Plant Science Research

ISSN 0972-8546

Mathematical modelling and simulation of a rice straw-based biogas plant

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ARTICLE INFO

Article history:
Received : 17 November 2018
Accepted : 11 December 2018

Keywords:

Biogas,
rice straw,
Anaerobic digestion,
methane production

ABSTRACT

India's failure to curb the current practice of burning millions of tons of rice crop residue each year is criticised worldwide as it is associated with environmental pollution and human health hazards. The aim of this work is to use a mathematical model to determine the biogas potential of rice straw when fed into a full-scale biogas plant. The Anaerobic Digestion Model No. 1 (ADM1) was utilized to explore the ideal operating conditions to run a rice straw-based plant for 60 days. The model predictions suggested feeding the industrial plant with rice straw co-digested with manure. Stable methane production was projected when 5 and 25% of the feed was rice straw and the rest was manure. An average methane content of 865 m^3 and 1100 m^3 was predicted by the model when 20m^3 of manure was fed with 1m^3 and 5m^3 of rice straw respectively. This mathematical model could be a useful, efficient and cost-effective tool for predicting energy generation from different organic waste materials.

1. Introduction

Every year nearly 90-140 million tons of rice crop residues are being burnt in India (Bisen, 2017). The burning of paddy stubbles and other residues in certain parts of India has been responsible for deterioration in air quality and is a serious national concern (Singh *et al*., 2017). Despite its adverse consequences, unfortunately till date, this is the most common practice followed to dispose the enormous volume of rice crop wastes. As an alternative to such unsustainable and hazardous practices, many researchers strongly advocate generating biogas, a carbon neutral 'clean' renewable source of energy and treat the carbon-rich rice waste as a resource instead (Rahman*et al*., 2017; Mussoline, 2013; Teghammar *et al*., 2012; Naresh, 2013). Biogas production from carbohydrate-rich substrates like that of rice residues offers an added advantage due to their high C/N ration resulting in higher methane production (Kataki *et al*., 2017; Daiem *et al*., 2018).

When operating biogas plants, it is extremely important to understand the process dynamics and deriving the ideal design and operational parameters applicable to the specific substrate fed. Mathematical models have proven to be useful tools to address this issue and are reliable for designing a biogas plant and the processes involved, for determining the optimal operating conditions and also enabling the users to effectively control the anaerobic digestion processes for a longer durations (Donoso*et al*., 2011).

1.1. Anaerobic Digestion Model No. 1

The Anaerobic Digestion Model No. 1 (ADM1) was developed by the International Water Association's (IWA) Task Group and is revered as the most advanced and reliable model for simulating biogas systems (Batstone *et al*., 2002). This widely applicable model includes the major processes involved in the bioconversion of complex organic materials into CH_4, CO_2 and inert by-products along with various metabolic intermediates (Biernacki *et al*., 2013). Numerous steps describing the biochemical as well as the physio-chemical processes are considered by the model. The ADM1 model considers the several processes occurring simultaneously and incorporates 31 processes, 19 of which

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are algebraic differential equations and 2 remain for the physio-chemical reactions (Batstone *et al*., 2002).

Organic substrates are characterized mathematically to degrade further to fractions of carbohydrate (XCh), proteins (XPr), lipids (XLi) and inerts (XI). The model's strength is also enhanced due to its mass conservation approach where the input is converted to solid, liquid and gaseous forms as output. The four stages of anaerobic digestion *i.e.* hydrolysis, acidogenesis, acetogenesis and methanogenesis are well interpreted considering the microbial activities in the model with the help of seven different biomass fractions and their decay (Biernacki, 2014). The strength of the model also remains in its applicability to different types of complex substrates under different conditions and for designing and operating biogas reactors of any size.

2. Materials and methods

2.1. Designing the system in the model

A lactate-included ADM1xp model designed specifically for carbohydrate-rich reactors by Satpathy *et al*. (2016a) was utilized in this study. A real-scale biogas reactor previously designed by Biernacki*et al*. (2013) using SIMBA was considered for this study (Fig.1). The industrial biogas plant had two parallel fermenters each with a capacity of 3500 m^3 and has a provision to feed the reactor hourly. SIMBA simulation software enables an appropriate representation of the real biogas plant and the hygienization, mixing tank, gas storage etc. was aptly presented in the model. This virtual design was used in an attempt to determine the biogas potential when rice straw co-digested with cattle manure is fed into industrial reactors in real-life scenarios. Simulations were performed using SIMBA 6 based on MATLAB R2013a (The MathWorks, 2011) for 60 days to study the performance of the biogas plant over a longer duration run.

2.2. Model's input parameters

The animal manure considered in the model as inoculum was derived from the experimental data from Biernacki *et al*. (2013). Experimental results from Daiem *et al*. (2018) was utilized for characterizing rice straw as feed. The characteristics of rice straw and manure are outlined in Table 1 and these data were put into the convertor block of the model. This step of incorporating the characterized substrate into the convertor block is highly significant in order to sensitize the mathematical model to the specific substrate. When the substrates considered during simulations are well characterized, the model's prediction capabilities also get strengthened.

The manure block in the model was additionally provided with the acid contents from experimental data derived from Satpathy *et al*. (2016a) and were kept to be 0.5, 0.9, 0.64, 0.69 kg COD/m^3 for acetic acid, propionic acid, lactic acid and butyric acid respectively. After incorporating these data, several trial and error tests were performed to determine the ideal proportion of mixing the rice straw with animal manure of this composition. After the model indicated the manure volume to remain at least 20 m^3 when simulating the reactor, failing which the reactor showed instability, different volumes of rice straw were tested to determine the ideal combination ratio.

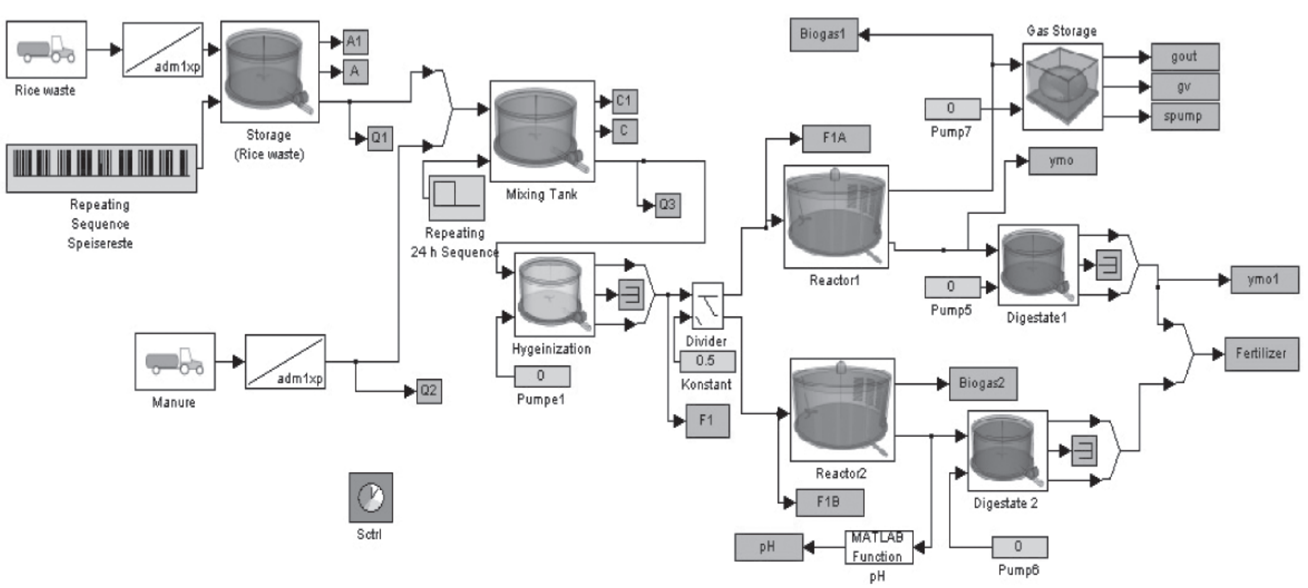

Fig 1. Model description of a full-scale industrial biogas plant prepared using SIMBA 6 simulation software derived from Satpathy *et al*. (2016b).

Table 1

Characterization of the rice straw and animal manure considered in this study (from experimental data of Daiem *et al*. (2018) and Biernacki *et al*. (2013) respectively).

Parameter (%)	Rice straw	Manure
Dry Matter (DM)	93.63	9
Organic Dry Matter (ODM)	69.38	80
Nitrogen (N)	0.52	3.5
Ammonium Nitrogen (NH_4)	0.01	2.2
Raw Protein	0.04	0.74
Raw Lipid	0.085	0.17
Raw Fibre	0.6	1.15
Inert fraction	0.3	0.509

3. Results and discussion

The ADM1 model demonstrated rice crop wastes to be a favourable substrate for biogas generation. A stable performance was predicted when the reactors were fed with 5 & 25% rice straw per day mixed with animal manure. Manures are significant since these provide effective buffering capacity and a healthy consortium of micro-organisms to generate biogas. The total CH_4 production daily on an average was determined to be 865m^3 and 1100 m^3 respectively when 1m^3 and 5m^3 of rice straw was mixed with 20m^3 of manure. Approximately, 50-51% of the biogas was predicted to be CH_4 with generation of 0 Hydrogen and the pH was maintained at 7. This in fact, is ideal for such carbohydrate-loaded biogas systems where maintaining stability is a challenge due to the increasingly available organic acids like acetic, propionic, butyric acid, valeric acid etc. resulting in further decrease in pH (Thamsiriroj *et al*., 2012; Satpathy, 2016).

When the digester was fed with 1m^3/day of rice straw (Fig. 2), the model displayed an immediate decrease in the amount of biogas which further revealed to have balanced with time. This could be due to the readily available intermediate organic compounds from the already degraded and hydrolysed rice straw and manure. This condition favoured the methanogens that ultimately resulted in a high methane formation at the initial stage. However, once the intermediate metabolic products were converted to biogas, degradation of a complex substrate like rice straw was slow as it is rich in lignin, cellulose and hemi-cellulose (Rahman *et al*., 2017). This leads to reduced availability of intermediate acids for different groups of bacteria and methanogens involved in the process of biogas formation. This is reflected in the decreased biogas production during the simulation trials. It is interesting to note that with time, the biogas production eventually starts improving. Such behaviour can be attributed to increased availability of the organic acids as the hydrolytic, acidogenic. acetogenic and methanogenic bacteria thrive and function efficiently while the conditions inside the digester become favourable with time (Luostarinen *et al*., 2011).

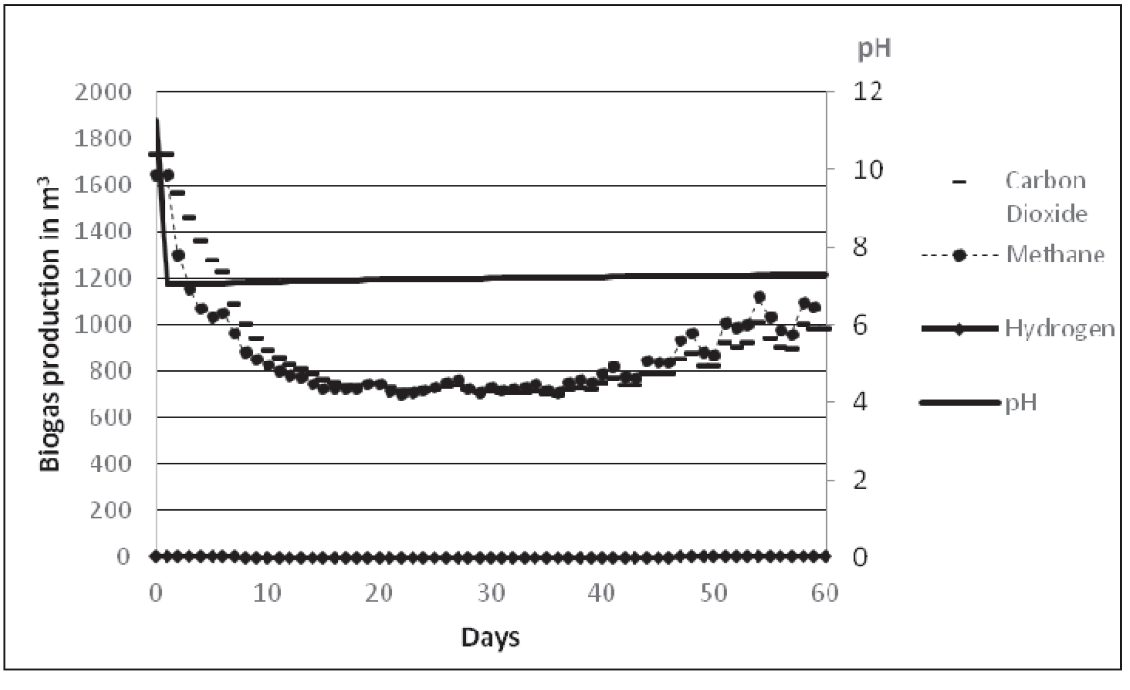

Fig. 2. Biogas formation predicted by the ADM1 model when 1m^3 of rice straw was fed with 20m^3 of animal manure.

With a rice straw feed of 5m[3]/ day, the CH_4 production showed similar trend (Fig. 3). One remarkable difference was that despite the decrease in biogas production, the recovery period was relatively faster compared to the system fed with 1m[3]/day. This is thought to be due to the increased C-content with the increased loads because of which the availability of the intermediate products for the methanogens and bacteria improved. The model's ability to predict the dynamic biological behaviour and simulate the processes reflecting the different stages and the several physio-chemical processes involved during formation of biogas production is noteworthy.

Digester instabilities are a common problem and there are many instances where initially the biogas reactors show extraordinary performance but with time there is an abrupt breakdown. The cause of such irregularities especially in carbohydrate-rich digesters can mostly be due to accumulation of organic acids which eventually lead to sudden drop in pH, thus disturbing the whole system (Seadi *et al*., 2014). During our simulation trials with an increased proportion of rice straw and comparatively less manure, we also observed such pH fluctuations and reactor failures. On the contrary, when simulated with a heavy manure load, the model clearly demonstrated steady operation over a longer duration. Thus, it is recommended to co-digest the carbohydrate-rich crop residue with higher volumes of animal manures to attain favourable conditions for successful biogas production.

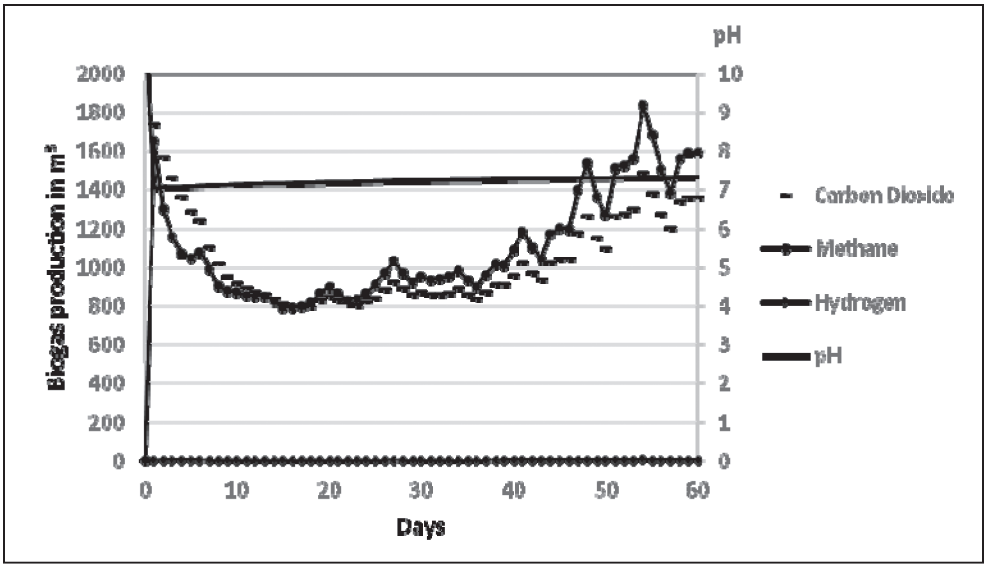

Fig. 3. Biogas formation predicted by the ADM1 model when 5m[3] of rice straw was fed with 20m[3] of animal manure.

4. Conclusion

Rice crop residues, being abundantly available and not finding applications either as a burning fuel or fodder due to its high silica content, offer additional scope for biogas generation (Rahman *et al*., 2017). The ADM1 model provided substantial insight into the biogas potential of rice straw to generate methane that can be utilized directly as a cooking gas or converted to electricity. The digestate attained from the output channel of such plants can also be effectively utilized as organic fertilizers. Thus, as an alternative to burning the millions of tons of the crop residues, generating the 'clean' carbon neutral biogas with minimal waste generation from such agricultural waste is strongly recommended. This would not only check the soil nutrient loss, environmental pollution and human health hazards but also help the farmers to generate additional revenues from the organic fertilizers.

The advantage of utilizing the ADM1 model is that it was instrumental in determining the ideal set of operational parameters specific to the substrate for maximum methane generation. The simulations also helped in understanding the possible inhibitions that might occur when operating with such complex substrates, thus pointing at taking necessary precautions beforehand. Biogas reactors have frequent encounters with reactor failures and sudden breakdowns. Such mathematical models could be effective in determining the ideal operating conditions and foresee the physio-chemical dynamics and performance of any type of biogas digester over a longer span of time *i.e*. even for several years. ADM1 model is thus recommended for designing and determining the ideal operating conditions for generating energy from different organic wastes that are otherwise discarded. Such models can be beneficial in determining the biogas potential on a virtual set-up without performing elaborate experimental work, thus saving both time and money.

Acknowledgements

The authors are thankful to the Head, P. G. Department of Botany, Utkal University, Odisha. Our gratitude also extends to Dr. Frank Uhlenhut from the University of Applied Sciences, Emden, Germany for providing support during mathematical simulations. The financial support to the first author from University Grants Commission under Dr. D.S. Kothari Fellowship is also gratefully acknowledged.

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