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Greenhouse gas emissions from broiler manure treatment options are lowest in well-managed biogas production

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ABSTRACT

The production of broiler meat has increased significantly in the last decades in Germany and worldwide, and is projected to increase further in the future. As the number of animals raised increases, so too does the amount of manure produced. The identification of manure treatment options that cause low greenhouse gas emissions becomes ever more important. This study compares four treatment options for broiler manure followed by field spreading: storage before distribution, composting, anaerobic digestion in a biogas plant and production of biochar. For these options potential direct and indirect greenhouse gas emissions were assessed for the situation in Germany. Previous analyses have shown that greenhouse gas balances of manure management are often strongly influenced by a small number of processes. Therefore, in this study major processes were represented with several variants and the sensitivity of model results to different management decisions and uncertain parameters was assessed. In doing so, correlations between processes were considered, in which higher emissions earlier on in the process chain reduce emissions later. The results show that biogas production from broiler manure leads to the lowest greenhouse gas emissions in most of the analysed cases, mainly due to the emission savings related to the substitution of mineral fertilizers and the production of electricity. Pyrolysis of the manure and subsequent field spreading as a soil amendment can lead to similarly low emissions due to the long residence time of the biochar, and may even be the better option than poorly managed biogas production. Composting is the treatment option resulting in highest emissions of greenhouse gases, due to high ammonia volatilization, and is likely worse than untreated storage in this respect. These results are relatively insensitive to the length of transport required for field spreading, but high uncertainties are associated with the use of emission factors.

1. Introduction

In the last 20 years, the production of poultry meat has more than doubled in Germany (DESTATIS, 2020) and worldwide (FAOSTAT, 2018a). Globally, in 2016 more than 70 billion poultry were slaughtered to produce 120 million tonnes of meat (FAOSTAT, 2018a), and further increases are projected for the future (OECD/FAO, 2017). The constantly growing production of poultry meat and associated manure makes it essential to identify treatment practices for the manure that lead to low greenhouse gas emissions. A number of alternatives are used in practice or under discussion to handle and utilize poultry manure (Kelleher et al., 2002). In this study the focus is on broiler manure, which refers to the mixture of animal excrements, feathers and bedding material of chickens purposely grown for meat production.

An advantage of broiler manure, in comparison to manures from other animals, are the high nutrient contents, fast mineralization rates and thus high plant availability of these nutrients when spread as a fertilizer (Eghball et al., 2002; Preusch et al., 2002). Altogether, fertilization with broiler manure can lead to similar crop yields as mineral fertilization (Lin et al., 2018). The global fertilization potential of broiler manure is substantial, as it is estimated that broilers excrete more than 5.4 million tonnes of nitrogen per year – about 5% of the amount distributed with mineral

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fertilizers (FAOSTAT, 2018b; 2018c). On the downside, the high nutrient contents and mineralization rates are part of the reason why broiler manure distribution threatens surface and groundwater quality (Shepherd and Bhogal, 1998), and makes it a significant source of greenhouse gas emissions. Treatment and land application of broiler manure can cause substantial emissions of carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3) and nitrous oxide (N_2O) (Moore et al., 2011; Rodhe and Karlsson, 2002). It is therefore essential to identify treatment options that offer the best balance between reducing emissions during treatment, utilizing the energy contained in the manure and retaining the nutrients for use as a fertilizer.

Spreading of untreated broiler manure on cropland or grassland, without any additional processing steps, is the simplest case of manure handling. After cleaning the stable, the manure is stored for a limited amount of time and then distributed to the field. The main advantage of this approach is the relatively low costs. Besides the space for storage (usually a concrete manure storage structure), only machinery for transport and distribution (manure spreader) are required. On the downside, the unprocessed distribution is associated with potentially high NH_3 and N_2O emissions, and also has the disadvantage that the energy potential of the manure remains unused.

Composting is proposed as an alternative to the spreading of untreated broiler manure, as some storage is often required in any case to bridge periods when spreading is not possible and composting helps to reduce the spread of pathogens (Thomas et al., 2020) and unpleasant odours of poultry manures (Ranadheera et al., 2017). In general, manure compost is a relatively stable substrate and a valuable soil amendment (Bernal et al., 2009). While being a relatively low-tech solution, composting still requires additional labour, infrastructure and energy compared to simple storage. To achieve optimal composting, the substrate needs to stay within a specific bandwidth of conditions. Composting requires aerobic conditions, which are either achieved via regular turning or forced-aeration. Well-adjusted aeration is essential to reduce CH_4 and N_2O emissions, and to achieve a thermophilic phase (Qasim et al., 2018; Shen et al., 2011). The initial moisture content is usually adjusted to about 65% (Qasim et al., 2018; Shen et al., 2011; Tiquia and Tam, 2002). While composting produces a relatively stable, sanitized substrate, this comes at the costs of high initial losses of nitrogen due to NH_3 volatilization (Tiquia and Tam, 2000).

Anaerobic digestion (AD) in biogas plants utilizes a share of the energetic potential of poultry litter to produce biogas, which can then be used to generate heat and electricity in combined heat and power plants (CHP) or be upgraded and fed into the natural gas grid. Manure-based biogas is usually associated with lower emissions than biogas from energy crops (Agostini et al., 2015; Meyer-Aurich et al., 2012; Venanzi et al., 2018). The high N content in broiler manure, and subsequent high concentrations of ammonia in the digester, however, have been shown to inhibit the methanogenesis (Abouelenien et al., 2014; Borowski and Weatherley, 2013), which represents a major process disturbance of biogas production (Theuerl et al., 2019). Co-feedstocks may be required to adjust the C/N ratio as well as to reduce the dry matter (DM) content to below a certain threshold (Bujoczek et al., 2000; Duan et al., 2018). Biogas digestates resulting from anaerobic digestion can at least partially replace mineral fertilizers (Ehmann et al., 2018).

Dry pyrolysis describes a process where organic substrates are thermochemically decomposed at temperatures typically ranging between 400 and 600 °C (Hadroug et al., 2019; Libra et al., 2011). The so produced biochar could be used as a soil amendment. Due to the low degradability of the biochar, and thus long residence time, this process is discussed as an option of carbon dioxide removal from the atmosphere (Smith, 2016; Tisserant and Cherubini, 2019). Biochars produced from dry pyrolysis have a much higher half-life in soils than hydrothermally carbonized (HTC) biochars, which are produced in the presence of water (Bach et al., 2016), so that pyrolysis is potentially more suitable if the main aim is to sequester carbon for a long period of time.

Previous assessments of greenhouse gas emissions from manure management pointed out that often only a limited number of processes are responsible for a large share of the overall emissions and thus the overall impact. Willeghems et al. (2016), for instance, assessed pig manure treatment options, and found that CH_4 emissions from manure storage and N_2O emissions from soil were the major source of emissions. Agostini et al. (2015) calculated emissions from manure digestion in a biogas plant, and the results were dominated by assumed negative CH_4 emissions from manure management. The calculation of emissions often relies on emission factors, for instance from the IPCC, that are associated with large uncertainty. Meyer-Aurich et al. (2012) considered the uncertainty in emission factors, and showed that computed greenhouse gas emissions of agricultural processes can vary strongly depending on the assumptions of the study.

The objective of this study was to identify broiler manure treatment options which lead to comparatively low direct and indirect greenhouse gas emissions under German conditions, and to learn more about the conditions under which this is the case. Therefore, this study assessed emissions of four broiler manure treatment options and considered different possible production conditions (e.g. necessary transport distances), management decisions (e.g. open or closed digestate storage) as well as the uncertainties arising from different emission factors. A new impact model was developed that could assess parameter sensitivity and the interdependencies between process emissions when comparing the different treatment options.

2. Methods

2.1. Impact model

A new model was developed to calculate mass flows and emissions of ammonia and greenhouse gases for different treatment options of broiler manure. The simulations were meant to represent German conditions of manure management. Storage and spreading of untreated manure on fields was compared to alternative scenarios with treatment before field spreading: composting, digestion in a biogas plant, and conversion to biochar. The model was programmed in Python 3.7 (Python Software Foundation, 2019); data analysis and the production of figures were done in R 3.6 (R Core Team, 2019).

In the model, individual processes (e.g. the composting process) were represented by functions converting certain inputs (in this case the broiler manure) into a set of outputs (e.g. manure compost, emissions) subject to a number of function parameters (e.g. composting time or emission calculation method). In doing so, it was assured that inputs of nitrogen and organic carbon equalled the outputs plus emissions of a function. The conversion functions were coupled to represent the scenarios which are described in more detail below. This modelling approach allowed considering parameter interdependence throughout the modelled processes.

For all assessed treatment options direct and indirect greenhouse gas emissions were calculated. The gases N_2O, NO_x and CH_4 were considered with global warming potentials of 265, -15.6 (Myhre et al., 2013) and 30.5 (Muñoz and Schmidt, 2016) respectively. Indirect N_2O emissions from the deposition of NH_3 and NO_x were calculated based on an emission factor of 0.014 kg N_2O-N/(kg NH_3-N + NO_x-N) following Hergoualc'h et al. (2019). In contrast to many LCA studies that exclude CO_2 emissions of biogenic origin, because they are considered “carbon neutral”, they were computed in this study for several reasons. Firstly, gaseous emissions were required to consider changes in the quantity and composition of the broiler manure along the process chain. For instance, the organic carbon content of broiler manure after storage was calculated by subtracting carbon losses due to CO_2 and CH_4 emissions. The consideration of CO_2 dynamics was also required to consider a scenario of biochar field spreading, which leads to carbon sequestration. Lastly, the accounting for CO_2 avoided the need to correct for different global warming potentials of biogenic and fossil CH_4 (Muñoz and Schmidt, 2016; Whitman and Lehmann, 2011).

2.2. Scenario setup

Four scenarios were defined where broiler manure is stored, composted, digested in a biogas plant or converted to biochar before being spread on a field as fertilizer or soil amendment. Assumed treatment and transportation pathways are illustrated in Fig. 1. In the model, processes are interdependent, since upstream processes may alter subsequent processes. Composting time for instance, influences mass and composition of the manure applied to the field, and thus emissions from subsequent transport and field spreading.

The functional unit in this study was one metric ton of broiler manure at the broiler farm gate. While calculations were done without explicitly defining a farm of a specific size, the scenarios were defined in a way that was considered realistic for a broiler farm with about 120,000 animal places (three stables of 40,000), a typical size in Eastern Germany (Landtag Brandenburg, 2017). This means that storage, composting and pyrolysis can be done on-site, while for biogas production the manure is transported for a short distance. The scenarios are described in more detail below.

Assumptions on the characteristics of the manure are summarized in Table 1. Since manure contents can vary substantially depending on manure management (Coufal et al., 2006; Nicholson et al., 1996) and animal diets (Belloir et al., 2017; Foy et al., 2014), two alternative CH_4 production potentials were considered. Impacts from the animal production stages including the production of broiler manure in the stables were neglected, as they were the same across all scenarios and since the manure was considered a waste stream. For the organic carbon contained in the manure, however, negative CO_2 emissions were assumed to represent the previous CO_2 uptake by plants.

2.3. Calculation of emissions

2.3.1. Uncertainty and parameter sensitivity assessment

Sensitivity of model results to process parameters, such as transport distances or composting duration on the one hand, and uncertainty introduced from different approaches to calculate emissions on the other hand, were assessed in a comprehensive manner in this study. Although still not very common (Bamber et al., 2020), an assessment of uncertainties is good practice for

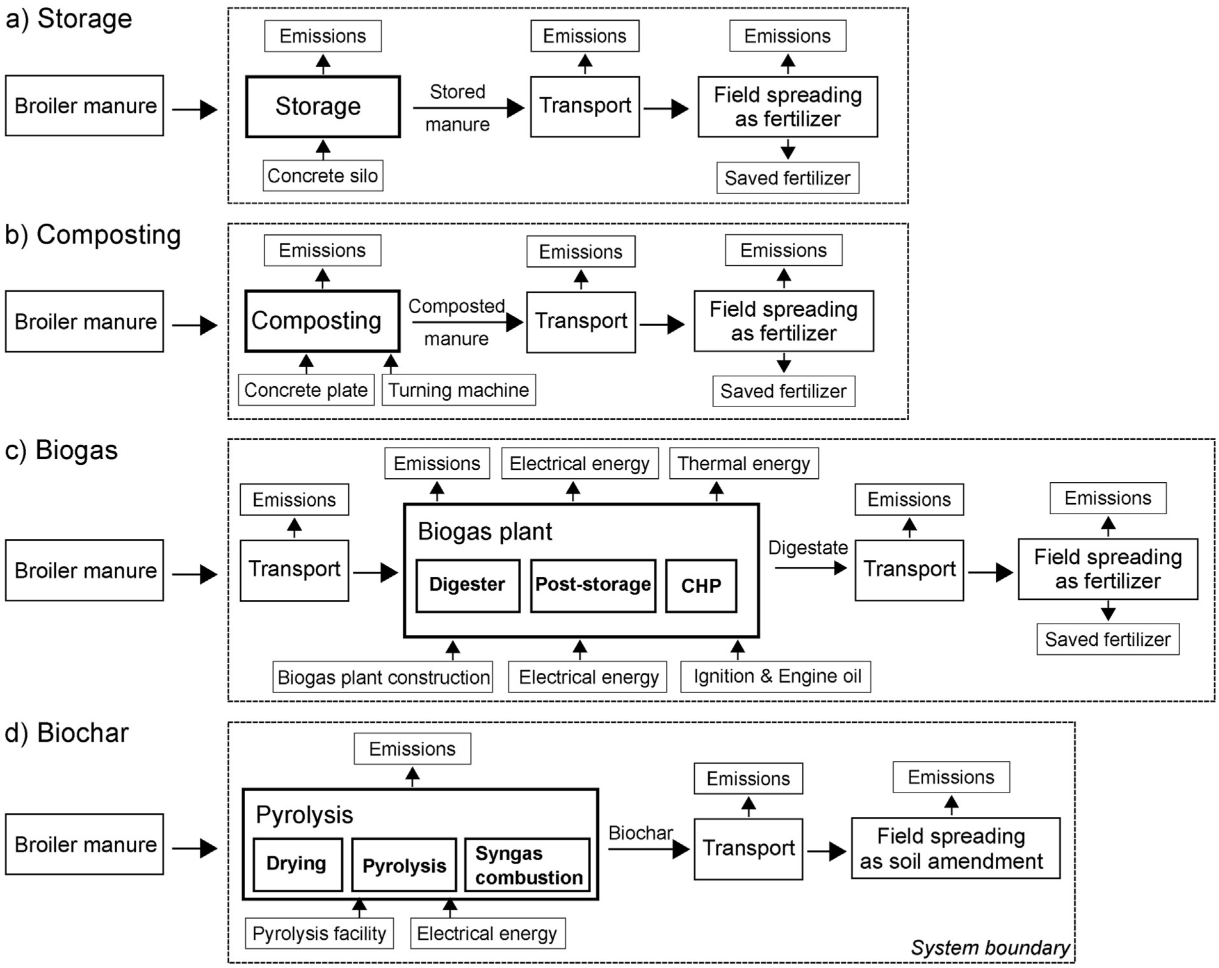

Fig. 1. Flow chart of the assessed scenarios. CHP refers to the combined production of heat and electric power from biogas.

Table 1
Assumptions on broiler manure characteristics. FM: fresh matter.

Parameter	Value	Unit	Reference
Dry matter (DM)	0.6	kg DM/kg FM	LWK NRW (2014)
Organic dry matter (oDM)	0.829	kg oDM/kg DM	Nicholson et al. (1996)
Organic carbon content (C_{org})	0.42	kg C_{org}/kg oDM	Nicholson et al. (1996)
Nitrogen content (N)	29.9	kg N/ton FM	LWK NRW (2014)
Ammonium content (NH_4-N)	10	kg NH_4-N/ton FM	LWK NRW (2014)
CH_4 production potential (B_0)	0.28 or 0.36	m^3/kg oDM	Döhler et al. (2013), Gavrilova et al. (2019)
CH_4 content in biogas	55	%	Döhler et al. (2013)

life cycle assessments. Monte-Carlo simulations, where parameters are randomly sampled from probability functions of parameters, and calculations are repeated numerous time ($\geq$1000 runs), is the most common approach (Bamber et al., 2020; Igos et al., 2019). Important correlations between inputs and outputs of one process, as well as between processes, however, are often neglected by this approach (Heijungs et al., 2019; Lloyd and Ries, 2008; Wolf et al., 2017). For the scenarios analysed here, it was assumed important to consider the interdependencies resulting from characteristics of the flows (e.g. the nutrient content of the broiler manure). Therefore in this study, correlations were taken into account whenever possible. However, for this reason it was not possible to perform Monte-Carlo simulations. Higher nitrogen emissions during storage, for instance, lower the amount of nitrogen available for subsequent processes, thus reducing the emissions from field, but also the amount of mineral fertilizer that can be replaced. Interdependent emission distribution functions avoided cases in the uncertainty assessment where more nitrogen is emitted than physically possible. Independent functions can lead to overestimating the range of possible outcomes.

In this study the focus was on those processes and functions that were identified as most important in terms of greenhouse gas emissions and function parameters were varied systematically. As functional relationships and all possible parameter combinations were tested, this approach was relatively computationally intensive, so that only a limited set of parameters could be varied. For each process those management parameters were systematically altered for which the largest influence on modelling results was expected. Furthermore, different approaches for calculating emissions were used, either based on established methods from the IPCC Guidelines (Gavrilova et al., 2019), or values identified from the literature. In this respect the present study is similar to Fantin et al. (2015). In total 48 parameter combinations were computed for the storage scenario, 72 for composting, 144 for biogas and 12 for biochar.

For practicality reasons, always one default case was defined, and the outcomes of the model variations were discussed separately in the results section. More details on used parameters are provided in the supporting information document.

2.3.2. Storage of broiler manure

For the spreading of untreated broiler manure limited storage was assumed to bridge the time span in which spreading is not allowed (winter) or not meaningful (established crops in summer). Manure storage was assumed to take place at the broiler farm in a concrete storage silo with 7 m width and 2 m high sidewalls on three sides, and emissions for the respective concrete production were taken from the ecoinvent 3.4 database (Wernet et al., 2016) and distributed over a lifespan of 25 years.

In the default case, emissions from the decomposition of broiler manure during storage were calculated similar to the German emission reporting methodology (Haenel et al., 2018). CH_4 and NO and N_2 emission were calculated based on emission factors from the IPCC Guidelines (Gavrilova et al., 2019). NH_3 and N_2O emissions were derived from EMEP/EEA (2016). CO_2 emission factors are not provided from these sources, since CO_2 emissions from decomposition are usually assumed to equal the previous uptake from photosynthesis. However, to consider the influence of emissions on total mass, and be able to compare storage to processes with lower CO_2 emissions from decomposition, CO_2 emissions from storage were calculated based on values reported in the metastudy by Pardo et al. (2015). Gaseous losses of nitrogen and carbon calculated this way were subtracted from the dry matter content, and used to adjust the remaining total nitrogen contents of the manure. No nitrate leaching was assumed during the storage of the manure in the concrete silo with concrete flooring. Emissions of non-methane volatile organic compounds (NMVOCs) were generally neglected in this study.

In order to get a better understanding of the uncertainty of emissions from storage, three variants were assessed in addition to the default case. In these variants, emissions were calculated with N_2O, NH_3 and NO_x emission factors from the IPCC (Gavrilova et al., 2019), CH_4, N_2O and NH_3 emission factors from Pardo et al. (2015), and lastly, CO_2, CH_4 and N_2O emissions were estimated based on results from an experimental study by Moore et al. (2011).

2.3.3. Composting

For emissions from composting the calculations considered windrow composting on a concrete plate. Windrows were assumed to be turned every three days with a compost turning machine to assure aerobic conditions. For this machine use, emissions for production (agricultural machinery, two tons, 1000 h lifetime) and diesel consumption for a tractor were considered according to the ecoinvent 3.4 database.

In the default case, emissions resulting from decomposition during the composting process were considered with emission factors for CH_4, N_2O and combined NH_3 and NO_x losses from Gavrilova et al. (2019). Similar to storage, CO_2 emissions were considered with factors from Pardo et al. (2015). The composition of the composted manure was calculated based on the losses of carbon and nitrogen. Water was added to achieve an initial water content of 55% at the beginning of the composting and consecutive losses of water similar to Tiquia and Tam (2000).

To estimate parameter sensitivity, two variants were created where emissions were calculated with emission factors from Pardo et al. (2015), or were estimated based on CO_2, CH_4, NH_3 and N_2O emission factors consistent with the results of an experimental study by Chen et al. (2018).

2.3.4. Anaerobic digestion in a biogas plant

Since mono-digestion of broiler manure is impractical due to the high nitrogen and dry matter content it was assumed that the manure is transported to a close by biogas plant, where it is co-digested without any prestorage together with wetter feedstock (e.g. liquid cow manure) and feedstocks with a higher C/N ratio (e.g. energy crops). However, since the focus was on the impacts associated with the broiler manure, these feedstocks were not modelled explicitly.

Emissions from biogas plant operation were derived similar to the methodology and data of Effenberger et al. (2016). Biogas was assumed to be used in a cogeneration unit with pilot injection engine to produce heat and electricity. The energy generation was calculated from the CH_4 production in the digester (and the post-storage in the case of a closed storage), and with an electrical efficiency of the CHP of 38% and thermal efficiency of 44%. Electricity produced was assumed to replace energy generation according to the German energy mix, and thus negatively accounted with a carbon intensity of 0.588 kg CO_{2eq} per kWh, while for the energy consumed by the biogas plant a factor of 0.615 kg CO_{2eq} per kWh (Moro and Lonza, 2018) was used. These values account for upstream emissions from extraction, refining and transport, as well as for trade between countries and losses in the grid. 40% of the generated heat were assumed to be used externally, which is in line with the current situation in the German state of Lower Saxony (Kralemann et al., 2018), to replace heating with natural gas. For the substituted natural gas use, losses of CH_4 of 2.3% during production and transmission were also accounted for (Alvarez et al., 2018). For the construction of the biogas plant an emission factor of 0.015 kg CO_{2eq} per kWh electrical energy production was assumed, ignition oil consumption was considered with 3.75 kg/h and engine oil usage with 0.0004 kg/kWh (Effenberger et al., 2016). CH_4 was assumed to leak from the digester, the closed post-storage tank and the CHP unit (1% of the produced gas at each stage). Furthermore, NO_x emissions from the CHP were considered with 1000 mg/m^3 exhaust gas (Aschmann et al., 2007).

Liebetrau et al. (2010) showed that the methane emissions from the co-generation unit can range quite significantly between 0.17 and 3.72%. The sensitivity analysis considered these two variants in addition to the default value of 1%. Also considered was a variant of open digestate storage, and one where the share of thermal energy use was reduced to 0%.

2.3.5. *Carbonization to biochar*

For the carbonization scenario it was assumed that the broiler manure was converted on site to biochar in a pyrolysis plant. This treatment option considered a container-sized pyrolysis plant (14 tons, 10 years lifetime) on a concrete foundation, and estimated the corresponding emissions for machinery and concrete production according to the ecoinvent 3.4 database. A system of this size is able to process about 750 tonnes dry matter per year (PYREG, 2020), which approximately matches the amount of broiler manure produced by a farm with 120,000 animal places and eight cycles per year. It was assumed that the gases from the pyrolysis process were combusted in a FLOX burner, and that the heat from this combustion process is used to pre-dry the manure, so that no additional energy is required for that purpose. A consumption of 16 kW of electrical energy was assumed for the operation (PYREG, 2020).

Biochar production was parameterized according to Song and Guo (2012), and considering the same temperature-dependent relative losses of nitrogen, and contents of remaining carbon in the biochar. This means that at a temperature of 400 °C about 60% of the nitrogen in the broiler manure are retained in the biochar, while at 600 °C almost all nitrogen is released during the pyrolysis process. A pyrolysis temperature of 400 °C was assumed as the default. Losses of organic carbon during the pyrolysis process were allocated to CO_2, CH_4 and CO emissions, assuming a CO_2 content in the exhaust gas of 15%, a CH_4 content of 100 ppm and a CO_2 content of 1000 ppm. Nitrogen was largely converted to N_2, and NO_x emissions from fuel-N and thermal origin were considered with 500 mg/m^3 exhaust gas volume.

The sensitivity of emission results to the pyrolysis temperature was assessed by also calculating emissions for pyrolysis temperatures of 500 °C and 600 °C. Additionally, a variant was defined that considered a CH_4 content of 1000 ppm in the exhaust gas.

2.3.6. *Transportation*

For the biogas scenario a transport distance of 5 km was considered from the broiler farm to the biogas plant. This transport was calculated by means of a tractor, according to the ecoinvent database. Secondly, broiler manure, compost, digestate and biochar were all assumed to be used as fertilizer or soil amendment. In order to transport them to the field emissions from a 10 km transport with a medium sized lorry (16–32 metric tons, EURO6) were considered. As German broiler production is concentrated in a few areas (Thobe, 2018), and fertilizer regulations set strict limits to nitrogen fertilization per hectare (DüV, 2017), longer distance transport may be required in regions with a regional oversupply of manure. A variant with 500 km transport distance accounted for this.

2.3.7. *Field spreading as fertilizer or soil amendment*

As a last step the manure, compost and digestate were assumed to be spread as a fertilizer on arable land. In the default case, emissions of N_2O were calculated from the amount of nitrogen spread and an emission factor from Gavrilova et al. (2019), NH_3 emissions were based on the emission factor from Haenel et al. (2018), and for NO emissions the EMEP/EEA (2016) approach was used. Furthermore CO_2 emissions from the decomposition of the substrate we assumed. All organic carbon that does not contribute to the formation of humus, as described by VDLUFA (2014), was emitted as CO_2. Potential mineral fertilizer savings resulting from the spread of the nitrogen-rich substrates were also considered. To this end, remaining nitrogen contents in the stored manure, compost or digestate were multiplied with a minimum N efficacy factor (LfL, 2018), and emissions that would occur when fertilizing with ammonium nitrate phosphate with the same amount of N fertilizer were accounted for with a negative sign. In order to consider the uncertainty of emissions from this process, NH_3 and NO emissions were also computed based on emission factors from Gavrilova et al. (2019) or EMEP/EEA, (2016).

Biochar was assumed to be spread as a soil amendment. In this case carbon losses of the biochar fraction that is not permanent for 100 years, which depend on the previous pyrolysis temperature (IPCC, 2019), lead to CO_2 emissions. No further emissions or fertilization effect were assumed for biochar. Machinery emissions for the spreading of the different substrates were derived from the ecoinvent database.

3. Results

3.1. *Emissions in the default cases*

In all modelled default cases, CO_2 emissions result mainly from the main treatment processes (i.e. the pyrolysis, the biogas plant, the compost heap and the manure storage) and the decomposition after field spreading (Fig. 2). This means that they mainly have biogenic origin, and represent a release of carbon that was previously bound in the manure (see also Fig. 3a). While CO_2 emissions are higher during the composting process than during storage, the opposite is true for the decomposition of composted or stored broiler manure on the field, so that net emissions are very comparable with −165 kg CO_2 in the case of composting, and −154 kg CO_2 per ton of manure in the case of storage. Even though significantly less CO_2 is emitted from the biochar after spreading than from decomposition of broiler manure or broiler manure compost over the assessed time horizon, net CO_2 emissions are still on a

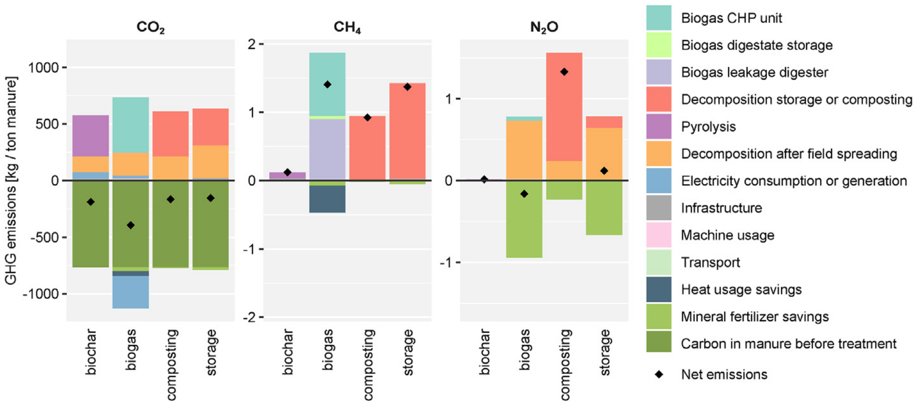

Fig. 2. Emissions of CO_2, CH_4 and N_2O for the four treatment options and differentiated according to the process causing the emissions. Mind the different scales for the different gases. The category "carbon in manure before treatment" accounts for the organic carbon bound in the manure, which has previously been removed from the atmosphere through photosynthesis. "Infrastructure" refers to the emissions caused by the production of the concrete structures required for composting and storage, as well as creation of the biogas plant and the pyrolysis machinery.

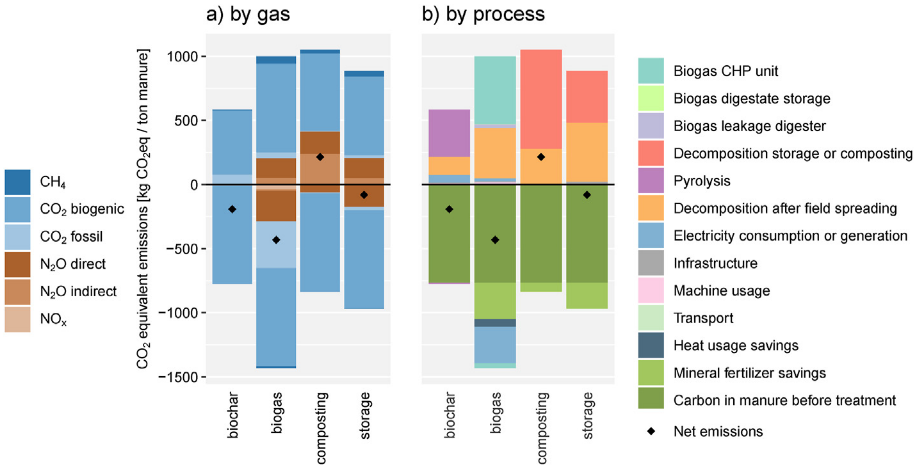

Fig. 3. Emissions in CO_2 equivalents (with 100-year global warming potentials) of the treatment options for the default cases.

similar level (−190 kg CO_2/ton manure) because of high carbon losses during pyrolysis. The biogas scenario results in the lowest net CO_2 emissions of −394 kg, which is a consequence of highest positive emissions of all scenarios on the one hand, but also highest emission savings mainly through electrical energy generation on the other hand.

Methane emissions arise almost exclusively during the main treatment processes (Fig. 2). The biogas treatment pathway shows the highest emissions of methane of the four assessed treatment options, with positive emissions of 1.87 kg CH_4 per ton of manure. These CH_4 emissions stem mostly from leakages from the digester and the cogeneration unit. Even though heat usage from the biogas cogeneration also avoids considerable CH_4 emissions that would occur for the supply of natural gas, the net emissions of 1.41 kg CH_4 are still the highest of all treatment options. Similar levels are observed only in the storage scenario with 1.37 kg CH_4 per ton of manure. Composting significantly reduces CH_4 emissions compared to storage by assuring more aerobic conditions. Pyrolysis is responsible for about 0.09 kg of CH_4 emissions in the biochar scenario, making this the treatment option with overall lowest CH_4 emissions (0.12 kg CH_4).

The emissions from on-field decomposition and the potential to replace mineral fertilizers dominate the result for N_2O emissions in the biogas and the storage scenario. In both scenarios the nitrogen losses before spreading are minor, in the case of biogas, however, the fertilization efficacy and thus the potential to replace mineral fertilizer is higher because the digestate is assumed to be spread in liquid form. As a consequence, the sum of net direct and indirect N_2O emissions is lowest in the biogas scenario with −0.16 kg N_2O per ton of broiler manure. These emissions are also low in the biochar scenario (0.01 kg N_2O) since no N_2O is emitted from the pyrolysis process. Composting causes the highest direct and indirect N_2O emissions of 1.33 kg N_2O per ton of manure. This is mainly explained by NH_3 volatilization during the composting, which leads to indirect N_2O emissions of 0.85 kg.

Summarized across all greenhouse gases, biogas production from broiler manure leads to emissions of −432 kg CO_2eq per ton of manure and therefore the lowest net emissions of the assessed treatment options (Fig. 3). Biochar production results in net emissions of −192 kg CO_2eq, storage in −81 kg CO_2eq. With emissions of 216 kg CO_2eq, composting is the only scenario which leads to positive net emissions.

The release of biogenic, manure-bound carbon as CO_2 during the treatment or after field spreading is the biggest factor in the greenhouse gas balance (Fig. 3a). Comparatively low biogenic CO_2 emissions resulting from the sequestration of carbon over a long time horizon improve the balance for biochar production, while with biogas production a larger share of the carbon is oxidized to

CO_2 so that resulting CO_2 emissions are higher than in the other scenarios. In general, however, the avoidance of fossil CO_2 emissions and nitrous oxide emissions are more important for the ranking of the options. The advantage of biogas production in terms of greenhouse gas emissions is mostly explained by the electricity production and the potential to reduce mineral fertilizer consumption (Fig. 3b). Emissions from composting are higher than for storage because of high NH_3 losses causing indirect N_2O emissions on the one hand, but also because they reduce the nitrogen content of the compost, thus lowering its potential to replace mineral fertilizers.

3.2. Sensitivity analysis

For the sensitivity analysis several variants were modelled for each scenario. The results for the default cases, discussed in the section above, are consistently found at the lower ends of the computed ranges of emissions (Fig. 4). A comparison of the results for all scenario variants across the four scenarios reveals that while the overlap between the ranges of emissions is not very big, there are several model parameter combinations where a scenario with low emissions in the default case results in higher emissions in the variant case. There are for instance several biogas scenario variants that lead to higher greenhouse gas emissions than biochar and a few combinations where emissions are higher than for storage.

The transport distance between processing and field distribution was the only parameter consistently modified for all scenarios. In contrast to what was expected, however, this transport is not a decisive factor according to the modelling results (Fig. 4). Longer distance transport increases net emissions only by a relatively small amount. Emissions are less sensitive to longer transport distances for treatment options that significantly decrease the mass of the manure. Therefore for biochar, which has only 30% of the initial mass, the effect of longer distance transport is lowest. The effect of the transport distance on emissions also depends on the other scenario parameters. A longer composting time, for instance, decreases the mass of the compost so that the effect of longer transport is smaller.

Calculated greenhouse gas emissions are strongly influenced by a limited number of management decisions and emissions calculation methods (Fig. 5). The two parameters varied for the biochar scenario – the pyrolysis temperature and the CH_4 content in the pyrolysis plant exhaust gas - have only little influence on the net emissions. While a pyrolysis temperature of 600 °C leads to 81 kg higher CO_2 emissions from the pyrolysis process, the CO_2 emissions during decomposition are about 106 kg lower due to the higher stability of the biochar, so that the effects almost balance each other out. For biogas, the form of digestate storage has the highest influence on the greenhouse gas emissions. On average, closed digestate storage leads to 167 kg lower CO_2eq emissions. Heat usage and smaller CH_4 leakage from the CHP unit also decrease the impact substantially. For both the composting and storage scenarios, net emission results are very sensitive to the chosen emission calculation method, i.e. the emission factors chosen to calculate emissions from microbial decomposition during storage and composting. If emissions are calculated with the emission factors found in the meta-study by Pardo et al. (2015), emissions are substantially higher for storage, and the difference to composting is much smaller. Emission estimates for composting are significantly higher when calculated according to factors by Chen et al. (2018). This underlines the high uncertainty associated with these emission factors.

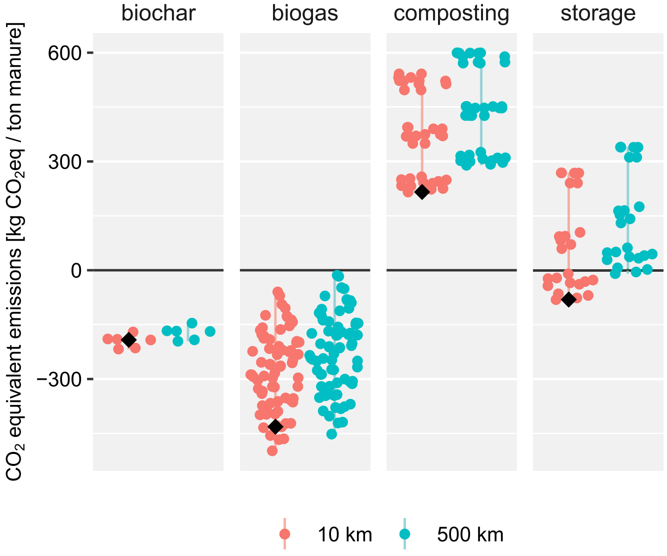

Fig. 4. Influence of the transport distance on net emissions (in CO_2 equivalents with 100-year global warming potentials) for all parameter combinations. Black diamonds highlight the default simulations (depicted also in Fig. 3).

4. Discussion

4.1. Biogas production from broiler manure results in lowest emissions

This study assessed greenhouse gas emissions of four broiler manure treatment options. Several previous studies had compared manure treatment in a more qualitative way, or used life-cycle assessment approaches with a focus on the broiler production. Kelleher et al. (2002), for instance, reviewed the advantages and disadvantages of poultry litter processing without providing quantitative numbers. Numerous life-cycle assessments (LCAs) have assessed production systems in different locations such as the broiler production in Portugal (González-García et al., 2014), in the UK (Leinonen et al., 2012), in Iran (Kalhor et al., 2016), the US (Pelletier, 2008), France and Brazil (Prudêncio da Silva et al., 2014), Italy (Cesari et al., 2017) and Serbia (Skunca et al., 2018). This study advances this research by providing a quantitative, comparative study on the impacts of broiler manure processing.

The results shows that overall anaerobic digestion and the production of biogas from broiler manure can be a treatment option resulting in low greenhouse gas emissions. This is in line with the findings by Beausang et al. (2020), who compared biogas production to the field spreading of poultry litter under Irish conditions. The current study found low emissions associated with biogas production because in this case electrical energy can be created, and because much of the manure nitrogen is retained, making the biogas digestate a replacement for mineral fertilizer. These two factors lead to a significant accounting of negative emissions. Replacing mineral fertilizers is effective because lower N_2O emission factors per kg of N distributed on field are assumed for manure nitrogen than for mineral fertilizers (Hergoualc'h et al., 2019). Together with the reduced emissions during decomposition (because of closed systems) this explains the overall low emissions.

4.2. Assessment of uncertainty ranges is important

The results highlight the importance of considering parameter uncertainty. Across all the modelled parameter combinations in the scenario variants, the range in emission values was quite substantial. For the biogas scenario, the computed range spans from −500 kg CO_2eq per ton of manure to about zero net emissions.

Fig. 5. Sensitivity of net greenhouse gas emissions to parameters assumptions. Depicted are only the variants with 10 km transport from processing to field. The unit of the maximum CH_4 production potential (B_0) varied for biogas, composting and storage is m^3 CH_4/kg manure oDM.

As a consequence, the analysis shows that the advantage of biogas does not hold in all cases. Biogas production with high emissions from open digestate storage and high methane leakage rates from the co-generation unit is not necessarily better than the simple storage of the manure and use as a fertilizer. This highlights the importance of good design and operation of biogas plants. The importance of gas-tight digestate storage to reduce emissions has been discussed before (Boulamanti et al., 2013), and is now mostly required for new biogas plants in Germany (Thrän et al., 2017). However, of the existing plants 40% still feature storage tanks without any covering (Daniel-Gromke et al., 2018). Biogas plants should also be regularly scanned for methane leakages from point sources, for instance by means of infrared cameras or portable methane lasers (Liebetrau et al., 2017). Similarly, emissions from the co-generation unit can be reduced by properly adjusted machinery, operation at full load, and the use of catalysers or thermal oxidizers (Aschmann et al., 2019). It is worth noting that the results for the biogas scenario are only true under the assumption that the manure can be fed to a biogas plant as a co-substrate, firstly because high nitrogen contents limit the biogas process, and secondly because the need for storage before usage in a biogas plant was neglected. Such additional storage could cause significant additional emissions of NH_3 and N_2O, whose emission rates are typically highest during the first few days (Moore et al., 2011).

The parameter sensitivity analysis also underlines the strong influence of emission factors on overall emission balances. This was expected and the reason why several approaches to calculate emissions were used in the first place. However, while this approach included different emissions factors, and different dependencies on how to calculate them (e.g. N_2O emissions during storage as a function of the N content following the IPCC guidelines, as a function of NH_4-N content when calculated according to EMEP/EEA (2016)), it still only partly covers the underlying uncertainty, as all emission factors are also associated with a certain uncertainty range. In this study, correlations between the different processes were considered to assure closed mass balances. The authors believe that this is an important feature of the model, since higher emissions earlier in the process chain leads to lower emissions later on, and such correlations are still often neglected in LCA studies (Heijungs et al., 2019; Lloyd and Ries, 2008). On the downside, however, because this approach was already more computationally intensive, it was not possible to perform Monte-Carlo simulations for parameters uncertainty ranges and for the high number of runs usually considered appropriate (Heijungs, 2020; Igos et al., 2019).

4.3. Challenges and limitations

Besides the uncertainty range associated with emission factors their definition also presents another source of uncertainty. For certain emission factors from EMEP/EEA (2016), Gavrilova et al. (2019) and Haenel et al. (2018), which were used to calculate emissions from composting and storage, it was not always possible to clearly distinguish between the housing period and the management after clearing the stable. The factors used may therefore partly comprise emissions from animal housing, which also means that the boundary system as depicted in Fig. 1 is not precise in this case, and emissions from these two processes could be overestimated. However, whenever possible additional independent emission estimates based on experimental literature data were used to tackle this problem.

The consideration of CO_2 emissions posed a challenge, as there are commonly no emission factors reported for this greenhouse gas by EMEP/EEA (2016), Gavrilova et al. (2019) and Haenel et al. (2018). This is because for biogenic substances it is usually assumed that the CO_2 emissions released during the life cycle where previously captured during plant growth. For the present study this meant that CO_2 emission calculations for the storage or the composting period were solely based on the values from Pardo et al. (2015). For the spreading of stored or composted poultry manure or digestate, it was assumed that all organic carbon that does not contribute to the formation of humus is emitted in the form of CO_2, while for biochar the fraction that is not permanent for 100 years was considered, even though the so computed emissions are not perfectly comparable.

Emission estimates for the biochar scenario are probably more uncertain than represented by the parameter sensitivity analysis. The two parameters varied, the pyrolysis temperature and the methane emissions from the pyrolysis resulted in the smallest range of net emission values of the four scenarios. Nevertheless, the parameters assumed for this scenario are probably more uncertain than for the other scenarios. In contrast to biogas for instance, where methane leakage rates and exhaust emissions have been measured at several commercial plants that have been in operation for several years and are managed differently well (Aschmann et al., 2007; Liebetrau et al., 2010), no such data exists for pyrolysis plants. Plausible emission estimates were used in this case. Gas measurements from lab scale experiments commonly find significant amounts of hydrogen, CH_4 and other hydrocarbons (Fernandez-Lopez et al., 2015; Ro et al., 2010), as well as NH_3, HCN and other NO_x predecessors (Chen et al., 2012). It is however not meaningful to assume these emissions for the scenario, since a commercial broiler manure pyrolysis plant would likely comprise a combustion of the produced syngases at high temperatures, significantly reducing such emissions.

The results found in this study are meant to represent the conditions in Germany, and may not be completely transferable to other regions of broiler production. In the USA, for instance, it is less common to clean the stable after each flock and this leads to a different composition of the litter (Wood and Heyst, 2016). In some cases, however, the calculations had to be based on measurements from the USA (Moore et al., 2011; Tiquia and Tam, 2000), assuming the same relative emission shares, because similar studies were missing for central Europe.

4.4. Impacts of treatment besides greenhouse gas emissions

This study assessed several treatment options of broiler manure with a focus on gaseous emissions, while other factors worth considering also differ between the options. Fresh manure often contains pathogens (Brooks et al., 2010; Skóra et al., 2016; Viegas et al., 2012) that can persist in soils for long periods (Hruby et al., 2018) and may also be washed out (Hruby and Shelley, 2016). Additionally, poultry manure is a source of unpleasant odour, which limits its application to agricultural land (Dunlop et al., 2016; Ranadheera et al., 2017). Manure treatment can reduce the amount of pathogens substantially. Composting is an effective way to sanitize manure, even when C/N ratios, moisture content and aerobic conditions are not optimally adjusted (Thomas et al., 2020; Tien et al., 2017), and this is considered a main motivation for composting. Anaerobic digestion of poultry manure in biogas plants can also lead to an inactivation of pathogenic bacteria, especially under elevated temperatures and with sufficient retention times (Anjum et al., 2017; Borowski and Weatherley, 2013; Thomas et al., 2019). Lastly, the different treatment options can have several indirect effects. The use of compost, for instance, can improve a number of soil quality parameters which were not assessed here (Martínez-Blanco et al., 2013). The use of poultry biochar can positively influence the release of phosphorous compared to raw poultry manure (Wang et al., 2015), decrease NH_3 and N_2O emissions from soils (Doydora et al., 2011; Harter et al., 2014; Lan et al., 2018), and may increase crop yields in some locations (Jeffery et al., 2017; Sikder and Joardar, 2019). These and other indirect effects were beyond the scope of this study.

4.5. Other treatment options not assessed

In this study the focus was on the options of storage, composting, anaerobic digestion and conversion to biochar used as soil amendment, while other options that are actually in practice or proposed were not assessed. Mau and Gross (2017) combusted biochar produced from poultry litter and suggest that there is considerable potential for electricity generation. Besides the use of pyrolysis to produce biochar their study also considered hydrothermal carbonization, where wet material is converted into hydrochar (Ghanim et al., 2016; Mau et al., 2016). Cotana et al. (2014) showed the potential of the gasification of poultry litter and combustion with a Stirling engine, while de Graaff et al. (2017) have assessed impacts of co-firing in a wood biomass plant. Furthermore, combinations of the treatment options described here could also be possible. Walker et al. (2012, 2009), for instance, describe advantages of a combined aerobic and thermophilic anaerobic digestion of municipal solid waste which could also be true for broiler manure. An assessment of additional treatment options should be subject to future research.

5. Conclusions

This study used a new model to assess greenhouse gas emissions from four broiler manure treatment options, which considered interdependencies between processes, and helped to identify important factors influencing the results. The results show that in most modelled cases, biogas treatment was the manure treatment resulting in the lowest emissions. This is due to a combination of several aspects. Anaerobic digestion utilizes the energetic potential contained in the manure for the production of heat and electricity, reduces nitrous oxide emission during the treatment through a relatively closed system, and results in biogas digestate which makes for a valuable fertilizer that still contains most of the nitrogen. However, the study also underlines that in order to result in low emissions biogas production needs to be managed well. This means that biogas digestate should be stored in a closed tank, and methane emissions from biogas storage and conversion should be kept as low as possible. High methane leakage rates from the gas storage and the cogeneration unit can partly offset the advantage of biogas production. Biochar production via pyrolysis and subsequent field spreading is the second best option according to this study, mostly since this method largely avoids CH_4 and N_2O emissions that occur in the other treatment options. The calculations for the biochar option, however, were not based on measurements from commercial plants in operation. Further research is needed to make emissions estimates for broiler manure pyrolysis, and the emissions from the decomposition of biochar over long time horizons more reliable. Composting results in higher emissions than storage of untreated broiler manure, in most assessed variants, mainly because of higher nitrogen volatilization under aerobic conditions. While this indicates for an advantage of storage over composting in terms of greenhouse gas emissions, other considerations not assessed in this study, such as the sanitizing effect of composting are also worth considering. Lastly, the analysis highlights that large uncertainties are related to the methods and parameters chosen for calculating emissions from the storage and composting of broiler manure. When emissions of composting were calculated corresponding to an experimental study this lead to about twice as high net emissions compared to the default case, in which factors for emission reporting were used. It is therefore good advice to consider this kind of uncertainty in emission inventories.

Author contribution

U.K.: conceptualized the study, developed the model, conducted the simulations, analysed the results, created the figures and drafted the manuscript. A.P.: conceptualized the study. J.B.: developed the model. C.H.: contributed to the definition of the treatment options. J.L.: contributed to the definition of the treatment options. All authors discussed the results and contributed to the final manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124969.

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