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Improvement of biodegradation in compact co-current biotrickling filter by high recycle liquid flow rate: Performance and biodegradation kinetics of ammonia removal

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ABSTRACT

As a microbial-environmental-control-type deodorizing system, we have developed a compact biotrickling filter system for small-scale livestock farms. The performance of the compact co-current biotrickling filter operated at high recycle liquid flow rates was systematically examined. In particular, we studied improvements in the nitrification ability of the system due to the resultant enhancement of absorption and dissolution of NH_3 and absorption of O_2 with the high flow rates of recycle liquid flowing downward co-currently with gas flow. At the empty bed residence time of 50 s, almost complete removal of NH_3 was obtained with recycle liquid flow rates of 103 and 205 $L\,m^{-3}\,day^{-1}$ for 20 days while the inlet NH_3 concentration was increased from 200 to 500 ppm. With a recycle liquid flow rate of 411 $L\,m^{-3}\,day^{-1}$ the removal efficiency remained above 95% for 57 days while the inlet NH_3 concentration was increased from 200 to 700 ppm. The biodegradation kinetics for NH_3 removal was successfully analyzed using the Haldane substrate inhibition kinetics. The present data and kinetic analyses showed that the substrate inhibition was suppressed and the biodegradation of ammonia in the compact biotrickling filter could be improved by the high recycle liquid flow rate.

1. Introduction

In Japan, the increasing number of complaints by the public regarding livestock farms remains a matter for serious consideration, and 60% of the complaints are to do with odor emissions [1]. The main sources of odor are livestock buildings, manure storage facilities and land spreading of manure. To avoid such odor nuisance complaints, the installation of effective odor control systems is required. Traditional air pollution control technologies such as incineration, adsorption or chemical scrubbing tend to be costly, and they create their own unique pollution disposal problems [2]. Biological air treatment processes have been demonstrated to be useful in commercial and industrial applications, offering cost-effective solutions for the treatment of large volume airstreams containing low-to-moderate levels of pollutants [3–8]. One suitable alternative air pollution control technology is biotrickling filtration, in which microorganisms immobilized on a support are utilized and an aqueous phase is trickled over the packing, with this liquid usually being recycled [9]. Although studies on biodegradation of pollutants in biotrickling filters have been reported by a number of researchers [3,9], an in-depth discussion of rational design and optimal operation is still required to develop a compact biotrickling filter system which can maintain consistently high removal efficiencies for long-term operation. Many factors influence performance, treatment costs and long-term stability of biotrickling filters [9]. The kinetics of biotrickling filtration including substrate inhibition at higher pollutant loadings are not well defined yet.

One of the primary odorants reported in waste gas from livestock farms is ammonia [10,11]. Therefore, several types of biological treatment systems used to treat ammonia have been reported in the literature [12–15]. The biodegradation of ammonia takes place through the nitrification process involving the oxidation of ammonia, and this process can be written as [16,17]:

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(absorption and dissociation)

$$NH_3(g) + H_2O(l) \leftrightarrow NH_3(aq) + H_2O(l) \leftrightarrow NH_4{}^+(aq) + OH^-(aq) \quad (1)$$

(oxidation of ammonium to nitrite)

$$NH_4{}^+(aq) + OH^-(aq) + 1.5O_2 \rightarrow NO_2{}^-(aq) + H^+(aq) + 2H_2O \quad (2)$$

(oxidation of nitrite to nitrate)

$$NO_2{}^-(aq) + 0.5O_2 \rightarrow NO_3{}^-(aq) \quad (3)$$

The nitrification rate may be enhanced under suitable conditions such as the presence of high dissolved oxygen and low ammonia concentration. Since the oxidation of NH_3 to $NO_2{}^-$ generates H^+, additional NH_3 is removed chemically via the acid–base titration reaction [18]:

$$H^+ + NH_3 \leftrightarrow NH_4{}^+ \quad (4)$$

Biotrickling filtration of NH_3 is a relatively new technology and still in development with research focus on, for example, robustness and cost effectiveness at higher NH_3 loadings. The Bio-oriented Technology Research Advancement Institute, National Agriculture and Food Research Organization, Saitama, Japan has developed a rock wool (RW) deodorizing system and at present the number of such systems operated in Japan is estimated to exceed 60 [19–21]. Although its operating cost is low, the installation cost is fairly high. Therefore, we examined the use of a compact biotrickling filter system that is robust and cost-effective for small-scale livestock farms. In this study, we have focused on the development of a compact deodorizing system by controlling microbial environments. In particular, we have studied the improvement in nitrification ability due to the enhancement of the absorption and dissolution of NH_3 and absorption of O_2. Systematic laboratory and pilot-scale studies are required to optimize the operation parameters and to develop models that describe and predict performance of biotrickling filters.

The objective of this study is to elucidate performance of a microbial-environment-control-based RW deodorizing system developed for small-scale livestock farms operated in the co-current mode using high recycle liquid flow rates. The kinetic analyses are required for optimal design and operation of biological treatment processes. The Monod equation has been widely applied to analyze the biodegradation of pollutants in biotrickling filters [17]. To discuss the inhibitory nature of ammonia at higher concentrations, the kinetic model including a term for substrate inhibition should be used instead of the Monod equation. In this study, the biodegradation kinetics was analyzed using a Haldane model taking into account substrate inhibition.

2. Materials and methods

2.1. Biotrickling filter

In the measurement of pressure drop, a bench-scale biotrickling filter of 0.5 m diameter and 1.8 m height was used. The effective RW packing depth was 1.8 m and its working volume was 357 L. The airflow rate utilized for the pressure drop measurements was varied from 0.024 to 0.050 $m\,s^{-1}$ with a corresponding change in the empty bed residence time (EBRT) being 75–36 s. The co-current water flow rates for the three filters used in the study were 103, 205, and 411 $L\,m^{-3}\,day^{-1}$.

The schematic of the three biotrickling filters (Filter 1, Filter 2, and Filter 3) used to examine the biotrickling filter performance is shown in Fig. 1. Each filter consisted of a fiber-reinforced plastic (FRP) cylinder with a diameter of 0.2 m and effective packing filter depth of 0.7 m, and the working volume of the filters was 22 L.

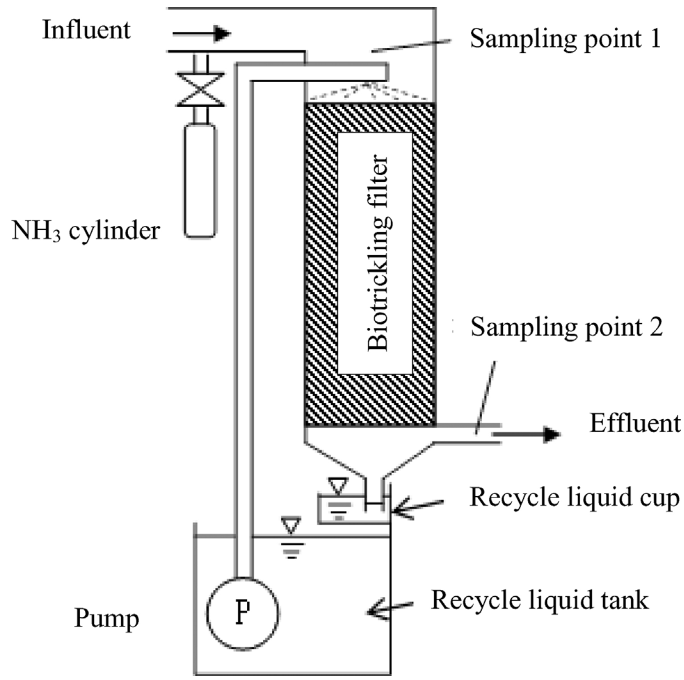

Fig. 1. Schematics of biotrickling filter for NH_3 removal.

The biotrickling filters were filled with a mixture of RW materials and chicken feces (MG deodorizer, NICHIAS Co., Japan). The packing was inoculated and acclimated with the recycle water for a period of 7 days prior to the experiments with an NH_3 loading of 200 ppm. No additional mineral nutrient source or pH buffer was added after beginning the experiments. Three filters were simultaneously operated at different recycle liquid flow rates, as mentioned below.

2.2. Operational conditions

For NH_3-removal measurements, the filter was fed a mixture of ammonia and air at a constant flow of 14 $mm\,s^{-1}$ with a corresponding EBRT of 50 s. The inlet NH_3 concentration was controlled to the desired concentration by varying the air and NH_3 flow rates. The NH_3 loading was varied in the range of 200–750 ppm.

The nitrification rate is proportional to the supply rates of $NH_4{}^+$ and O_2 under the appropriate conditions of temperature (5–37 °C) and pH (6.5–8.5) [22]. In the water treatment process, it is possible to establish a nitrification rate of 600–900 $g\text{-N}\,m^{-3}\,day^{-1}$ [23,24]. Considering reactions (2) and (3), we note that an oxygen supply rate of 2743 $g\text{-}O_2\,m^{-3}\,day^{-1}$ is theoretically required at the nitrification rate of 600 $g\text{-N}\,m^{-3}\,day^{-1}$. To maintain the dissolved oxygen (DO) concentration of 3 $mg\,L^{-1}$, which is fairly lower than the saturated DO concentration, 633 L of water held in a filter with a volume of 1 m^3 is required to ensure an oxygen supply rate of 2743 $g\text{-}O_2\,m^{-3}\,day^{-1}$. Therefore, we used a recycle liquid flow rate that was significantly higher than the typical flow rate of 8 $L\,m^{-3}\,day^{-1}$ used in large-scale RW biotrickling filters for an NH_3 loading of 200 ppm [19–21]. The large-scale biotrickling filters operated with gas fed counter-currently to liquid flow at an EBRT of 100 s have been designed on the basis of achieving a nitrification rate of 108 $g\text{-N}\,m^{-3}\,day^{-1}$ and oxygen supply rate of 494 $g\text{-}O_2\,m^{-3}\,day^{-1}$. In this study, liquid was recycled at 103, 205 and 411 $L\,m^{-3}\,day^{-1}$ for Filters 1–3, respectively.

Air controlled at 29 °C was supplied through a humidifier to maintain over 95%RH. Ammonia-contaminated air entered the biotrickling filter at its top (downflow mode). In other words, contaminated air and recycled liquid were fed co-currently to the top of the filter. To reduce pressure drop, the counter-current