Poultry Manure Biomass: Energetic Characterization and ADM1-based Simulation

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Abstract. Nowadays energy world awareness has been influenced by new targets, to reach the environmental pollution reduction and a renewable waste management. Anaerobic digestion represents an alternative way to product methane, without using of fossil sources, in accordance with the newest WtE (Waste to Energy) applications. The aim of this work was to define a specific model for the simulation of a poultry manure anaerobic digestion process, to identify some inhibition factors and minimize them. In fact, for a specific biomass model simulation, it is necessary to adapt the ADM1 model setting up some of its rate governing equations. First, the biomass has been experimentally characterized, then the ADM1 has been studied and adapted to implement the poultry manure organic degradation scenario. Determination of kinetic parameters has been conducted by using bibliographic sources. Then, the model has been implemented and computed through an open-source simulation software, that is AQUASIM. The simulation led to consistent numerical results, confirmed both by the published scientific articles and the conducted experimental campaigns.

1. Introduction

International awareness in terms of pollution reduction policies has been increasing in the very last years, due to a world growing energy demand [1]–[5]. Many strategies have been developed in the global energy efficiency field [6]–[8], trying to promote renewable energy sources exploitation, such as solar, wind, and geothermal, to face fossil-based fuels. Referring to European scenario, Directive 2009/28/EC – also known as Directive 20-20-20 – and Energy Roadmap 2050 set climate and energy goals to be achieved by 2020: gases emissions reduction and energy efficiency improvement are some of the requirements. In these terms, biomass conversion into energy is one of the most used methods to reduce emissions of pollutants and carbon dioxide directly into atmosphere: many studies have been conducted to optimize those conversion processes, increasing overall conversion rates [9]–[14]. Biomasses could be used to produce biofuels such as biodiesel and bioethanol, by means of transesterification and fermentation reactions, respectively. At the same time, residuals and waste biomasses should be valorized by their conversion into energy through anaerobic digestion process [13], [15]. The aim of this study is to simulate an anaerobic digestion process by using poultry manure as a feeding biomass. First, this kind of residual from chicken flocks has been submitted to an experimental characterization process. It follows the determination of parameters, such as C/N ratio, moisture, volatile substances and ashes contents. Furthermore, the initial conditions have been obtained by experimental campaigns, to conduct a transient
Anaerobic digestion (AD) is a biochemical conversion process that could be used to produce biogas (biomethane) from residual biomasses. No pollution is provided by the AD procedure, since it aims to exploit microorganisms’ activity which consume biomass substrate within the reactor. The synergy between different populations of anaerobic bacteria, which decompose the organic substrate, leads to biogas (BG) production. The BG is composed mainly by CH₄ and CO₂. Three types of microbes could be identified: hydrolytic, acidifying and methane-creating bacteria. AD process evolves correctly in the temperature range −5 to 70°C. Anaerobic bacteria could be also classified by using the temperature value: psychrophilic bacteria ($T_{react} < 20°C$), mesophilic bacteria ($20°C < T_{react} < 40°C$) and thermophile bacteria ($T_{react} > 45°C$). Reaction temperature deeply affects the digestion process, in detail its biochemical kinetics. The full process of anaerobic digestion could be divided into 3 phases:

- hydrolysis, due to the bacterial attack which degrade rapidly the biomass substrate. Organic complex molecules, that is polymers like carbohydrates, proteins, fats, are broken down to monomers and oligomers by biochemical depolymerization;
- acidification and acidogenesis, where fermentative microorganisms convert hydrolysis products into short chain fatty acids. At the end of this step, CH₃COOH, CH₂O₂, CO₂ and H₂ are obtained. Because of the presence of molecular hydrogen, the biochemical reaction could be inhibited. Then, removal of H₂ should be provided;
- the last reaction produces methane (CH₄) and it can happen in 2 ways: hydrogenotrophic methanogenesis and acetoclastic methanogenesis. Hydrogenotrophic bacteria act to oxidase hydrogen anaerobically. CO₂ and H₂ are converted into methane ad water. For this reason, this reaction could prevent an AD inhibition caused by molecular hydrogen. Acetoclastic methanogenesis involves acetic acid anaerobic dismutation to produce methane and carbon dioxide.

Resulting biogas is composed by methane, carbon dioxide and molecular hydrogen. On one hand CH₄ is insoluble and, being not trapped by the biomass liquid substrate once the anaerobic digestion process ended, it passes easily to the gaseous phase. On the other hand, CO₂ reaches a dynamic equilibrium between liquid and gaseous phase and so it’s involved in carbon acid production within the liquid phase; both carbon dioxide and ammonium influence the system’s buffering capacity. Small quantities of molecular hydrogen are used by methanogenesis bacteria, being trapped by liquid phase even if H₂ is insoluble. The gas release by the biomass substrate is called biogas desorption.

Feeding biomass, used for the scientific campaign and the scenarios simulation, is poultry manure diluted with water. Generally, this biomass is characterized by elevate contents of nitrogen (around 6% on dry basis) in the form of uric acid and phosphorus [16]. It is produced by laying hens and so it’s rich in calcium. Because of these properties, poultry manure is often used as fertilizer in agriculture activities. Due to high nitrogen content, poultry manure needs to be diluted for anaerobic digestion applications. Benefits of using poultry manure in anaerobic conversion are mainly:

- high level of dry substance, which means reduced transport costs, easy handling and loading of produced digestate volumes;
- relevant biogas production in terms of quantity and quality;
- relevant energetic capabilities.
In addition to this, the use of this by-hens produced biomass is advantageous both in economic and energetic terms. In fact, along Italian territory (e.g. in Grotte Santo Stefano, Viterbo, Italy) numerous chicken flocks could be found; for this reason, poultry manure energetic conversion should represent an alternative way to dispose livestock wastes.

2. Materials and Methods

Biomass characterization

The biomass used in this study was sampled at a rearing of laying hens in Viterbo, Italy. The poultry manure needs to be characterized before being involved in the energy conversion process. In fact, the anaerobic digestion process depends strictly on biomass composition. In more detail, parameters such as moisture content, ashes content, volatile substances content and C, H, N composition ratios have to be determined experimentally. Inoculum used for biomethanisation tests was sampled in an anaerobic digestion plant in Viterbo. Inoculum, as the biomass, was analyzed to determine the energy properties. To determine the biomass and inoculum moisture content, refer to UNI EN 14774-1, UNI EN 14774-2 and UNI EN 14774-3 [17]–[19], which describes the method of moisture calculation for a biofuel sample by drying in an oven. Furthermore, a laboratory scale sensitive to 0.1 g is required. Standards CEN/TS 14778-1 [20] and CEN/TS 14778-2 [21] give the procedures to prepare the biomass samples. The procedure should be summarized as follows: a WH sample is inserted into a clean and empty tank (both WH sample and the clean empty tank masses are known); once the system mass has been measured, it is dried in the oven at 105 ± 2°C. The drying process ends once a constant mass has been reached: this means the discrepancy between two successive weighing values is less than 0.2%. The standards provide reports for the percentage calculation of both moisture content on a wet basis and the moisture content on a dry basis. Once the humidity of the biomass sample has been computed, it is necessary to grind the dried mass to reduce its particle size. By using a sieve, particles with a maximum size of about 1 mm can be obtained. The UNI EN 14775 [22] standard provides indications for determining the ash content of a biomass and inoculum. In this case, the required instrumentations are an electric oven capable of reaching temperatures of about 550°C within the time established by the regulations, a laboratory scale with a resolution of 0.1 mg and a dryer that can prevent the absorption of ambient humidity. The UNI CEN/TS 14780 [23] standard describes sample preparation: the particles must have a maximum dimension of 1 mm. Two crucibles have to be placed in the oven at a temperature of 550 ± 10°C for 60 minutes. Then, they have to be extracted and cooled for 5-10 minutes on a heat-resistant surface, before being inserted in the dryer. Once the environmental temperature has been reached, each crucible is weighted by using the laboratory scale. Subsequently, 1 g of WH is added to each of the crucibles. The two samples are placed in the cold oven, increasing the temperature uniformly until reaching 250°C. After 60 minutes at constant temperature, the temperature is increased up to 550 ± 10°C. Biomass and inoculum crucibles are exposed to this temperature for the following 120 minutes. At the end of this high temperature thermal process, the crucibles are cooled and placed within the dryer as described above. Once the environmental temperature has been reached, the biomass crucibles are weighted. Measured mass values are used to compute ashes content on dry basis by standard. The procedure for calculating the content of volatile substances is described by the UNI EN 15148 standard [24]. In this case, instruments such as an oven capable of reaching 900 ± 10°C, cylindrical crucibles of inert material with lid and a scale with a resolution of 0.1 mg are needed. The CEN/TS 14780 standard [23] is used for sample preparation: the maximum particle size must be 1 mm. Crucibles with lids are placed in the oven until the temperature of 900 ± 10°C is reached, which is maintained for 7 minutes. Then, the crucibles are cooled at room temperature from 5 to 10 minutes, before being inserted into the dryer. This phase of the procedure is necessary to determine the reference masses. Therefore, 1 g of WH is inserted in the crucibles and the
The exposure time at 900 ± 10°C is equal to 7 min ± 1 s. Once the crucibles have been cooled again at room temperature, they are placed into the dryer and then the post-drying masses are determined again. The use of the formula reported by UNI EN 15148 [24] allows to calculate the percentage of the mass of volatile substances on a dry basis. To determine the biomass and inoculum content of C, H and N reference standard is UNI EN 15104 [25]. The tools needed in this case are a CHN, thin sheets of metal to wrap the sample to be analyzed and a scale with a precision of 0.1 mg. The procedure consists in placing in a metal capsule 0.15 g of WH, to be inserted into the CHN which, through the display, returns the values of carbon, hydrogen and oxygen. In Table 1, energy properties of biomass and inoculum are reported.

Table 1. Characteristics of poultry manure biomass.

| Parameter                    | Poultry Manure | Inoculum   | Unit   |
|------------------------------|----------------|------------|--------|
| C                            | 36.80 ± 0.90   | 34.30 ± 0.70 | %      |
| H                            | 5.70 ± 0.40    | 4.90 ± 0.30 | %      |
| N                            | 3.40 ± 0.30    | 3.80 ± 0.60 | %      |
| C/N ratio                    | 10.82 ± 2.90   | 9.02 ± 1.80 | --     |
| Total solids content         | 78.82 ± 0.90   | 5.48 ± 1.90 | %      |
| Moisture content             | 21.81 ± 0.90   | 94.52 ± 1.90 | %     |
| Ashes content (on dry basis) | 38.45 ± 0.90   | 0.98 ± 0.80 | %      |
| Volatile substance (on dry basis) | 48.51 ± 0.80 | 5.15 ± 0.70 | %      |
| pH                           | 8.70 ± 0.30    | 7.8 ± 0.12  | --     |

### Biomethanisation test

The potential of biomethanisation of poultry manure was determined experimentally by performing tests under controlled conditions, within the micro-digestion plant (Fig.1) of CIRDER Laboratory at University of Tuscia, Viterbo. Anaerobic digestion tests in wet mesophilic conditions were carried out within a 5 liters-capacity batch reactor considering an HRT of 35 days.
Figure 1. Micro-digestion plant.

The substrate, used for biomethanisation test, is constituted by inoculum, poultry manure and water, as showed in Table 2.

| Item         | Mass [kg] |
|--------------|-----------|
| Poultry manure | 0.590     |
| Inoculum     | 0.170     |
| Water        | 3.980     |

### ADM1 model

Anaerobic digestion processes could be optimized by implementing a detailed analysis of anaerobic conversion sub-processes. This analysis is performed by using models which describe every step of the conversion. In this sense, the most used schematic is the Anaerobic Digestion Model No.1 (ADM1) by IWA Task Group for Mathematical Modelling of Anaerobic Digestion processes[27]. The aim of the ADM1 is to provide a widely applicable model, predicting production of biogas from a specific feeding biomass. The model uses many variables, which values could be defined by literature or experimental data. The complexity of ADM1 is quite high, but its use could lead to specific results. The basic kinetics used by the model could be defined Monod-type. The model uses four types of variables and parameters to describe the processes: stoichiometric coefficients, equilibrium coefficients and constants, kinetic parameters and rates, dynamic state and algebraic. Conversion processes in anaerobic digestion could be divided into biochemical processes and physico-chemical processes, biologically mediated and not mediated, respectively. The ADM1 describes cellular kinetics through three expressions: uptake, growth and decay rate. To reduce the complexity of the implementation, the model introduces the following simplifications:

- substrate is considered to be homogeneous and composed only by carbohydrates, proteins, lipids and inert soluble;
- the products from hydrolysis are monosaccharides, amino acids and long chain fatty acids, respectively;
- lactate and ethanol are not included due to their low concentrations;
- aromatic carboxylic acids are not included;
- methane production by acetate oxidation in psychrophilic and mesophilic conditions is omitted;
- sulphate reduction inhibitions, nitrate reduction inhibitions and LCFA inhibition are not included;
- weak acids and bases inhibitions are largely implicitly included in the empirical pH function.

The ADM1 refers to biochemical processes by 19 processes and 24 compounds. Through Peterson matrix, the user could calculate rate coefficients and kinetic rate equations for every soluble or particulate
component. Kinetic rate equations are expressed as functions of constant values, concentrations of compounds involved in reactions and inhibition functions. Modelling inhibitions are:

- pH inhibitions caused by presence of amino acids, acetate or hydrogen;
- inert nitrogen inhibition;
- ammonia inhibition;
- carbon, fatty acids and propionate bimolecular hydrogen inhibition;

Physico-chemical processes are divided into three types:

- liquid-liquid processes, as ion association/dissociation;
- liquid-gas processes, as liquid-gas transfer;
- liquid-solid processes, as precipitation and solubilization. These ones are not included in the model due to their complexity.

Nomenclature utilized in this paper refers to the ADM1 one. Symbols needed to understand the equations are listed in Table 3.

| Symbol | Description | Units |
|--------|-------------|-------|
| $v_{i,j}$ | Rate coefficients for component I on process j | kg COD m$^{-3}$ |
| $f_{product,substrate}$ | Yield (catabolism only) of product on substrate | kg COD kg COD$^{-1}$ |
| $K_{acid}$ | Acid-base equilibrium coefficient | M |
| $K_H$ | Henry’s law coefficient | M bar$^{-1}$ |
| $k_{A,B}$ | Acid base kinetic parameter | M$^{-1}$ d$^{-1}$ |
| $k_{dec}$ | First order decay rate | d$^{-1}$ |
| $I_{inhibitor,process}$ | Inhibition function | - |
| $k_{process}$ | First order parameter | d$^{-1}$ |
| $K_{I,inhibit,substrate}$ | 50% inhibitory concentration | kg COD |
| $k_{m,process}$ | Monod maximum specific uptake rate | kg COD$_S$ kg COD$_X$ d$^{-1}$ |
| $K_{S,process}$ | Half saturation value | kg COD$_S$ m$^{-3}$ |
| $\rho$ | Kinetic rate of process j | kg COD$_S$ m$^{-3}$ d$^{-1}$ |
| $Y_{substrate}$ | Yield of biomass on substrate | kg COD$_X$ kg COD$_S$ d$^{-1}$ |
| $\mu_{max}$ | Monod maximum specific growth rate | d$^{-1}$ |
| $pH$ | -log$_{10}$[H$^+$] | - |
| $S_i$ | Soluble component i | kg COD m$^{-3}$ |
| $X_i$ | Particulate component i | kg COD m$^{-3}$ |
| $C$ | Bacterial concentration | kg COD m$^{-3}$ |

To carry out the simulations AQUASIM has been used. This software, developed in 1998, is largely used to simulate reactions in aquatic environment. AQUASIM allows also to conduct sensitivity analysis, being divided into variables, processes, compartments and links interfaces. Each one allows the user to perform different analysis. The time dependent concentration of a substance could be implemented through the processes interface. Each compartment shares data with the others by the linking interface. Results are shown by using user-editable graphics.

Using AQUASIM, two simulations have been carried out. The first one was implemented to describe uptake of involved components, while the second one has been computed to obtain the trend of bacterial growth. The aim of these scenarios was to model the biochemical anaerobic digestion processes in a 5
liters volume batch reactor for a 35 days conversion. The following assumptions were introduced to simplify and adapt the model to the specific studied feeding biomass [16], [26]:

- substrate is made up of carbohydrates, lipids and proteins, exclusively. It follows that the substrate reduction includes only hydrolysis, not disintegrations. Moreover, the inert nitrogen inhibition is neglected ($I_{in} = 1$) due to the absence of inert nitrogen;
- particulate concentrations of every compound involved in anaerobic digestion (except for carbohydrates, lipids and protein) should be neglected;
- in order to make the model consistent to the physical data, the inhibition equations are implemented as follows:

$$I_{pH,aa} = \exp \left[ -3 \frac{pH - pH_{UL,aa}}{pH_{UL,aa} - pH_{LL,aa}} \right]^2$$

(1)

$$I_{pH,ac} = \exp \left[ -3 \frac{pH - pH_{UL,ac}}{pH_{UL,ac} - pH_{LL,ac}} \right]^2$$

(2)

$$I_{pH,h2} = \exp \left[ -3 \frac{pH - pH_{UL,h2}}{pH_{UL,h2} - pH_{LL,h2}} \right]^2$$

(3)

- bacterial families considered in the second scenario are fermenters, oxidiser, acetogens, acetoclastic methanogens, hydrogenotrophic methanogens, referred with the subscripts $f$, $o$, $a$, $am$, $h$, respectively. Their kinetic rate equations, obtained adapting Monod equations to ADM1 variables, are listed in Tab. 4.

**TABLE 4.** Table of kinetic rate equations of bacterial concentration [16], [26].

| Bacteria     | Initial Concentration [kgCOD/m³] | Stoichiometric Coefficient | Kinetic Rate Equation |
|--------------|---------------------------------|---------------------------|-----------------------|
| Fermenters   | 1                               | 1                         | $\rho_f = \frac{C_f \cdot \mu_f}{1 + \frac{K_{S,aa}}{S_{aa}} + \frac{K_{S,am}}{S_{am}}}$ |
| Oxidiser     | 1                               | 1                         | $\rho_o = \frac{C_o \cdot \mu_o}{1 + \frac{K_{S,fa}}{S_{fa}}}$ |
The first scenario was implemented using hydrolysis and uptake equations from ADM1. The second scenario was based on the first one, but there were some adjustments concerning kinetic rate equations of involved compounds. Furthermore, to describe bacterial action on substrate and bacterial families, kinetic rate equation has been added to the model. The adjustments were expressed using ADM1 kinetic rate values and bacterial concentrations. First part of following formulas describes involved micro-organisms, while the second part defines substrate compounds attached by bacteria [26]:

\[
\rho_a = \frac{C_a \cdot \mu_a}{1 + \frac{K_{S,pro}}{S_{pro}}}
\]

\[
\rho_{am} = \frac{C_{am} \cdot \mu_{am}}{1 + \frac{K_{S,ac}}{S_{ac}}}
\]

\[
\rho_{hm} = \frac{C_{hm} \cdot \mu_{hm}}{1 + \frac{K_{S,h2}}{S_{h2}}}
\]

\[
\rho_{f,aa} = \rho_6 \cdot C_f
\]

\[
\rho_{f,su} = \rho_5 \cdot C_f
\]

\[
\rho_{o,fa} = \rho_7 \cdot C_o
\]

\[
\rho_{a,pro} = \rho_{10} \cdot C_a
\]

\[
\rho_{am,ac} = \rho_{11} \cdot C_{am}
\]

\[
\rho_{hm,h2} = \rho_{12} \cdot C_{hm}
\]

Tables 5 and 6 show the values of used parameters [26], [28].

**TABLE 5.** Numerical scenario coefficients.

| Coefficient | Value  | Unit   |
|-------------|--------|--------|
| $k_{hyd,eh}$ | 0.25   | $d^{-1}$ |
| $k_{hyd,pr}$ | 0.10   | $d^{-1}$ |
| $k_{hyd,li}$ | 0.20   | $d^{-1}$ |
| $k_{am,sa}$ | 30.0   | kgCOD/m$^3$ |
| $k_{am,aa}$ | 50.0   | kgCOD/m$^3$ |
| $k_{am,fa}$ | 6.0    | kgCOD/m$^3$ |
| $k_{am,c4}$ | 20.0   | kgCOD/m$^3$ |
\[ k_{m,pro} = 13.0 \text{ kgCOD/m}^3 \]
\[ k_{m,ac} = 8.0 \text{ kgCOD/m}^3 \]
\[ k_{m,h2} = 35.0 \text{ kgCOD/m}^3 \]
\[ K_{S,uu} = 0.50 \text{ kgCOD/m}^3 \]
\[ K_{S,ua} = 0.30 \text{ kgCOD/m}^3 \]
\[ K_{S,fa} = 0.40 \text{ kgCOD/m}^3 \]
\[ K_{S,c4} = 0.20 \text{ kgCOD/m}^3 \]
\[ K_{S,pro} = 0.10 \text{ kgCOD/m}^3 \]
\[ K_{S,ac} = 0.15 \text{ kgCOD/m}^3 \]
\[ K_{S,h2} = 7 \times 10^{-6} \text{ kgCOD/m}^3 \]
\[ K_{S,IN} = 1 \times 10^{-4} \text{ M} \]
\[ K_{I,h2,fa} = 5 \times 10^{-6} \text{ kgCOD/m}^3 \]
\[ K_{I,h2,c4} = 1 \times 10^{-5} \text{ kgCOD/m}^3 \]
\[ K_{I,h2,pro} = 3.5 \times 10^{-6} \text{ kgCOD/m}^3 \]
\[ K_{I,NH3} = 0.0018 \text{ M} \]
\[ pH_{UL,aa} = 5.5 \text{ --} \]
\[ pH_{LL,aa} = 4.0 \text{ --} \]
\[ pH_{UL,ac} = 7.0 \text{ --} \]
\[ pH_{LL,ac} = 6.0 \text{ --} \]
\[ pH_{UL,h2} = 6.0 \text{ --} \]
\[ pH_{LL,h2} = 5.0 \text{ --} \]
\[ Y_{aa} = 0.08 \text{ --} \]
\[ Y_{fa} = 0.06 \text{ --} \]
\[ Y_{c4} = 0.06 \text{ --} \]
\[ Y_{pro} = 0.04 \text{ --} \]
\[ Y_{ac} = 0.05 \text{ --} \]
\[ Y_{h2} = 0.06 \text{ --} \]
\[ Y_{su} = 0.10 \text{ --} \]
\[ f_{h2,su} = 0.19 \text{ --} \]
\[ f_{bu,su} = 0.13 \text{ --} \]
\[ f_{pro,su} = 0.27 \text{ --} \]
\[ f_{ac,su} = 0.41 \text{ --} \]
\[ f_{h2,aa} = 0.06 \text{ --} \]
\[ f_{bu,aa} = 0.26 \text{ --} \]
\[ f_{pro,aa} = 0.05 \text{ --} \]
\[ f_{ac,aa} = 0.40 \text{ --} \]
\[ f_{va,aa} = 0.23 \text{ --} \]

**TABLE 6.** Monod maximum specific growth rate.

| Coefficient | Value  | Unit |
|-------------|--------|------|
| \( \mu_f \) | 5.559  | d\(^{-1}\) |
| \( \mu_o \) | 0.382  | d\(^{-1}\) |
| \( \mu_a \) | 0.111  | d\(^{-1}\) |
| \( \mu_{am} \) | 0.167  | d\(^{-1}\) |
| \( \mu_{am} \) | 0.695  | d\(^{-1}\) |

Imposed initial conditions are listed in Tab. 7.
TABLE 7. Imposed initial conditions.

| Coefficient | Value   | Unit       |
|-------------|---------|------------|
| $X_{ch}$    | 14.557  | kgCOD/m³  |
| $X_{pr}$    | 2.740   | kgCOD/m³  |
| $X_{li}$    | 3.945   | kgCOD/m³  |
| $X_{su}$    | 1       | kgCOD/m³  |
| $X_{aa}$    | 1       | kgCOD/m³  |
| $X_{fa}$    | 1       | kgCOD/m³  |
| $X_{c4}$    | 1       | kgCOD/m³  |
| $X_{pro}$   | 1       | kgCOD/m³  |
| $X_{ac}$    | 1       | kgCOD/m³  |
| $X_{h2}$    | 1       | kgCOD/m³  |

3. Results

First simulation scenario results are exposed by Figures 2, 3 and Table 8. Figure 2 shows the trends of carbohydrates, proteins and lipids concentrations due to hydrolysis during the whole process. During the first ten days, these concentrations reach values close to one, starting from imposed initial condition. This is consistent to the theoretical knowledge about first phase of anaerobic digestion since hydrolytic bacteria decompose the complex substrate in simplest compounds. Referring to Tab. 8, it appears that concentration decline of every compound is faster during the first ten days. In fact, on the tenth day carbohydrates concentration is 8.58%, proteins one is 38.3% and lipids one is 14.44% of the respective initial conditions. After the twentieth day concentrations of the three compounds are asymptotic to the zero.

TABLE 8. Concentrations values for carbohydrates, proteins and lipids.

|       | Day 0 | Day 10 | Day 20 | Day 30 | Day 35 |
|-------|-------|--------|--------|--------|--------|
| $X_{ch}$ [kgCOD/m³] | 14.557 | 1.250  | 0.114  | 0.018  | 0.018  |
| $X_{pr}$ [kgCOD/m³] | 2.740  | 1.049  | 0.386  | 0.165  | 0.092  |
| $X_{li}$ [kgCOD/m³] | 3.945  | 0.570  | 0.114  | 0.018  | 0.018  |
Trends exposed by Fig. 2 and Fig. 3 could be related with each other, because of the relationship between uptakes and hydrolysis. In fact, fatty acids uptake concentration grows rapidly during the first ten days, concurrently with lipids consumption (Fig.4). Then fatty acids concentration undergoes a significant decline due to oxidiser activity. It’s the same with carbohydrates/ sugar concentrations (Fig. 5) and proteins/amino acids (Fig.6) concentrations. Both couples are linked by hydrolysis decomposition of the first member and consequent uptake of the second one. After a quick growth, sugar and amino acid trends decrease due to fermentation process, producing acetate and propionate. At the end of the transient simulation, acetate and propionate concentrations decline because they are digested by acetoclastic methanogens to produce methane. Hydrogen trend also decreases due to the action of hydrogenotrophic methanogens. It follows that methane concentration sensitively builds up during the whole time of simulation, with a maximum on the 35th day. It follows that methane is located at the bottom of the trophic chain.
FIGURE 4. Lipids and fatty acids sugars concentration trends.

FIGURE 5. Carbohydrates and sugar concentration trends.
Fig. 7 is obtained by the second scenario simulation, once solved, and represents concentration trends of involved bacterial families. According to the evidence that the most elevate concentrations compounds are sugar and fatty acids (Fig. 3), which are digested by oxidiser and fermenters, Fig. 7 shows that these two bacterial families are characterized by the highest values of concentration.

Model validation is obtained by using Bio-methane potential BMP. It is defined as the methane production which could be observed for a limitless degradation time and it’s expressed with the following formula:

\[ BMP = \sum \frac{V_{CH_4}}{V_{S_s}} \cdot \frac{V_S}{V_S} \]  

(4)

where
\[ V_{CH4} \] is the produced methane volume (in liters);
\[ VS \] are the volatile solids in substrate (ingVS/l);
\[ V_S \] is the substrate volume (in liters).

The validation of the simulation results was made by comparing the results obtained from the experimental tests with those of the simulation. Calculating the \( BMP_A \) obtained from the simulation results, the methane volume was calculated from data exposed by Figure 8:

\[
BMP_A = 545.0 \text{ml/gVS}
\]

For the calculation of the \( BPM_S \) obtained from the experimentation, the \( CH_4 \) volumes produced during the tests were considered, (Fig. 9):

\[
BMP_S = 550.9 \text{ml/gVS}
\]
4. Conclusions

Anaerobic conversion application in energy production is an innovative and green solution to reduce environmental pollution. The feeding biomass chosen for experimental campaign and simulation scenarios is poultry manure, very rich in calcium, phosphorus and nitrogen. Along Italian territory (e.g in Grotte Santo Stefano, Viterbo, Italy) numerous chicken flocks could be found; for this reason, poultry manure energetic conversion should represent an alternative way to dispose livestock wastes. First, poultry manure has been characterized by experimental procedures to determine contents of moisture, ashes, volatile substance, solid substance, carbon, hydrogen and nitrogen. Due to obtained characteristics, the poultry manure needs to be diluted with water before being inserted into the anaerobic digester. Using software AQUASIM, two simulation scenarios have been carried on. The first one describes uptake of substrate and methane production using ADM1 model; the second one shows bacteria families growth. By simulated methane production values, the biomethane potential has been also calculated. Adapted ADM1 model has been validated by comparing computed BMP with literature values. In conclusion, the proposed adaptation of the general ADM1 to the poultry manure substrate is consistent to experimental data. Further works will involve the constitution of a database which parameters, for a given biomass, should be used for ADM1 simulations, predicting methane production and optimizing feeding substrate composition.

References

[1] J. Cheng, R. Lin, W. Song, A. Xia, J. Zhou, and K. Cen, “Enhancement of fermentative hydrogen production from hydrolyzed water hyacinth with activated carbon detoxification and bacteria domestication,” *Int. J. Hydrogen Energy*, vol. 40, 2015.

[2] R. Lin et al., “Characterisation of water hyacinth with microwave-heated alkali pretreatment for
enhanced enzymatic digestibility and hydrogen/methane fermentation,” *Bioresour. Technol.*, vol. 182C, pp. 1–7, 2015.

[3] O. Merino-Pérez, R. Martinez-Palou, J. Labidi, and R. Luque, “Microwave-Assisted Pretreatment of Lignocellulosic Biomass to Produce Biofuels and Value-Added Products,” *Prod. Biofuels Chem. Microw.*, vol. 3, pp. 197–224, 2015.

[4] M. Carlini and S. Castellucci, “Modelling the vertical heat exchanger in thermal basin,” *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 6785 LNCS, no. PART 4, pp. 277–286, 2011.

[5] M. Carlini, S. Castellucci, E. Allegrini, and A. Tucci, “Down-hole heat exchangers: Modelling of a low-enthalpy geothermal system for district heating,” *Math. Probl. Eng.*, vol. 2012, 2012.

[6] E. M. Mosconi, M. Carlini, S. Castellucci, E. Allegrini, L. Mizzelli, and M. Arezzo Di Trifiletti, “Economical assessment of large-scale photovoltaic plants: An Italian case study,” *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 7972 LNCS, no. PART 2, pp. 160–175, 2013.

[7] M. Carlini, S. Castellucci, S. Cocchi, and A. Manzo, “Waste wood biomass arising from pruning of urban green in viterbo town: Energy characterization and potential uses,” *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 7972 LNCS, no. PART 2, pp. 242–255, 2013.

[8] M. Carlini, S. Castellucci, and M. Moneti, “Biogas production from poultry manure and cheese whey wastewater under mesophilic conditions in batch reactor,” *Energy Procedia*, vol. 82, pp. 811–818, 2015.

[9] P. Priya, S. O. Nikhitha, C. Anand, R. S. Dipin Nath, and B. Krishnakumar, “Biomethanation of water hyacinth biomass,” *Bioresour. Technol.*, vol. 255, no. November 2017, pp. 288–292, 2018.

[10] L. da Costa Sousa, S. P. Chundawat, V. Balan, and B. E. Dale, “‘Cradle-to-grave’ assessment of existing lignocellulose pretreatment technologies,” *Curr. Opin. Biotechnol.*, vol. 20, no. 3, pp. 339–347, 2009.

[11] A. J. Rodrigues, M. Omondi, P. O. Hayombe, W. Akuno, D. Kerich, and I. Maobe, “Converting Water Hyacinth to Briquettes : A Beach Community Based Approach,” vol. 15, no. 1, pp. 358–378, 2014.

[12] O. Ellabban, H. Abu-Rub, and F. Blaabjerg, “Renewable energy resources: Current status, future prospects and their enabling technology,” *Renew. Sustain. Energy Rev.*, vol. 39, pp. 748–764, 2014.

[13] C. Hu, B. Yan, K. J. Wang, and X. M. Xiao, “Modeling the performance of anaerobic digestion reactor by the anaerobic digestion system model (ADSM),” *J. Environ. Chem. Eng.*, vol. 6, no. 2, pp. 2095–2104, 2018.

[14] M. A. Khan *et al.*, “Optimization of process parameters for production of volatile fatty acid, biohydrogen and methane from anaerobic digestion,” *Bioresour. Technol.*, vol. 219, pp. 738–748, 2016.

[15] A. Khalid, M. Arshad, M. Anjum, T. Mahmood, and L. Dawson, “The anaerobic digestion of solid organic waste,” *Waste Manag.*, vol. 31, no. 8, pp. 1737–1744, 2011.

[16] M. Moneti, “Analisi di impianti a biomasse e ricadute su altre fonti alternative di produzione di energia,” 2016.

[17] “UNI EN 14774-1:2009. Biocombustibili solidi - Determinazione dell'umidità' - Metodo di essiccazione in stufa - Parte 1: Umidità' totale - Metodo di riferimento.” 2009.

[18] “UNI EN 14774-2:2010. Biocombustibili solidi - Determinazione dell’umidità - Metodo di essiccazione in stufa - Parte 2: Umidità totale - Metodo semplificato.” 2009.

[19] “UNI EN 14774-3:2009. Biocombustibili solidi - Determinazione dell’umidità - Metodo di essiccazione in stufa - Parte 3: Umidità del campione per l’analisi generale.” 2009.

[20] “UNI CEN/TS 14778-1:2006. Biocombustibili solidi - Campionamento - Parte 1: Metodi di campionamento.” 2006.
[21] “UNI CEN/TS 14778-2:2005. Biocombustibili solidi - Campionamento - Parte 2: Metodi di campionamento di materiale particolato trasportato su autocarri.” 2005.
[22] “UNI EN 14775:2010. Biocombustibili solidi - Determinazione del contenuto di ceneri.” 2010.
[23] “UNI CEN/TS 14780:2005. Biocombustibili solidi - Metodi per la preparazione del campione.” 2005.
[24] “UNI EN 15148:2010. Biocombustibili solidi - Determinazione del contenuto di sostanze volatili,” 2010.
[25] “UNI EN 15104:2011. Biocombustibili solidi - Determinazione del contenuto totale di carbonio, idrogeno e azoto - Metodi strumentali.” 2011.
[26] S. Selli, “Caratterizzazione energetica delle biomasse: analisi, implementazione e simulazione numerica mediante modello ADM1,” 2017.
[27] D. J. Batstone et al., “The IWA Anaerobic Digestion Model No. 1 (ADM1),” Water Sci. Technol., vol. 45, no. 10, pp. 65–73, 2002.
[28] C. Rosen and U. Jeppsson, “Aspects on ADM1 Implementation within the BSM2 Framework,” Tech. Rep., pp. 1–37, 2006.
[29] S. Piccinini, “Convegno Pollina e energia: un binomio strategico per le aziende avicole Situazione e prospettive delle tecnologie per la valorizzazione energetica della pollina,” 2014.