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Kinetics of temperature effects and its significance to the heating strategy for anaerobic digestion of swine wastewater

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HIGHLIGHTS

- Quantitative effects of temperature on the treatment of swine wastewater was evaluated.
- The maximum volumetric biogas production rates (R_{pmax}) for digestion of swine wastewater between 15 and 35 °C were found.
- Temperature–activity coefficients (θ) of R_{pmax} between 15 and 35 °C were obtained.
- The optimal heating strategy is an increase in digestion temperature from 15 to 20 °C.

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ABSTRACT

The effects of temperature on biogas production and the heating strategy for anaerobic digestion of swine wastewater were investigated. Through a kinetic model, the maximum volumetric rate of biogas production (R_{pmax}) for digestion at 15, 20, 25, 30, and 35 °C were found to be 0.282, 1.189, 1.464, 1.789, and 2.049 L L^{-1} d^{-1}, respectively. The temperature–activity coefficient of R_{pmax} was 1.332 at 15–20 °C, 1.043 at 20–25 °C, 1.041 at 25–30 °C, and 1.028 at 30–35 °C. Anaerobic digestion appeared to be more sensitive to temperature variation within 15–20 °C than to variation within 20–35 °C. In terms of energy input–output ratio and total annual cost, the optimal heating strategy is an increase in the fermentation temperature from 15 to 20 °C.

1. Introduction

Anaerobic digestion has been widely used in the treatment of swine wastewater because of its ability to produce renewable energy sources such as methane with concurrent reduction of emissions of organic pollutants and greenhouse gas. Many countries have adopted it, including China, Germany, Austria, Denmark, Italy, and The Netherlands [1,2]. Factors influencing the efficiency of anaerobic digestion include feedstock, microbial biomass, inhibitor, reactor, mixing, pH, and trace elements [3], among which temperature, has a great influence on microbial availability, biogas yield, methane content [4,5], ammonia concentration [6], is an important one. In general, the higher is the temperature, the higher is the microbial activity up to an optimum temperature. There are three ranges of temperature in which anaerobic digestion is carried out, namely, ambient range (15–25 °C), mesophilic range (35–37 °C), and thermophilic range (50–60 °C). Anaerobic digestion at ambient temperature is vulnerable to changes in environmental temperature; it has low efficiency at low temperature. To increase its efficiency, most reactors are operated at either mesophilic or thermophilic temperatures, which have optima at 35 and 55 °C, respectively. Anaerobic digestion under mesophilic or thermophilic conditions results in higher metabolic rates and greater destruction of pathogens and weed seeds. However, mesophilic or thermophilic treatment has drawbacks such as higher risk for inhibition caused by ammonia toxicity at higher temperature, as well as higher energy requirements than those of ambient-temperature systems. The increase in methane yield or production rate has to be balanced against the increased energy requirement to maintain operation of the reactor at higher temperature. Therefore, the digestion temperature applied depends on the local climate, feedstock, and economical efficiency of heating.

Over the last decades, the effect of temperature on anaerobic digestion has been widely investigated [5,7–17]. Reducing the operating temperature could considerably slow down microbial

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activity and affect treatment efficiency. For instance, the methanogenic activity of biomass adapted to landfill leachate was found to be 1.6–5.2 times higher at 22 °C than at 11 °C [18]. When concentrated slaughterhouse wastewater was treated in anaerobic sequencing batch reactors (ASBRs), the reactors showed high average methanogenic activity of 0.37, 0.34, and 0.12 g CH_4COD g^{-1} VSS d^{-1} (22.4, 12.7, and 11.8 LCH_4 d^{-1}) respectively at 30, 25, and 20 °C. In particular, 90.8%, 88.7%, and 84.2% of the COD removed was transformed into methane at 30, 25, and 20 °C, respectively [13]. A nonlinear decrease in the maximum specific substrate removal rate (k_{max}) was also observed when the temperature of the ASBR was reduced from the mesophilic to the psychrophilic range. The k_{max} value was 28.3% lower at 20 °C compared with that at 25 °C, whereas it only decreased by 7.0% between 15 and 20 °C. The temperature correction coefficient at 7.5–25°Cwas determined to be 1.08 [19]. Masse et al. [17] used anaerobic sequencing batch reactors to treat swine manure and observed that the soluble chemical oxygen demand decreased from 94.2 ± 1.1% at 20 °C to 78.8 ± 3.0% at 15 °C and to 60.4 ± 6.4% at 10 °C. Removal of the total chemical oxygen demand (COD) also tends to decrease as temperature is lowered. The effects of water temperature and hydraulic retention time (HRT) on the treatment efficiency of the anaerobic filter process were investigated, and the relationship between system temperature and first-order rate constant for each anaerobic filter system was developed [16,20]. Most of the research on the effects of temperature examines methanogenic activity, removal rate of pollutants, effluent quality, and process stability. However, very limited information is available on the quantitative effects of temperature on the treatment capacity, which is more important for the design of wastewater treatment plants. For instance, the volume of digesters for anaerobic treatment of swine wastewater should be designed to operate at temperatures of 15, 20, 25, 30, and 35 °C.

A new model describing the relationship between the treatment capacity (in terms of the volumetric biogas production rate, R_p) and the OLR was developed. On the basis of this finding, anaerobic digestion of swine wastewater was carried out at temperatures of 15, 20, 25, 30, and 35 °C and at different loading rates to obtain the temperature–activity coefficient (θ) and to reveal the quantitative effects of temperature on the treatment capacity for anaerobic digestion of swine wastewater at various OLRs. Subsequently, the heating efficiency of anaerobic digestion at various temperature ranges was evaluated to determine a cost-efficient heating strategy.

2. Materials and methods

2.1. Swine wastewater and inoculum

The swine wastewater used for this study was collected from a farm 35 km away from the laboratory. Swine wastewater samples for the experiment were collected form a homogenization tank and then stored at 4 °C until use for experiments. In the experiments, the average concentration of the total solids (TS) in the influent wastewater was 1.08%. Sludge obtained from laboratory-scale digesters used for treating swine wastewater was used as inoculum for the experimental digester.

2.2. Anaerobic digestion experiments

The experimental equipment (digesters) was the same as that used in a previous study [1]. A digester with an effective volume of 1000 mL was constructed from a plastic bottle. It was sealed with a plastic cap and attached to a pipe for venting biogas. A 1000 mL wide-mouth glass bottle was used as a biogas collector. It was sealed with rubber stoppers to contain the flow of biogas. Water discharged from the biogas collector was collected by using a 1000 mL wide-mouth glass bottle. The amount of discharged water that was identical to the biogas output was measured by using a graduated cylinder [1]. Each digester was inoculated with 500 mL of anaerobic sludge at the beginning of the experiments. In order to distinguish the amount of biogas produced by the inoculum, control experiments were performed with digesters containing 500 mL of sludge and 500 mL of tap water. The digester was operated in draw-and-fill mode twice a day. A specified volume of supernatant from the digester was decanted, and was then replaced with the same volume of influent. The influent volume, HRT, and OLR of the experiments at different temperatures are listed in Table 1. Each experiment was done in duplicates. A water bath was used to maintain the temperature of the digesters. When biogas production for each experiment was found to be stable for at least 10 days, the experiment was stopped. Biogas production was determined once or twice a day, and the pH of the liquid mixture was determined once a day. Analysis for COD, ammonia nitrogen (NH_3–N), and biogas were done once a week.

2.3. Analytical methods

Analyses for TS, volatile solids (VS), COD, and NH_3–N were performed according to standard methods [21]. In addition, biological oxygen demand (BOD_5) was measured by using a BOD meter (Oxide® Control A12; WTW-Wissenschaftlich Technische Werkstatten GmbH, Germany). The pH of the wastewater and liquid mixture in the digesters was determined by using a pH electrode (inoLab® pH 7200; WTW-Wissenschaftlich Technische Werkstatten GmbH, Germany). Biogas production was measured on a biogas analyzer (Biogas 401; ADOS GmbH Instrumentation and Control, Germany).

Origin software (version 8.0) was used to fit the experimental data and create mathematical model presented in this work.

3. Results and discussion

3.1. Performance of digesters at various temperatures and OLRs

The best treatment of wastewater not only removes pollutants but also produces useful product. The rate of product generation from pollutants reflects the conversion of pollutants by microorganisms. The sum of all gas compounds in the product of anaerobic digestion is most commonly determined by online measurements and, consequently, is widely used in modeling applications [22]. In many studies, biogas is used for estimating parameters [23,24]. Thus, the biogas production rate is the most accurate and direct parameter that reflects the conversion of pollutants by microorganisms. However, this rate only reflects biogas production per unit time (L d^{-1} or m^3 d^{-1}). Biogas production of digesters with different volumes is not comparable. The biogas production rate (L d^{-1} or m^3 d^{-1}) divided by digester volume, referred to as R_p (L d^{-1} L^{-1} or m^3 d^{-1} m^{-1}), reflects the productivity of the biogas plant and thus indicates the efficiency of the plant. Therefore, R_p could be used as a design parameter. R_p values at different OLRs and temperatures are shown in Fig. 1. Digestion experiments began at 35and 20 °C. R_p

Table 1
The operation parameter in anaerobic digestion experiment.

Item	Experimental parameters				
Influent volume (mL)	112	152	202	270	360
HRT (d)	8.93	6.58	4.95	3.70	2.78
Loading rate (g TS L^{-1} d^{-1})	1.21	1.64	2.17	2.91	3.87