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ScienceDirect
Bioresource Technology 98 (2007) 2102–2108
BIORESOURCE TECHNOLOGY

Anaerobic membrane reactor with phase separation for the treatment of cheese whey

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Received 18 February 2005; received in revised form 15 August 2006; accepted 18 August 2006
Available online 13 October 2006

Abstract

Two-phase anaerobic digestion of cheese whey was investigated in a system consisting of a stirred acidogenic reactor followed by a stirred methanogenic reactor, the latter being coupled to a membrane filtration system to enable removal of soluble effluent whilst retaining solids. The acidogenic reactor was operated at a hydraulic retention time (HRT) of one day, giving maximum acidification of 52.25% with up to 5 g/l volatile fatty acids, of which 63.7% was acetic acid and 24.7% was propionic acid. The methanogenic reactor received an organic load up to 19.78 g COD/l d, corresponding to a HRT of 4 days, at which 79% CODs and 83% BOD_5 removal efficiencies were obtained. Average removals of COD, BOD_5 and TSS in the two-phase anaerobic digestion process were 98.5%, 99% and 100%, respectively. The daily biogas production exceeded 10 times reactor volume and biogas methane content was greater than 70%.

Keywords: Cheese whey; Acidogenesis; Methanogenesis; Cross-flow microfiltration

1. Introduction

Whey is a by-product of the dairy industry in which the principal components are lactose, proteins and mineral salts (Vasala et al., 2005). Approximately 47% of the 115 million tons of whey produced world-wide every year are disposed of in the environment (Leite et al., 2000; Zhou and Kosaric, 1993; Siso, 1996). This represents a significant loss of resources and causes serious pollution problems since whey is a high strength organic pollutant with high BOD_5 and COD, with values of 40,000–60,000 mg/l and 50,000–80,000 mg/l, respectively (Ben-Hassan and Ghaly, 1994; Fournier et al., 1993). More than 90% of whey BOD_5 is due to lactose (Kisaalita et al., 1990).

Currently, the whey production in Tunisia is estimated at 35,000 tonnes/year. During the last few decades, this production has increased very rapidly with the development of the dairy industry. Thus, the problem of whey disposal will worsen. Indeed, the continuous discharge of whey onto land can endanger the chemical and physical structure of the soil, reduce crop yields and lead to serious groundwater pollution problems (Ben-Hassan and Ghaly, 1994).

For medium size cheese factories, that have growing disposal problems and cannot afford high investment costs for whey valorisation technologies (such as whey protein and lactose recovery, spray drying, etc.), physico-chemical and/or biological treatment of this effluent is imperative. Due to the high organic content of whey, the basic biological treatment process to be used can only be anaerobic digestion, whereas regular treatment processes such as the

Abbreviations: AD, anaerobic digestion; AR, acidogenic reactor; BOD_5, biochemical oxygen demand; COD, chemical oxygen demand; CODs, soluble chemical oxygen demand; CSTRs, continuous stirred tank reactors; CSMR, continuous stirred methanogenic reactor; HRT, hydraulic retention time; TMP, trans-membrane pressure; TN, total nitrogen; TP, total phosphorous; TS, total solids; TSS, total suspended solids; VCR, volumetric concentration factor; VFAs, volatile fatty acids; VS, volatile solids; VSS, volatile suspended solids; MR, methanogenic reactor; CFM, cross-flow microfiltration; MS, mineral solids.

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doi:10.1016/j.biortech.2006.08.013

activated sludge process are completely inappropriate (Gavala et al., 1999).

Anaerobic digestion of cheese whey offers an excellent solution in terms of both energy saving and pollution control (Ergüder et al., 2001). The major advantages of this process are low cost, high energy efficiency and process simplicity compared to other waste treatment methods.

However, despite these advantages, anaerobic digestion is not widespread in the dairy industry, largely due to the problems of slow reaction, which requires longer HRT, and poor process stability, especially for effluents rich in components that are subject to rapid acidification. Indeed, Malaspina et al. (1996) stated that raw whey is a quite problematic substrate to treat anaerobically because of very low bicarbonate alkalinity (50 meq l^{-1}), high COD concentration (70 g COD l^{-1}) and a tendency to acidify very rapidly.

The idea of developing anaerobic digestion as a two-phase process originated from the view that it is generally a process involving two different sets of activities. Overall, the two-phase process takes advantage of the phase separation phenomenon, deriving naturally from different kinetic rates. This provides separate acidogenic and methanogenic reactors to decrease the cost, and to improve treatment efficiency, energy production and process stability of anaerobic systems (Ke and Shi, 2005).

Anaerobic digesters are widely used for treatment of agro-industry by-product wastewaters. These digesters are single pass reactors with no selective solids recycle. This limits the organic loading rates and operating biomass concentrations (Pillay et al., 1994). One way to overcome these problems is to include a membrane to enable independent control of hydraulic and solid retention times (Dhouib et al., 2003). Indeed, in recent years, considerable attention has been focused on development of a novel anaerobic process in which a membrane separation unit is incorporated in place of a settlement system. So far, several investigators have studied anaerobic-membrane processes for treatment of wastewaters such as wine distillery effluents (Ross et al., 1990), palm oil mill effluent (Fakhru'l-Razi and Noor, 1999) and dairy wastes (Li et al., 1985).

This study examined the feasibility of applying an anaerobic membrane bioreactor with phase separation (acidogenesis/ methanogenesis) to treat cheese whey.

2. Methods

2.1. Whey

The whey used in this study was obtained from the "Tunisian Cheese Factory" (Sfax, Tunisia) which used traditional technologies for cheese manufacture. The whey samples were drained directly from the cheese vats, collected in 20 l tanks and transported to the laboratory freezer and stored there at a temperature of −20 °C to avoid the acidification and the chemical composition modification of cheese whey. About one week before it was needed, a proportion of the frozen whey was moved into a cold room at 4 °C for defrosting. During the adaptation phase diluted whey at pH 6.5 was fed into the reactor.

Table 1
Chemical characteristics of raw cheese whey

Characteristics	Sample
COD (g/l)	68.6 ± 3.3
BOD_5 (g/l)	37.71 ± 2.84
COD/BOD_5	1.83 ± 0.05
TSS (g/l)	1.35 ± 0.06
Lactose (g/l)	45.9 ± 0.88
Proteins (g/l)	2.71 ± 0.05
TS (%)	5.93 ± 0.38
VS (%)	5.61 ± 0.36
MS (%)	$0.31 \pm 6.3 \times 10^{-4}$
Fat (g/l)	9.439 ± 1.14
pH	4.9 ± 0.27
TKN (g/l)	1.12 ± 0.01
TP (g/l)	$0.5 \pm 1.8 \times 10^{-3}$

The chemical composition of cheese whey is shown in Table 1. The notable characteristics of this effluent are the high COD and especially BOD_5 values. Indeed, more than 90% of whey BOD_5 is due to lactose (Kisaalita et al., 1990).

2.2. Experimental apparatus

The experimental set-up used in this study is shown schematically in Fig. 1. It consisted of a continuously stirred reactor used as an acidogenic reactor and a continuously stirred reactor coupled to a membrane module used as a methanogenic reactor.

The seed sludge for both reactors was obtained from a full-scale anaerobic wastewater treatment plant.

2.3. Acidogenesis

The acidogenic phase was carried out in a 7 l stirred reactor (diameter 16.4 cm; height 33 cm), with 5 l working volume. The acidogenic reactor was kept at room temperature (37 ± 2 °C). Agitation was provided by a magnetic stirrer. The pH of the feed was regulated at the beginning of the tests at 6.5.

2.4. Methanogenesis

The methanogenic phase was carried out in a 20 l (diameter 22 cm; height 52 cm) Biolafite thermostatic reactor with a working volume of 15 l and a stirring speed of 200 rpm. The temperature of the reactor was maintained constant at 37 °C by circulating water through the thermostatic column in the reactor.

Solids (anaerobic sludge) separation prior to recycling was achieved by gravity settlement using a conventional decanter during the first 25 days. After this period, a membrane module was attached to the methanogenic reactor and the retentate was recycled into the reactor.