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# Life cycle analysis of anaerobic digestion processes of poultry litter

## Análise de ciclo de vida de processos de digestão anaeróbia da cama de aviário

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## ABSTRACT

This article presents results of life-cycle assessment of anaerobic digestion processes of poultry litter (PL) preceded or not by thermal pretreatment (autohydrolysis). For this, the environmental impact categories, greenhouse gas (GHG) emissions, eutrophication, and soil acidification were evaluated using the ReCiPe Midpoint (H) method. Based on primary data provided by a partner company, life-cycle inventories were constructed for three forms of poultry waste management: i. disposal of *in natura* PL into the soil, which is the commonly used management technique; ii. anaerobic digestion of *in natura* PL; and iii. thermal pre-treatment by autohydrolysis of PL before its anaerobic digestion. It is concluded that anaerobic digestion of PL reduces GHG emissions compared to the "business as usual" scenario of soil disposal. The use of digestate (liquid fraction generated by PL anaerobic digestion) as soil fertilizer would result in avoided GHG emissions of 34%, while thermal pre-treatment by autohydrolysis of PL prior to its anaerobic digestion would result in a slightly lower reduction (27%) in GHG. Anaerobic digestion of *in natura* PL would also reduce the eutrophication potential by 98.2% (kg eq $PO_4^{-3}$/t litter) and the acidification potential by 98.4% (kg eq $SO_2$/t litter) compared to its soil disposal. These results show that anaerobic digestion is a more sustainable way to manage PL than its environmental discharge.

**Keywords:** poultry bed; chicken waste; environmental assessment; sustainability; thermal treatment; waste management.

## RESUMO

Este artigo apresenta resultados de análise do ciclo de vida dos processos de digestão anaeróbia de cama de aviário (CA) precedida ou não de pré-tratamento térmico (auto-hidrólise). Para tanto, foram avaliadas as categorias de impacto ambiental, emissões de gases de efeito estufa (GEE), eutrofização e acidificação do solo por meio do método ReCiPe Midpoint (H). Com base em dados primários fornecidos por uma empresa parceira, foram construídos inventários de ciclo de vida para três formas de manejo de dejetos de aves: i. descarte de CA *in natura* no solo, que é a técnica de manejo comumente utilizada; ii. digestão anaeróbia de CA *in natura*; e iii. pré-tratamento térmico por auto-hidrólise da CA antes da sua digestão anaeróbia. Conclui-se que a digestão anaeróbia da CA reduz as emissões de GEE em comparação ao cenário *business as usual* de disposição no solo. O uso do digestato (fração líquida gerada na digestão anaeróbia da CA) como fertilizante de solo resultaria em emissões de GEE evitadas de 34%, ao passo que o pré-tratamento térmico por auto-hidrólise da CA previamente à sua digestão anaeróbia resultaria em redução de emissões de GEE um pouco menor (27%). A digestão anaeróbia da CA *in natura* reduziria ainda o potencial de eutrofização em 98,2% (kg eq $PO_4^{-3}$/t cama) e o potencial de acidificação em 98,4% (kg eq $SO_2$/t cama) em relação à sua disposição no solo. Tais resultados mostram que a digestão anaeróbia é uma forma mais sustentável de manejo da CA do que o seu lançamento no ambiente.

**Palavras-chave:** cama de frango; resíduo avícola; avaliação ambiental; sustentabilidade; tratamento térmico; gerenciamento de resíduos.

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## Introduction

In view of the constant changes occurring in the market due to the effects of globalization and its new mechanisms, socio-environmental responsibility (SER) has become an increasingly important issue regarding behavioral changes in companies, leading to transformations in their objectives, goals, and strategies as well as in the meaning of the term company/organization itself.

Food of animal origin is an important source of nutrients such as vitamins and minerals and contains a significant number of essential amino acids for maintaining human health (Weindl et al., 2020). In this way, poultry production has been gaining prominence on the global stage, especially in Brazil, due to researches and investments made. According to the Organization for Economic Cooperation and Development (OECD), poultry production is one of the fundamental pillars for supplying the world with animal protein in the coming decades, and Brazil is one of the world's largest producers and exporters of chicken meat (OECD, 2023). This is due to poultry production having a short and relatively fast cycle, in addition to being efficient in feed conversion and making less use of land in the animal-rearing stage (FAO, 2020; OECD, 2023).

A by-product of chicken meat production is poultry litter (PL), which is generated during the growth cycle of chickens and, due to its characteristics, has reduced applicability and commercial value, so it is most often considered waste. Most commonly, PL is sold cheaply or donated to local farmers to be used as a "soil conditioner", even though it still contains unstabilized organic matter and other contaminants (e.g., ammonia, pathogens), which contribute to greenhouse gas (GHG) emissions and other environmental damage.

An alternative way of managing PL would be solid-state anaerobic digestion (AD), which would promote the stabilization of organic matter and energy recovery (in the form of methane), as well as contribute to the reduction of pathogens and nutrients, especially if a heat treatment stage is added to this process. Although the energy analysis of the AD process of PL indicates that the methane produced can provide 7.1 to 25.2% of the total energy used in chicken farming (Paranhos et al., 2020), little is known about the environmental impact of this process, especially when the heat treatment step is included. In fact, the energy recovery of PL by AD has already been studied by other authors (Crippen et al., 2016; Jeswani et al., 2019; Rajendran and Murthy, 2019; Beausang et al., 2020; Paranhos et al., 2020; Valenti et al., 2020) who considered it technically feasible and with a neutral energy balance when using thermal pre-treatment (i.e., the energy spent on PL pre-treatment could, at the limit, be recovered by burning the biogas generated during the AD). However, the incorporation of other benefits from this technological route such as the sale of biosolids (produced from the sludge generated during AD), carbon credits from avoided GHG emissions, and the reduction of other impacts associated with the disposal of PL on the soil, may help to make AD viable as an alternative way of managing poultry waste.

The aim of this study was to evaluate, by means of a life-cycle assessment (LCA), the main environmental impacts caused by traditional forms of management (disposal on the soil) and others under development (AD preceded or not by heat treatment) of PL generated in broiler chicken rearing. More specifically, the aim was to assess the environmental impact related to GHG emissions and soil acidification/eutrophication resulting from the disposal of PL on the soil compared to its previous AD, whether or not combined with the thermal pre-treatment of autohydrolysis.

## Methodology

Primary data collection was carried out through *in loco* and documentary research at the partner poultry farm, whose name will not be disclosed for confidentiality reasons.

### Research design

The stages in the LCA of PL included defining the objectives and scope, inventory analysis, impact assessment, and interpretation for an approach starting with the generation of litter. Besides, the techniques used to manage it did not consider any infrastructure processes, such as constructing biodigesters and the thermal treatment plant.

Secondary data for the LCA study were obtained from the Ecoinvent® v3.7 and Agri-Footprint 5.0 databases (Wernet et al., 2016), LCA literature on AD plants and other sources regarding GHG emissions, acidification and eutrophication of the processes involved. The LCA models for quantifying the impacts were developed specifically for this study.

A sampling unit of PL was used for the characterization and building of inventories, based on the scenarios proposed according to the functional unit adopted. This sample of real litter was collected *in loco* after six productive cycles (CA-6U) at the partner company and subjected to AD conditions optimized according to Paranhos (2021). This sample refers to the more stabilized PL (lower volatile solids/total solids ratio - VS/TS) since it is removed from the breeding shed after several production cycles. There are fugitive emissions of GHG in the shed itself, which were not computed in this study, but represent the reality of Brazilian poultry farming according to the Manual for the Environmental Management of Poultry Litter issued by the Brazilian Agricultural Research Corporation (Embrapa).

All aspects and GHG emissions as potential environmental impacts were obtained from the functional unit adopted (1 ton of PL) in order to carefully assess GHG emissions, acidification, and eutrophication as environmental impacts resulting from the management of waste generated in the poultry industry. Therefore, the boundary of the system was defined in the poultry house with the generation of litter, i.e., the focus was on the environmental assessment of the techniques used to manage it.

Thus, three operational scenarios were considered in this study: (C1) disposal of *in natura* PL on the soil; (C2) generation of energy (biogas) from the AD of *in natura* litter; and (C3) AD of litter preceded by hydrothermal treatment, which aims to deconstruct the lignocellulosic material of chicken litter and thereby increase methane production. These scenarios are described in more detail below.

### *Scenario C1: disposal of poultry litter in natura on the soil*

The purpose of this study was to assess the environmental impacts based on methane gas emissions resulting from the disposal of PL on the soil (Figure 1), compared to carbon dioxide (CO2) emissions when burning biogas collected from a controlled environment (anaerobic reactor) to generate heat (Scenarios C2 and C3, in Figures 2 and 3, respectively).

### *Scenario C2: Biogas production from the anaerobic digestion of poultry litter*

In scenario C2 (Figure 2), anaerobic digestion of poultry litter was considered as a way of recovering energy from the waste by producing biogas.

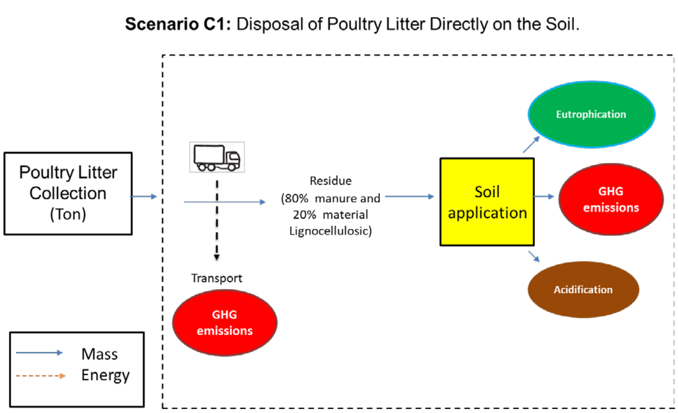


**Figure 1 – Flowchart of scenario C1.**
Source: Carneiro (2022).
GHG: greenhouse gases.

Therefore, for the calculations of GHG emissions corresponding to scenarios C2 and C3, it was assumed that 30% of the nitrogen ($N_2$, $N_2O$, $NO_x$, including $NO_2$) was consumed by the microorganisms during anaerobic activity in the digester (Gavrilova et al., 2019; Ecoinvent, 2022).

### *Scenario C3: Biogas production from the anaerobic digestion of thermally pre-treated poultry litter*

Scenario C3 (Figure 3) differs from C2 by considering the heat treatment of PL prior to the AD process since this procedure results in significant increases in methane yield (Paranhos, 2021). The calculations of GHG emissions for this scenario were based on the assumption, according to Ecoinvent v3.7 and Gavrilova et al. (2019), that 30% of the nitrogen ($N_2$, $N_2O$, $NO_x$, including $NO_2$) was consumed by the microorganisms during anaerobic activity in the digester, while the biogas produced is composed of 65% methane, excluding losses of 3% methane, the same as in scenario C2 (Hassanein et al., 2022).

## Life-cycle assessment

The environmental impact assessment of each scenario, as well as the calculation of GHG emissions, acidification, and eutrophication were carried out using the ReCiPe method, fully complying with the recommendations of ISO 14040 and ISO 14044 standards. The ReCiPe method has global applications for categories that affect climate change, leading to the depletion of the ozone layer and a reduction in the availability of natural resources. Therefore, in order to assess the environmental impact of PL as poultry production waste, three impact categories were selected from the ReCiPe Midpoint (H) v1.12 method (Goedkoop et al., 2013): climate change (GHG emissions), acidification, and soil eutrophication.

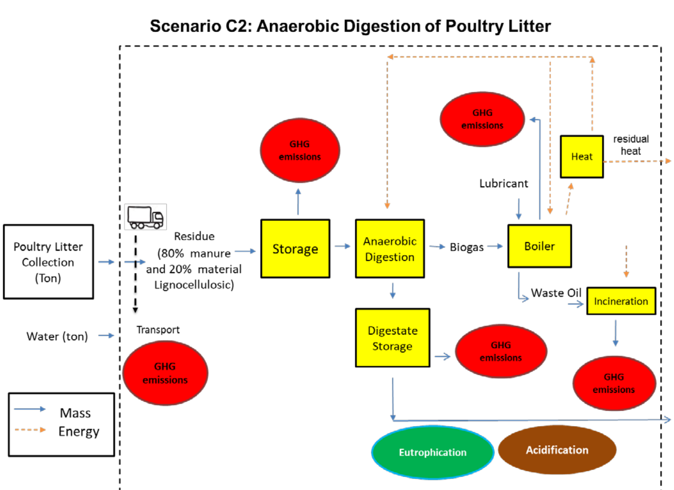


**Figure 2 – Flowchart of scenario C2.**
Source: Carneiro (2022).
GHG: greenhouse gases.

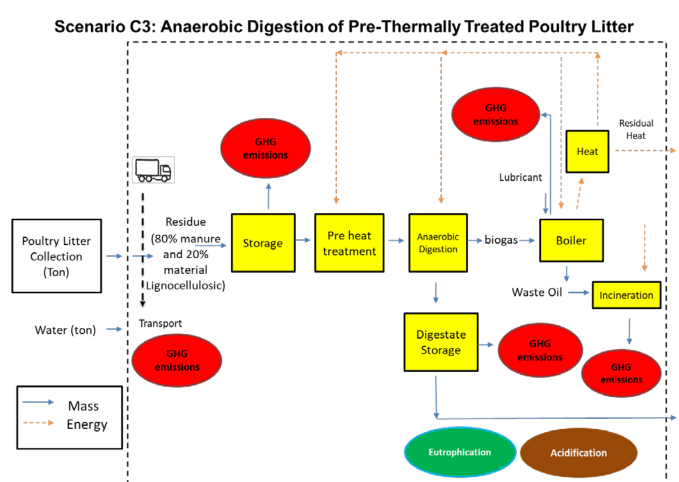


**Figure 3 – Flowchart of scenario C3.**
Source: Carneiro (2022).
GHG: greenhouse gases.

Values of 1, 23, and 298 in kg $CO_2$ eq $kg^{-1}$ were adopted in this study for carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), and methane ($CH_4$) respectively, in order to obtain total emissions in terms of kilograms of $CO_2$ equivalent (kg CO2 eq) following the methodology recommended by the International Panel on Climate Change (IPCC) (Gavrilova et al., 2019).

The acidification potential (AP) was also calculated according to the model proposed by the IPCC by adopting the AP values associated with the parameters considered in this study (Gavrilova et al., 2019). This parameter indicates the amount of sulphur dioxide ($SO_2$) emissions corresponding to the same potential effect of acidification. Regarding the eutrophication potential, emissions to both air and water were considered, according to the IPCC methodology described in Gavrilova et al. (2019).

### *Inventory of poultry litter disposed of in natura in the environment*

Equations 1, 2, and 3 were used to calculate the average annual population of animals produced (Gavrilova et al., 2019).

$$AAP = \frac{\text{Live Days x NAPA}}{365} \quad (1)$$

Where:
AAP = average annual population (poultry/year);
NAPA = number of animals produced annually (poultry/year).

In the case of the company studied, the animals remain alive for 45 days. Therefore, Equation 1 can be simplified as shown in Equation 2.

$$AAP = \frac{45 \text{ x NAPA}}{365} = 0.12 \text{ x NAPA} \quad (2)$$

Based on the average annual value of the population, Equation 3 can be used to estimate ammonia ($NH_3$) emissions, which are responsible for various environmental impacts.

$$NH_3 = \text{AAP x EF} \quad (3)$$

Where:
$NH_3$ = ammonia emissions, kg $NH_3$;
EF = emission factor, kg $AAP^{-1}$ $year^{-1}$ $NH_3$.

Methane ($CH_4$) emissions from manure management were estimated by Equation 4, using the emission factors defined by the IPCC (Gavrilova et al., 2019).

$$CH_{4(manure)} = \frac{\Sigma_{(T)} EF_{(T)} \text{x } N_{(T)}}{10^6} \quad (4)$$

Where:
$CH_4$ *(manure)* = $CH_4$ emissions from manure management in a defined population, kg $CH_4$ $year^{-1}$;
$EF_{(T)}$ = $CH_4$ emission factor from manure, kg CH4 $head^{-1}$ $year^{-1}$;
$N_{(T)}$ = number of heads of a species (no. of poultry/species);
T = species/livestock category (to identify the species in the calculation, according to IPCC, 2019);
$10^6$ = correction factor for unit of measurement.

The value of the $CH_4$ emission factor $EF_{(T)}$ was chosen according to the species of animal (chicken) and the average annual temperature observed at the site studied, in accordance with the parameters defined by the IPCC (Gavrilova et al., 2019). Direct $N_2O$ emissions were calculated using Equation 5:

$$N_2O_D = \frac{[\Sigma_{(s)}[\Sigma_{(T)}(N(T) x \, Nex_{(T)} \text{x } MS_{(T,S)})] \text{ x } EF_{3(S)}] \text{ x } 44}{28} \quad (5)$$

Where:
$N_2O_D$ = direct $N_2O$ emissions from manure management, kg $N_2O$ $year^{-1}$;
S = Manure management system;
T = livestock species/category (to identify the species in the calculation, according to IPCC);
$N_{(T)}$ = number of heads of a species (no. of poultry/species);
Nex $_{(T)}$ = average annual N excretion per head of species/category (T), kg N/animal per year;
MS $_{(T,S)}$ = fraction of total annual nitrogen excreted for each species/category (T) in a manure management system (S) in %;
$EF_{3(S)}$ = emission factor for direct $N_2O$ emissions from the manure management system (S) in a country, kg $N_2O$-N/kg N;
44/28 = conversion of $N_2O$-N emissions to $N_2O$ emissions.

Methane ($CH_4$) and nitrous oxide ($N_2O$) emissions were calculated in accordance with the model proposed by the IPCC (Gavrilova et al., 2019) on animal emissions and manure management. The IPCC also indicates the use of the standard $N_{rate}$ value of 1.1 kg N (1000 kg animal mass)$^{-1}$ $day^{-1}$) for broilers in any region of the world, according to Equation 6.

$$N_{ex(T)} = \frac{N_{rate(T)} \text{x TAM}}{(1000 \text{ x } 365)} \quad (6)$$

Where:
N*rate*$_{(T)}$ = standard N excretion rate, kg N (1000 kg animal mass)$^{-1}$ $day^{-1}$;
$TAM_{(T)}$ = typical weight of a chicken, kg $animal^{-1}$.

The typical weight of a chicken ($TAM_{(T)}$) was considered 2.6 kg, which is the average weight of chickens ready for slaughter at the company involved in this study. In turn, the choice of the fraction of total annual nitrogen excreted (MS (%)) — used in Equation 5 — was based on how the company studied treats its manure in the poultry growth and finishing stages, as shown in Table 1.

Since in scenario C1 the manure is disposed of on the soil without treatment, the percentage of MS was set at 3.77%. In turn, the $EF_3$ adopted (used in Equation 5) was 0.001 kg $N_2O$-N/kg N, a value normally employed for raising poultry for slaughter and which has poultry droppings along with litter as waste (Gavrilova et al., 2019).

In addition to the direct emissions estimated by Equation 5, there are also indirect $N_2O$ emissions, which have been estimated according to Equation 7.

$$N_2O_I = \frac{(N_{volatilization-MMS} \text{x } EF_4) \text{ x } 44}{28} \quad (7)$$

Where:

$N_2O_I$ = indirect $N_2O$ emissions due to N volatilization from manure management, kg $N_2O$ year$^{-1}$;

$N_{volatilization\text{-}MMS}$ = amount of nitrogen from manure that is lost due to volatilization of $NH_3$ and $NO_x$, kg N year$^{-1}$;

$EF_4$ = $N_2O$ emission factor from atmospheric deposition of nitrogen in soils and surface water, kg $N_2O$-N (kg $NH_3$-N + $NO_x$-N volatilized)$^{-1}$.

The emission factor $EF_4$ has a standard value of 0.01 kg $N_2O$-N (kg $NH_3$-N + $NO_x$-N volatilized)$^{-1}$, as suggested in Chapter 11 of the IPCC (Gavrilova et al., 2019). Furthermore, $N_{volatilization\text{-}MMS}$, which is volatilization in the forms of $NH_3$ and $NO_x$, can be calculated through Equation 8.

$$N_{volatilization-MMS} = \Sigma_S[\Sigma_T[\,(N_{(T)}Nex_{(T)} \text{x } MS_{(T,S)})] \text{ x } \frac{Frac_{(GasMS)}}{100_{(T,S)}}] \quad (8)$$

Where:

$N_{volatilization\text{-}MMS}$ = amount of nitrogen from manure that is lost due to volatilization of $NH_3$ and $NO_x$, kg N year$^{-1}$;

$N_{(T)}$ = number of heads of a species (no. of poultry/species);

$Nex_{(T)}$ = average annual N excretion per head of species/category of T, kg N animal$^{-1}$ year$^{-1}$ (this value is identical to the one used previously);

$MS_{(T,S)}$ = fraction of the total annual nitrogen excreted for each species/category (T) in a manure management system (S) (this value is identical to the one used previously);

$Frac_{GasMS}$ = percentage of nitrogen managed in manure for livestock category T that volatilizes as $NH_3$ and $NO_x$ in the manure management system (S).

In this study, a $Frac_{GasMS}$ value of 40% was used since the poultry manure was deposited in the litter, as shown in Table 2.

The calculation of carbon emissions generated by the process of transporting the PL to its final application took into account the use of a backhoe loader and a truck, whereby the backhoe loader transported the material from its resting place to the truck.

### *Inventory of poultry litter subjected to anaerobic digestion*

Table 3 shows the characterization of the inoculum and the residue used (PL) in the AD tests carried out at the Laboratory of Technological and Environmental Chemistry of the Federal University of Ouro Preto (LQTA/UFOP) as detailed in Paranhos (2021).

The results optimized by Paranhos (2021) led to a maximum methane production from PL of 123.64 standard deviation±1.14 Nm L $CH_4$. g $VS^{-1}$ (or 61.80±3.99 NmL $CH_4$. g $COD^{-1}$) under conditions where the initial pH was ~9.0 and the A/M ratio ~0.50. These results, together with the physical-chemical characterization of PL, were used to carry out the environmental assessment of scenario C2.

The environmental assessment of scenario C3, in which PL is thermally pre-treated prior to AD, was based on the data presented in Paranhos (2021), as presented in Table 4.

**Table 1 – Fraction of total annual nitrogen excreted by chickens.**

| Manure Management System | Fraction of total nitrogen excreted annually — DW (%) |
|---|---|
| Anaerobic lagoon | 0.83 |
| Solid storage | 71.64 |
| Pasture | 3.77 |
| Storage <30 days | 6.96 |
| Biodigester | 3.23 |
| Others | 13.57 |

Source: Embrapa (2018).
DW: dry weight.

**Table 2 – Loss of nitrogen from manure due to volatilization of N-NH3 and N-$NO_x$.**

| Type of animal | Manure management system (MMS) | $Frac_{GasMS}$ % (range) |
|---|---|---|
| Poultry | Poultry without litter | 55 (40–70) |
| | Anaerobic lagoon | 40 (25–75) |
| | Poultry with litter | 40 (10–60) |

Source: IPCC (2019) and Gavrilova et al. (2019).

**Table 3 – Characterization of the inoculum and sample in terms of nitrogen content, proteins, solids, and chemical oxygen demand.**

| Sample | TKN (%, g/100g) | Proteins (%, g/100g) | COD (mg $O_2$/g) | TS (g/g sample) | VS (g/g sample) | Ash (%) | Humidity (%) |
|---|---|---|---|---|---|---|---|
| INOCULUM | Nm | Nm | Nm | 0.203±0.033 | 0.091±0.35 | 11.18% | Nm |
| PL | 1.37 | 8.17 | 462.20 | 0.805±0.005 | 0.350±0.010 | 45.51% | 24.27% |

Source: Paranhos (2021).
TKN: Total Kjeldahl Nitrogen; COD: chemical oxygen demand; TS: total solids; VS: volatile solids; Nm: not measured; ± standard deviation; PL: poultry litter (made up of rice straw and excreta).

**Table 4 – Physio-chemical characterization of poultry litter samples *in natura* and after thermal pre-treatment at 80°C and 98°C.**

| Sample | VSS (g) | TSS (g) | VSS/TSS | $M_{sludge}$ (g) | $M_{substrate}$ (g) |
|---|---|---|---|---|---|
| PL | 0.2859 | 0.6818 | 0.419 | 20.31 | 4.33 |
| HPT80 | 0.0903 | 0.2356 | 0.383 | 19.70 | 13.31 |
| HPT98 | 0.0871 | 0.2346 | 0.371 | 19.48 | 13.64 |

Source: Paranhos (2021).
VSS: volatile suspended solid; TSS: total suspended solids; VSS/TSS: volatile suspended solids to total suspended solids ratio; $M_{sludge}$: sludge mass; $M_{substrate}$: substrate mass; PL: poultry litter (composed of ground rice straw and poultry droppings); HPT80: hydrothermal pre-treatment at 80°C; HPT98: hydrothermal pre-treatment at 98°C.

## Results and Discussion

### Greenhouse gas emissions

The GHG emission calculations performed for scenario C1 (disposal of PL on the ground) are shown in Table 5. It can be seen that the emissions resulting from loading and transporting the PL to the final disposal point (a radius of 100 km from the generator point) are negligible when compared to the emissions ($CH_4$, $N_2O$, and $CO_2$) occurring in the soil due to the uncontrolled decomposition of the organic matter which constitutes this waste. Most GHG emissions come from direct and indirect nitrogen oxides, which are present in the nitrogenous material comprising PL. It is worth noting that the lignocellulosic fraction of PL (accounting for ~1/5 of its mass) does not contribute to $CO_2$ emissions. It would be carbon neutral since it comes from plantations (in this case rice) which have absorbed $CO_2$ from the atmosphere during their growth until harvest.

As previously mentioned, one option for minimizing these uncontrolled emissions would be to conduct PL anaerobic digestion and use the solid by-product of this process (anaerobic sludge) to produce biosolids for application to the soil, as recommended by National Environment Council (CONAMA) Resolution 498/2020. Such management would prevent uncontrolled PL emissions into the soil and would also enable energy to be recovered in methane gas, which could be used as a source of heat at the farm (Paranhos et al., 2020). This proposal comprises scenarios C2 and C3, which will be discussed from the point of view of environmental viability.

Based on the calculations performed and presented in Table 6, the emissions of PL disposed of *in natura* on the soil can be compared with those arising from its previous stabilization in anaerobic reactors. Anaerobic digestion of PL reduces GHG emissions by 30%, which would otherwise continue to be generated as a result of the nitrogen oxides produced by the decomposition of nitrogenous organic matter disposed of on the soil as biosolids/sludge (Hassanein et al., 2022). Furthermore, emissions from burning biogas and generating steam, as well as from storing and applying digestate to the soil, are negligible compared to emissions due to nitrogen oxides.

**Table 5 – Greenhouse gas emissions for scenario C1.**

| Emissions | $kgCO_2$/ton PL | % |
|---|---|---|
| Diesel for backhoe loaders | 5.7 | $3x10^{-3}$ |
| Diesel for trucks | 45.4 | $2.4x10^{-2}$ |
| Emission of $CO_2$ eq => $CH_4$ into the air | 0.0094 | $5x10^{-6}$ |
| Emission of $CO_2$ eq => $N_2O$ (D) into the air | 37,465.3 | 19.99 |
| Emission of $CO_2$ eq => $N_2O$ (I) into the air | 149,861.2 | 79.98 |
| Total | 187,377.6 | 100% |

Source: Carneiro (2022).
$CO_2$: carbon dioxide; PL: poultry litter; $CH_4$: methane; $N_2O$: nitrous oxide; D: direct; I: indirect.

**Table 6 – Greenhouse gas emissions under scenario C2.**

| Emissions | $kgCO_2$/ton PL | % |
|---|---|---|
| Anaerobic digestion | 17.5 | $1.3x10^{-2}$ |
| Boiler | 7.8 | $6x10^{-3}$ |
| Incineration of lubricating oil | 2.5 | $2x10^{-3}$ |
| Digestate storage | 7.1 | $5x10^{-3}$ |
| Diesel for digestate application | 1.1 | $1x10^{-3}$ |
| Nitrogen (N, $N_2O$, $NO_x$, including $NO_2$) | 131,194.3 | 99.95 |
| Digestate application | 24.5 | $1.9x10^{-2}$ |
| Total | 131,254.8 | 100% |

Source: Carneiro (2022).
$CO_2$: carbon dioxide; PL: poultry litter.

**Table 7 – Greenhouse gas emissions for scenario C3.**

| Emissions | $kgCO_2$/ton PL | % |
|---|---|---|
| Anaerobic digestion | 80.2 | $6x10^{-2}$ |
| Boiler | 64.6 | $5x10^{-2}$ |
| Incineration of lubricating oil | 11.3 | $9x10^{-3}$ |
| Digestate storage | 5.8 | $4x10^{-3}$ |
| Diesel for digestate application | 1.0 | $4x10^{-2}$ |
| Nitrogen (N, $N_2O$, $NO_x$, including $NO_2$) | 131,194 | 99.85 |
| Energy expended on HPT | 5.0 | $4x10^{-3}$ |
| Digestate application | 19.9 | $8x10^{-4}$ |
| Total | 131,381.8 | 100% |

Source: Carneiro (2022).
PL: poultry litter; HPT: hydrothermal pre-treatment: CO2: carbon dioxide

The emissions related to scenario C3, in which the PL is thermally pre-treated before it is processed, are shown in Table 7. It can be observed that inserting the thermal pre-treatment stage (heating the PL with steam) does not imply a significant increase in GHG emissions, mainly because this study considered the use of methane generated in AD as a source of heat, after burning it to produce steam. The main emissions would remain from the decomposition of the nitrogenous fraction of the sludge (biosolids) in the soil, which would lead to nitrogen oxide formation.

Considering these results, it appears that the scenarios of PL anaerobic digestion combined with thermal treatment (scenario C3) or not (scenario C2) would reduce GHG emissions by ~30% compared to scenario C1 ("business as usual") of disposal of PL on the soil, as summarized in Figure 4.

Although there is a reduction in GHG emissions due to PL anaerobic digestion, attention should be paid to the unwanted emissions of $CH_4$ and $N_2O$ in the storage of digestate and biomass. Similar considerations could be applied to $NH_3$, which was disregarded in this study as the IPCC has not categorized it as a GHG. In addition to leading to higher GHG emissions, scenario C1 also results in economic losses due to energy and fertilizer costs, since the nutrients N and P in the anaerobic sludge/biosolid (generated by the PL, whether or not it has been thermally pre-treated) would be more available than those in the PL *in natura* (Hassanein et al., 2022). Estimates of the emissions avoided by replacing fertilizers by applying sludge/biosolids and digestate to the soil are shown in Figure 5.

While the nutrients present in digestate and sludge can contribute to agricultural production, on the other hand, their excessive use can lead to contamination of groundwater and surface water. For this reason, the environmental assessment of the PL managements considered in this study (scenarios C1, C2, and C3) from the perspective of acidification and eutrophication impacts is presented in the next section.

## Acidification and eutrophication potentials

Table 8 shows the typical composition of PL and the similarities with pig litter. This information was used to estimate the impact of discharging PL on the soil regarding the adverse effects of acidification and eutrophication.

Assuming the conversion value in phosphorus equivalents for nitrogen (N), phosphorus (P), and ammonium ion ($NH4^+$) using the emission factors and calculations defined according to the model proposed by the IPCC 2019 (Gavrilova et al., 2019), estimated emissions in phosphate ion equivalents were obtained, allowing the eutrophication potential associated with the three PL management scenarios to be assessed (Table 9).

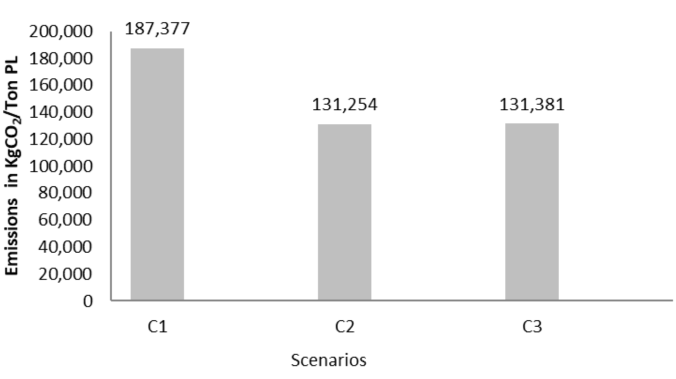


**Figure 4 – Comparison of total greenhouse gas emissions between the three proposed scenarios.**
Source: Carneiro (2022).

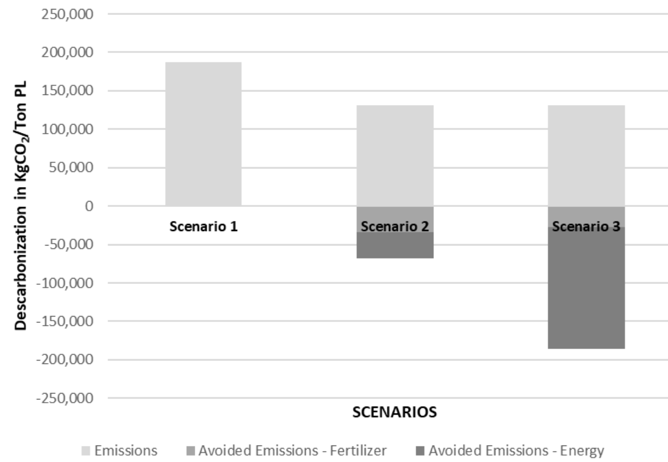


**Figure 5 – Estimated decarbonization potential from the anaerobic digestion of poultry litter and the use of digestate and sludge/biosolids as soil fertilizers.**
Source: Carneiro (2022).
PL: poultry litter; $CO_2$: carbon dioxide.

**Table 8 – Average content (mass percentage) of nutrients in pig and poultry litter.**

| Residue/Element | % m/m | | | | | |
|---|---|---|---|---|---|---|
| | N | P | K | Ca | Mg | S |
| Pig litter | 2.96 | 4.00 | 3.75 | 2.20 | 0.69 | 0.62 |
| Poultry litter | 3.00 | 2.40 | 3.65 | 2.30 | 0.73 | 0.62 |

Source: Carneiro (2022).
N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; S: sulphur.

**Table 9 – Estimated eutrophication potential for the three poultry litter management scenarios.**

| Scenario | Release of N and P | Equivalent emission (kg $PO_4^{3-}$ eq / ton PL) | Complete eutrophication (kg $PO_4^{3-}$ eq / ton PL) |
|---|---|---|---|
| C1 | 30 kg N / ton PL | 12.6 | 794.7 |
| | 24 kg P / ton PL | 73.7 | |
| | 2,109 kg $NH_3$ / ton PL | 708.4 | |
| C2 | 0.3 kg N / ton PL | 0.1 | 13.6 |
| | 0.6 kg P / ton PL | 1.9 | |
| | 35.1 kg $NH_4$/ ton PL | 11.6 | |
| C3 | 0.06 kg N/ ton PL | 0.03 | 7.4 |
| | 1.3 kg P / ton PL | 3.9 | |
| | 10.6 kg $NH_4$ / ton PL | 3.5 | |

Source: Carneiro (2022).
N: nitrogen; P: phosphorus; PL: poultry litter; $NH_3$: ammonia; $NH_4$: ammonium; $PO_4$: phosphate.

Table 9 shows that the greatest potential for eutrophication of PL *in natura* is associated with the presence of ammoniacal nitrogen, which accounted for 89% of emissions. These results are in agreement with data presented by Crippen et al. (2016) and Nusselder et al. (2020) who found that the presence of nutrients in PL depends on the moisture content and the number of reuse cycles. In other words, the reuse of PL proves to be a process of accumulation of phosphorus and nitrogen because of the excreta and food scraps from the birds left in the litter over the cycles. It should be pointed out that PL was used for six cycles in this case study (Paranhos, 2021), as instructed by Embrapa (2018) and widely adopted in Brazil.

The data presented in Table 9 also show that the adoption of a previous stage of PL anaerobic digestion, either combined (scenario C3) or not (scenario C2) with thermal treatment, would reduce total phosphate emissions between 98.4% and 99.1% when compared to scenario C1, where PL was disposed of *in natura* on the soil. This is because the inclusion of AD guarantees the production of energy (burning biogas) and biofertilizer (digestate), which, if used by the farm, would lead to avoided GHG emissions and a reduction in the potential for eutrophication (Nusselder et al., 2020; Hossain et al., 2023) when compared to scenario C1.

The acidification potential was calculated based on the same data as Paranhos (2021) to calculate the eutrophication potential. In this case, the conversion values in equivalent sulphur dioxide ($SO_2$ eq) for nitrogen (N), ammonia ($NH_3$), ammonium ion ($NH_4^+$), and sulphur (S) found in the PL were considered. Applying the emission factors and calculations defined according to the model proposed by the IPCC 2019 (Gavrilova et al., 2019), the following $SO_2$ eq emissions were obtained, as shown in Table 10.

**Table 10 – Acidification potential for the three poultry litter management scenarios.**

| Scenario | Release of N and S | Equivalent Emission (kg $SO_2$ eq / ton PL) | Total Acidification (kg $SO_2$ eq / ton PL) |
|---|---|---|---|
| C1 | 30 kg N / ton PL | 21.1 | 1,989.1 |
| | 2,109.6 kg $NH_3$ / ton PL | 1,961.9 | |
| | 6.2 kg S / ton PL | 6.2 | |
| C2 | 0.3 kg N / ton PL | 0.2 | 32.2 |
| | 35.1 kg $NH_3$ / ton PL | 31.2 | |
| | 0.8 kg S / ton PL | 0.8 | |
| C3 | 0.06 kg N / ton PL | 0.04 | 15.5 |
| | 10.6 kg $NH_3$ / ton PL | 9.5 | |
| | 6 kg S / ton PL | 6 | |

Source: Carneiro (2022).
N: nitrogen; S: sulphur; $NH_3$: ammonia; $SO_2$ eq: equivalent sulphur dioxide; PL: poultry litter.

It can be noted that the equivalent emissions of sulphur dioxide from the disposal of PL *in natura* on the soil (scenario C1) are mainly (98.6%) due to the $NH_3$ present in the PL. Despite this seeming contradiction, since ammonia is an alkaline gas, it must be pointed out that biological conversion of ammonia into nitrite and nitrate is an oxidative process leading to the production of protons ($H^+$) and a consequent decrease in pH of unbuffered water.

Anaerobic digestion of CA, whether subjected (scenario C3) or not (scenario C2) to thermal pre-treatment, substantially reduces $SO_2$ emissions by reducing ammonia levels, as discussed previously with regard to the "eutrophication" impact. Similarly, as observed for the 'eutrophication' impact, thermal pre-treatment of PL prior to AD would contribute little (~1%) toward the reduction of $SO_2$ emissions compared to the scenario of anaerobic digestion of PL *in natura*.

Comparing the results obtained for the acidification and eutrophication potential according to the data obtained by Paranhos (2021), it can be noted that the percentage reduction in environmental impact is practically the same for scenarios C2 and C3. Thus, from a strictly environmental point of view, there would be no justification/incentive for adopting thermal pre-treatment of the PL prior to its AD.

## Conclusions

The environmental assessment of the disposal of PL on the soil, which is currently the practice adopted by most companies in the farming sector, results in GHG emissions (~187 ton $CO_2$ eq / ton PL), as well as emissions of elements with the potential to cause eutrophication (~0.8 kg $PO4^{3-}$ eq / ton PL) and acidification (~2 ton $SO_2$ eq / ton PL) of soil and water. Anaerobic digestion of PL would contribute to reducing these emissions by around 30%, in addition to recovering energy from the manure in the form of methane, a non-fossil fuel that could be used to provide heating on the farm itself. Anaerobic digestion would also reduce phosphate equivalent emissions by 98.2% if carried out with PL *in natura* and by 99.1% if PL is thermally pre-treated. Similarly, the equivalent emissions of sulphur dioxide would be reduced to 32.2 kg $SO_2$ eq/ton PL or 15.5 $SO_2$ eq/ton PL, depending on whether the AD is performed with PL *in natura* or thermally pre-treated, respectively. From an environmental point of view, and considering the impact criteria evaluated (GHG emissions, acidification, eutrophication), there would be no incentive to thermally pre-treat PL prior to its AD. Therefore, the anaerobic digestion of PL *in natura* would already contribute to avoiding emissions, providing environmental benefits in addition to the obvious economic/energy benefits of using methane gas as an energy source on the farm itself.

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## Authors' contributions

CARNEIRO, G.N.B.V.: investigation; methodology; software; writing - original draft. ADARME, O.F.H.: data curation; methodology; software; writing - review & editing. AQUINO, S.F.: funding acquisition; project administration; resources; supervision; writing - review & editing.


## References


Beausang, C.; McDonnell, K.; Fionnuala, M., 2020. Anaerobic digestion of poultry litter – a consequential life cycle assessment. Science of The Total Environment, v. 735, 139494. https://doi.org/10.1016/j.scitotenv.2020.139494

BRASIL. Ministério do Meio Ambiente. Conselho Nacional do Meio Ambiente. Resolução CONAMA no 498, de 19 de agosto de 2020. Define critérios e procedimentos para produção e aplicação de biossólido em solos, e dá outras providências. Brasília, DF, 2020.

Carneiro, G.N.B.V., 2020. Análise de ciclo de vida de processos de digestão anaeróbia da cama de aviário. Master Thesis, Escola de Minas, Universidade Federal de Ouro Preto, Ouro Preto. Retrieved 2022-12-15, from https://www.repositorio.ufop.br/jspui/handle/123456789/16076

Crippen, T.L.; Sheffield, C.L.; Byrd, J.A.; Esquivel, J.F.; Beier, R.C.; Yeater, K., 2016. Poultry litter and the environment: Physiochemical properties of litter and soil during successive flock rotations and after remote site deposition. Science of the Total Environment, v. 553, 650-661. https://doi.org/10.1016/j.scitotenv.2016.02.077

ECOINVENT. Ecoinvent version 3.7 (Accessed December 22, 2022) at:. https://www.ecoinvent.org/.

Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), 2018. Apresentação. Embrapa suínos e aves. Portal Embrapa v.3.59.2, p. 01 (Accessed April 05, 2023) at:. https://www.embrapa.br/suinos-e-aves/apresentacao

Food and Agriculture Organization of the United Nations (FAO), 2020. World Food and Agriculture - Statistical Yearbook 2020. FAO, Rome. https://doi.org/10.4060/cb1329en

Gavrilova, O.; Leip, A.; Dong, H.; Macdonald, J.; Gomez-Brvo, C.A.; Amon, B.; Barahona, R.; Del Prado, A.; Lima, M.A.; Oyhantçabal, W.; Van Der Weerden, T.; Widiwati, Y., 2019. Emissions from livestock and manure management. In: Calvo Buendia, E.; Tanabe, K.; Kranjc, A.; Baasansuren, J.; Fukuda, M.; Ngarize, S.; Osako, A.; Pyroshenko, Y. Shermanau, P.; Federici, S. (Eds.), 2019 Refinement to the 2006 guidelines for National Greenhouse Gas Inventories. Agriculture, forestry and other land use. IPCC, Geneve, pp. p. 10.9-10.167.

Goedkoop, M.; Heijungs, R.; Huijbregts, M.; Schryver, A. Struijs, J.; Zelm, R., 2013. ReCiPe (2008) – a life cycle impact assessment method which comprises harmonized category indicators at the midpoint end endpoint level. Ministry of Housing, Spatial Planning and Environment, Boca Raton (FL).

Hassanein, A.; Moss, A.; Cloyd, N.; Lansing, S., 2022. Evaluation and life cycle assessment of a poultry litter anaerobic digester with nutrient capture. Bioresource Technology Reports, v. 19, 101186. https://doi.org/10.1016/j.biteb.2022.101186

Hossain, S.; Akter, S.; Saha, C.K.; Reza, T.; Kabir, K.B.; Kirtania, K., 2023. A comparative life cycle assessment of anaerobic mono- and co-digestion of livestock manure in Bangladesh. Waste Management, v. 157, 100-109. https://doi.org/10.1016/j.wasman.2022.12.011

Intergovernmental Panel on Climate Change (IPCC). Appendix 4: Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, Geneva.

Jeswani, H.K.; Whiting, A.; Martin, A.; Azapagic, A., 2019. Environmental impacts of poultry litter gasification for power generation. Energy Procedia, v. 161, 32-37. https://doi.org/10.1016/j.egypro.2019.02.055

Nusselder, S.; De Graaff, L.G.; Odegard, I.Y.R.; Vandecasteele, C.; Croezen, H.J., 2020. Life cycle assessment and nutrient balance for five different treatment methods for poultry litter. Journal of Cleaner Production, v. 267, 121862. https://doi.org/10.1016/j.jc lepro.2020.121862

Organisation for Economic Co-operation and Development (OECD), 2023. OECD-FAO Agricultural Outlook 2023-2032. https://doi.org/https://doi.org/10.1787/08801ab7-en

Paranhos, A.G.O. Efeitos da tilosina na digestão anaeróbia do resíduo avícola: produção de biogás, resistência a antibióticos e comunidade microbiana. Doctoral Thesis, Núcleo de Pesquisas e Pós-Graduação em Recursos Hídricos, Universidade Federal de Ouro Preto, Ouro Preto. Retrieved 2021-04-30, from https://www.repositorio.ufop.br/jspui/handle/123456789/13305

Paranhos, A.G.O.; Adarme, O.F.H.; Barreto, G.F.; Silva, S.Q.; Aquino, S.F., 2020. Methane production by co-digestion of poultry manure and lignocellulosic biomass: kinetic and energy assessment. Bioresource Technology, v. 300, 122588. https://doi.org/10.1016/j.biortech.2019.122588

Rajendran, K.; Murthy, G.S., 2019. Techno-economic and life cycle assessments of anaerobic digestion – A review, (2019). Biocatalysis and Agricultural Biotechnology, v. 20, 101207. https://doi.org/10.1016/j.bcab.2019.101207

Valenti, F.; Liao, W.; Porto, S.M.C., 2020. Life cycle assessment of agro-industrial by-product reuse: a comparison between anaerobic digestion and conventional disposal treatments. Green Chemistry, v. 22, 7119-7139. https://doi.org/10.1039/D0GC01918F

Weindl, I.; Ost, M.; Wiedmer, P.; Schreiner, M.; Neugart, S.; Klopsch, R.; Kühnhold, H.; Kloas, W.; Henkel, I. M.; Schlüter, O.; Bußler, S.; Bellingrath-Kimura, S. D.; Ma, H.; Grune, T.; Rolinski, S.; Klaus, S., 2020. Sustainable food protein supply reconciling human and ecosystem health: a Leibniz position. Global Food Security, v. 25 (March), 100367. https://doi.org/10.1016/j.gfs.2020.100367

Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. International Journal of Life Cycle Assessment, v. 21, (9), 1218-1230. https://doi.org/10.1007/s11367-016-1087-8