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Bioresource Technology 78 (2001) 127–131

BIORESOURCE TECHNOLOGY

Simulation of low temperature anaerobic digestion of dairy and swine manure ☆

D.T. Hill *, S.E. Taylor, T.E. Grift

Biosystems Engineering Department, Auburn University and Alabama Agricultural Experiment Station, Auburn University, 204 Tom E. Corley Building, Auburn, AL 36849-5417, USA

Received 6 October 2000; received in revised form 11 December 2000; accepted 22 December 2000

Abstract

The data reported by L.M. Safley, P.W. Westerman [Bioresource Technology 47 (2) (1994) 165–171] from the laboratory digestion of dairy and swine manure at psychrophilic temperatures (i.e., 10–23°C) have been used to determine the response of the latest comprehensive dynamic mathematical model of methanogenesis [D.T. Hill, S.A. Cobb, Transactions of the ASAE 39 (2) (1996) 565–573] in this low temperature range. Extensive performance data from digesters using animal waste in this temperature range have been lacking, thus allowing limited validation of the comprehensive model. The results of the comprehensive model simulations were compared with the actual data reported by Safley and Westerman (loc. cit.) and with their empirical regression models. Results indicate that the comprehensive model is as accurate as Safley and Westerman's models for three of the four cases reported, but shows a great dissimilarity for the fourth case.

Keywords: Animal-waste; Simulation; Anaerobic-digestion; Swine-waste; Dairy-waste

1. Introduction

Recent concern over effects of the gaseous release of hydrocarbons into the atmosphere on the degradation of the ozone layer and consequential health effects and global warming has led to an increased awareness of the release of methane from animal waste production facilities. With this new concern has come an increased interest in low temperature methanogenesis, since most confined animal waste in the United States is treated in anaerobic lagoon systems. Because of this relatively new realization that extensive methane release from these lagoon systems can potentially cause severe ozone depletion, research into the low temperature biological production of methane is increasing. However, to this point, research into the psychrophilic (operating temperatures between 10°C and 25°C) anaerobic digestion of animal waste has been very limited.

One proposed method of limiting the release of methane from these lagoon systems involves capturing the gas using a plastic film cover (Chandler et al., 1983; Safley and Westerman, 1992a). Allen and Lowery (1976) and Safley and Westerman (1988, 1989, 1992b) have demonstrated that reasonable quantities of methane can be collected with these recovery systems. Lagoons operated in this manner have been termed low temperature-lagoon digesters (LTLD) (Safley and Westerman, 1992a).

The limited work with psychrophilic methane production, however, has suggested that reasonable methane yields can be expected at low temperatures if digester loading rates are reduced appropriately by extending the detention time (θ) to the 100–300 day range (Safley and Westerman, 1990). Extending the detention time simply makes them extremely lightly loaded "process anaerobic digesters". Indeed, Stevens and Schulte (1979) reported that methane yield at lower temperatures (20–25°C) and increased detention time approaches that of conventional digestion at higher temperatures (35°C) and shorter detention times.

Cullimore et al. (1985) demonstrated that biogas production from swine wastes was initiated between 3°C and 9°C and that methane became the primary biogas component at approximately 10°C. Thus, digestion

☆ This article is approved for publication by Auburn University and the Alabama Agricultural Experiment Station (AAES). This research was conducted as part of Southern Regional Research Project S-275 with funds provided by the AAES.

* Corresponding author. Tel.: +1-334-844-3531; fax: +1-334-844-3530.

E-mail address: dhill@eng.auburn.edu (D.T. Hill).

0960-8524/01/$ - see front matter
PII: S0960-8524(01)00006-2

above 10°C would be desirable. Sutter and Wellinger (1985) indicated that gas production increases linearly in the range 10–20°C.

Based on both previous and recent research, it appears that these "outside digesters", or LTLDs, can be treated as process anaerobic digesters with appropriate modification to the design and operating parameters. With this hypothesis in mind, it would be reasonable to assume that the comprehensive mathematical model developed by Hill (1982) along with its most recent modifications (Hill and Cobb, 1993, 1996), can be used to simulate these LTLDs with reasonable accuracy. Accordingly, the study reported here was initiated to determine the response of this comprehensive model when simulating low temperature–long detention time anaerobic digesters. The actual test data reported by Safley and Westerman (1994) for swine and dairy waste at psychrophilic temperatures and their associated empirical regression models were used as the comparative basis of this study.

2. Model parameters and simulation protocol

The comprehensive model used in this study is a chemical process model consisting of mass balances of materials and the biological interaction and interconversion of these materials and was developed in 1982 by Hill. The original model has been modified (Hill and Bolte, 1987; Hill and Cobb, 1993, 1996) to include modeling predictive stress indicators and volatile organic acid levels. This model was originally developed with broad range simulation capabilities. Over the years, modifications have been added that allow the simulation of 8 animal waste types ranging from flushed swine to separated dairy waste and a continuous range of input temperatures from 10°C to 70°C at practically any conceivable volatile solids (VS) loading concentration and detention time with reactor types ranging from pure plug flow to complete mix. The predictive ability of this model reported originally in 1982 has been maintained and even improved with each modification (Hill, 1982; Hill and Bolte, 1987; Hill and Cobb, 1993, 1996).

This model has been validated using volumetric methane productivity (VMP) data for a wide range of influent VS concentrations, temperatures, θ's and waste types. It has been used to develop optimum operational design criteria (Hill, 1983a,b,c) and to project the methane productivity (Hill, 1984a) of all four major animal waste types. The economically optimized design of digestion systems for swine productions facilities (Hill, 1984b) also was studied using this mathematical model.

In the study reported here, the model was used to simulate the conditions of the laboratory study reported by Safley and Westerman (1994). They reported the methane productivity (β, L CH_4/g VS added) for dairy and swine manure at 0.1 and 0.2 kg VS/m^3 day loading rates for temperatures between 10°C and 23°C. The primary function being validated in the model with the data reported by Safley and Westerman is the specific bacterial growth rate (μ, day^{-1}), since it is this function that determines the effect of temperature on the bacterial population dynamics. Fig. 1 shows this function (MU1). It was initially developed by Chen and Hashimoto (1979) and was incorporated into the comprehensive model in 1982 and has remained unchanged since.

Safley and Westerman (1994) reported the swine waste in their study was "whole" (i.e., not flushed) and the dairy waste was "manure" only. These two types of waste are valid input types for the mathematical model. They also reported the loading parameters for their laboratory digesters as 0.1 and 0.2 kg VS/m^3 day. These loading rates were accomplished using a 17 kg VS/m^3 and a 15.7 kg VS/m^3 influent loading concentration for the dairy and swine manure, respectively. Thus, for the given loading rate of 0.1 kg VS/m^3 day, this makes θ 170 and 157 days for the dairy and swine waste, respectively. For the 0.2 kg VS/m^3 day loading rate, θ was maintained at 170 and 156.5 days respectively, for the dairy and swine manures, while the loading concentration was doubled. These were the input parameters used in the model to simulate the reported loading rates.

For each waste type, temperature and loading rate, the model was started and allowed to reach steady-state. Fig. 2 shows a typical simulation run used to generate the simulated β (BETA) data to compare with the real β data. This specific simulation is of swine waste at 0.1 kg VS/m^3 day loading rate and a temperature of

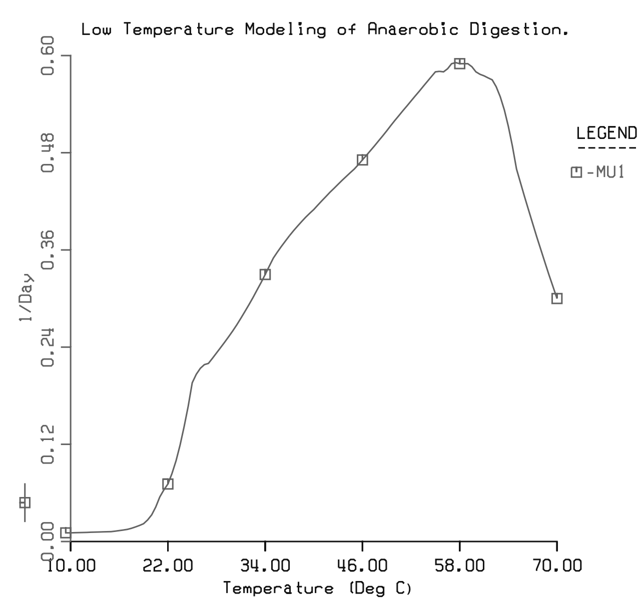

Fig. 1. Bacterial growth rate as a function of temperature (°C).

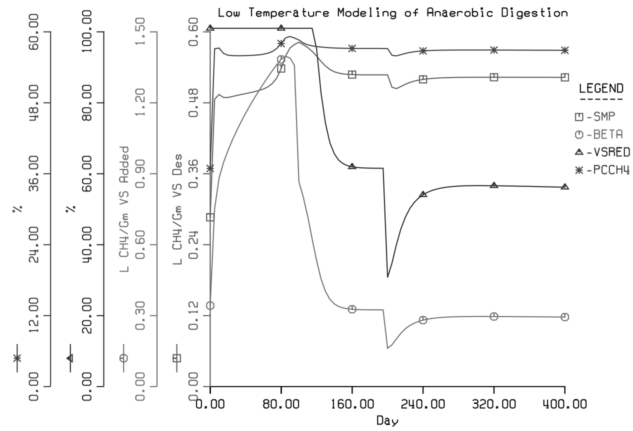

Fig. 2. Typical output used to validate the comprehensive model.

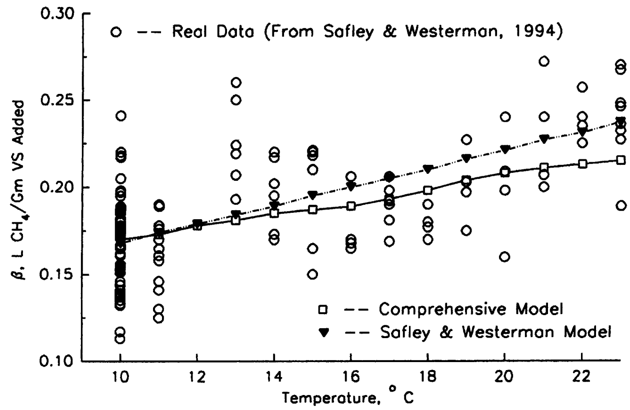

Fig. 3. Methane yield at 0.1 Kg VS/m^2 day loading rate for dairy manure.

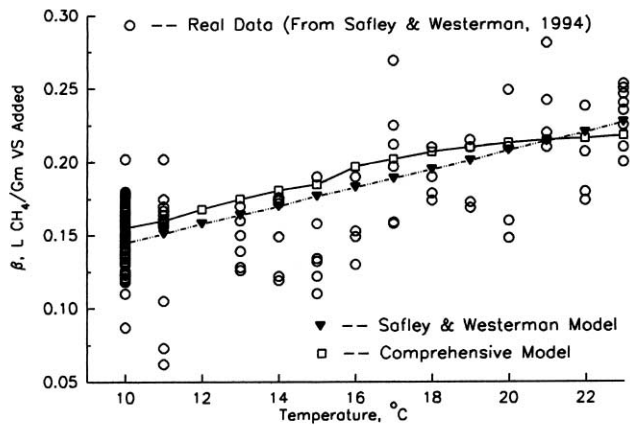

Fig. 4. Methane yield at 0.2 Kg VS/m^2 day loading rate for dairy manure.

16°C. A typical run to steady-state lasted 400 days (Fig. 2). Performance parameters also shown in Fig. 2 include SMP (specific methane productivity, L CH_4/g VS destroyed), $PCCH_4$ (% CH_4 in the biogas) and VSRED (% VS reduction).

3. Results and discussion

The results of the simulation analysis for β are contained in Table 1 and Figs. 3–6. Table 1 gives the correlation coefficients for the Safley and Westerman (1994) empirical regression models with their actual data; the correlation coefficients of the comprehensive model with the actual data reported by Safley and Westerman (1994); and the correlation coefficients of the comprehensive model with the regression models of Safley and Westerman (1994). Figs. 3–6 are respectively, the data for each of the cases: (1) dairy waste, 0.1 kg VS/m^3 day loading; (2) dairy waste, 0.2 kg VS/m^3 day loading; (3) swine waste, 0.1 kg VS/m^3 day loading; and (4) swine waste, 0.2 kg VS/m^3 day loading. These figures contain the real data of Safley and Westerman (1994); the regression data of Safley and Westerman (1994); and the simulated data from the comprehensive model. Figs. 3–6 contain, respectively, 119, 123, 100, and 104 points for the real data and 14 data points each for the regression models of Safley and Westerman (1994) and the comprehensive model reported here.

The models reported by Safley and Westerman (1994) were empirical regression models specifically developed from the actual data. These models are linear and are based on the suggestion of Sutter and Wellinger (1985) that biogas production increases linearly between temperatures of 10°C and 20°C. Due to the high variation of the actual test data, the correlation coefficients between

Table 1
Correlation coefficients (R) of the β[a] data predicted by the various methanogenesis models to the actual test data

Waste type	Loading rate (kg VS/m^3 day)	Safley and Westerman[b]	Comprehensive model[c]	Comprehensive model[d]
Dairy	0.1	0.624	0.628	0.998
	0.2	0.664	0.640	0.987
Swine	0.1	0.384	0.388	0.996
	0.2	0.427	−0.423	−0.984

[a] β = Methane productivity (L CH_4/g VS added).
[b] Correlation of the data predicted by the Safley and Westerman models to the actual test data.
[c] Correlation of the data predicted by the comprehensive model to the actual test data.
[d] Correlation of the data predicted by the comprehensive model to those predicted by the Safley and Westerman models.

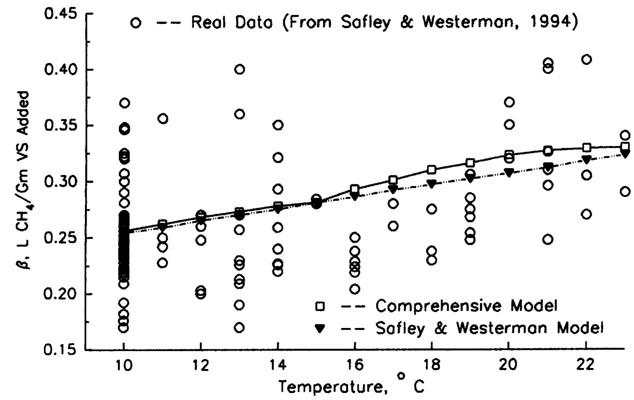

Fig. 5. Methane yield at 0.1 Kg VS/m^2 day loading rate for swine manure.

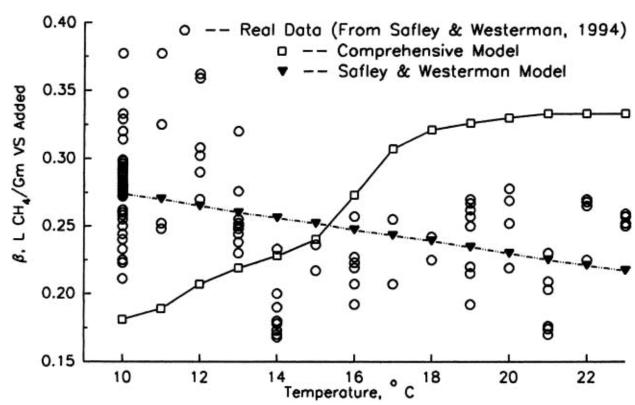

Fig. 6. Methane yield at 0.2 Kg VS/m^2 day loading rate for swine manure.

the values predicted by these regression models and the actual data range from 0.39 to 0.66, which are not extremely high (Table 1). Examining Figs. 3–5, it can be seen that the Safley and Westerman models do show linearly increasing methane productivity as a function of temperature. Case 4 (swine, 0.2 kg VS/m^3 day loading) will be discussed separately.

The comprehensive model also shows an approximately linear increase in methane productivity with temperature, and indeed is only slightly less correlated with the actual test data when compared to the regression models of Safley and Westerman. The greatest utility of the comprehensive model is that it is not limited to the specific parameters of the Safley and Westerman study. Since the comprehensive model is a process model, it can also simulate, for example, beef feedlot waste at 4.00 kg VS/m^3 day loading rate and 40°C, whereas the regression models are limited to the specific operating parameters for which they were developed. The correlation coefficients for cases 1–3 of the comprehensive model ranged 0.39–0.64 (Table 1).

Comparing the comprehensive model with the regression models for cases 1 through 3, the correlation coefficients are extremely high (0.998, 0.987 and 0.996) indicating that the predictive ability of the comprehensive model is very similar to the regression models. Indeed, the results from a *t*-test performed on the data predicted by the two models indicates that the null hypothesis (i.e., that the means of the two data sets are the same) could not be rejected at the 20% level of significance. It is easier to reject the null hypothesis as the sample size and level of significance increases. This demonstrates the validity, at psychrophillic temperatures, of the specific bacterial growth rate function (μ, Fig. 1) utilized in the comprehensive model.

The Safley and Westerman case 4 (swine, 0.2 kg VS/m^3 day loading) is, by the very nature of the actual test data (Fig. 6), a special case. These data show a trend towards increasing methane productivity as temperature decreases from 23° to 10°C. This clearly is in contrast to the other three reported cases and is in direct contrast with reported literature data (Stevens and Schulte, 1979; Sutter and Wellinger, 1985). It is also intuitively wrong, unless other factors are controlling in this case. The regression model developed by Safley and Westerman (1994) shows a negative slope (i.e., β decreasing with increasing temperature). This indicates possibly one or both of two controlling factors: (1) the digesters never reached steady-state (which is suggested by Safley and Westerman themselves) or; (2) some sort of inhibition or process instability is occurring.

Examining the results from the comprehensive model, which are in direct contrast with the actual test data (Fig. 6), may provide some insight as to what is occurring in this case. First, the comprehensive model data are non-linear over the temperature range (23–10°C). This indicates that a 0.2 kg VS/m^3 day loading rate for swine waste may be some sort of borderline loading rate at temperatures below 20°C. Apparently, this is from some sort of inhibition due to a temperature/θ effect. This would be expected in swine waste but not in dairy waste (case 2), because swine waste is much more biodegradable than dairy waste (0.9 vs. 0.36 g VS destroyed/g VS added, Hill (1985)). This higher biodegradability of swine waste would provide a greater concentration of intermediate products (i.e., acids and ammonia) and, at the reduced temperature, could inhibit bacterial growth more than at an elevated temperature.

In any event, the negative correlation between the actual data and the simulated data from the comprehensive model (Table 1) indicates that there are problems with this case. And, in fact, the validity of the actual data must be questioned since the trend opposes all known explanations and previous research findings. The disagreement between the actual data and the simulated data is another case where a ‘red flag’ has been raised by the comprehensive model. Some unknown factor has been observed here, which can only be resolved by repeating this case (swine, 0.2 kg VS/m^3 day loading) study with a much tighter research protocol.

4. Conclusions

Recent interest in the greenhouse effects of the release of methane from animal production waste management facilities has made low temperature-anaerobic digestion a target of research interest. Accordingly, research into these processes has increased in recent years. These new data have begun to provide a basis for validation of various process models of methanogenesis at psychrophilic temperatures.

The study by Safley and Westerman (1994) was used to validate a comprehensive dynamic process model of animal waste methanogenesis in the temperature range 10–25°C. Three of the cases studied show excellent agreement between actual and simulated data. The simulated data from the model and the regression data from Safley and Westerman (1994) indicate an instability in the fourth case. The comprehensive model output for this case (case 4) indicates either a non-steady-state data collection period (for the actual data) or some kind of process instability or inhibition due to a temperature/detention time interaction for swine manure at a 0.2 kg VS/m^3 day loading rate. Speculation is that 0.2 kg VS/m^3 day loading may be the upper limit for swine manure at temperatures below 20°C. This would be due to the high biodegradability of swine manure (0.9 g VS destroyed/g VS added) and the effect of a low temperature environment. The results of this validation study suggest that a much more controlled experiment using swine manure is needed to determine the phenomena occurring in the high loading case.

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