# Anaerobic co-digestion of chicken litter and raw glycerol as a sustainable tool for the waste management of a Slovak poultry farm and to reduce its energy consumption

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**Abstract**

The present study was oriented to estimate the energy potential of chicken litter generated in a poultry farm (158,000 chicken heads per growth cycle), through its anaerobic co-digestion (AcoD) with raw glycerol. Besides manure, chicken litter contains urine and straw. Since biodegradability of chicken litter is high, anaerobic digestion is considered an interesting alternative to composting. Nevertheless, due to low C/N ratios in litter, ammonia inhibition is a common problem faced in praxis. Fresh samples of chicken litter were collected from the poultry farm (438 VS $kg^{-1}$). Raw glycerol (814 g VS $kg^{-1}$, 1372 g COD $l^{-1}$) was collected from a biodiesel plant. A laboratory-scale stirred reactor was operated at mesophilic conditions for 158 days with organic loading rates (OLR) that ranged from 1.5 to 3 g VS $L^{-1}d^{-1}$ and co-digestion ratios of 2:1 and 1.5:1 (chicken litter-to-glycerol) on a VS basis. Water was added to the process to adjust reactor's retention times (RT) to 36, 51 and 54 days. The addition of water and raw glycerol as co-substrate helped to optimize the operational parameters (TAN, VFA) and performance of the reactor. The specific biogas production averaged 460 L $kg^{-1}$ VS (54 % $CH_4$). Experimental results were later used to estimate the outcomes of its real application on the poultry farm. The results put in evidence that AcoD is a sustainable tool that could enable waste management, generate new jobs, reduce the impact of GHG emissions on the environment and reduce the energy consumption of the poultry farm.

**Keywords**
Anaerobic digestion, chicken litter, manure, raw glycerol, poultry farm, digester design

## 1. Introduction

According to FAO (2016), there are about 21 billion stocks of chicken worldwide. In most developed countries, poultry farming has become more industrialised in order to satisfy the growing demand for meat and other animal products. According to the [1], about 74 % of the poultry meat and 68 % of eggs are produced in industrial farms. Therefore, modern poultry farms require higher inputs of animal feed, water, medical inputs and other commodities from external suppliers. Moreover, such farms are in most cases in need of an external partner to do the waste management of poultry manure *ex situ*. Poultry manure is rich in nitrogen and phosphorus and therefore, the traditional utilization of manure was to enrich soil and fertilise crops. However, if manure is poorly managed, significant water pollution can occur. According to Hong et al [2], it is not unusual to see ponds covered with algae near poultry farms because of excess nutrients. Nitrogen to phosphorus (N/P) ratios in manure are usually narrower than uptake ratios of plants, leading to excessive application of P in the soil if application rates of manure are based on N requirement. On the other hand, animal manure can lead to large productions of methane ($CH_4$) and nitrous oxide ($N_2O$), greenhouse gases with a global warming potential 25 and 310 times higher than $CO_2$, respectively. Additionally, the emissions of carbon dioxide ($CO_2$), ammonia ($NH_3$), hydrogen sulphide ($H_2S$), sulphide dioxide ($SO_2$) and volatile organic compounds (VOCs); contributes to the acidification process in soil, eutrophication of waters and ground-level ozone pollution [3]. Since the biological degradability of poultry manure is high, anaerobic digestion (AD) has been successfully applied on manure management as a good choice to reduce the negative impact of manure on the environment, recover energy and produce an organic digestate of better characteristics [4]. Nevertheless, due to the high content of nitrogen in poultry manure and its low C/N ratio, ammonia inhibition has been a major problem faced in praxis.

The main sources of nitrogen present in poultry manure come from proteins and urine. These are decomposed into ammonia during the anaerobic digestion process [5]. Nitrogen is an essential nutrient for the growth of bacteria involved in the fermentation and ammonia is an important nitrogen source in the fermenter. However, high accumulation of ammonia in the anaerobic system can inhibit methanogenesis [6; 7], cause toxicity to AD microbiome or shift the prevalence of bacterial communities and metabolic pathways of methane formation [8].

Anaerobic co-digestion (AcoD) has been previously introduced as a feasible technique to mitigate ammonia accumulation and inhibition when treating poultry litter [9; 10]. Crude or raw glycerol (GLY) is a carbon-rich liquid by-product of biodiesel production, which represents about 10 % of the weight of the initial raw matter. GLY is soluble in water and due to its high anaerobic biodegradability, allows significant increases in reactor organic loading rates with a minimum impact on solid retention times. Common components in GLY include glycerol, alcohol, water, salts, heavy metals, fatty acids, unreacted mono-, di- and triglycerides and methyl esters. Even though GLY has been described as an ideal co-substrate, there is a major inhibition risk associated to overloading of reactors, if co-digestion ratios are not chosen adequately [11]. Astals et al [12] reported that the addition of GLY to other manures not only increased biogas production, but it also helped to optimize C/N ratios, balancing ammonia concentrations in reactor sludge. Nevertheless, co-digestion ratios must be carefully managed in order to achieve the necessary degree of mineralization for anaerobic sludge in order to accomplish restrictive limits for its safe application on agricultural land.

This study aims to illustrate the technical potential of a poultry farm to produce biogas from its chicken litter in co-digestion with raw glycerol, through the long-term operation of a laboratory model and the estimation of the optimal operational parameters of the reactor. A brief analysis of the outcomes is also introduced, based on the current operational characteristics of the poultry farm and obtained results.

## 2. Materials and methods

### 2.1 Case study

A modern poultry farm located in western Slovakia raises chicken for sale. The poultry farm has 13 broiler sheds and produces a total number of 158,000 chicken heads in a growth cycle, which consists of 42 days. In this time, the chickens are raised into its final size, weighing about 2700 g.

Afterwards, the chickens are prepared for expedition and thus, the broiler sheds are emptied. Chicken litter is collected during the cleaning process of the sheds and placed temporary on a manure pit *in situ* for its further transport and disposal by external partners. The transition period between every growth cycle is about 18 days, in which the broiler sheds are cleaned, disinfected and prepared for incoming chicks.

The economic balance for the poultry farm is basically positive, i.e. the owner gets some money from the sales of chicken manure or at least does not have to pay for its transport and disposal. An external partner does the complete waste management for the poultry farm, i.e. both internal and external transport, as well as the final disposal of manure in a composting facility located nearby. Recently, a biogas plant has also expressed its interest on collecting the manure for anaerobic digestion *ex situ*.

However, an even more attractive option for the poultry farm could be to construction and operation of its own biogas plant. A biogas plant could be able to supply farm’s own needs for natural gas, electricity and/or heat; executing simultaneously the waste management of the farm. Moreover, taking into consideration that the poultry farm already counts with enough space for the building of digesters, silos and pits, as well as basic manipulation equipment such a tractor-scraper, a bulldozer and dump trucks; it could be affordable to build and run a biogas plant *in situ*. Additionally, the implementation of a biogas plant would contribute to a more circular economy of the poultry farm, reducing greenhouse gas emissions (GHG) and generating more local jobs.

In table 1 are shown the operational characteristics of the poultry farm that were taken into consideration for the further development of this study.

Table 1 Selected operational characteristics of the poultry farm

| | | |
|---|---|---|
| - Number of chicken heads in a growth cycle | heads per cycle | 158,000 |
| - Chicken litter produced in a growth cycle | | |
| Growth cycle 42 d | Mg | 360 |
| [1]Specific production of chicken litter 0.054 kg $hd^{-1}$ $d^{-1}$ | Mg TS | 184 |
| Dry matter (TS) for chicken litter 512 g TS $kg^{-1}$ | Mg VS | 158 |
| Organic dry matter (VS) for chicken litter 438 g VS $kg^{-1}$ | | |
| - Available amount of chicken litter in a day | Mg | 6 |
| | Mg TS | 3.1 |
| | Mg VS | 2.6 |
| - Daily average consumption of natural gas, mainly for heating of broiler sheds (operational temperature 33 °C) | | |
| - In summer days (84 d) | $Nm^3$ $d^{-1}$ (GJ $d^{-1}$) | 1,200 (39.2) |
| - In winter days (84 d) | $Nm^3$ $d^{-1}$ (GJ $d^{-1}$) | 2,500 (81.6) |
| - Transitional weather (84 d) | $Nm^3$ $d^{-1}$ (GJ $d^{-1}$) | 100 (3.3) |
| - Daily average consumption of electrical energy (mainly lights, feeding system, exhaust and ventilation fans, pumps) | kWh $d^{-1}$ | 2,000 |
| - Estimated energy consumption for the operations of a complete calendar year (252 d) | MWh $y^{-1}$ | 630 |
| | $Nm^3$ $y^{-1}$ (GJ $y^{-1}$) | 319,200 (10,423) |

**Notes:**
- [1]*Ordinance SR No. 199/2008 [15]*
- Gross calorific value (GCV) of methane 39,820 kJ $Nm^{-3}$ $CH_4$
- *Thermal conversion efficiency of the boiler: 82 %*

Based on the operational characteristics of the poultry farm shown in table 1, the feedstock parameters of a biogas plant are proposed. Additionally, based on feedstock parameters, the long-term operation of a laboratory-scale reactor was carried out in order to determine the operational parameters of a biogas plant for the poultry farm. All input parameters used later for the equations in table 3 were obtained experimentally. The results of the long-term operation of the reactor can be later observed in table 4 and figures 2-5.

### 2.2 Substrates and inoculum

Fresh samples of chicken litter (Figure 1a) were collected directly from the poultry farm and stored in a laboratory freezer at -18 °C. Besides dung, chicken litter contains urine and straw (5 – 10 % of total amount of litter). Regarding the content of organic matter in litter, all collected samples averaged 438 g VS $kg^{-1}$. Feeding doses for the reactor were prepared in individual bags two weeks in advance and stored at 4 °C for its immediate use.

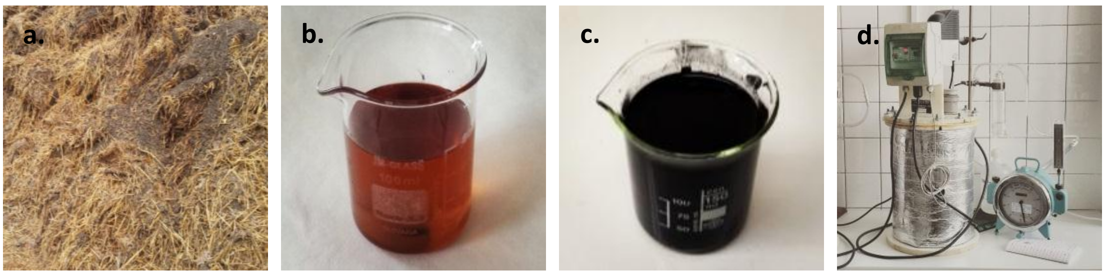


Figure 1 Chicken litter pit from the poultry farm (a.), raw glycerol from the bio-diesel plant (b.), sludge used as inoculum (c.) and the laboratory continuous-stirred reactor used for the experiment (d.)

Samples of residual raw glycerol (814 g VS $kg^{-1}$, 1,372 g COD $l^{-1}$) were collected from a bio-diesel plant located 80 km away from the poultry farm and stored in a *jerry can* at laboratory temperature (Figure 1b).

Anaerobic sludge from another laboratory reactor with a previous experiment using poultry litter as main substrate was used as inoculum (Figure 1c).

The characteristics of chicken litter, raw glycerol and inoculum can be seen in table 2.

Table 2 Quality parameters of substrates and inoculum

| Sample | Analysis | Units | Value |
|---|---|---|---|
| Chicken litter | TS | g TS $kg^{-1}$ | 512 ± 135 |
| | VS | g VS $kg^{-1}$ | 438 ± 131 |
| Raw glycerol (GLY) | $COD_t$ | g $L^{-1}$ | 1,372 ± 28 |
| | TS | g TS $kg^{-1}$ | 872 ± 8 |
| | VS | g VS $kg^{-1}$ | 814 ± 4 |
| Inoculum | $COD_s$ | g $L^{-1}$ | 8.5 ± 0.5 |
| | VFA | g $L^{-1}$ | 3.2 ± 0.2 |
| | TAN | g $L^{-1}$ | 1.7 ± 0.12 |
| | $NH_3$-N | mg $L^{-1}$ | 65 ± 6 |
| | $PO_4$-P | mg $L^{-1}$ | 107 ± 2 |
| | TS | g TS $kg^{-1}$ | 37 ± 5 |
| | VS | g VS $kg^{-1}$ | 20 ± 3 |

### 2.3 Experimental set-up

A laboratory-scale continuous stirred reactor (Figure 1d), with a volume of sludge $V_R$ = 15 L was operated at mesophilic conditions (37 °C) for 160 days with an organic loading rate (OLR) that ranged from 1.5 to 3 g VS $L^{-1}d^{-1}$, as it can be seen in figure 2. During the first 36 days, the reactor was fed only with chicken litter. From the $36^{th}$ to $68^{th}$ day, the reactor was fed with both chicken litter and raw glycerol at a co-digestion ratio 2:1 (chicken litter-to-raw glycerol). In figures 2-5, the start point for co-digestion is marked with a dashed line. From the $68^{th}$ day till the end of the experimentation, the co-digestion ratio was adjusted to 1.5:1. Fresh tap water was added to the process from the $36^{th}$ day in order to adjust reactor's solid retention times (SRT) from the initial value of 167 d to 36, 51 and 54 d, respectively (Figure 3). There was neither recirculation of digestate nor supernatant back to the reactor.

### 2.4 Analytical methods

Analyses of the total fraction were performed directly on the raw samples of poultry litter and raw glycerol. For analyses of the soluble fraction, the samples were filtered through a 0.45 μm SYNPOR® filter. Analysis of the soluble fraction (COD, TAN, $PO_4$-P) and the total fraction (TS, VS, NL) were determined spectrophotometrically and gravimetrically respectively, following standard methods [13]. Volatile fatty acids (VFA) were determined in the soluble fraction according to Kapp [14]. Free ammonia nitrogen ($NH_3$-N) concentration was calculated using the following acid-base equilibrium formula:

$$\mathrm{NH_3-N} = \frac{\mathrm{K_a \cdot TAN}}{\mathrm{K_a + 10^{-pH}}} \qquad \text{(a)}$$

where the equilibrium constant $K_a$ at the assay temperature (T, Kelvin degrees) is calculated using the Van't Hoff equation (eq. 2):

$$\mathrm{K_a} = \mathrm{K_{a(298.15)}} \cdot e^{\left(\frac{51965}{8.314} \cdot \left(\frac{1}{298.15} - \frac{1}{T}\right)\right)} \qquad \text{(b)}$$

The composition of biogas was measured with an infrared gas analyser GA2000 (Geotechnical Instruments). The gas analyser monitors the concentration of $CH_4$, $CO_2$, $O_2$, $N_2$, $H_2S$ and $H_2$.

Table 3 Recommended equations used for the estimation of the main technological parameters of the biogas plant for the poultry farm (Scale-up approach)

| N | Technological parameter | Equation | Units |
|---|---|---|---|
| (1) | Feeding rate | $\mathrm{M_{total,in} = M_{litter} + M_{GLY} + M_{water} + M_r}$<br>$\mathrm{TS_{total,in} = TS_{litter} + TS_{GLY} + TS_{rec}}$ | $\mathrm{Mg\ d^{-1}}$ |
| (2) | Organic feeding rate | $\mathrm{VS_{total,in} = VS_{litter} + VS_{GLY} + VS_{rec}}$ | $\mathrm{Mg\ VS\ d^{-1}}$ |
| (3) | Organic loading rate | $\mathrm{OLR} = \dfrac{\mathrm{VS_{total,in}}}{\mathrm{V_R\ \ t}}$ | $\mathrm{Mg\ VS\ L^{-1}d^{-1}}$ |
| (4) | Solids retention time | $\mathrm{SRT} = \dfrac{\mathrm{V_R}}{\mathrm{Q_{total}}}$ if $\rho_{\mathrm{total}} \approx 1$, $\mathrm{M_{total,in} = Q_{tot,in}}$ | d |
| (5) | Biogas production rate | $\mathrm{Q_{biogas} = VS_{total}\ \ SBP}$ | $\mathrm{m^3\ d^{-1}}$ |
| (6) | Electrical energy | $\mathrm{E_{el} = Q_{biogas}\ \%CH_4\ GCV_{CH4}\ \eta_{td}\ \eta_{el}}$ | $\mathrm{kWh\ d^{-1}}$ |
| (7) | Thermal energy (heat) | $\mathrm{E_{th} = 3.6\ Q_{biogas}\ \%CH_4\ GCV_{CH4}\ \eta_{td}\ (1 - \eta_{el})}$ | $\mathrm{MJ\ d^{-1}}$ |
| (8) | Engine power (CHP) | $\mathrm{P_{CHP}} = \dfrac{\mathrm{E_{el}}}{\tau}$ | kW |
| (9) | Income for electricity | $\mathrm{I_{el} = E_{el}\ \Pi_{kWh}}$ | $€\ \mathrm{d^{-1}}$ |
| (10) | Digestate production rate | $\mathrm{M_{total,out} \approx M_{total,in} - VS_{total,in}}$<br>$\mathrm{TS_{total,out} = M_{total,out}\ TS_{sludge,out}}$ | $\mathrm{Mg\ d^{-1}}$<br>$\mathrm{Mg\ TS\ d^{-1}}$ |
| (11) | Supernatant production rate | $\mathrm{M_{supernatant} = M_{total,out}} - \left(\dfrac{TS_{total,out}}{25\%}\right)$ | $\mathrm{Mg\ d^{-1}}$ |
| (12) | Nitrogen recovery potential | if $\rho_{\mathrm{supernatant}} \approx 1$<br>$\mathrm{N_{out} \approx M_{supernatant}\ TAN}\ \dfrac{\mathrm{M_N}}{\mathrm{M_{NH4}}}\ \dfrac{1}{1000}$ | $\mathrm{kg\ N\ d^{-1}}$ |
| (13) | Phosphorus recovery potential | $\mathrm{P_{out} \approx M_{supernatant}\ PO_4 - P}\ \dfrac{\mathrm{M_P}}{\mathrm{M_{PO4}}}\ \dfrac{1}{1000}$ | $\mathrm{kg\ P\ d^{-1}}$ |
| (14) | Sulphur recovery potential | $\mathrm{S_{out} = Q_{biogas}\ C_{H2S}}\ \dfrac{\mathrm{M_S}}{\mathrm{M_{H2S}}}\ \dfrac{1}{1000}$ | $\mathrm{kg\ S\ d^{-1}}$ |

**Notes:**
- Gross calorific value (GCV) of methane 11.06 kWh $Nm^{-3}$ $CH_4$
- Thermodynamic conversion efficiency of the CHP unit is $\eta_{td}$=95%; electrical efficiency $\eta_{el}$=40 %; thermal efficiency $\eta_{th}$=60 %
- Π = 110 €/MWh is the subsidized price for electricity produced in the Slovak Republic through anaerobic technology in the category from 250 to 500 kW, valid for digesters operating from 1/7/2015 [16]
- A centrifuge commonly allows to dewater to a 25%-TS digestate
- Fresh water consumption ($M_w$) could be substituted by a fraction of supernatant or digestate, if recirculation is enabled
- Nitrogen recovery potential from total ammonia nitrogen in the soluble fraction ($M_{NH4}$=18, $M_N$=14)
- Phosphorus recovery potential from phosphate-phosphorus in the soluble fraction ($M_{PO4}$ = 94.97, $M_P$ = 30.97)
- Sulphur recovery potential from hydrogen sulphide in biogas ($M_{H2S}$ = 34.08, $M_S$ = 32.07)

## 3. Results and discussions

The first 20 days, the feeding of chicken litter as single substrate helped to increase the production of biogas. Nevertheless, after the concentration of ammonia (TAN) reached values around 2 g $L^{-1}$, the production of biogas decreased (Figure 2). It was expected that the addition of GLY as co-substrate in a ratio 2/1 (chicken litter-to-GLY) would help to increase biogas production rates again. However, even though the OLR was doubled with the addition of GLY, the increase in biogas production was slowly, reaching its maximum 30 days later and followed by a significant decrease. This suggested us that inhibition of the process could be happening, either by accumulation of volatile fatty acids (overloading of reactor) or by still high concentrations of ammonia (TAN). Therefore, the co-digestion ratio was set at 1.5/1 and thus, the OLR was reduced to 2.5 g $L^{-1}$(Figure 2). The addition of water was adjusted so the SRT of the reactor was kept constant (Figure 3). At this OLR, the production of biogas doubled and was stable for about 40 days till the end of the experimentation. The concentration of $CH_4$ moderately increased from 50.7 to 54.1 % and the concentration of $H_2S$ decrease from 3140 to 2523 ppm and maintained at similar values, after the addition of GLY.

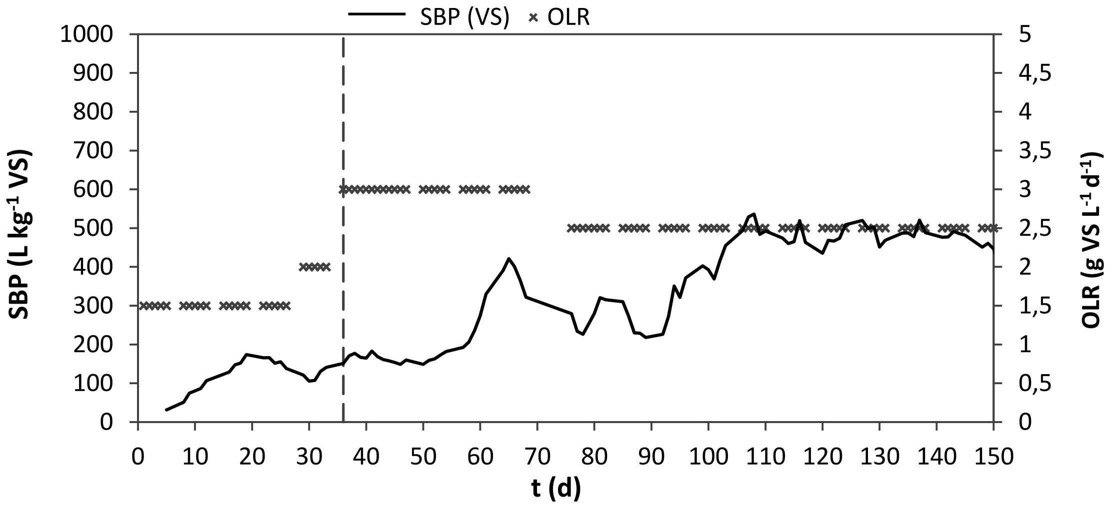


Figure 2 Specific biogas production (SBP) in relation to reactor organic loading rate (OLR). SPB values are represented by a trend line conformed by a moving average (5 days-period)

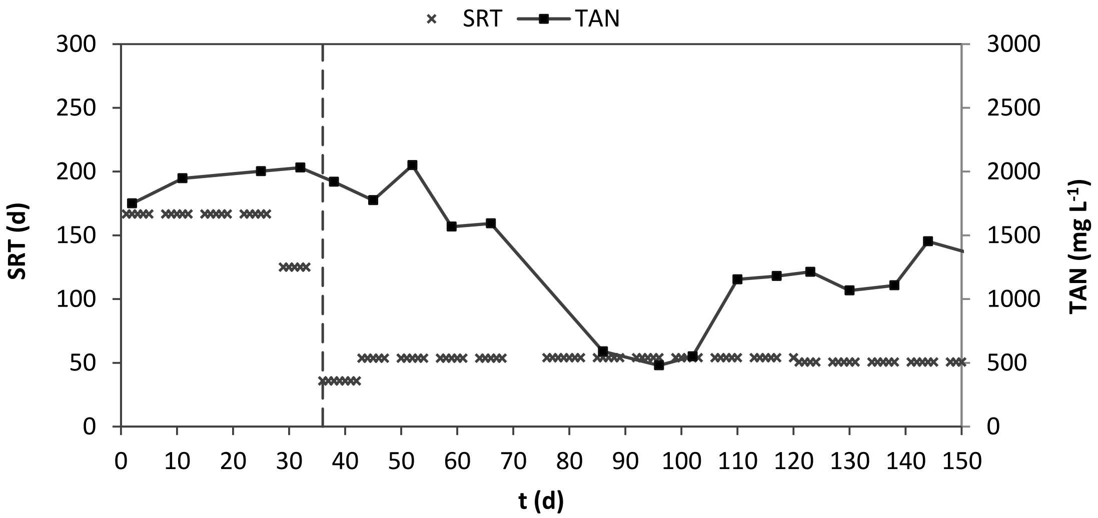


Figure 3 Solid retention times (SRT) in relation to the variation of TAN concentration

On the other hand, the concentration of TAN and VFA had in general a positive response after the addition of GLY (Figure 4a/b). Initially, TAN concentration decreased to less than 25% of the initial value (500 mg $L^{-1}$), but slowly increased back to values around 1300 mg $L^{-1}$ by the end of the experiment, as ammonia slowly started to accumulate again in the system.

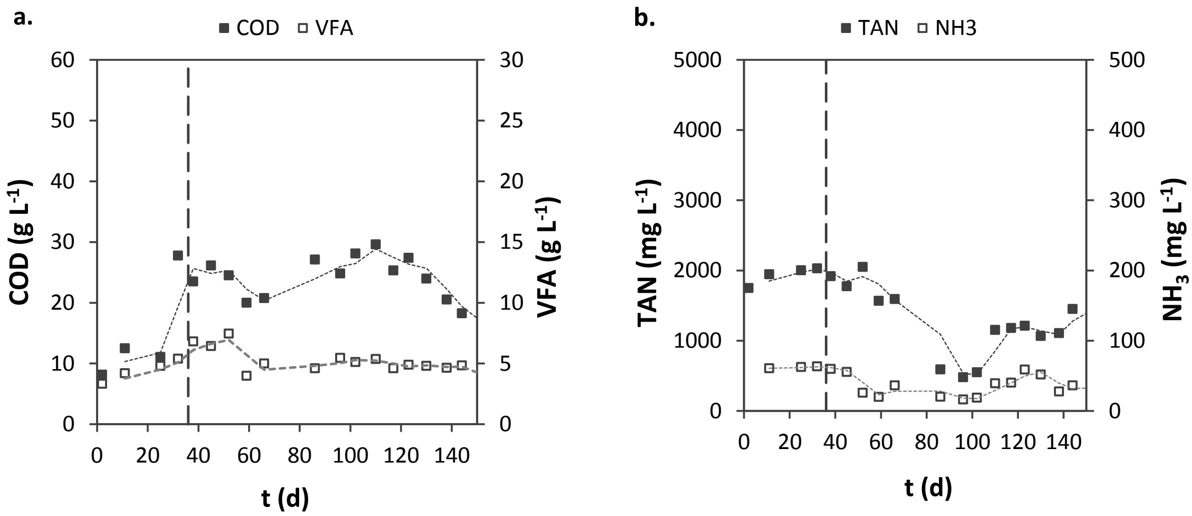


Figure 4 Variation of COD and VFA (a.) and ammonia (b.) as response to changes in OLR and SRT

Regarding the organic content of reactor sludge, COD concentration significantly increased after the addition of GLY and remained in the range 20 – 30 g $L^{-1}$ for the rest of the experiment (Figure 4a). C/N and C/P ratios varied in course of time, but were optimized in general with the introduction of the co-substrate (Figure 5a). However, by the end of the experimentation, the C/N ratio decreased again to values close to 15, which may cause inhibition if ammonia keeps accumulating in the system [6]. Analysis of the total fraction (Figure 5b) showed that solids content of sludge increased when reactor OLR was set at 3 g $L^{-1}$ but start a slowly decrease when OLR was changed to 2.5 g $L^{-1}$. VS of reactor sludge was about 60 % (% TS, i.e. loss on ignition) and kept stable after the addition of GLY. The presence of inorganic compounds initially increased along with the OLR but slowly decreased together with reactor's solids content.

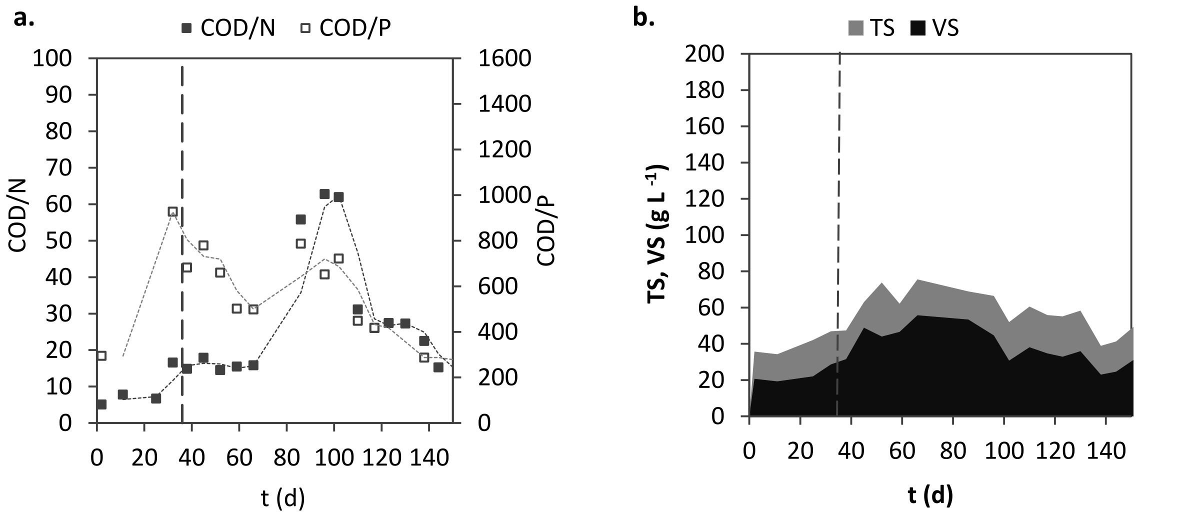


Figure 5 Variation of COD/N, COD/P (a.) and solids content (b.) as response to changes in OLR and SRT

In table 4, the main operational parameters towards the end of the experimentation can be seen. Although, the operation of the reactor was generally stable after the addition of GLY as co-substrate, there are still some technical issues, related to the consumption of water and the accumulation of ammonia that can be optimized. At an industrial scale, recirculation of sludge's supernatant could considerably reduce water consumption of the plant. Nevertheless, recirculation of supernatant would accelerate the accumulation of TAN and COD in the soluble fraction of reactor sludge, resulting in ammonia inhibition or overloading of reactor. Therefore, supernatant must be treated externally in order to reduce the concentration of TAN and reactor's OLR has to be re-adjusted and optimized.

Table 4 Main operational parameters and sludge quality towards the end of the experimentation

| Sample | Parameter | Units | Value |
|---|---|---|---|
| Soluble fraction | $COD_s$ | g $L^{-1}$ | 18.5 |
| | VFA | g $L^{-1}$ | 4.6 |
| | TAN | mg $L^{-1}$ | 1,400 |
| | $NH_3$-N | mg $L^{-1}$ | 29 |
| | $PO_4$-P | mg $L^{-1}$ | 198 |
| Total fraction | TS | g TS $kg^{-1}$ | 58 |
| | VS | g VS kg $^{-1}$ | 38 |
| Biogas | DBP | L $L^{-1}_{reactor}$ $d^{-1}$ | 1.15 |
| | SBP | L $kg^{-1}$ VS | 460 |
| | $CH_4$ | % | 54.1 |
| | $CO_2$ | % | 43.2 |
| | $H_2S$ | ppm (g $m^{-3}$) | 2,520 (3.78) |
| Operational parameters | OLR | g VS $L^{-1}$ | 2.5 |
| | SRT | d | 51 |
| | SPS | g TS $d^{-1}$ | |
| | θ | °C | 37 |
| | pH | - | 7.23 |

Table 5 illustrates the technological design of a biogas plant for the poultry farm, based on the results obtained experimentally (Table 4) and the equations described in table 3.

Table 5 Main technological parameters of a biogas plant for the poultry farm

| | Parameter | Abb. | Units | Value |
|---|---|---|---|---|
| Feedstock parameters | Feeding rate | $M_{total,in}$ | Mg $d^{-1}$ or $m^3$ $d^{-1}$ | 34.2 |
| | Dry matter feeding rate | $TS_{total,in}$ | Mg TS $d^{-1}$ | 4.9 |
| | Organic feeding rate | $VS_{total,in}$ | Mg VS $d^{-1}$ | 4.4 |
| | Co-digestion ratio | $VS_{litter}/VS_{GLY}$ | - | 1.5 |
| | Chicken litter feeding rate | $M_{litter}$ | Mg $d^{-1}$ | 6.0 |
| | Daily chicken litter input (TS) | $TS_{litter}$ | Mg TS $d^{-1}$ | 3.1 |
| | Daily chicken litter input (VS) | $VS_{litter}$ | Mg VS $d^{-1}$ | 2.6 |
| | Raw glycerol feeding rate | $M_{GLY}$ | Mg $d^{-1}$ | 2.1 |
| | Daily raw glycerol input (VS) | $VS_{GLY}$ | Mg VS $d^{-1}$ | 1.7 |
| | Fresh water input | $M_{water}$ | Mg $d^{-1}$ | 26.1 |
| Operational parameters | Organic loading rate | OLR | g VS $L^{-1}$ | 2.5 |
| | Solid retention time | SRT | d | 51 |
| | Volume of sludge | $V_R$ | $m^3$ | 1,744 |
| | Volume of digester | $V_d$ | $m^3$ | 2,200 |
| Biogas and energy | Biogas production rate | $Q_{biogas}$ | $Nm^3$ $d^{-1}$ | 2,005 |
| | Methane production rate | $Q_{CH4}$ | $Nm^3$ $d^{-1}$ | 1,085 |
| | Electrical energy | $E_{el}$ | kWh $d^{-1}$ | 4,560 |
| | Thermal energy (heat) | $E_{th}$ | MJ $d^{-1}$ | 24,624 |
| | Engine power (CHP) | $P_{CHP}$ | kW | 190 |
| | Income for electricity | $I_{el}$ | € $d^{-1}$ | 502 |
| Digestate and nutrients | Digestate production rate | $M_{total,out}$ | Mg $d^{-1}$ | 29.8 |
| | Digestate (TS) production rate | $TS_{total,out}$ | Mg TS $d^{-1}$ | 1.7 |
| | Supernatant production rate | $M_{supernatant}$ | Mg $d^{-1}$ | 22.9 |
| | Nitrogen recovery potential | $N_{out}$ | kg N $d^{-1}$ | 25.0 |
| | Phosphorus recovery potential | $P_{out}$ | kg P $d^{-1}$ | 1.5 |
| | Sulphur recovery potential | $S_{out}$ | kg S $d^{-1}$ | 7.1 |

According to the information obtained from the poultry farm and results shown in table 5, if a co-generation unit (CHP) is used, the energy balance in one calendar year can be estimated as follows:

- Electrical energy consumption of the poultry farm : 730 MWh $y^{-1}$
- Electrical energy from the biogas plant: 1664 MWh $y^{-1}$
- Heat consumption of the poultry farm: 319,200 GJ $y^{-1}$
- Heat given by the biogas plant: 8988 GJ $y^{-1}$

As it can be seen, the electrical energy from the biogas plant could cover all the consumption of the poultry farm, generating a yearly surplus of about 934 MWh. Additionally, the production of electricity from biogas would generate an extra income for every MWh generated from biogas, thanks to the Slovak subsidiary policy for electricity generated from renewable energy [16; 17]. Regarding heat consumption of the poultry farm, the biogas plant would be able to cover less than 3% of the heat needs, if a CHP unit is installed. Although biogas production could be enough to cover all the heat consumption of the plant, the installation of a boiler for direct combustion of biogas to produce heat is not recommended, as the consumption of heat markedly varies during the seasons of the year.

Even though the potential for nutrients recovery is mentioned in table 5 and could help to generate more profit from the anaerobic process, its contribution was not estimated. Additional costs related to the consumption of glycerol and water, the post-treatment of digestate (or supernatant) and the removal of hydrogen sulphide from biogas are not considered in this study.

## 4. Conclusions

Anaerobic co-digestion of chicken litter and raw glycerol showed in general, a positive impact on the anaerobic process. At a AcoD ratio of 1.5, OLR 2.5 g VS $L^{-1}$ and SRT 51 d; the operational parameters of the anaerobic reactor and biogas production rates were optimized and remained relatively stable until the end of the experimentation. Through anaerobic co-digestion, it would be technically possible to take advantage of the 360 Mg of chicken litter produced in the farm during a growth cycle, which in combination with 1.7 Mg $d^{-1}$ of raw glycerol and water, would generate enough biogas to cover the electrical energy needs of the poultry farm, with a yearly surplus of about 934 MWh. Anaerobic co-digestion is a feasible and sustainable waste management tool that simultaneously helps to reduce the impact of greenhouse gas emissions, generates new jobs and contributes to reduce the energy consumption of poultry farms.

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