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Kinetic models of an anaerobic bioreactor for restoring wastewater generated by industrial chickpea protein production

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Abstract

To assess the accuracy of kinetic models in predicting the behaviour of an anaerobic biodegradation process for cleaning up wastewater derived from the production of protein isolates from chickpea flour, the process was conducted in a laboratory-scale fluidised-bed reactor with saponite (magnesium silicate) as support for the mediating bacteria at 35 °C. The reactor operated satisfactorily at organic loading rates between 0.58 and 2.70 g total chemical oxygen demand (TCOD) L^{-1} d^{-1}, hydraulic retention times between 14.9 and 3.5 d, and an average feed TCOD of 9.1 g L^{-1}. The methane yield coefficient value, $Y_{G/S}$, of 0.33 L CH_4 (at STP) g^{-1} $TCOD_{removed}$, calculated on the basis of a substrate balance (TCOD) model, was virtually identical to that obtained from the experimental data. The cell maintenance coefficient, k_m, obtained by means of this balance was found to be 0.0057 g TCOD g^{-1} volatile suspended solids (VSS) d^{-1}. The volumetric methane production rates correlated with the biodegradable TCOD concentration based on the Michaelis–Menten equation. In addition, the specific rate of substrate uptake, r (g soluble COD (SCOD) g^{-1} VSS d^{-1}), also correlated with the concentration of biodegradable substrate, S_b (g SCOD L^{-1}), according to the Michaelis–Menten equation. These proposed models predict the behaviour of the reactor accurately showing deviations $<10\%$ between experimental and theoretical values of methane production and substrate uptake rates, respectively.

Keywords: Anaerobic biodegradation; Kinetic evaluation; Wastewater; Protein isolates; Chickpea flour

1. Introduction

Chickpeas are consumed throughout the world and offer important nutritional advantages (Cayot and Olsson, 1997). Ways of taking greater advantage of the proteins present in chickpeas were considered with respect to standardization of traditional products; nutritional enrichment, particularly of cereal products; the substitution of more conventional protein sources with chickpea (or other plant) protein(s); and the development of more original products (Cayot and Olsson, 1997).

Production of a high protein product from low commercial grade chickpeas (*Cicer arientinum* L.) was investigated for possible inclusion as an ingredient for increasing the nutritional value of cereal products (Romero-Baranzini et al., 1995). When a flat-plate ultrafiltration system, direct ultrafiltration and discontinuous diafiltration (DD) were used to produce a high protein product, chickpea extract (3.3% total solids) was concentrated to 65% protein by DD (Romero-Baranzini et al., 1995).

The manufacturing of protein isolates from chickpea flour requires various operations that together produce between 20–25 L wastewater kg^{-1} processed flour (Borja et al., 2004). The wastewater obtained from combining the effluents from all steps of the process is a viscous yellow liquid with a TCOD of 8.6–9.4 g L^{-1}. The final effluent (Borja et al., 2004) is highly polluting and is characterised by low pH and high chemical and biological oxygen demands and total solids (TS). The high pollution charge and large volumes can pose environmental problems.

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A recent report showed that an anaerobic biodegradation treatment was an efficient means of restoring a proteinaceous wastewater generated from a similar manufacturing process and containing a moderate-to-high concentration of organic matter (Fang and Chung, 1999). For moderate-to-high strength wastes, anaerobic processes have considerable advantages over aerobic processes. The most noteworthy of these (Olthof and Oleskiewicz, 1982) are (a) it demands little energy, (b) anaerobic bacteria efficiently transform the organic substances present in the waste into methane, (c) sludge formation is minimal, (d) nutrient demands are very low, and (e) unpleasant odours are avoided.

The low-growth rate of anaerobic microorganisms has encouraged the development of various techniques for their immobilization within bioreactors so as to avoid loss of biomass in the effluent stream that diminishes process rates. Among the bioreactors used for this purpose are fluidized-bed reactors, where bacteria colonize particles of a support medium, thereby increasing the surface available for bacterial growth. Fluidized-bed reactors are also capable of treating either high- or low-strength wastewaters at high volumetric throughputs; in both cases, the organic loading which can be treated is far higher than in a conventional continuous stirred tank reactor system (Jeris, 1983; Gujer and Zehnder, 1983; Speece, 1983; Shieh et al., 1985; Chen et al., 1985a,b; Yoda et al., 1987; Wheatley, 1990; Kida et al., 1990; Iza, 1991; Martín et al., 1993; Fiestas and Borja, 1996; Maqueda et al., 1998).

The fluidised-bed reactor therefore offers many advantages for the processing (Iza, 1991; Rozzi, 1988), including high concentration of biomass, attached to a support, which cannot be easily washed out from the reactor; very large surface area for biomass attachment; high mass transfer properties (low concentration gradients around the particles are possible, allowing the treatment of low-strength wastes); no plugging, channelling or gas hold-up; ability to control and optimise biofilm thickness; and biomass support can be tailored to a specific application to enhance performance.

In a previous report (Borja et al., 2004), it was shown that an anaerobic process based on a fluidised-bed reactor containing microorganisms immobilised on saponite (magnesium silicate) was effective in cleaning up wastewater from the production of protein from chickpea flour. In the present report, previously published data (Borja et al., 2004) obtained from this bioreactor have been used to assess the accuracy of kinetic models for predicting the behaviour of such a bioreactor.

2. Materials and methods

2.1. Equipment

The laboratory-scale fluidised-bed reactor used in this study has been described previously (Borja et al., 2001, 2004). It operated at 35 °C, with total and working volumes of 1.5 and 1.0 L, respectively, and had a settling mechanism intended to avoid loss of the solid particles that acted as microbial supports. The biogas was evacuated in a continuous fashion; the volume of methane produced being measured after removing CO_2 by adsorption into NaOH. The reactor was inoculated with biomass from an industrial anaerobic reactor processing brewery wastewater. Its composition was: total suspended solids (TSS), 27.2 g L^{-1}; volatile suspended solids (VSS), 15.0 g L^{-1}; mineral suspended solids (MSS), 12.2 g L^{-1}.

2.2. Support material

An elongated saponite (magnesium silicate) in the form of particles of 0.4–0.8 mm diameter. was used for retention of the bacteria required to effect anaerobic digestion. The support had low fragility, medium porosity (19%), low apparent density (0.55 g mL^{-1}) and a high specific surface area (200 $m^2 g^{-1}$), which facilitates attachment of anaerobic microorganisms (Maestrojuán and Fiestas, 1988; Pérez-Rodriguez et al., 1989). It was selected because of its favourable kinetic behaviour in previous experiments with other types of food industry wastewaters (Maestrojuán and Fiestas, 1988; Fiestas et al., 1990; Martín et al., 1993; Borja and Banks, 1994; Borja et al., 2001). A detailed description of the composition and features of this packing medium is given elsewhere (Fiestas et al., 1990).

2.3. Wastewater

The wastewater used was collected after a flow equalisation step to minimise any variation that might occur as a result of the batch nature of the manufacturing process. The composition and features of the wastewater derived from the production of protein isolates from chickpea flour were (mean values of seven determinations ± S.D.): pH, 4.1 ± 0.2; TCOD, 9.1 ± 0.4 g L^{-1}; soluble chemical oxygen demand (SCOD), 7.2 ± 0.3 g L^{-1}; TS, 10.8 ± 0.5 g L^{-1}; mineral solids (MS), 3.0 ± 0.1 g L^{-1}; volatile solids (VS), 7.8 ± 0.3 g L^{-1}; TSS, 0.90 ± 0.04 g L^{-1};VSS, 0.90 ± 0.04 g L^{-1}; volatile acidity (as acetic acid), 0.37 ± 0.02 g L^{-1}.

2.4. Operational parameters for the anaerobic reactor

The operational parameters for the anaerobic reactor have been described in detail by Borja et al. (2004). The reactor was loaded initially with 300 mL distilled water, 1000 mL inoculum (see section 2.1), 200 mL nutrient-trace element solution and 15 g support. The composition of the nutrient solution and trace element solution used at the start-up of the reactor were as in Borja et al. (2004).

The reactor was started up by stepwise increases in COD loading and substrate concentration. During the 1-month acclimatisation, the organic loading rate (OLR) was increased from 0.4 to 1.9 g COD L^{-1} d^{-1} and the influent COD from 4.35 to 9.10 g L^{-1}.

As described previously (Borja et al., 2004), this preliminary step was followed by a series of continuous experiments using feed flow-rates of 67, 77, 90, 105, 150, 166, 182, 202, 224, 245, 266, 288 and 357 mL d^{-1} of the wastewater, which correspond to hydraulic retention times (HRTs) of 14.9, 13.0, 11.1, 9.5, 6.7, 6.0, 5.5, 5.0, 4.5, 4.1, 3.8, 3.5 and 2.8 days, respectively. The bacterial biomass concentration estimated according to Chen et al. (1985b), remained virtually constant at 15 g VSS L^{-1} throughout the experiments.

At each feed flow-rate, the volume of methane produced, COD, pH, volatile acidity and alkalinity were analysed daily. All analyses for determining the various parameters (TCOD, SCOD, pH, TS, MS, VS, TSS, MSS, VSS, volatile acidity, and alkalinity) were carried out according to the APHA (1989). It was considered that pseudo steady-state conditions were achieved when the deviation of average parameters values were < 3% over a period of 6 days. The values used in this work are the mean of those taken for 6 consecutive days after achieving pseudo-steady-state conditions. The length of each experiment was 3–4 times the corresponding HRT.