Influence of Ammonium Concentration on the Performance of an Inorganic Biofilter Treating Methane

Marc Veillette, Antonio Avalos Ramirez, and Michèle Heitz

Abstract—Among the technologies available to reduce methane emitted from the pig industry, biofiltration seems to be an effective and inexpensive solution. In methane (CH₄) biofiltration, nitrogen is an important macronutrient for the microorganisms growth. The objective of this research project was to study the effect of ammonium (NH₄⁺) on the performance, the biomass production and the nitrogen conversion of a biofilter treating methane. For NH₄⁺ concentrations ranging from 0.05 to 0.5 gN-NH₄⁺/L, the CH₄ removal efficiency and the dioxide carbon production rate decreased linearly from 68 to 11.8 % and from 7.1 to 0.5 g/(m³-h), respectively. The dry biomass content varied from 4.1 to 5.8 kg/(m³ filter bed). For the same range of concentrations, the ammonium conversion decreased while the specific nitrate production rate increased. The specific nitrate production rate presented negative values indicating denitrification in the biofilter.

Keywords—Methane, biofiltration, pig, ammonium, nitrification, denitrification.

I. INTRODUCTION

With a total production of 109 million tons of pig meat in 2010 [1], the world pork industry was also responsible for water, air and soil pollution [2]. Among the compounds responsible for air pollution, this agricultural sector released volatile fatty acids, ammonia (NH₃), hydrogen sulphide (H₂S) and greenhouse gases (GHG) such as carbon dioxide (CO₂) and methane (CH₄) [3]. In Canada (2009), CH₄ emissions represented 13% of the total GHG emissions (690 Mt eq. CO₂) which corresponds to 90 Mton eq. CO₂[4]. In 2004, the world CH₄ anthropogenic emissions represented around 6.9 Gton eq. CO₂[5]. With a heat of combustion of 890 kJ/mol (25 °C, 1 atm) [6], CH₄ is an interesting compound produced by anaerobic digestion of organic matter [3]. However, CH₄ emissions, even if they are lower than CO₂ emissions, are not neglectable in terms of global warning because CH₄ has a global warming potential 25 times higher than CO₂ over a period of 100 years [7].

Even if CH₄ can theoretically be thermally oxidized, the latter requires a minimal CH₄ concentration in air ranging from 5 to 15% (v/v) [8]. In case of CH₄ emitted from slurry storage, the concentrations are generally lower than 3% (v/v), which is not enough to use thermal oxidation [9]. On the other hand, several studies have shown that low CH₄ concentrations can be treated effectively and relatively non-expensively by biofiltration [9]. In order to increase the biofilter performance, some parameters must be controlled such as moisture, temperature and nutrients [10]. Among the nutrients, microorganisms require nitrogen because it represents up to 14% of dry cell weight [11]. Usually, nitrogen is supplied to inorganic bed biofilters as a form of nitrate (NO₃⁻) [12] because ammonium (NH₄⁺) had a negative effect (inhibiting potential on CH₄ oxidation) on methanotrophic bacteria in soil studies [13, 14], but also had a positive effect (stimulation of CH₄ oxidation) in other soils studies [15].

The objective of this study was to test the effect of NH₄⁺ concentration in the nutrient solution of the performance of an inorganic packed bed biofilter treating CH₄. The performance of the biofilter was determined by analyzing the carbon and the nitrogen balance.

II. MATERIALS AND METHODS

Fig. 1 presents the inorganic packed bed biofilter used for the experiments. The biofilter was a Plexiglas cylinder with an inlet diameter of 15 cm, divided into 3 sections. The biofilter was packed with an inorganic material for a total bed height of 1 m (volume of 18 L). The exact nature of the filter bed cannot be revealed for confidential reasons.

A mixture of pure CH₄ (Praxair) and compressed air containing oxygen (O₂) was fed at the bottom of the biofilter and the treated air was released at the top. In order to avoid filter bed desiccation, the air mixture was previously saturated with water by passing through a humidification column. A nitrate salts medium (NMS) was used to supply nutrients and moisture to the filter bed [17]. At the top of the biofilter, the nutrient solution was fed (1.5 L; once a day) while the leachate was collected at the bottom of the biofilter. Concurrently, NO₃⁻ (as sodium nitrate) concentration was decreased by 0.05 gN-NO₃⁻/L increasing steps and NH₄⁺ (as ammonium carbonate)concentration was increased in order to keep the total nitrogen concentration in the nutrient solution at 0.5 gN/L. The NO₃⁻ concentration was decreased from 0.45 to 0 gN-NO₃⁻/L while the NH₄⁺ concentration was increased from 0.05 to 0.5 gN-NH₄⁺/L.

M. Veillette is a Ph.D. candidate in the Chemical and Biotechnological Engineering Department, Université de Sherbrooke, 2500, boulevard de l’Université, Sherbrooke, Québec, J1K 2R1, Canada (e-mail: Marc.Veillette2@USherbrooke.ca).

A. Avalos Ramirez is a post-doctoral researcher in the Chemical and Biotechnological engineering department at Université de Sherbrooke, 2500, boulevard de l’Université, Sherbrooke, Québec, J1K 2R1, Canada (e-mail: antonio.ramirez@irda.qc.ca).

M. Heitz is a full professor in the Chemical Engineering and Biotechnological Engineering Department, Université de Sherbrooke, 2500, boulevard de l’Université, Sherbrooke, Québec, J1K 2R1, Canada (Corresponding Author e-mail: Michele.Heitz@USherbrooke.ca).
Suspended biomass contained in leachate samples was removed using filter paper. Ionic chromatography (Dionex ICS-1000, Canada) was employed to determine the dry biomass concentration in the gas phase. A gas ionisation detector (Horiba model FIA-510, USA) was utilized to measure the CH₄ concentration in the gas phase. A total hydrocarbon analyser equipped with a continuous flame ionisation detector (Ultramat 22P, Simens, Germany) was also employed to measure the CO₂ concentration in the gas phase. Table I summarizes the main parameters considered to evaluate the performance of the biofilter. The theoretical dry biomass production rate (DBR), listed in Table I, was used to evaluate the theoretical dry biomass production. This parameter is evaluated by means of a molar balance of CH₄ and CO₂.

### III. RESULTS AND DISCUSSION

#### A. Biofilter Performance

Fig. 2 presents the methane removal efficiency (CH₄-RE) and the P<sub>CO₂</sub> as a function of the NH₄⁺ concentration in the nutrient solution. For NH₄⁺ concentrations from 0.05 to 0.5 gN-NH₄⁺/L, the CH₄-RE decreased linearly from 68 to 12%. For NH₄⁺ concentrations ranging from 0.2-0.25 gN-NH₄⁺/L, the CH₄-RE decreased quickly from 50 to 24%. For NH₄⁺ concentrations ranging from 0.05 to 0.15 gN-NH₄⁺/L, the P<sub>CO₂</sub> increased from 7.1 to 12.4 g/(m³-h) and from 0.15 to 0.5 gN-NH₄⁺/L, the P<sub>CO₂</sub> decreased from 12.4 to 0.5 g/(m³-h).

The fact that CH₄-RE decreased with the NH₄⁺ concentration shows the effect of NH₄⁺ on the populations of methanotrophic bacteria present in the biofilter. Many studies have shown that NH₄⁺ reduces the CH₄ oxidation rate in soil [20, 21, 22, 23], compost [24] and biofilters [18, 25, 26]. For example, in paddy soil, for CH₄ inlet concentrations of 1500 ppmv, Cai and Mosier [20] found that for an increase of NH₄⁺ concentration from 0 to 0.05 mgN-NH₄/kg soil, the CH₄ oxidation rate decreased from 338 to 166 ngC-CH₄/(g soil-h). In the present study, the decrease of CH₄-RE from 68% to 12% (-83%) was more important because, in soil, the nitrifying bacteria are already present, which reduced the NH₄⁺ concentration in the filter bed. This could also mean that a NH₄⁺ concentration of 0.5 gN-NH₄⁺/L has more negative effect on CH₄ oxidation than the NH₄⁺ concentration used by Cai and Mosier [20](0.05 mgN-NH₄/kg soil).

Between 0.05 and 0.15 gN-NH₄⁺/L, the P<sub>CO₂</sub> increased from 7.1 to 12.4 g/(m³-h) (+76%) even if CH₄-RE decreased from 68% to 57% (-16%). This may means that less carbon was used to produce biomass inducing a lower methanotrophic

![Biofilter set up for the biofiltration of CH₄](image)

**Table I**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Equations</th>
<th>Units</th>
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<tbody>
<tr>
<td>Methane removal efficiency (CH₄-RE)</td>
<td>CH₄-RE = ( \frac{C_{gin} - C_{gout}}{C_{g}} )</td>
<td></td>
<td>Dimensionless</td>
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<tr>
<td>Carbon dioxide production rate (P&lt;sub&gt;CO₂&lt;/sub&gt;)</td>
<td>P&lt;sub&gt;CO₂&lt;/sub&gt; = ( \frac{Q \cdot (C_{din} - C_{dout})}{V} )</td>
<td>g/(m³-h)</td>
<td></td>
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<tr>
<td>Theoretical dry biomass production rate (DBR)</td>
<td>DBR = ( \frac{[C_{gin} - C_{gout}] \cdot (C_{din} - C_{dout})}{W_{CO₂}} ) ( \frac{Q \cdot W_{H₂}}{V} )</td>
<td>g biomass/(m³-h)</td>
<td></td>
</tr>
<tr>
<td>Nitrate production rate (P&lt;sub&gt;NO₃&lt;/sub&gt;)</td>
<td>P&lt;sub&gt;NO₃&lt;/sub&gt; = ( \frac{(NO₃_{out} - NO₃_{in}) \cdot Q_{NS}}{V \cdot DB} )</td>
<td>gN/(g biomass-h)</td>
<td></td>
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a: C<sub>gin</sub> and C<sub>gout</sub> are the inlet and outlet concentrations of CH₄ (g/m³) ; Q is the air flow ; V is the volume of the biofilter (0.018 m³) ; C<sub>din</sub> and C<sub>dout</sub> are the inlet and outlet concentrations of carbon dioxide (g/m³) ; W<sub>CO₂</sub> and W<sub>H₂</sub> are the molecular weights of CH₄, CO₂ and biomass produced (g/mol), assuming an empirical formula of C₅H₇NO₂ for biomass with an average value of 113 g/mol [16]; NO₃<sub>in</sub> and NO₃<sub>out</sub> are the concentration of NO₃⁻ in the nutrient solution and the leachate, respectively (gN/L) ; Q<sub>NS</sub> is the flow of nutrient solution (L/h) ; DB is the dry biomass in the filter bed (g biomass/(m³-h)).
activity, explaining the CH4-RE decrease. For NH4+ concentrations higher than 0.15 gN-NH4+/L, the PCO2 followed the same tendency than the CH4-RE. Between 0.20 and 0.25 gN-NH4+/L, the quickly decrease of PCO2 from 9.0 to 4.7 (-48%) confirms the assumption that for this concentration range, a major change in bacteria population occurred in the biofilter as observed in a previous study [19].

B. Biomass

Fig. 3 presents the average dry biomass content (DB) and the theoretical dry biomass production rate (DBR) as a function of the inlet NH4+ concentration in the nutrient solution. For NH4+ concentrations ranging from 0.05 to 0.5 gN-NH4+/L, the DB decreased with the NH4+ concentration and varied from 5.8 to 2.5kg/m3 filter bed. The DBR decreased also with the NH4+ concentration and followed a logarithmic tendency with values ranging from 30 to 5 g/(m3-h).

The decrease of DBR with the NH4+ concentration was also observed by Wilshusen et al. [24]. In order to explain this phenomena, the authors hypothesized that the exopolymeric substances could serve “as a carbon cycling mechanism for type I” methanotrophic bacteria. The fact that DBR decrease could also indicate that more carbon was transformed into CO2, which explains the decrease of CH-RE observed in Fig. 2 as less new biomass was formed.

The fact that the DB (linear) followed a different tendency than DBR (logarithmic) indicates that some microorganisms other than methanotrophic bacteria (like denitrifying and nitrifying bacteria) can generate biomass. However, a visual inspection of the biofilter shows a decrease of the biomass in the filter bed which may means that the biomass produced by other microorganisms may be more soluble in water. The dry biomass content is also influenced by the amount of biomass washed out of the filter bed at each daily watering. The decrease of DB observed in the filter bed (-57%) was lower than the DBR(-83%). As a consequence, for the NH4+ concentrations tested, less biomass would be lost in the leachate as the NH4+ concentration increased.

C. Nitrogen Conversion

Fig. 4 presents the NH4+ conversion and the specific NO3- production rate (PNO3) as a function of the NH4+ inlet concentration in the nutrient solution. For NH4+ concentrations in the nutrient solution ranging from 0.05 to 0.5 gN-NH4+/L, the NH4+ conversion decreased linearly from 48 to 26 % while the PNO3 increased from -0.01 to 0.16 gN/(m3-h).

The fact that the NH4+ conversion decreased with the NH4+ concentration could be due to the decrease of CH4-RE (Fig. 2). In fact, the increase of CH4 concentration could lead to the decrease of NH4+ conversion as CH4 is an inhibitor of nitrifying bacteria [27]. Moreover, the increase of CH4 concentration in the biofilter could also lead to changes of number and kind of microorganisms specific to NH4+ conversion which could lead to the NH4+ conversion decrease. The PNO3 presented some negative values at 0.05 and 0.10 gN-NH4+/L of -0.01 and -0.02gN-NO3-/g biomass-
h), respectively. This indicated that there was a consumption of \( \text{NO}_x \) by methanotrophic bacteria or a denitrification.

IV. CONCLUSION

Increasing the \( \text{NH}_4^+ \) concentration in the nutrient solution reduced the performance of an inorganic biofilter treating \( \text{CH}_4 \) at an inlet concentration of 1500 ppmv, as follows: the \( \text{CH}_4 \)-RE, the \( \text{P}_{\text{NO}_3} \) and the dry biomass content decreased respectively from 68 to 12 %, from 7.1 to 0.5 g/(m\(^3\)-h) and from 5.8 to 4.1 kg/m\(^3\) filter bed. For the same range of concentrations, the \( \text{NH}_4^+ \) conversion also decreased from 48 to 26% whereas the \( \text{P}_{\text{NO}_3} \) increased from -0.01 to 0.16 gN/(m\(^3\)-h) which suggests that denitrification occurred. This study shows that the nature and the concentration of the macronutrients (nitrogen) present in the nutrient solution are important for the performance of an inorganic biofilter treating \( \text{CH}_4 \).

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