

In this section we combine the results of the five system expansions for all the poultry-litter processing routes described in Sections K.1 to K.5. For each route, Figure 54 depicts the outcome of system expansion for the addition of EOM, potassium, phosphorus and nitrogen and additional electricity production. Each system expansion is shown in a different colour.

Figure 54 Environmental impact of the additional products per route

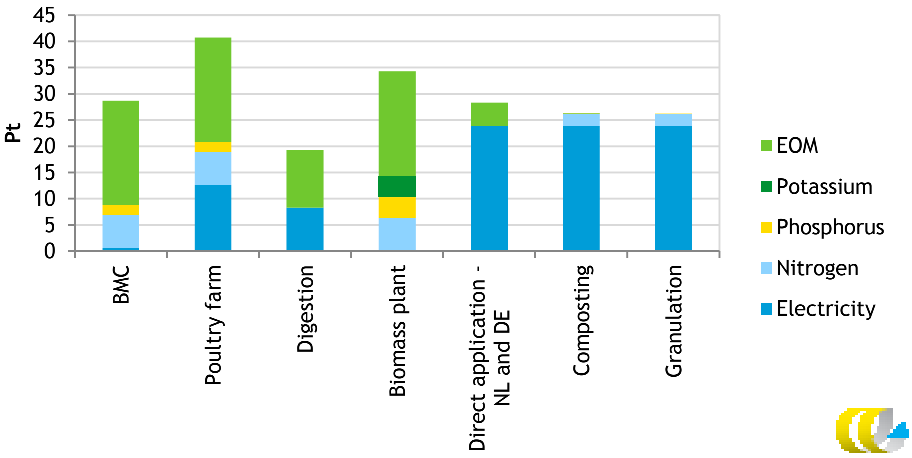


Figure 55 shows the total environmental burden of each route after system expansion. In this figure it can be seen what fraction of the burden is due to processing 1 tonne of poultry litter and what fraction to production of additional products in order to arrive at the functional unit.

The environmental burden associated with processing 1 tonne of poultry litter is shown in Figure 9; this is the part above the x-axis in that figure. In this system expansion, the environmental advantage shown in Figure 9 below the x-axis is not presented as a benefit but as a disadvantage of the other routes. To illustrate: for the BMC route, electricity production is shown in Figure 9 below the x-axis as an environmental benefit. In the LCA with system expansion, in contrast, it is shown as an environmental burden due to the additional product 'electricity' for the routes without power production (such as direct litter application).

Figure 55 Comparison of environmental impact with system expansion

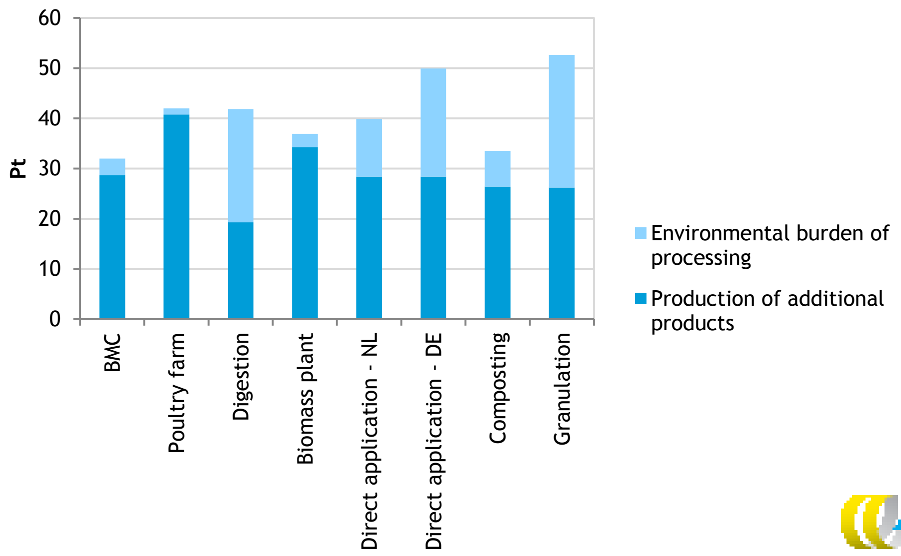


Table 42 provides the exact quantitative data for the LCA with system expansion.

Table 42 Environmental burden per route including system expansion

	Environmental burden, production of additional products (Pt)	Environmental burden, poultry litter processing (Pt)	Total environmental burden, system expansion (Pt)
Thermal processing at BMC	28.7	3.3	32.0
Poultry farm	40.7	1.3	42.0
Biomass plant	19.3	22.6	41.8
Digestion	34.3	2.6	36.9
Direct application - NL	28.3	11.5	39.9
Direct application - DE	28.3	21.6	49.9
Composting	26.4	7.1	33.5
Granulation	26.2	26.4	52.6

K.7 Conclusion

From the LCA with system expansion we can conclude that the BMC route has the lowest environmental burden. In environmental terms this is therefore the most attractive route, just as it was in the basic LCA. Composting now scores similarly, while in the basic LCA this did not score as well.

This change is surprising, because the absolute differences between the various routes using the substitution method and system expansion should in principle be the same. In other words, the relative ranking should remain unchanged: the route scoring worst should continue to score worst, that scoring best should remain best. Comparing Figure 17 with Figure 8 we see that composting moves from fifth to second place, and direct litter application in the Netherlands from sixth to fourth.

The change is due to the fact that in the model used for the basic LCA the EOM added to the soil is not regarded as a product that can be substituted, because in farming practice this EOM in not supplemented. In the basic LCA we instead assumed CO_2 fixation. Because EOM is added in the system expansion version, this leads to a shift in the results.

As an illustration, in the case of additional electricity in the basic LCA we assume substitution (and thus an environmental benefit), while in the LCA with system expansion extra electricity must be produced (with an environmental burden). In this case the environmental benefits of the biomass plant in the basic LCA and the environmental drawbacks of direct litter application are precisely the same. Because the environmental benefit associated with the EOM in the basic LCA is different (viz. CO_2 fixation) from that for the EOM in the LCA with system expansion (additional EOM), this leads to a shift in results.

In the LCA with system expansion, thermal conversion at BMC has the lowest environmental burden. This is in line with the basic LCA, which showed that this route has the greatest environmental benefits.

In the LCA with system expansion, granulation and direct application of raw litter in Germany have the greatest environmental burden. These two routes also scored worst in the basic LCA.