IRA-International Journal of Applied Sciences
ISSN 2455-4499; Vol.19, Issue 02 (Q.2 2024)
Pg. no. 65-75.
IRA Academico Research

Evaluation of the Specific Growth Rate to Predict the Biogas Production Process in a Mini-Biodigester

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Type of Work: Peer Reviewed.
DOI: https://dx.doi.org/10.21013/jas.v19.n2.p3

Review history: Submitted: Dec 07, 2023; Revised: March 26, 2024; Accepted: June 30, 2024.

How to cite this paper:
Bagaya, N., Koumbem, W.N.D., Baldé, Y.M., Diop, S., Ouédraogo, I., Korgo, B., & Kam, S. (2024). Evaluation of the Specific Growth Rate to Predict the Biogas Production Process in a Mini-Biodigester. *IRA-International Journal of Applied Sciences* (ISSN 2455-4499), 19(2), 65-75. https://dx.doi.org/10.21013/jas.v19.n2.p3

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ABSTRACT

In this work, we are interested in the mathematical analysis of the model of a $4m^3$ bioreactor based on the results of a model already implemented in ADM1. The study is based on the expectations of Burkinabè households with biodigesters of $4m^3$, $6\ m^3$, $8\ m^3$ or more in terms of biogas production capacity. It is an observability analysis and estimation scheme for specific growth rates for an anaerobic digestion (AD) process of cow dung. A 1- *stage* model of 3 dynamic states is assumed describing all anaerobic digestion with a different population of microorganisms, and the evaluation of biogas production (methane + carbon dioxide). The result of specific growth rates ($\mu_{max} = 0.44d^{-1}$) of bacterial populations' concentration ($24gL^{-1}$ ± 2.3%) and substrate concentration ($6.5gL^{-1} \pm 0.5\%$) are estimated from the dilution rate and biogas. Thus, biogas production ranges from 0 to 3.5 m^3 per day, more than sufficient for three daily meals for a 4-person household. Overall, the dynamics of anaerobic digestion appear to depend on the type of organic matter contained in cow substrates.

Keywords: Anaerobic Digestion, Organic Matter, Biogas, Specific Growth

I. Introduction

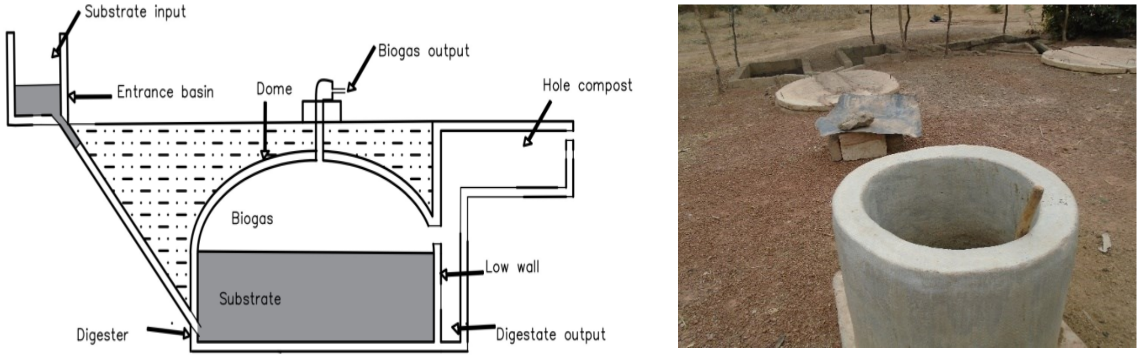
The analysis of livestock numbers in Burkina Faso reveals a large deposit of waste(Ressources et al., 2007). We have 9 million oxen, 35 million poultry, 2 million pigs, and also a lot of agricultural and invasive plants("Cadre d'action Pour l'investissement Agric. Au Burkina Faso," 2012). The subsidized price of a 12.5kg bottle of butane gas is 8.5 euros, still unaffordable for the majority of the population (Service d'Information du Gouvernement (SIG) du Burkina Faso, 2022). In 2011, the electricity network supplied just 2% of the energy consumed in Burkina Faso, with 84% of the energy used by the population coming from traditional sources (wood and agricultural residues) and imported hydrocarbons accounting for the remaining 14%. According to figures from the national electricity company, only 308,000 households had access to electricity in 2008. At the time of the last census in 2022, 75.4% of households in Burkina Faso used firewood with a single hearth to cook food, with only 16.1% using gas or biogas(Faso, 2022). Although solar energy is a well-presented source of energy in the area, it is far from meeting the energy needs of most developing societies. Methane (LHV = 50.1 MJ/kg) escapes from garbage cans, forests and swamps and is produced as long as something organic is rotting, but unfortunately most of this energy escapes into our atmosphere. The only reasonable option is to capture, store and use this energy to replace fossil fuels and solid biomass combustion. This can be achieved by setting up a station to collect and fill surplus biogas into cylinders for distribution to communities without digesters. This approach to clean, renewable energy starts with mastering the production process. Waste-to-energy conversion using simple, less expensive technology will be an attractive proposition, especially in rural areas. Anaerobic digestion is a natural process whereby micro-organisms decompose organic matter to produce biogas (methane and carbon dioxide) in the absence of oxygen. (Cotutelle & Université, 2018). Obtaining control to avoid the shutdown of biodigesters is now an important priority in research. This allows a perfect integration of wastewater treatment and waste by mechanization in the development of renewable energy in West African countries where access to energy remains less. The theology of anaerobic digestion breaks down into five stages: disintegration, hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Normak et al., 2015). Among the existing models, the number 1 model of anaerobic digestion (ADM1) remains the most referenced with these 34 inputs and 105 outputs (Girault et al., 2011). To arrive we consider that the bioreactor operates in continuous mode, that is to say that the input flow Q_{in} is equal to the output flow Q_{out}. We also note $D = V/Q$, the dilution rate of the system with V, the reactor volume.

In the literature, several empirical methods following even the nature of the substrate are proposed but remain very expensive technically to express these specific growth rates. The originality of this work is to propose an even simpler method for estimating specific growth rates from quantities that are supposed to be easy to measure, such as the dilution rate and the biogas flows (Sette Diop, 2013). The objective of this study, compared to the previous ones, is to provide the estimation following a general approach to the problems of observation in differential algebraic geometry. The document is organized starting with the description of the anaerobic bioreactor studied. Then, we will describe the theory of the observability of specific growth rates with the analysis of the differential algebraic approach. Finally, the results of the estimation are illustrated. In perspective, the work will continue by strengthening the quality of the model and a comparison with experimental data.

2.Materials and Methods

2.1. Presentation of the Studied Bioreactor

The bioreactor is an enclosure containing a nutrient medium composed of a diversity of molecules called substrates on which a variety of populations of microorganisms still known as biomass grow (Garelli & Vignoni, 2012). The biodigester of this study is a continuous volume of $4m^3$, in mesophilic operation with a temperature of $35^\circ C$. A substrate of mass between20 kg and 30 kg mixed equitably with water is introduced each day into the reactor with a hydraulic retention time of $100\ days$. The ADM1 using 34 input variables is used to represent the bioreactor. The resulting biogas flow is $0.05\ m^3 d^{-1}$ and $3.4\ m^3 d^{-1}$. The biodigester pilot studied is shown in Figure 1, where Figure 1.a is a representation of the model and Figure 1.b is a photo of a family in operation in the field.



(a) Model of bioreactor used in our study (b) real model in rural households

Figure 1. Diagrams of the cross section of a biodigester and the real model implemented in the field

2.2. Input flow Dilution Rate

The digester operates in continuous mode (the output flow Q_{out} = input flow Q_{in}), giving a constant culture volume. Dilution is defined as the ratio of influent flow (Qin) to reactor liquid volume (V_{liq}). The dilution obtained experimentally in 100 days is a key parameter of anaerobic digestion. Low dilution may cause the substrate to crumble, and high dilution may cause the reactor to leach. The dilution rate is obtained by equation 1.

$$D = \frac{Q_{in}}{V_{liq}} \qquad \text{Equation (1)}$$

In this equation, Q_{in} = the concentration of the substrate to vent (in $m^3.d^{-1}$); V_{liq} = the liquid volume (m^3) and D = dilution flow-rate (d^{-1}).

2.3. Anaerobic Digestion Simulation Process

Model development: The whole process is developed by reducing the anaerobic digestion of the five stages into a single stage comprising 3 dynamic states. Bacteria consume the substrates of cow dung to produce biogas. The dynamics are presented by the system of equations 2.

$$\begin{cases} \dot{X} = (\mu - \mathrm{D})X \\ \dot{S} = -k_1\mu\mathrm{X} + \mathrm{D}\left(\mathrm{S}_{(0)} - \mathrm{S}\right) \\ Q = k_2\mu\mathrm{X} \end{cases} \qquad \text{Equation (2)}$$

In this method, the specific growth rate of microorganisms is estimated by simply simulating the process dynamics from experimental measurements of D and Q. With X is the biomass concentration ($kgCOD.m^{-3}$), S is the substrate concentration ($kgCOD.m^{-3}$), D is the dilution rate (d^{-1}), μ is the specific growth of biogas-producing biomass (d^{-1}), $S_{(0)}$ is the concentration of influential organic pollutant ($kgCOD.m^{-3}$), k_1 and k_2 have the production coefficients that are stoichiometric parameters, and are also constant and the flow of biogas produced (m^3d^{-1}).

2.4. Estimation Study

Observability is a method of determining or estimating the state of variables to reconstruct inaccessible states of a system. Also, the observability of a system is the property that allows one to say if the state can be determined only from the knowledge of the input and output signals. In the case of nonlinear systems, the notion of observability is unwieldy and is related to inputs and initial conditions. When in a process there are no techniques for measuring unmeasured variables, estimation techniques are then solicited. Among the approaches, differential algebraic approach methods quickly find partial answers to the problem of estimating specific growth rates of biomass based on some available measures.

The problem presented in this study, the results on the observability of the specific rate of growth of microorganisms dependent on dilution rate D, the flow of biogas Q, the initial concentration of substrate $S_{(0)}$, and the coefficients k_1 and k_2, can be accepted based on a characteristic set of differential polynomial (S Diop et al., 2013). A system {u} entry including the model parameters, {y} as the system output, {z} the estimated variable, and an epsilon {Ɛ} the state variables. The equation system becomes the dynamics presented by equation 3.

$$\begin{cases} \dot{X} - (\mu - \mathrm{D})X = 0 \\ \dot{S} + k_1\mu \mathrm{XD} - \left(\mathrm{S}_{(0)} - \mathrm{S}\right) = 0 \\ Q - k_2\mu \mathrm{X} = 0 \\ \dot{k}_1 = 0 \\ \dot{k}_2 = 0 \end{cases}$$

Equation (3)

The classification of the differential algebraic approach used gives us a $\{\{\mathbf{u},\ \mathbf{y}\},\{\mathbf{z}\},\{\varepsilon\}\} = \{\{\mathbf{D},\ \mathbf{Q},\ \mathbf{S}_{(0)},\ \mathrm{k}_1,\ \mathrm{k}_2\},\{\boldsymbol{\mu}\},\{\mathbf{X},\ \mathbf{S}\}\}$.

The derivation followed by a reduction of the system leads us to the system of equations 4.

$$\begin{cases} \dot{k}_1 = 0 \\ \dot{k}_2 = 0 \\ Q\ \dot{\mu} + Q\mu^2 - \dot{Q}\ \mu - DQ\mu - k_2\mu \mathrm{X} + \mathrm{Q} = 0 \\ k_2\dot{S} + k_2 DS - k_2 DS_{(0)} + k_1 Q = 0 \end{cases}$$

Equation (4)

The observability concerning parameters D, Q, $S_{(0)}$, k_1, and k_2 proves the existence of an undetermined non-differentiated polynomial being a function of D, Q, $S_{(0)}$, k_1, and k_2, as μ admits a null value. This observability would yield results according to which the biomass concentration dynamics (X) depend only on D and Sin, not dependent on the substrate concentration (S), which is an aberration. It appears that the specific growth rate of bacteria in the anaerobic digestion when the latter process evolves according to the simple model described here is not observable for *D*, Q, $S_{(0)}$, k_1 and k_2. The differential equation with coefficients undetermined and dependent on the derivative of D, Q, $S_{(0)}$, k_1 and k_2, of lower order is given by equation 5.

$$\mu\ \dot{Q} - \dot{\mu}\ Q - \mu^2 Q + Q\mu D = 0$$

Equation (5)

Assuming that we estimate X and S are observable from the parameters: *D*, Q, $S_{(0)}$, k_1, and k_2. Compared to X, the answer is positive and is directly given by the third term of the equation. The answer to S is in equation 6, describing all anaerobic digestion of beef manure at a Sin concentration with observability analysis as differential polynomials 5. The reader can refer to Baldé, Diop et al 2021(Younoussa Moussa BALDE, Sette DIOP, Sihem Tebbani & Process, 2021) for further details and references on the differential-algebraic resolution methods that provide this observability test.

$$\dot{S} + DS - D\,S_{(0)} + \frac{k_1}{k_2}Q = 0$$

Equation (6)

The estimation of the specific growth rate of bacteria is made from a differential algebraic approach of equation 2 and is reformulated to obtain equation 7.

$$\mu\dot{Q} - \mu^2 Q = \dot{\mu} Q - Q\mu D$$

Equation (7)

It can then be noted that in time intervals where it is not identical to zero, μ can be put in the form of the expression 8.

$$\frac{d}{dt}\left(\frac{Q}{\mu}\right) = -D\left(\frac{Q}{\mu}\right) + Q$$

Equation (8)

Given the quantities of D and Q are known and constant and not negative, it is possible to introduce an auxiliary variable Z defined by the quotient of biogas flows by the growth rate presented by equation 9.

$$Z = \left(\frac{Q}{\mu}\right)$$

Equation (9)

The quantity Z in 10, is estimable given the exponential stability of the previous dynamic equation.

$$\begin{cases} \dot{Z} = -D(Z) + Q \\ \hat{\mu} = \dfrac{Q}{Z} \end{cases}$$

Equation (10)

The equation of Z is initialized in Z (t_0) to take the initial values of the bioreactor loading presented by equation 11.

$$Z(t_0) = Z_0 = \frac{Q(t_0)}{D(t_0)}$$

Equation (11)

Thus, this observer is an open-loop estimator, whose convergence is directly dictated by the strictly positive dilution rate (D). The identified parameters are calibrated using the one stage method described in Figure 2, highlighting the results of adm1 and this model in a continuous bioreactor. The simplification of the model was based on the grouping of parameters of the different ADM1 steps in a single parameter (single step). Thus, biomass X represents degraded sugars, degraded amino acids, long chain fatty acid, specific acetic acids, hydrogen, valerates and propionates, and degraded propionates. The total substrate S is the sum of monosaccharides, amino acids, fatty acids, composites, carbohydrates, proteins and lipids. Starting from the reaction scheme of X and S of ADM1, the flow rate of biogas Q and the dilution rate (D) accessible experimentally, an algorithm makes it possible to obtain the growth rate in the first place. Second (part) of this μ, the data of substrates S, biomass X, are new introduced in the language C modified to support the coefficients k_i, X initial and S initial. In the end, the identified results of S, X and Q are obtained by estimating the reactor-specific setting parameters k_1 and k_2 according to the nature of the substrate. In this study, inhibition was not taken into account.

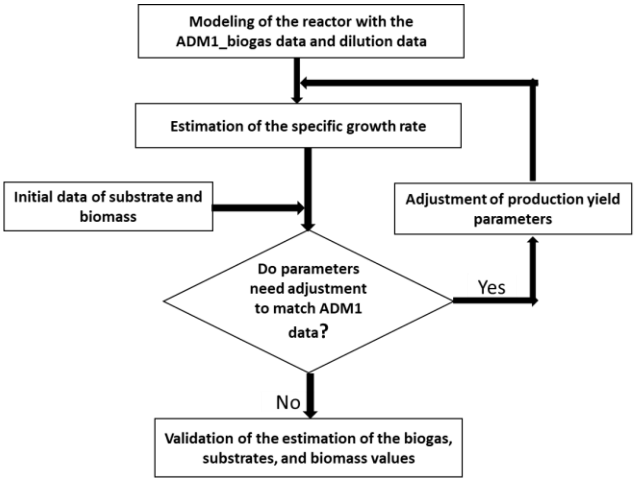


Figure 2. Calibration framework of the One-Stage model

3. Results and Discussion

3.1. Daily Profile of Substrate Dilution

The dilution in substrate experimentation is between $0.095d^{-1}$ and $0.28d^{-1}$ in increasing evolution over 100 days. The choice of increasing feed per piece is chosen to observe its effect on biogas production. The values of this dilution rate are shown in Figure 3.

3.2. Identification of Specific Growth Rate

The following figures illustrate the performance of the estimator. Dilution data from Figure 3 and biogas production from ADM1 were used to feed this estimator. The specific growth rate is shown in Figure 4. Dilution is a function of the amount of organic matter, that is, the sum of the total biomass of the total substrates (proteins, lipids, carbohydrates, composites, etc.) at the introduction of the reactor. We say that the loading of the substrate between 20 and 30 kg equally with water is very rich giving an average dilution ratio of $0.2d^{-1}$. At this dilution rate, a household with a digester of 4 m^3, with a permanent water point close to the household, 2 head of oxen are enough for this daily feed.

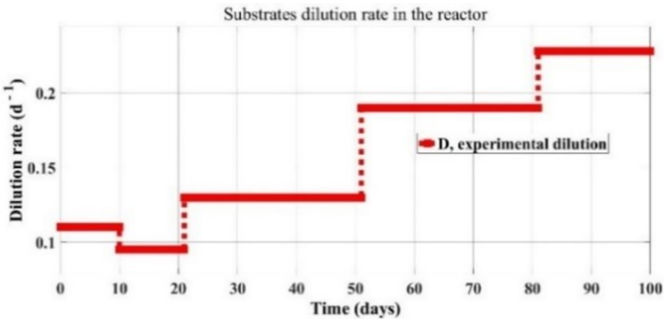


Figure 3. Profile of the dilution rate used experimentally

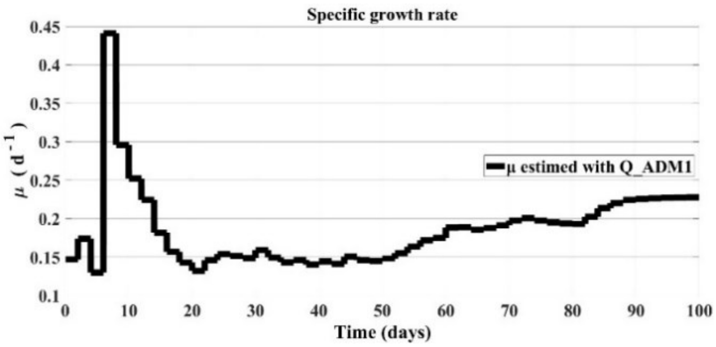


Figure 4. Specific growth rate in the reactor

The increasing and increasing value observed between 0 and 40 days that appears is due to the low output of biogas. The maximum value is $\mu_{\max =} 0.44d^{-1}$. The drop would therefore correspond to a case of maximum reduction in cow substrate to be consumed in the reactor. Also, the periods of stability we observed are due to the phenomena of stable biogas production, given the acclimatization of bacteria in the bioreactor.

3.3. Identification of the Rate of Substrates S and Biomass X

Figures 5.a and 5.b show a comparison of bacterial and substrate concentrations (with ADM1 and 1-Stage model).

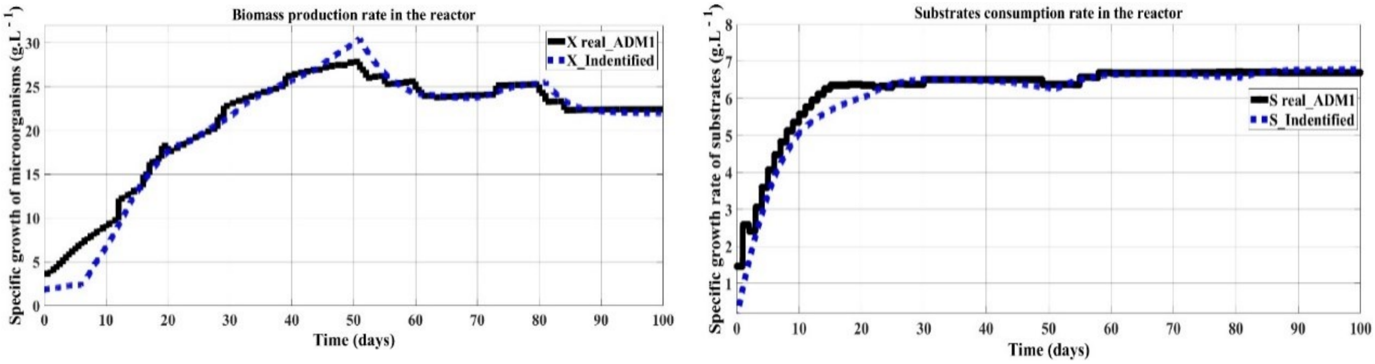


Figure 5.a **Figure 5.b**

Figure 5. Evolution of growth rates of biomass X and substrates S

When the piecewise constants of the dilution rate increasing and stable, the convergence of X and S is well guaranteed between the 40th and 100th day. A low convergence is obtained with unstable D values. Figure 5.a, from biomass X, shows that the bacteria acclimatized to the operating conditions of the bioreactor. The relative error of the mid-time estimate (50 days) is high and is around a 3% threshold. We say that the estimate of X at this level is a bit biased because it is overestimated compared to real data. The two curves are very close, especially after 70 days. We conclude that the model identifies the process implemented in ADM1.

Figure 5.b compares the results of ADM1 substrate concentrations (S) with those obtained with the identified 1-stage model to validate bioreactor performance. We find that the substrate concentration of the simplified model (maximum value = 6.4 $kg.m^{-3}$) is close to that of the ADM1 model (maximum value = 6.7 $kg.m^{-3}$ throughout the process. This makes it clear that the volume of waste to be treated by the digester must be increased. The study provided a diagnosis of the state (load) of the digester by predicting an under-load compared to the number of bacteria in the digester. In our situation, biomass production has remained constant, which prevents leaching from occurring as predicted in the Kouas study (Kouas et al., 2017). Therefore, this model helps to understand and anticipate the digester behavior. In our situation, biomass production has remained constant (triple the production of substrate consumption), which prevents the phenomenon of leaching from occurring. We can say that the cow dung produced in Burkina Faso is rich in bacteria, so we can even increase the daily load without stopping the reactor.

3.4. Identification and Validation of Biogas Production

The comparison of biogas (Q) production with both models is illustrated in Figure 6. The biogas produced with the two simulation methods during the 100 days of experimentation are very close. This shows the quality of the prediction model that can be used by design offices for sizing and maintenance of digesters.

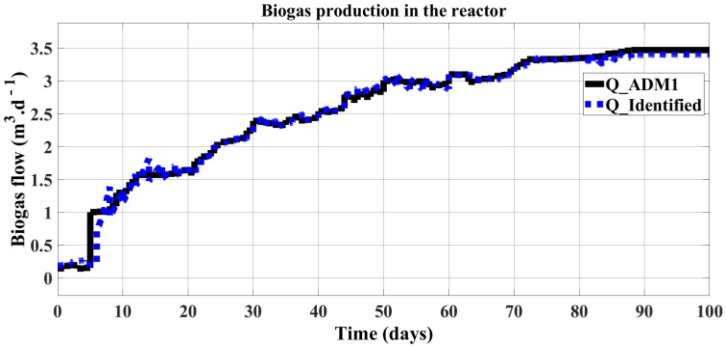


Figure 6. Daily flow rate of biogas produced in the reactor

The $4m^3$ biodigester produced an average flow rate of 2.5 m^3d^{-1} ± 0.2% with the two ADM1 models and the simplified model. Therefore, any lower production in the future is due either to a malfunction of the bioreactor or a sharp variation in the composition of organic matter. At this moment a correction becomes necessary. To solve the dynamics of the system of differential equations, initial conditions, the method of which is called estimates or model adjustment to obtain consistent results. To estimate the parameters, a *S-Function* in *MATLAB/Simulink*® R2021 (License No: 595687) allowed to write computer codes of mathematical formulas in language C. The initial parameters of the substrate $S_{(0)}$= 0.05gL^{-1} and bacteria is $X_{(0)}$=1.88 gL^{-1}. The parameters of the growth of the bioreactor k_1= 0.06 g/L and k_2= 0.68 gL^{-1}. Studies on the consumption of biogas stoves (energy efficiency 54%) show maximum consumption of 1.5 L/min, including a maximum of 3 hours for cooking a rice-sauce meal for 4 people (Bagaya et al., 2021). With this volume of production, there's more than enough to go around in a day. We can therefore say that the biodigester is an enviable alternative to butane gas, especially in rural areas.

4. Conclusion

In this work, we studied a model of substrate degradation in a reduced bioreactor of $4m^3$. The process of increased biogas production is observed from 70 days to the end of the study. The substrate in the reactor presented a stable ecosystem, in particular biomass production being triple the evolution of substrate rates. Using the differential algebraic approach to observability and algebraic methods, we demonstrated that the specific growth rates of cow waste are estimable from experimentally measured data (dilution rate D and biogas flow rate). This saves time in empirical modeling and the identification of specific growth rates, and allows the use of a wide variety of wastes without repeating this empirical modeling. The originality of this work allowed us to highlight the substrate rates necessary for the degradation of a quantity of substrates to obtain qualitative behaviors on the leaching of species and possible inhibition of substrates. In addition, we can say that this One-Stage estimate will become a valuable tool for the control and monitoring of anaerobic digestion processes for design offices and large-scale facilities. The modeling thus illustrated the verifiable mathematical results. As a result, the model was able to reproduce biogas production in the reactor in a representative way, averaging 2.5 m^3d^{-1}. It is now expected that any beneficiary of biodigester technology will be able to achieve a similar output to this study. This study will help establish a protocol for testing digester performance in the event of unsatisfactory biogas production data.

Author Contributions

NB: Design and execution of the simulation and writing of the manuscript. DWNK; YMB: Improvement of parametric identification work and analysis. Author SD: Verification of simulation and estimator quality, and adjustment of model parameters. SK; IO; BK: Analysis of results, interpretation and comments on writing quality. All authors reviewed and approved the complete manuscript.

Conflict of Interest Statement

The authors declare that they have no competing interests. The different authors certify that this manuscript is the original work of the authors, and all data collected during the study are as presented in this article, and no data from the study has been or will be published separately elsewhere. All authors state that no additional information is available for this article.

Acknowledgment

The authors thank the Laboratoire d’Energies Thermiques Renouvelables (L.E.T.RE) and Institut de Recherche en Sciences Appliquées et Technologies (IRSAT) for accepting to host this study. The authors also acknowledge the financial support of the International Science Programme (ISP) through the BUF01 project. The authors would also like to thank the l’Ambassade de France au Burkina Faso pour sa contribution financière aux recherches de Bagaya Noufou à l’Université Paris Saclay à travers le SCAC (Service de Coopération et d’Action Culturelle).

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