Bioresource Technology 102 (2011) 10371–10376

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

A kinetic analysis and experimental validation of an integrated system of anaerobic filter and biological aerated filter

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ARTICLE INFO

Article history:
Received 9 July 2011
Received in revised form 31 August 2011
Accepted 3 September 2011
Available online 7 September 2011

Keywords:
Anaerobic filter
Biological aerated filter
Dairy wastewater
Organic matter
Nitrogen

ABSTRACT

An anaerobic/aerobic filter (AF/BAF) system was developed treating dairy wastewater. The influent was blended with recirculated effluent to allow for pre-denitrification in the AF followed by nitrification in the BAF. The recirculation ratio ranged 100–300%. The average chemical oxygen demand (COD) removal efficiency was 79.8–86.8% in the AF and the average total nitrogen removal efficiency was 50.5–80.8% in the AF/BAF system. Steady-state mass balances on the AF were used to analyze removal kinetics in the AF. The kinetic model values for effluent COD in the AF were overestimated as compared with experimental data. The integrated suspended and attached biomass growth rates in the AF were estimated. The specific growth rate of the integrated biomass at each recirculation ratios was 0.6213, 0.6647, and 1.2083 1/day, respectively. The increase in specific growth rate corresponded to increases in biomass sloughing as the recirculation ratio increased.

1. Introduction

Dairy wastewater is usually composed of lactose, proteins, fat at high concentrations resulting in high organic and nitrogen loads that fluctuate significantly. Besides, dairy wastewater is high pH variability caused by the use of acid or base cleaning compounds in the process (Andreottola et al., 2002; Banu et al., 2007; Kushwaha et al., 2010; Omil et al., 2003; Perle et al., 1995). The characteristics of dairy wastewater effluent generated in dairy factories are well reviewed in Omil et al. (2003). Milk is commonly consists of 87.5% water, 13.0% solids, 3.9% fat, 3.4% proteins, and 4.8% lactose. In dairy factories, the wastewater generation is mainly due to the milk and milk loss in the process. Milk loss is commonly 0.5–2.5%, but can be as high as 3–4%. Most compounds in milk are biodegradable, but fat is known to be refractory in a bioreactor.

The characteristics of dairy wastewater make treatment by high-rate anaerobic digestion advantageous and aerobic treatment may result in sludge bulking and excessive sludge production problems (Timmermans and Van Haute, 1984). Several investigators reported anaerobic digestion of dairy wastewater. Anaerobic systems that have been successfully evaluated include the upflow anaerobic sludge blanket (UASB), the hybrid anaerobic filter, and the membrane bioreactor (Banu et al., 2007; Córdoba et al., 1995; Gavala et al., 1999). Biological aerated filters (BAFs) are capable of treating both organic matter and ammonia. Several investigators reported performance and mathematical models for treating municipal and/or industrial wastewaters using BAFs (Feng et al., 2010; Qiu et al., 2010; Rogalla et al., 1990; Ryu et al., 2008; Shen et al., 2009; Wang et al., 2006). According to Wang et al. (2006), an empirical model of BAF was a function of the concentrations of soluble chemical oxygen demand (COD) in influent and effluent and the height of medium bed. Kinetics and/or mass balances for an anaerobic digester were also developed by several investigators for years (Canovas-Diaz and Howell, 1988; Pavlostathis and Giraldo-Gomez, 1991; Seckin et al., 2011; Yu et al., 1998). Yu et al. (1998) reported that the modified Stover–Kincannon model was the best fit for performance of the anaerobic filter (AF). Meanwhile, Seckin et al. (2011) stated that the gene-expression programming model that involved computer programs of different sizes and shapes in chromosomes was better approach than the Stover–Kincannon model to simulate performance of upflow AF. Anaerobic digester/aerobic filter systems including the UASB, two phase anaerobic digester (TPAD), and the AF were coupled to a BAF to simultaneously remove organic matter and nitrogen. Organic matter and nitrogen could be very efficiently removed using these systems (Akunna et al., 1994; Cheng et al., 2009; Lim et al., 2009; Tilche et al., 1994). Documentations of these systems, however, did not include mass balance and/or kinetic analyses. In this study, an integrated system consisted of anaerobic filter and biological aerobic filter (AF/BAF) simultaneously removed organic matter and nitrogen with recirculation ratio of 100–300%. The evaluation of a system for treating target contaminants using

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doi:10.1016/j.biortech.2011.09.005

mass balances and kinetic analyses is necessary to understand performance of a system and develop general design parameters. Thus, in this study, the steady-state substrate COD and biomass mass balances in the AF were evaluated to characterize the AF/BAF system since the BAF usually can treat the remaining COD and the effluent concentration of biomass in the BAF is low in anaerobic digester/aerobic filter systems (Cheng et al., 2009; Lim et al., 2009). A simulation model was used to estimate effluent COD in the AF and the results were compared with experimental data. In addition, integrated suspended and attached growth rates were analyzed in the AF.

2. Methods

2.1. AF/BAF system

A schematic diagram of an AF/BAF system is described in Fig. 1. The active volume of the AF was 36.8 L and filled with polyvinylchloride cross-flow media (thickness: 3 mm) with a specific surface area of 115 m^{-1}. Porosity of cross-flow media was 95% and channel slope was 60°. Anaerobic digested sludge from a domestic wastewater treatment plant in Gwacheon, Republic of Korea, was used to inoculate the AF. Gas produced from the AF was collected in a cylinder containing saturated saline water and 5% sulfuric acid. The active volume of the BAF was 7.2 L containing ceramic ball media. The diameter, surface area, and porosity of ceramic ball media were 3.7–4.5 mm, 224.9 mm^2, and 2.5, respectively. The BAF usually does not need to be inoculated since biofilm composed of heterotrophs and autotrophs in the BAF forms without inoculation. The nitrified effluent from the BAF was recirculated and denitrified in the AF. The recirculation ratio was operated at 100%, 200%, and 300% in the AF/BAF system. A schematic diagram of flow rate, substrate, and biomass in the AF is shown in Fig. 2.

2.2. Characteristics of dairy wastewater

The main sources of dairy wastewater are usually from washing process lines and unused/expired dairy products or milk (Andreottola et al., 2002; Omil et al., 2003; Sarkar et al., 2006). In this study, a synthetic dairy wastewater, which represented washing process line wastewater, was used. A 10 ppt milk solution was prepared daily to make the synthetic wastewater. In addition, NH_4Cl was and $NaHCO_3$ were added to study nitrification/denitrification and the COD/N ratio was 14.1. US EPA (1993) recommended greater than 6 of COD/N ratio to obtain the higher denitrification efficiency. The characteristics of the synthetic dairy wastewater used in this study are shown in Table 1. A 20 mL volume of buffered nutrient solution was added to 20 L of influent following the supplemental nutrients added by Kelly and Switzenbaum (1984) which they reported to enhance reactor performance for treating dairy wastewater in an AF.

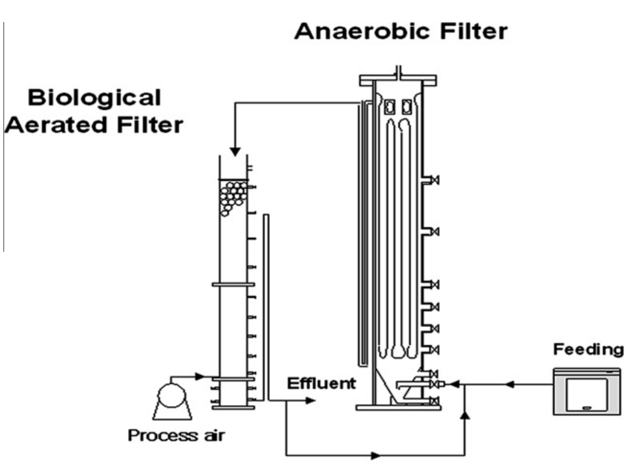

Fig. 1. Schematic diagram of the AF/BAF system.

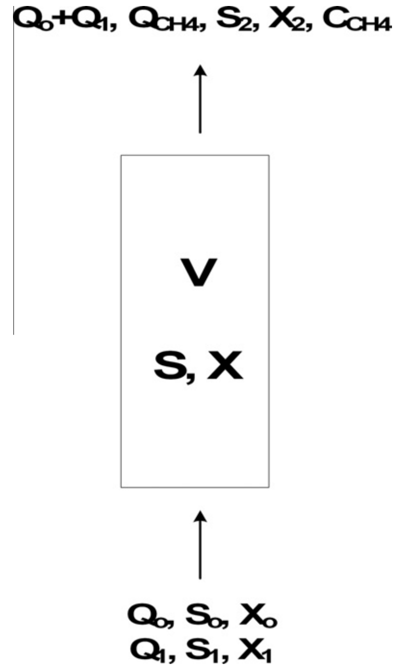

Fig. 2. Schematic diagram of flow rate, substrate, and biomass in the AF (V: volume of the AF, Q_0: flow rate of influent, Q_1: flow rate of effluent recirculated from the BAF, Q_{CH4}: flow rate of produced methane in the AF, S_0: influent COD concentration, S_1: effluent COD concentration recirculated from the BAF, S_2: effluent COD concentration in the AF, S: COD concentration in the AF, X_0: influent biomass concentration, X_1: effluent biomass concentration recirculated from the BAF, X_2: effluent biomass concentration in the AF, X: biomass concentration in the AF, C_{CH4}: concentration of methane in digested gas).

2.3. Operation of the AF/BAF system

The AF/BAF system was operated for 220 days. The nominal hydraulic retention time (HRT) in the AF/BAF system was 3.30 ± 0.17 days. The operating conditions in the AF, the BAF, and the AF/BAF system with variations from changing the recirculation ratios are shown in Tables 2 and 3.

2.4. Mathematical development of kinetic analysis

2.4.1. Mass balance in the anaerobic filter

In order to characterize the AF/BAF system and predict the effluent COD concentration from the AF, biomass mass balances for the AF were established as follows:

Table 1
Characteristics of a synthetic dairy wastewater used in this study.

Parameter	Value (Ave. ± Std.)[a]
pH	6.6–8.4 (7.7 ± 0.9)
Alkalinity (mg $CaCO_3$/L)	480.0–655.0 (592.0 ± 56.0)
Total volatile acids (mg/L)	38.1–450.0 (150.1 ± 130.6)
COD (mg/L)	1810.0–2431.0 (2078.0 ± 194.4)
TSS (mg/L)	194.0–548.0 (275.3 ± 113.9)
VSS (mg/L)	178.0–534.0 (258.7 ± 108.4)
T-N (mg/L)	131.1–160.2 (147.1 ± 8.9)
TKN (mg/L)	130.0–159.6 (146.0 ± 8.7)
NH_3-N (mg/L)	51.5–140.6 (97.5 ± 18.6)

[a] Minimum–maximum (average ± standard deviation).