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Kinetics of poultry litter in a leach bed reactor with agitation based on two mechanisms: Enzymatic hydrolysis and direct solubilization

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ABSTRACT

Two-phase anaerobic digestion including a hydrolyzer is considered necessary for solid waste treatment. In this study, a novel hydrolyzer with agitation was developed to treat poultry litter. Four experiments at temperature 35 °C were conducted under these conditions: 1200 and 800 g poultry litter with agitation (200 and 133 g L^{-1}), and 800 and 400 g without agitation (133 and 67 g L^{-1}). The experiments showed that agitation accelerated the hydrolytic rate of poultry litter, and the highest destruction of TS and VS was 92.4 and 91.9%, compared to 58.2 and 48.7% without agitation. Butyric acid and its isomers accounted for the highest equivalent COD among VFAs for all experiments. Two hydrolytic mechanisms were also identified, i.e., direct solubilization and enzymatic hydrolysis, and the corresponding kinetic model was developed. The rate constants determined by the model and the simulated kinetic curves indicated that direct solubilization was more significant than enzymatic hydrolysis under agitation, while the opposite was true without agitation. Use of agitation also reduced the time to reach stable concentrations under same substrate loading schemes.

1. Introduction

Anaerobic digestion is a traditional technology for utilization of carbon and hydrogen contents in wastewater and solid wastes to produce energy (methane). However, application of anaerobic digestion for poultry litter treatment has not made headways and suffers from more difficulties than in treating liquid wastes. One of the reasons lies in the extremely low hydrolysis rate in the dry litter. To overcome this huddle, a high efficient hydrolyzer must be included in the system for hydrolysis and acidogenesis of solid waste prior to entering a digester for methanogenesis [1]. It was identified that the anaerobic process to convert the carbon and hydrogen contents in wastewater containing a high solid content and solid wastes to biogas consists of three stages: hydrolysis, acidogenesis, and methanogenesis, in which hydrolysis was the slowest, a rate-limiting step [2]. The three stages can be combined, referred to as one phase digestion, or separated, referred to as two-phase digestion with the first phase for hydrolysis combined with acidogenesis, and the second phase for methanogenesis. Besides the common advantages of two-phase digestion over the one-phase digestion: such as more stability, higher methane yield, and higher heavy metal removal efficiency [3], the two-phase process is generally considered necessary for solid waste digestion as a result of the physical difficulties in mass transfer [4], and a low ratio of carbon to nitrogen for some feedstocks in a one-phase digestion [5]. A separated hydrolyzer in a two-phase digestion will increase the efficiency of the subsequent methanogenic process.

Leach bed reactors as the hydrolyzers are commonly used in two phase digestions, in which the water is sprinkled to the substrates filling the reactors to produce high carbon content streams for further utilization in the following digesters by methanogenic bacteria. Recently, hydrolysis of several feedstocks, such as bale and pit silages and perennial ryegrass [6,7], the whole crop of maize (*Zea Mays*) [3,8], kitchen wastes [9], food waste [10], and municipal solid and cow manure [11], has been investigated in the leach beds. Because of the limited contact between the sprinkling water and substrates in the leach beds without agitation, the hydrolyzing rate converting bulk materials to soluble carbon molecules represented by chemical oxygen demand (COD) is slow, and becomes a rate-limiting step in the three stages [12]. Therefore, sprinkling water coupled with agitation will increase hydrolysis for the bulk materials. Typically for cellulosic materials, the most commonly

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identified mechanism of hydrolysis is enzyme driven, which converts solid carbon in the substrates, such as cellulosic materials, into soluble carbon in leachates by various enzymes produced by bacteria. However, for manures and poultry litter that mainly consists of bedding materials (cellulosic materials) and chicken feces, another mechanism, directly solubilization, may be as significant as enzymatic hydrolysis, depending on the residence time of feedstocks in the leach beds. The shorter the residence time, the less significant the direct solubilization of manures and poultry litter because the solubilization process is much faster than the enzymatic process. To our best knowledge, direct solubilization as a hydrolytic mechanism has not been extensively reported in literature.

Hydrolytic kinetics is an important factor influencing design and performance of leach beds. A leaching kinetic model was developed by Pelillo et al. [13] for two-phase aerobic degradation of olive mill effluent in a batch reactor, and used by Nizami et al. [6] in investigating the leaching kinetics in a two-phase digestion system for digesting bale and pit silages. However, the kinetic model by Pelillo et al. [13] only involves enzymatic hydrolysis, without considering direct solubilization. Thus, development of a novel leaching kinetic model including both hydrolytic mechanisms is beneficial for description and understanding of the hydrolytic process of manures and poultry litter in the leach beds.

On the other hand, the northwestern area in Arkansas is a main base of poultry industry, which generates about 1.3 billion metric tons of poultry litter annually [14], ranking Arkansas the second largest state of poultry production in the United States. Poultry litter is traditionally disposed of in agricultural land as a fertilizer for utilization of its nutrient contents. However, this disposal method has caused several environmental issues, such as air, soil, and water contaminations [15], deterioration of soil quality as a result of long term application of poultry litter [16,17] and land availability.

Lab-scale, one phase batch anaerobic digestion of poultry litter has been widely investigated [5,18,19]. The continuous upflow anaerobic biofilm digester from leachates derived from poultry litter at different organic loading rates and hydraulic retention times has also been studied by Shen and Zhu [20]. These studies demonstrated that anaerobic digestion of poultry litter alone at a high total solid (TS) content produced a poor methane yield due to the inhibition to methanogenic activity caused by high concentrations of free ammonia resulting from the low carbon to nitrogen ratio in poultry litter. What these studies did not address is the hydrolysis of poultry litter in the leach bed and the associated hydrolytic kinetics.

The objectives of this study were to [1] develop a leach bed reactor with agitation to hydrolyze poultry litter; [2] investigate the effects of solid loading and agitation on hydrolysis of poultry litter in the leach bed; [3] develop a novel kinetic model describing two hydrolytic mechanisms, i.e., enzymatic hydrolysis and direct solubilization; [4] fit the kinetic data obtained in the experiments to the developed model to reveal the significance of enzymatic hydrolysis and direct solubilization during hydrolysis.

2. Materials and methods

2.1. Materials

The poultry litter used in the experiments was obtained from the University of Arkansas System Division of Agriculture Broiler Farm in Savoy. The collected litter was sieved through a 2.38 mm screen, and stored in a refrigerator at −4 °C before use. The physical characteristics of the poultry litter used, such as the ratio of carbon to nitrogen, fractions of total solid (TS), volatile solids (VS) based on TS, and moisture content based on the raw sieved particles of poultry litter, were measured and presented in Table 1.

Table 1
The physical properties of the poultry litter.

	Poultry litter
TS fraction	0.7504 ± 0.0256
VS fraction	0.7085 ± 0.0462
Moisture	0.2497 ± 0.0256
C/N	6.93

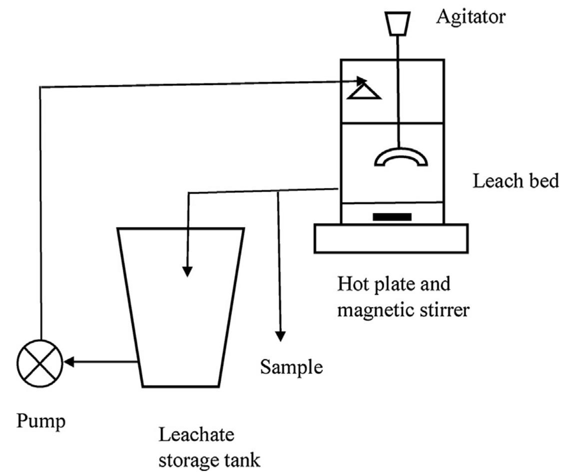

Fig. 1. A schematic diagram of the leach bed reactor.

2.2. Experimental methods

The poultry litter was hydrolyzed in a 9.8 L leach bed reactor (PVC column (Standard-Wall Clear PVC)) with an internal diameter of 0.203 m (8 in) and a total height of 0.305 m (12 in) (Fig. 1). The stainless net with a net diameter of about 1 mm supported on a Fluon plate with 12 mm holes was installed 2 cm from the bottom to prevent the big particles in poultry litter from entering into the leachates. The bottom of the reactor was heated by a hot plate (StableTemp, Cole-Parmer, Vernon Hills, IL) to maintain the broth temperature at 35 ± 1 °C, measured by a digital thermometer (Digi-Sense, Cole-Parmer), and also to provide agitation (200 rpm) with a magnetic stirrer to mix the leachates between the Fluon plate and reactor bottom. An agitator (Cole-Parmer, Vernon Hills, IL, 50007-10 Model: SSM31) installed at the top of the reactor mixed the poultry litter and water (about 100 rpm). The recycling water (25 L) was sprinkled to the poultry litter from the top of the reactor and flowed out into a 25 L storage tank. A digital dispensing pump (MasterFlex77921-75) transported the leachates in the storage tank to the leach bed reactor at the required flow rate, and liquid samples were taken from the outlet of the reactor according to the experimental design for composition analysis. Three poultry litter loadings (1200, 800, and 400 g, corresponding concentrations 200, 133, and 67 g L^{-1}) accompanied with 100 g anaerobic activated sludge were examined. Four experiments were conducted according to the following conditions: Run 1 - the substrate loading 1200 g with agitation for 12 days with the sampling time at 1, 2, 4, 8 h, 1 day, daily after that; Run 2 - the substrate loading 800 g with agitation for 11 days with the same sampling time as in Run 1; Run 3 - the substrate loading 800 g without agitation for 28 days with the sampling time at 1, 2, 4, 7, 9, 11, 14, 16, 18, 21, 23, 25, and 28 day; Run 4 - the substrate loading 400 g without agitation for 15 days with daily sampling.

2.3. Analytical methods

The carbon and nitrogen contents in the used poultry litter were analyzed by an organic elemental analyzer (The Thermo-Scientific