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Removal of ammonia from contaminated air in a biotrickling filter – Denitrifying bioreactor combination system

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ABSTRACT

The removal of gaseous ammonia in a system consisting of a biotrickling filter, a denitrification reactor and a polishing bioreactor for the trickling liquid was investigated. The system allowed sustained treatment of ammonia while preventing biological inhibition by accumulating nitrate and nitrite and avoiding generation of contaminated water. All bioreactors were packed with cattle bone composite ceramics, a porous support with a large interfacial area. Excellent removal of ammonia gas was obtained. The critical loading ranged from 60 to 120 $g\,m^{-3}\,h^{-1}$ depending on the conditions, and loadings below 56 $g\,m^{-3}\,h^{-1}$ resulted in essentially complete removal of ammonia. In addition, concentrations of ammonia, nitrite, nitrate and COD in the recycle liquid of the inlet and outlet of each reactor were measured to determine the fate of nitrogen in the reactor, close nitrogen balances and calculate nitrogen to COD ratios. Ammonia absorption and nitrification occurred in the biotrickling filter; nitrate and nitrite were biologically removed in the denitrification reactor and excess dissolved COD and ammonia were treated in the polishing bioreactor. Overall, ammonia gas was very successfully removed in the bioreactor system and steady state operation with respect to nitrogen species was achieved.

1. Introduction

Ammonia emissions are very common in operations such as composting, fertilizer manufacturing, and intensive swine, poultry or cattle production (NRC 2003; Arogo et al., 2003). Ammonia has a moderate odor threshold (5–20 ppm_v) and emissions are regulated both because of odor nuisances and air pollution concerns. Ammonia can be easily scrubbed chemically, although the costs of chemicals for scrubbing can be very significant and scrubbing results in large amounts of an acidic ammonium solution that needs to be disposed of.

Biological treatment of odorous air is an interesting alternative to conventional treatment which has been shown to be efficient and cost effective in a number of cases (Devinny et al., 1999; Gabriel and Deshusses, 2003). With respect to ammonia gas treatment, the complexity of the biological nitrogen cycle offers several possibilities for biotransformation, although many have so far not been fully exploited for gas treatment. For example, ammonia gas can be absorbed and then nitrified to nitrite and nitrate, and subsequently denitrified (autotrophically or heterotrophically) to nitrogen gas. There is a vast body of literature on nitrogen removal in wastewater treatment plants (see e.g., Metcalf and Eddy, 2003) on which researchers can draw to develop bioreactors for air pollution control.

Various studies have focused on the treatment of ammonia gas in biofilters and biotrickling filters. Unfortunately, in many

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cases, the ultimate fate of nitrogen is not clearly identified. This is because of the difficulty of closing the nitrogen balance in systems such as compost beds which already contain significant concentrations of ammonium and nitrate, and which are often operated in a pseudo-steady state with slow accumulation of substrates and metabolites (e.g., ammonium, nitrite, nitrate) in the packing. Thus, in most cases, treatment relied mostly on the absorption of ammonia, which was followed by partial nitrification to nitrite and nitrate, and accumulation of these species in the packing and sometimes partial purging from the system by leaching (Hartikainen et al., 1996; Smet et al., 2000; Chou and Wang, 2007; Taghipour et al., 2008). However, both free ammonia and free nitrous acid are known inhibitors of nitrification (Weckhuysen et al., 1994; Baeza et al., 1999; Baquerizo et al., 2005), and when considering the importance of pH effects on both ammonia absorption and on nitrification, it is not surprising to see reactors fail after some time due to the accumulation of metabolites (Hartikainen et al., 1996; Sorial et al., 2001; Smet et al., 2000). Thus, unless a flushing schedule and relatively tight control of pH are implemented, biofilters treating ammonia will be much more susceptible to failure than biotrickling filters. This is illustrated by Liang et al. (2000) studies which wrongfully concluded that ammonia inlet concentration over 200 ppm_v should be avoided because of the toxic effect of ammonia to the nitrifiers. A deeper insight into the fate of nitrogen, ammonia concentration and pH effects was provided by Baquerizo et al. (2007) who modeled the various parallel processes involved during the treatment of ammonia. The model simulations illustrated the importance of moisture and free water in the treatment of ammonia.

When high concentrations of ammonia need to be treated and water consumption should be minimized, nitrification to nitrite or nitrate, followed by denitrification to nitrogen gas is probably the most desirable route, since it will prevent generation of a stream of water contaminated with nitrate and/or nitrite. However, this requires several biotransformation carried out by different microorganisms. Typically, achieving successful nitrification and denitrification requires a careful control of pH, substrate and chemical oxygen demand (COD) concentrations, dissolved oxygen, etc. and preventing toxic or inhibitory metabolites such as free ammonia and free nitrous acid to accumulate. Hence, the purpose of this research was to determine technical feasibility and the performance of a biological treatment system comprising of a biotrickling filter and a separate denitrification reactor to treat high concentrations (300–500 ppm_v) of ammonia in air with conversion of ammonia to nitrogen gas.

2. Materials and methods

2.1. Biotrickling filter and packing material

Three reactors (biotrickling filter, denitrification, and later a post-treatment) were used in this study. All the reactors were constructed from clear polyvinyl chloride (PVC) piping and were 1.2 m in length and 10 cm in internal diameter. Fig. 1 provides a schematic of the setup. Synthetic waste air for the experiments was prepared passing compressed air through a humidifier and adding pure ammonia gas to reach the desired

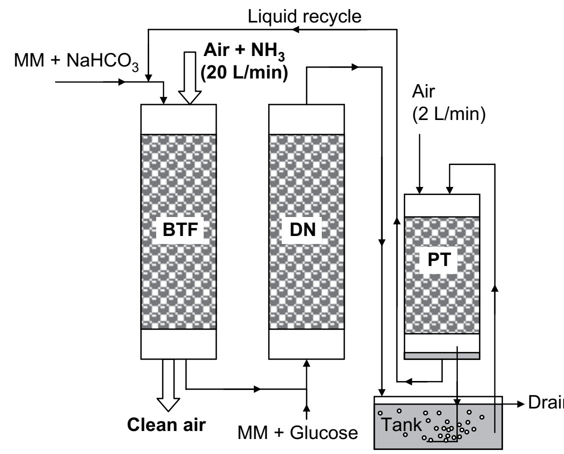

Fig. 1 – Schematic diagram of the experimental system (not to scale). BTF = biotrickling filter, DN = denitrification reactor, PT = post-treatment bioreactor, MM = mineral medium.

concentration. The synthetic contaminated air stream was supplied to the top of the biotrickling filter (downflow mode). Only the biotrickling filter and denitrification bioreactors were operated for the first 15 days after acclimation, after which the post-treatment bioreactor was added. The purpose of the latter (an aerated trickling filter) was to avoid feeding back residual organic substrate to the biotrickling filter. This will be discussed later. The effluent of the denitrification was directed to a holding tank (15 L) aerated (2 L min^{-1}) with the air from the post-treatment. The liquid recycle for the biotrickling filter was taken from this tank (see Fig. 1). The biotrickling filter and denitrification reactors were packed to a bed depth of 60 cm, while the post-treatment reactor had a bed depth of 40 cm. Cattle bone composite ceramic (CBP) beads (4 mm diameter, Aisin Takaoka Co, Ltd., Toyota, Japan) were used as a packing in this study. CBP had been shown to outperform other packings for toluene vapor removal in biofilters (Sakuma et al., 2006). It is made with 80% volume of the raw material used in the making of standard porous ceramics and 20% volume of cattle bone powder. During the making of the ceramic beads, part of the cattle bone powder burns leaving pore space and ashes, while the remainder of the cattle bone is believed to act as a slow release nutrient source for microorganisms.

2.2. Startup of the bioreactors and operating conditions

The biotrickling filter and denitrification reactors were inoculated with activated sludge from a local wastewater treatment plant. Mineral medium (2 L, see composition below), activated sludge (0.3 L) and 3 g $(NH_4)_2SO_4$ were circulated through the biotrickling filter and the denitrification beds for 24 h. The suspended solids were not monitored during this phase. The biotrickling filter was then incubated for a period of 4 months prior to the experiments to establish a dense culture of nitrifying organisms. The duration of the initial incubation period was not optimized. For the first 3 months, the biotrickling filter was operated as nitrification reactor fed with dissolved ammonium salt instead of ammonia in air.