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# Evaluation of the specific growth rate to predict the biogas production process in a mini-biodigester

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**Abstract** The paper proposes an online estimation of biogas production for a household digester. The specific growth rate of aggregated biomass of a standard chemostat is estimated from the online measurements of dilution rate and biogas flow rate. That estimation is based upon usual 1-stage model without additional assumption on the online availability of neither yield coefficients nor concentrations of biomass or substrate. Next, ADM1 is used, in an empirical way, to identify yield coefficients. Finally, biomass concentration is estimated from the 1-stage model equations allowing the reconfirmation of biogas flow rate measurements at a 4 m<sup>3</sup> digester in a rural area in Burkina Faso.

## 1 Introduction

The analysis of livestock figures in Burkina Faso reveals a large amount of waste [6]. There are 9 million oxen, 35 million poultry, 2 million pigs, and also a lot of agricultural and invasive plants [1]. The subsidized price of a 12.5 kg bottle of butane gas is 8.5 euros, still unaffordable for the majority of the population. 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. 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. Biodigesters may be unstable in the sense of inhibition under unpredictable conditions. Their stabilization thus is a quite challenging issue for control systems engineering. Anaerobic digestion breaks down into five stages: disintegration, hydrolysis, acidogenesis, acetogenesis, and methanogenesis [5]. Among the existing models, the anaerobic digestion

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model number 1, ADM1, is the most used one [4]. It is a quite complex model with 34 inputs and 105 outputs.

For control systems analysis a simpler model is used. First, continuously steered digesters, also known as CSTR or chemostat, are considered with influent dilution rate  $D$  and output flow rate  $Q_{\text{gas}}$ , and two first order differential equations representing mass/volume balance of totalities of biomass and substrate. The complexity of such a simple model is actually hidden in a quantity called specific growth rate of biomass.

The literature invokes empirical models of specific growth rates, namely Monod, Contois, Haldane, etc. empirical formulas. Such empirical models contain parameters which assume a quite involved quantity of work for their estimation. The present work proposes, instead, an online estimation of the specific growth rate from quantities that are easy to measure, namely, the dilution rate and the biogas flow rate [3]. The estimation scheme uses a general approach of observation problems using differential algebraic geometry techniques. The paper starts with the description of the anaerobic bioreactor model. Next, a brief account of observability of specific growth rates in the words of the differential algebraic approach of observation problems is provided. The resulting estimation scheme is illustrated with data from a 4 m<sup>3</sup> digester in a rural area of Burkina Faso.

## 2 Materials and methods

### 2.1 The bioreactor

The digester is a CSTR as depicted in Figure 1 with a volume of 4 m<sup>3</sup>, in mesophilic operation with a temperature of 35 °C. A substrate of mass between 20 kg and 30 kg which is uniformly diluted in water is introduced each day into the reactor with a hydraulic retention time of 100 days. The resulting biogas flow is between 0.05 m<sup>3</sup>/d and 3.4 m<sup>3</sup>/d.

For simulations, a couple of parameters of the ADM1 are identified according to data from the digester.

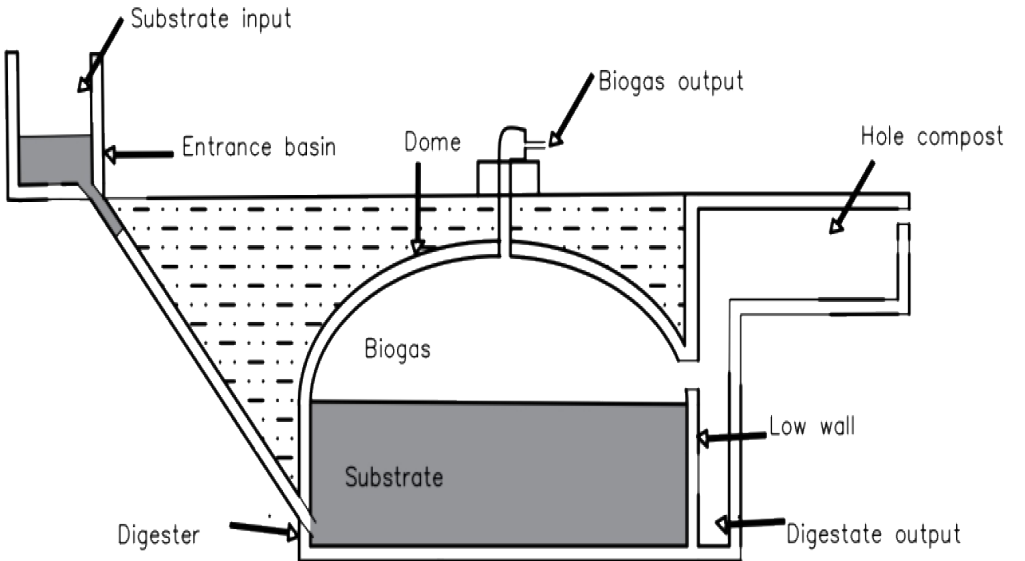


Figure 1: Digester schematic diagram and photo

### 2.2 Influent dilution rate

Dilution is defined as the ratio of influent flow  $F$  to reactor liquid volume  $V_{\text{liq}}$

$$D = \frac{F}{V_{\text{liq}}} \quad (1)$$

where  $F$  is the substrate influent volume flow rate (in  $\text{m}^3/\text{d}$ ),  $V_{\text{liq}}$  the liquid volume (in  $\text{m}^3$ ) and  $D$  is the dilution rate (in  $\text{d}^{-1}$ ).

The dilution which is 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.

### 2.3 Specific growth rate estimation

Anaerobic digestion is a complex process involving families of micro-organisms transforming a large number of chemical components of the substrate. The most complete model describing these processes is accomplished by IWA ADM1. It invokes more than a hundred parameters, the values of some of them are still under investigation. Most of the time ADM1 is too complex to be used for control design. In lieu of ADM1, a much simpler model is used, one of mass/volume balance. The simplest mass/volume balance model that is often invoked is [system \(2\)](#).

$$\begin{cases} \dot{X} &= \mu X - D X, \\ \dot{S} &= D S^{\text{in}} - D S - \frac{1}{Y_{\text{x/s}}}\mu X, \\ Q_{\text{gas}} &= K_{\text{gas}} \mu X, \end{cases} \quad (2)$$

where  $X$  (in  $\text{kgCOD}/\text{m}^3$ ) is the aggregated micro-organisms concentrations,  $S$  (in  $\text{kgCOD}/\text{m}^3$ ) the whole organic nutrient concentration inside the liquid volume of the bioreactor,  $S^{\text{in}}$  the inlet nutrient concentration,  $\mu$  (in  $\text{d}^{-1}$ ) is the specific growth rate of the micro-organisms,  $Q_{\text{gas}}$  (in  $\text{m}^3/\text{d}$ ) is the biogas flow rate and  $Y_{\text{x/s}}$  and  $K_{\text{gas}}$  are constant yield coefficients.

Actually, [system \(2\)](#) is simple thanks to the recourse to the notion of specific growth rate. The latter is a rather complex function of other reactor variables.

The usual practice consists of *postulating an empirical* model of the specific growth rate as Monod, Contois, Haldane, etc. models then doing the hard work of identifying parameters of such a model. That empirical identification of  $\mu$  needs to be redone for every substrate with new composition.

A brief account on how to estimate specific growth rates from dilution rate and biogas flow rate using differential algebraic decision methods is presented. The reader who is not familiar with these techniques may refer to [\[2\]](#) for more details.

Equations in [system \(2\)](#) are converted into differential algebraic ones and collected in a set of differential polynomials

$$\left\{ \dot{X} - (\mu - D) X, Y_{\text{x/s}} \dot{S} + \mu X - Y_{\text{x/s}} D (S^{\text{in}} - S), Q_{\text{gas}} - K_{\text{gas}} \mu X \right\} \quad (3)$$

whose characteristic set with respect to some ranking

$$\left\{ \{Y_{\text{x/s}}, K_{\text{gas}}, S^{\text{in}}, D, Q_{\text{gas}}\}, \{\mu\}, \{X, S\} \right\}. \quad (4)$$

needs to be calculated.

The choice of the above ranking follows from the observability test asking whether  $\mu$  may be estimated or not from supposedly online available quantities, namely the parameters, the dilution rate and biogas flow rate.

The resulting characteristic set is the following set of differential polynomials

$$\left\{ \begin{aligned} & \dot{Y}_{x/s}, \dot{K}_{\text{gas}}, Q_{\text{gas}} \dot{\mu} + Q_{\text{gas}} \mu^2 - \dot{Q}_{\text{gas}} \mu - D Q_{\text{gas}} \mu, -K_{\text{gas}} \mu X + Q_{\text{gas}}, \\ & Y_{x/s} K_{\text{gas}} \dot{S} + Y_{x/s} K_{\text{gas}} D S - Y_{x/s} K_{\text{gas}} D S^{\text{in}} + Q_{\text{gas}} \end{aligned} \right\}. \quad (5)$$

For  $\mu$  to be observable, the previous characteristic set should contain a differential polynomial with *order zero* in  $\mu$  and coefficients depending only on  $Y_{x/s}$ ,  $K_{\text{gas}}$ ,  $D$  and  $Q_{\text{gas}}$ .

Since this is not the case,  $\mu$  is not observable with respect to  $Y_{x/s}$ ,  $K_{\text{gas}}$ ,  $D$  and  $Q_{\text{gas}}$  and seemingly, neither  $X$  nor  $S$  is observable with respect to  $Y_{x/s}$ ,  $K_{\text{gas}}$ ,  $D$  and  $Q_{\text{gas}}$ .

The previous characteristic set exhibits the following differential polynomial (third element in the set (5))

$$Q_{\text{gas}} \dot{\mu} + Q_{\text{gas}} \mu^2 - \dot{Q}_{\text{gas}} \mu - D Q_{\text{gas}} \mu, \quad (6)$$

as the one in  $\mu$  (depending only on  $Y_{x/s}$ ,  $K_{\text{gas}}$ ,  $D$  and  $Q_{\text{gas}}$ ) with *lowest order*.

This differential polynomial may be re-written as

$$\dot{z} = -D z + Q_{\text{gas}}, \quad (7)$$

where

$$z = \frac{Q}{\mu}. \quad (8)$$

This is obtained merely by dividing [equation \(6\)](#) by  $\mu^2$  which *assumes time intervals where  $\mu$  does not vanish*.

In each such time interval, if in addition  $D$  remains positive then the differential equation (7) is *exponentially stable*. If  $\bar{Q}_{\text{gas}}$  is the online measurements of  $Q_{\text{gas}}$  then the estimation error  $\tilde{z} = z - \hat{z}$  evolves according to the following dynamics

$$\dot{\tilde{z}} = -D \tilde{z} + \tilde{Q}_{\text{gas}} \quad \text{with} \quad \tilde{Q}_{\text{gas}} = Q_{\text{gas}} - \bar{Q}_{\text{gas}}.$$

where  $\hat{z}$  is the solution of [equation \(8\)](#) where  $Q_{\text{gas}}$  takes the value  $\bar{Q}_{\text{gas}}$ .

In every time interval  $[r, s]$ , where the quantity  $D$  is positive the estimation error *exponentially decreases in norm* as follows

$$\tilde{z}(t) = \tilde{z}(r) \exp\left(-\int_r^t D(\sigma) d\sigma\right) + \int_r^t \tilde{Q}_{\text{gas}}(\sigma) \exp\left(-\int_\sigma^t D(\tau) d\tau\right) d\sigma$$

when  $t$  tends to  $s$ .

In summary, *specific growth rate  $\mu$  is not observable with respect to  $Y_{x/s}$ ,  $K_{\text{gas}}$ ,  $D$  and  $Q_{\text{gas}}$  but it may be estimated by merely simulating [equation \(7\)](#) and taking*

$$\hat{\mu} = \frac{Q}{z} \quad (9)$$

*This estimator exponentially converges in all time intervals where the dilution rate is nonzero.*

## 2.4 Estimation of yield parameters

The parameters  $Y_{x/s}$  and  $K_{\text{gas}}$  are initially identified using ad hoc measurements and ADM1. Their values may be reconfirmed by time to time new identification process using again ad hoc data from the bioreactor and ADM1. A forthcoming publication will provide more details on this part of the work consisting in the estimation of digester model parameters. Here are the values of the parameters which were found though this identification process:  $Y_{x/s} = 16.67$  and  $K_{\text{gas}} = 0.68$ .

### 3 Results and discussion

The dilution rate profile over 100 days is shown in Figure 3. It is piecewise constant, and takes values between  $0.095 \text{ d}^{-1}$  and  $0.28 \text{ d}^{-1}$ . Such daily values of dilution rate may be obtained from 2 head of oxen.

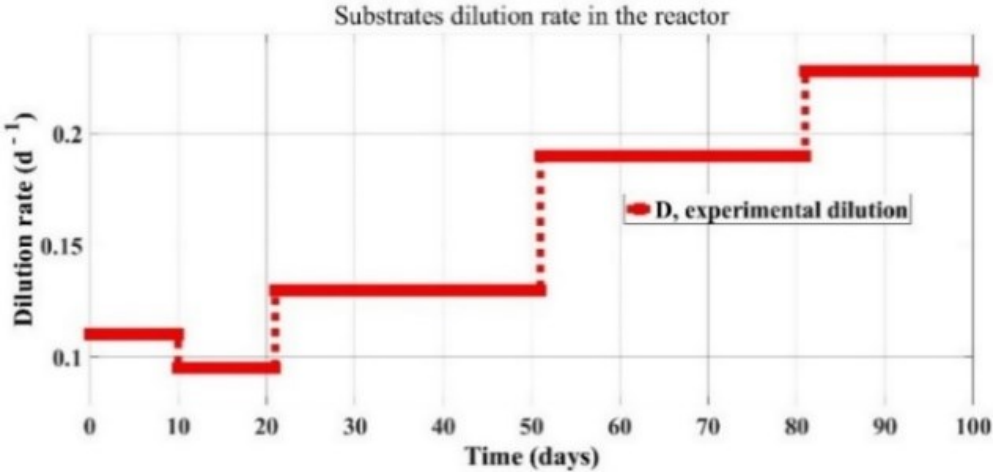


Figure 2: Dilution rate

The performance of the specific growth rate estimator is shown in Figure 3. The estimator needs some initial period of time to converge. That initial period of convergence depends on the values of the dilution rate: the higher  $D$  is the faster  $\hat{\mu}$  converges. Estimator performs well after about 40 days for the given dilution rate profile.

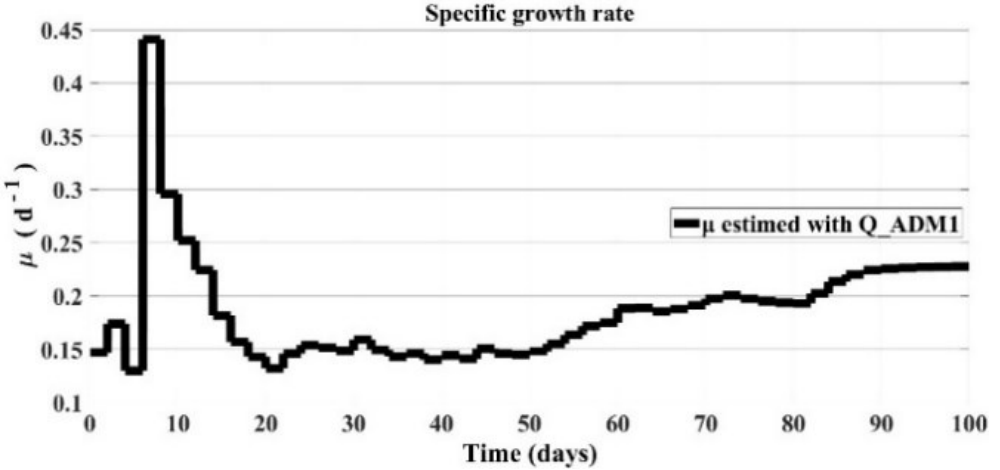


Figure 3: Specific growth rate estimation

Estimation of the biomass concentration is provided in two ways: one from ADM1 and the other one from its dynamics in system (2) where  $\mu$  is replaced with  $\hat{\mu}$ . The two estimates are shown in Figure 4. After the initial period of convergence of  $\hat{\mu}$  the two estimates are very close except around day 50 where the abrupt change of  $D$  implies new convergence period for  $\hat{\mu}$ .

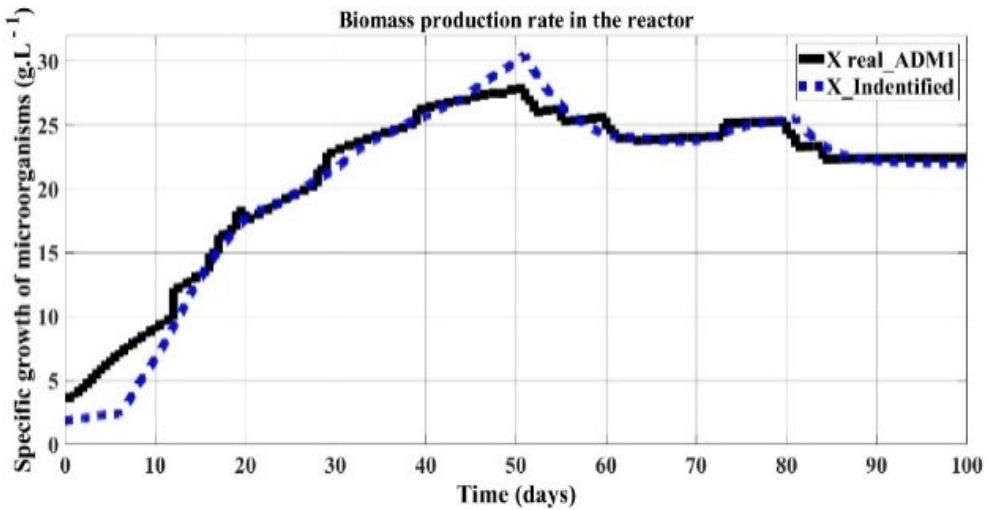


Figure 4: Biomass estimation

Illustration of the performance the estimation scheme provided in the present work is also shown in Figure 5 where the biogas flow rate is compared to its estimate from the 1-stage model.

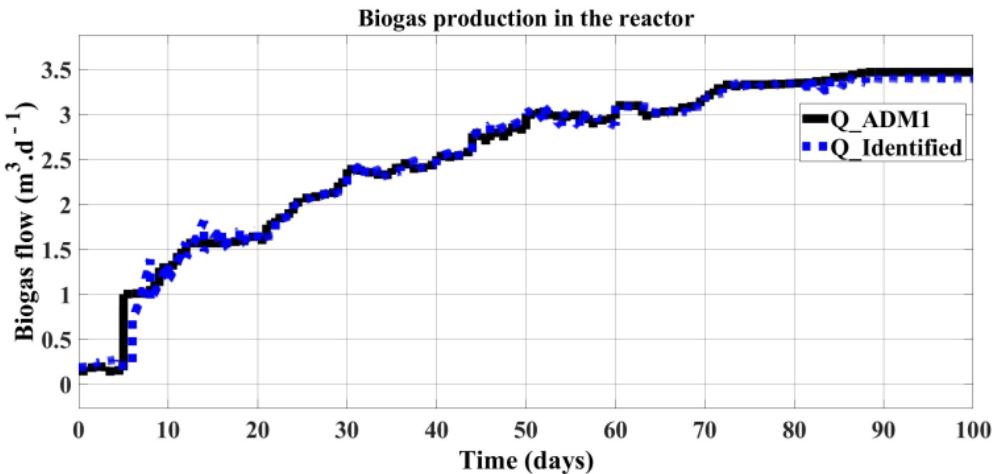


Figure 5: Validation of biogas flow rate

## Conclusion

In this work, we studied a model of substrate degradation in a 4 m<sup>3</sup> bioreactor. The biogas production was monitored 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 can be estimated from experimentally measured data (dilution rate and biogas flow rate). This saves time in empirical modeling and 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 1-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 at  $2.5\text{ m}^3/\text{d}$ . It is now expected that any beneficiary of biogas technology will be able to achieve a similar output. This study will help establish a protocol for testing digester performance in the event of unsatisfactory biogas production.

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## References

- [1] Cadre d'action pour l'investissement agricole au Burkina Faso, 2012, DOI: [10.1787/9789264169098-fr](https://doi.org/10.1787/9789264169098-fr)
- [2] E. Chorukova, S. Diop and I. S. Simeonov, On differential algebraic decision methods for the estimation of anaerobic digestion models, in H. Anai, K. Horimoto and T. Kut-sia, Editors, *Proc. Second International Conference on Algebraic Biology*, Lect. Notes Comput. Sci., Vol. 4545, pp. 202-216, Springer-Verlag, Berlin Heidelberg, 2007, DOI: [10.1007/978-3-540-73433-8\\_15](https://doi.org/10.1007/978-3-540-73433-8_15)
- [3] S. Diop, J. P. Steyer & I. S. Simeonov, A dynamic estimation scheme for specific growth rates of bacteria for an anaerobic wastewater treatment process, in the *Proc. of the 17th International Conference on System Theory, Control and Computing*, IEEE Press, New York, 2013, DOI: [10.1109/ICSTCC.2013.6688955](https://doi.org/10.1109/ICSTCC.2013.6688955)
- [4] R. Girault, P. Rousseau, J. P. Steyer, N. Bernet and F. Béline, Combination of batch experiments with continuous reactor data for ADM1 calibration: Application to anaerobic digestion of pig slurry *Water Sci. Technol.*, 63(11) (2011), 2575–2582, DOI: [10.2166/wst.2011.594](https://doi.org/10.2166/wst.2011.594)
- [5] A. Normak, J. Suurpere, I. Suitso, E. Jõgi, E. Kokin and P. Pitk, Improving ADM1 model to simulate anaerobic digestion start-up with inhibition phase based on cattle slurry, *Biomass and Bioenergy*, 80 (2015), 260–266, DOI: [10.1016/j.biombioe.2015.05.021](https://doi.org/10.1016/j.biombioe.2015.05.021)
- [6] Ressources, M. D. E. S., Élevage, S. D. E. L., Faso, B., Statistiques, L. E. S., & Secteur, D. U. (2007). Les statistiques du secteur de l'élevage au Burkina Faso *Sante, 1D115*.