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Effects of moisture content on the performance of a two-stage thermophilic biofilter and choice of irrigation rate

Song Xue[a,c], Wenhe Chen[b], Mingjia Deng[b], Hui Luo[b], Wensheng Huang[b], Yunping Han[a,c], Lin Li[a,c,*]

[a] State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[b] Guangzhou Heidelberg Yuexiu Cement Co. LTD., Guangzhou 510800, China
[c] National Engineering Laboratory for VOCs Pollution Control Material & Technology, University of Chinese Academy of Sciences, Beijing 101408, China

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ABSTRACT

The stabilization, innocuity, and reutilization of sludge can be obtained via the co-combustion of sewage sludge in cement producing kilns. Off-gases containing odours and volatile organic compounds (VOCs) are generated during the process of sewage sludge drying. A two-stage thermophilic biofilter was constructed in a cement plant to remove SO_2, NH_3, and total VOCs (TVOCs) from the plant's exhaust. The average concentrations of TVOCs, NH_3, and SO_2 in the inlet stream were 164.33, 38.46, and 51.12 mg/m^3, and in the outlet stream were 44.54, 9.18, and 3.91 mg/m^3, respectively. During biofilter operation, nutrient solution was circularly pumped onto the packing material to ensure the packing material remained moist. The moisture content of the packing material increased from 40 to 85% as the irrigation rate varied from 0.05 to 0.42 m^3/h. The removal efficiencies of NH_3 and TVOCs changed accordingly. When the irrigation rate was 0.3 m^3/h, removal efficiencies were 88.71% for NH_3 and 81.38% for TVOCs. More than 90% SO_2 removal occurred throughout the operation. The polymerase chain reaction-denaturing gradient gel electrophoresis (PCR-DGGE) method was used to assay the microbial population. Both microbial counts and diversity increased when the irrigation rate increased.

1. Introduction

Sewage sludge co-processing in cement kilns for the safe treatment and resource utilization of sludge has become a hot topic in recent years. Oxides, such as CaO, Al_2O_3, Fe_2O_3, and SiO_2, in the dried sludge can be utilized as substitutes for raw materials, and organics in the dried sludge can replace a portion of the fossil fuels used in the co-treatment process in cement kilns, which leads to a reduction of fossil fuel consumption (Dewil et al., 2006). More than 20 cement plants that use sewage sludge co-processing have started operation in China in the last few years.

Sewage sludge usually contains over 80% moisture content and should be dewatered before incineration in cement kilns. Exhaust containing NH_3, SO_2, and volatile organic compounds (VOCs) is generated during the process of sewage sludge drying. This exhaust requires proper purification before it is discharged into the air because of its toxicity and pollution risk to the environment. Biological processes (bioscrubbers, trickling beds, and biofilters) have been widely applied

* *Corresponding author at*: State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China.
E-mail addresses: xuesongxsyy@126.com (S. Xue), Chen.WenHe@ccc.com.cn (W. Chen), Deng.MingJia@ccc.com.cn (M. Deng), luo.hui@ccc.com.cn (H. Luo), huang.wensheng@ccc.com.cn (W. Huang), yphan@rcees.ac.cn (Y. Han), leel@rcees.ac.cn (L. Li).
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for treatment of these waste gases. VOCs, including dimethylsulfide (Van der Heyden et al., 2015) and carbon disulphide (Prenafeta-Boldu et al., 2014); NH_3 (Yang et al., 2014b); and SO_2 (Zhang et al., 2015) emitted from industrial facilities can be removed effectively by these methods (Giri et al., 2014). The flue gases from sludge drying are usually 50–60 °C. Such gases can be treated directly using a thermophilic biofilter inoculated with thermophilic microorganisms (Cho et al., 2007; Datta et al., 2007), which has the advantages of low cost and high microbial metabolism rate (Mohammad et al., 2007). A thermophilic biofilter at 50 °C for the treatment of ethyl acetate obtained a higher elimination capacity (> 100 g/(m^3 h)) than that of a biofilter operated under mesophilic condition (Deshusses et al., 1999). SO_2 can also be removed by a thermophilic biofilter. A thermophilic biofilter was inoculated with *Bacillus* and *Paenibacillus*, which are usually employed to remove sulfur-containing compounds, and SO_2 was oxidized to sulfate by the microorganisms (Zhang et al., 2015).

Biofiltration is a method of using microorganisms for the removal of environmentally undesirable compounds via biodegradation (Leson and Winer, 1991). Along with enough oxygen and sufficient nutrients, adequate moisture should be supplied to maintain metabolic activity of the microorganisms and performance of biofilters (Mudliar et al., 2010). A bioreactor is generally filled with packing materials that serve as the foundation for microorganism attachment. The packing material can also hold moisture and nutrients for microbial growth (Auria et al., 1998). In addition, the packing material provides a large interfacial area between the air and the aqueous layer (Campbell and Connor, 1997). The absorption of gaseous contaminants is slowed by a decrease in moisture content of the packing material (Yang et al., 2014a). The removal efficiency of a biofilter thus changes as the moisture content in a bioreactor varies. A maximum elimination capacity (27 g/(m^3 h)) of ethanol vapour was achieved when the water content of the packing material was maintained at 70%. It dropped to 4 g/(m^3 h) when the moisture content decreased to 59% (Auria et al., 1998). A similar result was observed for a biofilter treating toluene (Sun et al., 2002). At an initial moisture content between 30 to 40%, 0.2 g/(m^3 h) of toluene removal capacity was reached. When the initial moisture content increased to 60%, the removal capacity rose to 20 g/(m^3 h), accordingly. For most packing materials, at least 40–65% moisture content is needed for optimal performance (Cox et al., 1996).

Besides the influence of moisture content on the removal capacity of biofilter media, the response of biofilter microorganisms to moisture changes is another key issue regarding the performance of a biofilter (Bohn and Bohn, 1999). Microbial activity in such will be decreased by a loss of moisture content (vanLith et al., 1997). Biofilter microorganisms can obtain only a fraction of available water. Thus, when water availability decreases greatly with increased moisture loss, microbial activity slows down rapidly as well (Bohn and Bohn, 1999).

Yang found that both microbial counts and diversity could be changed with a variation of moisture content when treating NH_3 and N_2O with a set of biofilters. The microbial counts of ammonia oxidizers increased when the moisture content increased from 35 to 55%, and the removal efficiency of NH_3 also increased during this period. The amount of ammonia oxidizers decreased when the moisture content increased to 63%, and the counts of bacteria that generated N_2O increased (Yang et al., 2014a).

In this study, a two-stage thermophilic biofilter (TSTB) was constructed in a cement plant to treat tail gases from sludge drying. The temperature of the tail gas was 50–60 °C. The performance of the biofilter was investigated by varying the irrigation rates. Traditional and polymerase chain reaction-denaturing gradient gel electrophoresis (PCR-DGGE) methods were used to analyse the microbial counts, diversity, and structure. The effects of moisture content of packing material on biofilter performance and microbial population were also studied. The aim of this work was to provide an effective method for maintaining optimal moisture content to sustain a real thermophilic biofilter operated stably for long periods.

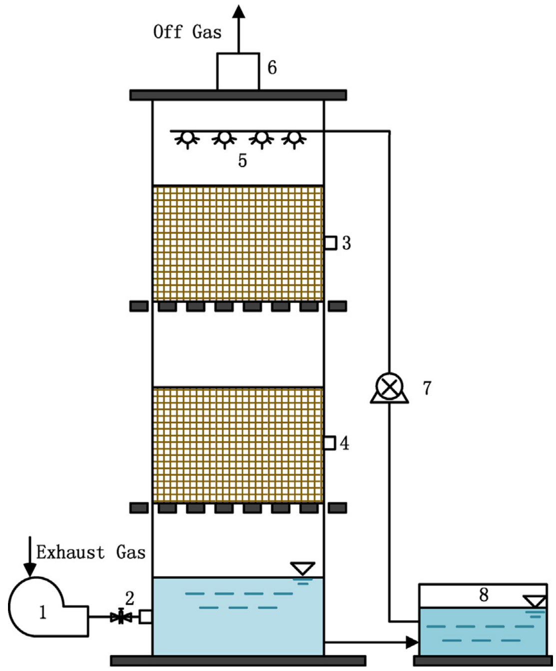

Fig. 1 – The schematic diagram of the full scale bioreactor ((1) air pump; (2–4, 6) sampling ports; (5) sprinkler; (7) water pump; and (8) circulating pool).

2. Materials and methods

2.1. *TSTB setup*

A TSTB was constructed in a cement plant for off-gas treatment. About 500 t of sewage sludge containing 80% water content was co-treated in a cement kiln in this cement plant each day. The tail gas of sludge drying contained mainly SO_2 and VOCs. The wet flue gas desulfurization method was used to remove most of the SO_2 from the tail gas. Desulfuration gypsum, the product of this process, can be used as raw material for cement production. However, ammonia will be produced during the process of desulfurization. Thus, the exhaust contained mainly SO_2, NH_3, and VOCs. The temperature of the exhaust was 60–65 °C. Therefore, the TSTB was applied for the treatment of tail gases discharged via the desulfurization tower.

The biofilter was cylindrical, constructed of stainless steel, and had a length of 25 m and an internal diameter of 2.0 m (Fig. 1). For microorganism attachment, 12.56 m^3 of polyurethane foam cubes (PUFCs) were packed in the first and second stages as packing materials. The density and porosity of the polyurethane foam were 18 kg/m^3 and 98%. The size of each cube was 3 cm × 3 cm × 3 cm. The sampling ports were located at the inlet and outlet of the TSTB. The exhaust from the desulfurization tower was provided in an up-flow mode at a total flow rate of 2700–3200 m^3/h, providing an empty bed residence of 21.19–25.12 s.

Before start-up, the packing material of the thermophilic biofilter was inoculated with the mixed culture obtained from a lab-scale bioreactor that treated sulfur-containing compounds. A nutrient solution containing 2.0 g of KH_2PO_4, 2.0 g of KNO_3, 0.25 g of NH_4Cl, 0.005 g of $FeCl_2 \cdot 7H_2O$, and 0.2 g of glucose per litre was sprayed in the bioreactor to feed the microorganisms. To supply nutrients continuously, a recirculation pump circulated the liquid in the TSTB.