Biotechnol. Prog. 1991, 7, 369–376 369

Kinetic Model for Substrate Utilization and Methane Production in the Anaerobic Digestion of Organic Feeds

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A kinetic model for anaerobic digestion of organic substrates is presented. Two complementary kinetic equations, one each for substrate utilization and methane production, are derived. The model equations take into account extracellular hydrolysis of complex substrates and consider the hydrolyzed products as the limiting substrates for cell growth and product formation according to Monod kinetics. The equations are applied to the experimental data on the anaerobic digestion of a variety of feeds reported in the literature with reasonable agreement of the predicted and observed values. When substrate hydrolysis is poor and rate limiting, the equations are reduced to a Contois-type equation. On the other hand, if no hydrolysis of the substrate is involved as in the case of simple and soluble substrate, the equations take the form of a Monod-type relationship. Thus, the equations represent a generalized kinetic expression for fermentation relating the Monod and Contois equations, which hold good in two extreme cases.

Introduction

Various kinetic models have been advanced for anaerobic digestion of waste biomass and methane production. Most of the early models were based on a single-culture system and used the Monod equation or its variations (*1–3*). Recently, several dynamic simulation models were developed on the basis of a continuous multiculture system corresponding to major bioconversion steps in anaerobic digestion with the assumption of culture growth according to Monod-type kinetics (*4–7*). Doubt was, however, expressed by several investigators on the validity of applying the Monod equation in waste treatment (*8–10*). In the Monod equation (*11*), specific growth rate is expressed as a function only of the concentration of the limiting substrate in the reactor. It does not contain any term for influent substrate concentration, implying that effluent substrate concentration is independent of the influent substrate concentration. Experimental results of various investigators on anaerobic and aerobic digestion of waste, however, were not in accord with this implication of the Monod equation. Dependence of the effluent substrate concentration on the influent was observed on examination of the experimental results of the anaerobic digestion of dairy manure (*2*), of beef cattle manure at mesophilic and thermophilic temperatures (*12, 13*), of rice straw (*14*), of poultry litter (*15*), and of water hyacinth (*16*). In aerobic chemostat operations with glucose as the growth-limiting substrate, Grady et al. (*8*) showed that effluent concentration of the growth-limiting substrate expressed as chemical oxygen demand (COD) was not independent of the concentration of substrate entering the reactor when pure or heterogenous cultures were used. However, when the substrate was measured as glucose, the Monod equation was found to be true in pure cultures but not in heterogenous cultures.

In the models proposed by Contois (*17*) and Fujimoto (*18*), specific growth rate (μ) was considered as a function of the growth-limiting nutrient in both the influent and effluent and it was expressed in terms of microbial concentration (X) as

$$\mu = \frac{\mu_m S}{CX + S} \quad (1)$$

where S is the growth-limiting substrate concentration in the reactor, μ_m is the maximum specific growth rate, and C is an empirical constant. On the basis of the Contois equation, Chen and Hashimoto (*10, 19*) developed kinetic models for substrate utilization and methane production and showed that the models were in accord with the experimental data of various investigators on aerobic and anaerobic digestion of various organic feeds. A Contois-type relationship was also used to describe the kinetics of cell growth on nonmiscible liquid hydrocarbon (*20, 21*) where substrate transfer could be a limiting factor. The Contois equation has a drawback as it contains an empirical constant C that is ill-defined and ill-understood.

The basic validity of the Monod equation was demonstrated in chemostats using pure cultures and simple substrates (*8, 22*). Deviation from the Monod relationship in many digestion systems may be due to the complexity of the systems. In the digestion of organic wastes, growth-limiting substrate, due to necessity, was generally expressed in terms of COD or volatile solids (VS), which may not truly reflect the nature of the growth-limiting substrate. Digestion of complex organic wastes involve the hydrolysis of polymeric compounds (cellulose, hemicellulose, protein, etc.) constituting the waste by exoenzymes in the extracellular medium or on the surface/vicinity of the cells. Only the hydrolyzed assimilable compounds may be considered as the growth-limiting substrate in terms of the Monod relationship. There are various reports that extracellular hydrolysis is the rate-limiting step in the anaerobic digestion of organic wastes (*7, 23–25*). It is necessary to take into account the hydrolysis process in model building for organic waste digestion.

From theoretical consideration, kinetic treatment of anaerobic digestion on the basis of a multiculture system may be desirable in view of the heterogenous nature of the microbial population bringing about the various bioconversion steps involved. However, the kinetic models based

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8756-7938/91/3007-0369$02.50/0