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Monitoring moisture content of gas-phase biofilter based on impedance under different conditions

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ABSTRACT. *The woodchips-based gas phase biofilter is capable of mitigating airborne ammonia efficiently. The ability to monitor real-time moisture content of biofilter media is preferred for maintaining the ammonia mitigation efficiency. The focus of this study is to enhance the understanding of impedance-based moisture content measurement and improve methodologies to monitor the moisture content of gas phase ammonia mitigation biofilters more accurately. A proposed sensor consisting of a sensing unit (three parallel plates) and a circuit generating DC voltage outputs was used in the study. The sensor readings changed with step-wise increase of moisture content as well as different particle size distribution and nitrogen (ammonia-nitrogen, nitrate-nitrogen) concentrations of biofilter media. The results showed the particle size distribution and nitrogen concentrations have significant impacts on impedance-based moisture sensing. A mathematical model was established to correlate the sensor reading of the impedance-based moisture sensor with moisture content, ammonia-nitrogen concentration, and nitrate-nitrogen concentration based on experimental results. Further studies are needed to improve the performance of the sensor considering other potential factors.*

Keywords. *Gas phase biofilter, Impedance, Moisture sensor, Nitrogen concentration, Particle size distribution.*

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1. INTRODUCTION

Excessive ammonia emissions have posed serious problems to the environment, e.g., reactive nitrogen cascade, a phenomenon which causes a wide variety of environmental changes (Galloway, 1998). A typical example of the reactive nitrogen cascade is the overgrowth of plant life (eutrophication), which leads to depletion of dissolved oxygen and impacts aquatic life and vegetation (Erisman et al., 2007; Hong et al., 2013). And, excessive ammonia emission negatively impacts human health through deposition and the formation of particulate matter (Pope et al., 2006). Ammonia emissions from agricultural sources are dominant over other natural emissions and are the biggest contributors to global emissions (Allen et al. 2011; Beusen et al., 2008; Bouwman et al., 2002) with a range of 27-38 Tg (1 Tg=10^{12} g) per year. Livestock production accounts for 59–71% global agricultural ammonia emission (Beusen et al., 2008). It is therefore of great importance to control ammonia emissions from livestock production.

Gas phase biofiltration has been designated by the Illinois State Office of the Natural Resource Conservation Service as a prospective technology for livestock ammonia emission control attributed its high ammonia mitigation efficiency (Delhoménie & Heitz, 2005; Yang et al., 2013). The process of ammonia mitigation is a combination of sorption, degradation, and desorption of gas-phase contaminants. The air is forced to pass through the biofilter media via mechanical ventilation (Nicolai et al., 2006). The byproducts of the above reactions are harmless, which consist of water (vapor), carbon dioxide, mineral salts, etc. (Nicolai & Janni, 2001).

Biofilter media is one of the major determinants for biofilter operation (Pagans et al., 2005). Organic media were shown to have superior ammonia mitigation performance as compared to inorganic packing materials at the ammonia range of 0-300 ppm (Kim et al., 2000). Recent research suggested the woodchips-based biofilter was capable of mitigating airborne ammonia efficiently (Chen et al., 2009). Among the other factors that influence the operation performance of such biofilter, the moisture content of wood chips appears to be the most important (Maia et al., 2012). It affects biofilter performance both chemically and biologically (Yang et al., 2013) since biofilter can be considered as an aerobic reaction environment where air passes through continuously and microorganisms need water to maintain their metabolic reactions. If too much water fills biofilter media pores, it will inhibit the transfer of reactants so that limits reaction rates; while too little moisture content deprives microorganisms of water, which can result in significantly reduced, and even completely impeded biological activities (Wani et al., 1997). Additionally, nitrous oxide (N_2O), a greenhouse gas, can be produced during the nitrification and denitrification processes within a biofilter. The generation of nitrous oxide is closely related to media moisture content, especially at high moisture content conditions (Maia, et al., 2012). There is no precise moisture content setting for biofilter operation, but a certain recommendable moisture content range for woodchips (hereinafter referred to as biofilter media) is required (Chen et al., 2009). In addition to the moisture content of biofilter media, another concern is the particle size distribution of biofilter, since it directly affects the airflow resistances across biofilter media, which is important to the installation and operation of biofilters (Yang et al., 2011).

The ability to monitor real-time moisture content of biofilter is preferred for maintaining the ammonia mitigation efficiency. However, because of the much larger and varied particle size distribution of woodchips compared to soil (Yang et al., 2011), regular moisture sensing technologies (soil moisture sensors, etc.) are inapplicable to biofilter media. To monitor biofilter media moisture changes in real time, several approaches have been tried (D’Amico et al., 2010; Hartmann & Böhm, 2000; Hultnäs & Fernandez-Cano, 2012), but none of them were perfect to tackle the sensing issue. Recently, an impedance-based moisture sensor was developed (Yang et al., 2013). The principle of this sensing method takes advantage of the dielectric characteristic of biofilter media. In a biofiltration system, the dielectric constant (an important index for the dielectric properties) of liquid water (80.1 at 20℃) is much higher than the air (1 at 20℃) and woodchips (1 to 5). The dielectric constant of ammonia is 16.61 at 20℃ (Billaud & Demortier, 1975), which may influence this sensing result significantly. The performance tests regarding the impedance-based moisture sensor were conducted only with respect to moisture content, without considering other potential interference factors. A biofilter does not only compose of free water, air, and woodchips, but also different forms of nitrogen. Particularly, ammonia nitrogen and nitrate nitrogen are the two major compounds in the media, which account for 50% to 100% of total nitrogen in biofilter (Yang et al., 2012). Particle size distribution is another key issue which influences the impedance of biofilter media by changing the contact area between the sensing components of the sensor and the biofilter media. The selection of particle size distribution of biofilter media may vary from one location to another. To our knowledge, no study on the response of biofilter media impedance to different forms of nitrogen and particle size distributions has been conducted. Therefore, it is quite necessary to research these factors.

The objectives of this research are to enhance the understanding of impedance-based moisture content measurement and improve methodologies to monitor the real time moisture content of gas phase biofilter. The performance of the moisture sensor regarding different particle size distribution of biofilter media, as well as two typical operation scenarios, ammonium hydroxide enriching and ammonium nitrate enriching were tested and analyzed.

2. MATERIALS AND METHODS

2.1 Overview of the procedures and methods

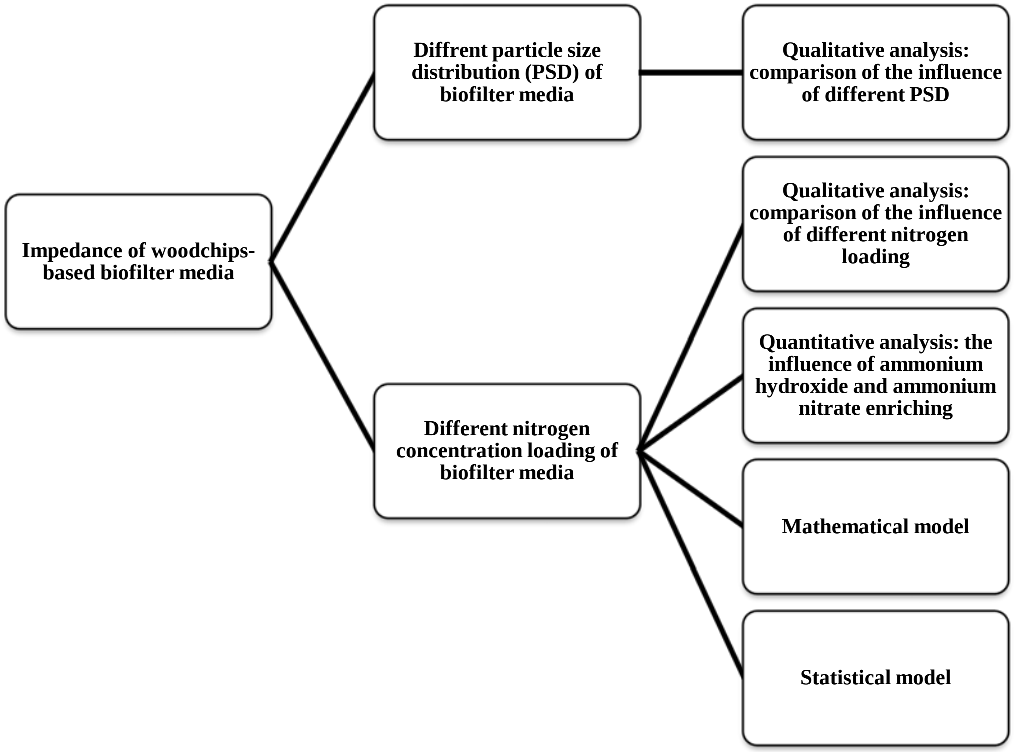

Figure 1. Schematic overview of the procedures and methods.

Figure 1 shows a schematic overview of the procedures and methods conducted for this study. The influences of different particles size distribution as well as different nitrogen concentration loading of biofilter media were investigated. To understand the impact of different particle size distribution on the impedance of biofilter media, qualitative analysis was performed to compare the difference of sensor reading. To study the impact of different nitrogen concentration loading on the impedance of biofilter, the procedures are divided into four steps. The aim of qualitative analysis was compare the sensor reading of biofilter with same ammonia-nitrogen but different nitrate-nitrogen. The quantitative analysis were applied to have a deeper insight into the impact of ammonium hydroxide enriching and ammonium nitrate enriching, respectively. Finally, the mathematical model as well as the statistical model was employed to describe the impact of ammonia-nitrogen and nitrate-nitrogen individually.

2.2 Media selection

Woodchips consisting of shredded woodchips and chipped woodchips were obtained from a landscape recycling center in Urbana, IL. They were dried naturally to 10-15% wet basis moisture content for three to five days. Two media groups (particle size distribution: 0.2-0.8cm and 0.8-1.9cm) were selected using a Penn State Forage Particle Separator (Product No. C24682N, NASCO, Fort Atkinson, Wisc.).

2.3 Sensor construction

The impedance-based moisture sensor was employed as an indicator of impedance of the biofilter media. The sensor was designed based on the impedance of sensing materials, and it was composed of a circuit and a sensing unit (Yang et al., 2013). The circuit unit of this sensor consisted of a voltage-divider circuit and a peak-detector circuit. The principle of the circuit unit is to compare the impedance of biofilter media mounted between sensor plates $Z_{biofilter}$ to a reference capacitor Z_{ref}. The size-wave AC voltages with ±2.0V P-P were used, and they were converted to two DC voltages V_{in} and V_{out}, which can be recorded through a data acquisition system (Personal Daq/56, Measurement Computing, Norton, Mass.). The acquired data then were applied into the following equation to calculate the ratio.

$$reading = \frac{|V_{in}|}{|V_{out}|} = \frac{|Z_{biofilter}| + |Z_{ref}|}{|Z_{biofilter}|} = 1 + \frac{|Z_{ref}|}{|Z_{biofilter}|} \quad (1)$$

Previous tests on the sensor showed that the impedance was very distinguishable at high frequency of 100 kHz. The ratio of V_{in}/V_{out} was a function of media impedance, which was highly related to moisture content of biofilter media. The sensing unit consisted of three parallel steel plates (80% hollow with 2.54 mm holes allow gas), separated by sets of three plastic bars between each plate pair. The top and the bottom plates were grounded while the middle plate was connected with above circuits. The size of each plate was 30 cm × 30 cm, the distance between the inside and outside plates was 7.5 cm. The sensor plates were installed in the center of a sealed plastic testing chamber (62.5 cm × 47.6 cm × 35.2 cm, L × W ×H) filled with biofilter media.

2.4 Particle size and moisture content

To control the particle size of biofilter media, two groups (particle size distribution: 0.2-0.8 cm and 0.8-1.9 cm) were re-mixed at volume ratio of (1) 1:1 and (2) 1:4. The moisture content of woodchips was increased gradually by adding DI water manually with a 5% increment. For each operation, biofilter media were taken out of the testing chamber and mixed with water on a tray, and then placed back into the chamber as soon as possible. The sensor outputs V_{in} and V_{out} were continuously recorded every 10 min for 2-3 days. For each batch, the biofilter media were sealed by a plastic testing chamber (62.5 cm × 47.6 cm × 35.2 cm, L × W ×H), insulated from the air, and located at normal room temperature.

2.5 Nitrogen enriching

Biofilter media with 1:4 mixture ratio was used for this investigation. Nitrogen enriching was carried out by adding: (1) ammonium hydroxide, and (2) ammonium nitrate. The objective of adding ammonium hydroxide was to introduce the ammonia-nitrogen only into the biofilter media and determine the influence of ammonia-nitrogen on the impedance of biofilter media. While the ammonium nitrate enriching was to introduce both the ammonia-nitrogen and nitrate-nitrogen at the ratio of 1:1 into the biofilter and study their influence. The biggest challenge of this series of experiments is that neither the added ammonia-nitrogen nor nitrate can be completely absorbed/adsorbed by the biofilter media. In addition, the nitrogen might be lost in the forms of ammonia gas during the mixing and measurement steps. The measured nitrogen concentration may have deviated from the desired concentration based on calculation.

The ammonium hydroxide/ammonium nitrate were added at the beginning of operation when the moisture content was 30%. The moisture content of biofilter media was increased with a 5% increment. To increase the moisture content, the biofilter media were taken out of the testing chamber and mixed with water as evenly as possible, and then were placed back into the chamber. Sensor outputs V_{in} and V_{out} were continuously recorded every 10 min for 2-3 days. Limited by time and experimental conditions, only three batches were available for each experiments. For the purpose of covering more ranges of nitrogen concentrations and some special scenarios, the parameter of each biofilter batch as well as the procedure of the experiment are shown in Table 1:

Table 1. Experimental design of nitrogen enriching (nitrogen concentration: mg ammonia-N/nitrate-N per gram dry media)

Testing chamber	Comparison of the influence of different nitrogen loading	Ammonium-hydroxide	Ammonium-nitrate
Batch A	Control group	0.25 ammonia-N	0.0625 nitrate-N + 0.0625 ammonia-N
Batch B	0.75 ammonia-N	0.50 ammonia-N	30% MC: 0.125 nitrate-N + 0.125 ammonia-N 50% MC: 0.50 nitrate-N + 0.50 ammonia-N
Batch C	0.75 nitrate-N + 0.75 ammonia-N	0.75 ammonia-N	0.50 nitrate-N + 0.50 ammonia-N

Scenario 1: To analyze the influence of different nitrogen loading on the impedance of biofilter at the same time, batch B was treated with 0.75 mg ammonia-N per gram dry media of ammonium hydroxide enriching, and batch C was treated with 0.75mg nitrate-N per gram dry biofilter media of ammonium nitrate enriching. The moisture content of the biofilter media was ranging from 35% to 65%.

Scenario 2: To analyze the change of the impedance of biofilter media caused by ammonia nitrogen, three concentration levels of ammonia hydroxide enriching were used for the test: the biofilter batch A was treated with 0.25mg ammonia-nitrogen per gram dry biofilter media, the biofilter batch B was treated with 0.50mg ammonia-nitrogen per gram dry biofilter media, and the biofilter batch C was treated with 0.75mg ammonia-nitrogen per gram dry biofilter media. The moisture content of the above batches was ranging from 30% to 65%.

Scenario 3: To analyze the influence of the nitrate-nitrogen associated with ammonia-nitrogen on the impedance of biofilter media, three concentration levels of ammonia nitrate enriching were used for the test: the biofilter batch A, B, C were treated with nitrate-nitrogen associate with the same ammonia-nitrogen at the concentration of 0.0625, 0.125, 0.5 mg per gram dry biofilter media. The first adjustment regarding this series of experiments was that the increment for moisture content was uneven. The starting moisture content for measurement was 35%, and then all were increased to 50% immediately. Another adjustment is that a second ammonia nitrate enriching was applied for batch B to validate the change of impedance was caused by the enriching of ammonium nitrate.

2.6 Sampling and analysis

Media were sampled from the upper (2 samples), middle (2 samples), and lower layers (2 samples) of testing chamber. Then the samples were re-mixed as a whole. The moisture content was measured 2 hours after each operation, while the nitrogen concentrations, and the pH of biofilter media were measured 36 hours after each operation. 30 g sample was dried in a 105℃ oven for 24 hours to determine the wet-basis moisture content of the media. Samples were given to measure the results in triplicate. Nitrogen concentrations were measured based on modified TMECC 04.02 standards (Thompson et al., 2001). The samples with four grams of the media were extracted by 40 mL DI water. Each sample was mixed using a mixer for five minutes to dissolve the molecules, ions and gases in DI water. The mixture was centrifuged (3000 rpm for 30 minutes), and the pH value of supernatant was measured using a pH meter (PH1100 Series, Oakton Instruments, Vernon Hills, IL.) according to the TMECC 04.11 method (Thompson et al., 2001). The nitrogen concentrations of filtrate was analyzed in a Hach DR/2010 spectrophotometer (Hach Co., Loveland, CO.) Ammonia-nitrogen was measured using method 8155 [0~0.50mg/L], and nitrate-nitrogen was measured using method 8171 [0~4.50mg/L].

2.7 Mathematical and statistical model construction

To our knowledge, a model correlating the sensor readings along with the moisture content of biofilter media, as well as, the different forms of nitrogen concentrations hasn't been built yet. This is the first time establishing a model to describe the relationships among these variables. The relationship between sensor reading and moisture content can be established by a mathematical model. Since the causation between nitrogen concentrations and sensor reading is far from certain, to make use of data, statistical models were used to explore correlation patterns.

The impedance of the biofilter can be regarded as a simplified parallel connection of a resistor and capacitor with single time constant (Kandala et al., 1996; Yang et al., 2013). Equations (1) – (3) were the impedance sensing principle of the impedance-based moisture sensor.

$$reading = \frac{|V_{in}|}{|V_{out}|} = \frac{|Z_{biofilter}| + |Z_{ref}|}{|Z_{biofilter}|} = 1 + \frac{|Z_{ref}|}{|Z_{biofilter}|} \quad (1)$$

$$Z_{ref} = \frac{1}{j\omega C_{ref}} = \frac{1}{j2\pi f C_{ref}} \quad (2)$$

Since the impedance of biofilter media can be regarded as a parallel connection of resistor and capacitor, the impedance can be calculated as:

$$Z_{biofilter} = R_{biofilter} \,//\, \frac{1}{j\omega C_{biofilter}} = \frac{R_{biofilter} \times \frac{1}{j\omega C_{biofilter}}}{R_{biofilter} + \frac{1}{j\omega C_{biofilter}}} \quad (3)$$

Where

C_{ref} : Capacitance of reference capacitor (constant)

ω : Angular frequency

$R_{biofilter}$: Resistor of biofilter media

f : Frequency of the imposed alternating field

j : Index of imaginary part

3. RESULTS AND DISCUSSION

3.1 Sensor response to different particle size distributions with changing moisture

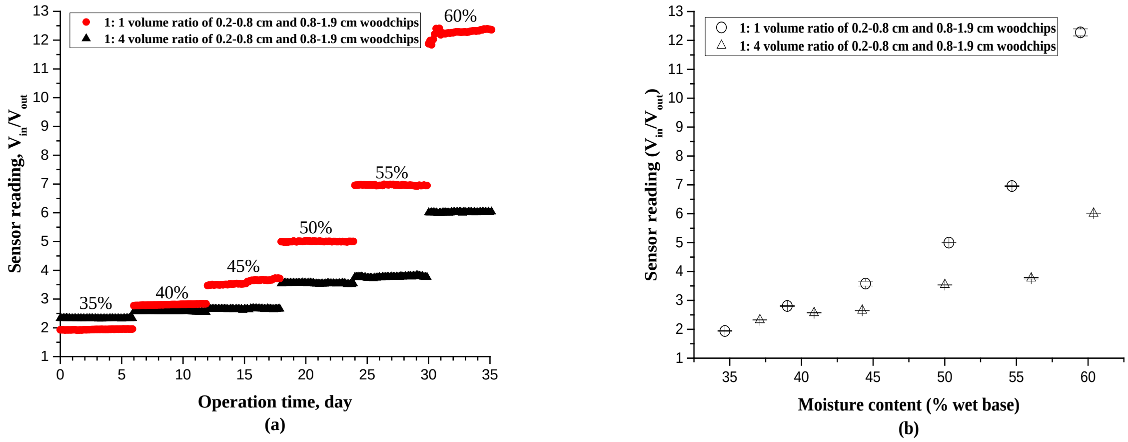

Figure 2 Sensor responses to different particle size distribution: (a) real-time sensor reading at varied moisture content, and (b) averages and standard deviation of sensor readings at varied moisture contents.

The Figure 2 showed there was an obvious difference between the sensor readings (V_{in}/V_{out}) of these two batches with different particle size distributions. The sensor reading remained steady during each moisture measurement with very small standard deviations, which indicated the stability of the sensor. For moisture content ranging from 40% to 60%, the sensor reading of biofilter with 1:1 volume ratio is higher than that with 1:4 volume ratio. The disparity of sensor reading increased with moisture content. A t-test was applied to determine if the particle size distribution cause a difference in moisture sensing. The sensor reading obtained from these two batches ranging from 40% to 60% were used as the inputs for t-test. The Table 2 presents the result of the paired t-test, which shows that there is significant difference caused by particle size distribution.

Table 2. Paired t-test of sensor reading regarding different particle size distribution

Data: 1:1 and 4:1 volume ratio of 0.2 - 0.8 cm and 0.8 - 1.9 cm of woodchips
t = -17.292, df = 239, p-value < 2.2e-16
Alternative hypothesis: true difference in means is not equal to 0

One potential explanation for this result is the contact area between woodchips particles and sensing unit of sensors. When the volume percentage of small particle decreased from 50% (1:1 volume ratio) to 20% (1:4 volume ratio), the small particles had fewer chances to contact with the plates of the sensors, which led to the decrease of total contact area, and resulted in higher impedance, thus lower sensor reading. Another possible reason is the compaction effect of the media. The small particles have the ability to adsorb more water molecules than the large particles on their surface, and they tend to settle down due to gravitational force. The more small particles the biofilter contained, the more compressed the biofilter media would be, resulting in more water within sensing unit of the sensor. Since the water has lower impedance than air and woodchips, impedance of the biofilter media with many smaller particles would decrease, thus increased sensor reading.

3.2 Sensor response to nitrogen concentration with changing moisture

3.2.1 Influence of different nitrogen loading

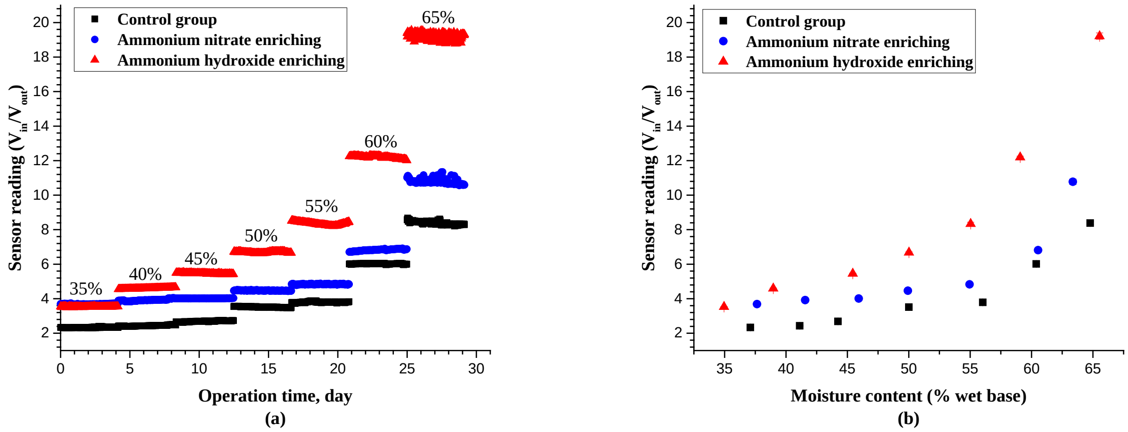

Figure 3. Sensor response regarding different ways of nitrogen enriching: (a) real-time recording of sensor reading at each moisture step, and (b) averages and standard deviation of sensor readings at varied moisture contents (0.2-0.8cm: 0.8-1.9cm = 1:4 of particle size distribution, 0.75mg nitrate-nitrogen per gram dry biofilter media of ammonium nitrate enriching, 0.75mg ammonia-nitrogen associated 0.75mg nitrate-nitrogen per gram dry biofilter media of ammonium hydroxide enriching).

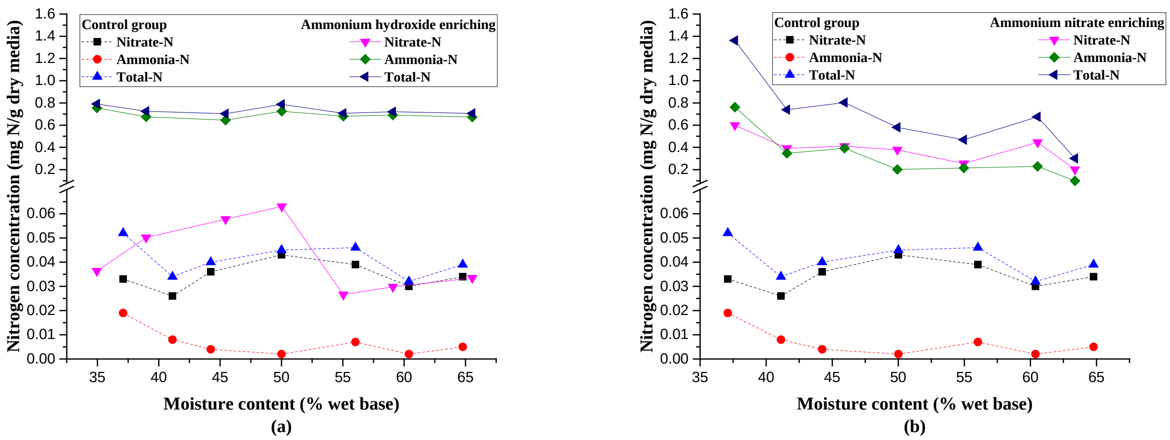

Figure 4. Profiles of nitrogen concentrations regarding different ways of nitrogen enriching: (a) 0.75mg ammonia-nitrogen per gram dry biofilter media of ammonium hydroxide enriching, and (b) 0.75mg ammonia-nitrogen associated with 0.75mg nitrate-nitrogen per gram dry biofilter media of ammonium nitrate enriching.

The sensor response regarding different ways of nitrogen enriching was shown in Figure 3. The sensor reading of the control group was in the range of 2.3~8.5 during the test, while the sensor readings of nitrogen loading batches were in the range of 3.6~10.8 for ammonia nitrate enriching and 3.5~19.3 for ammonia hydroxide enriching. The figure reflected the great differences that exist between the nitrogen loading batches and control group. The most rapid increase of all three batches was the batch with ammonium hydroxide enriching. During the same period, there was a large increase of the sensor reading for this batch when the moisture content was higher than 50%. As to the other batch with ammonium nitrate enriching, though the growth rate was not so high, it was indeed remarkable and impressive. The disparities of sensor reading between each two groups were increased along with the increase moisture content. The contribution of moisture content to the increase of sensor reading has been demonstrated by previous research (Yang et al., 2013). These results showed that the nitrogen loading can affect sensor reading.

To correlate the sensor reading with different forms of nitrogen, the Figure 4 shows the concentration of N during the ammonium hydroxide enriching and ammonium nitrate enriching tests. With respect to the ammonium hydroxide enriching, the most telling feature of the figure was that ammonia-nitrogen concentration remained constant, which is also the dominant form of nitrogen within the biofilter media during the test. There is no significant difference in terms of the nitrate-nitrogen concentration between the control group and ammonium hydroxide enriching. With respect to the ammonium nitrate enriching, both the concentrations of nitrate-nitrogen and ammonia-nitrogen are far higher than those of the control group. However, a very noticeable trend was that both these two forms of nitrogen decayed over time. Though same concentration of were added at the beginning, the concentrations of these two forms of nitrogen differed from each other. This phenomenon can be explained by the transport and fate of nitrogen compounds (Yang et al., 2012).

When coupled with the graphic information, this leads to some possible conclusions. The distinctions of sensor response may be explained by the introduction of the nitrogen, which changed the impedance of biofilter media. The lower sensor reading of ammonium-nitrate enriching compared with ammonium-hydroxide enriching might be attributed to the introduction of nitrate-nitrogen, which increased the impedance of the biofilter media, resulting in the decrease of the sensor reading. The impedance of biofilter media is determined by the dielectric constant, the smaller the dielectric constant, the larger the impedance would be. In this test, the introduction of nitrate-nitrogen dissolved as nitrate ion, which decrease the dielectric constant of the media. This result is in agreement with the study conducted by Lileev et al. (2003), since they found the values of dielectric constant of the solution containing nitrate ion decreased with the increase of salt concentration.

3.2.2 Influence of ammonium-hydroxide and ammonium-nitrate

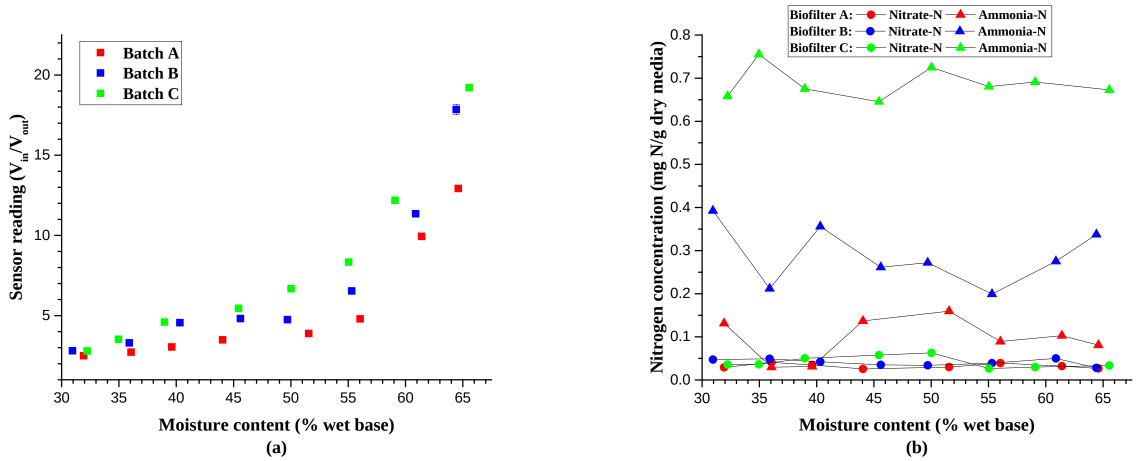

Figure 5. Results regarding ammonium hydroxide enriching: (a) averages and standard deviation of sensor readings at varied moisture contents, and (b) nitrogen concentrations of biofilter media at varied moisture contents (biofilter batch A, B, and C was treated with 0.25, 0.50, and 0.75 mg ammonia-nitrogen per gram dry biofilter media, respectively).

Figure 5 showed the sensor output for different batches as well as the profiles of different nitrogen along with the increasing moisture content treated by ammonium-hydroxide enriching. This figure unfolded a clear comparison between the sensor reading (a) as well as the concentration (b) of ammonia-nitrogen and nitrate nitrogen. It was illustrated that ammonia-nitrogen was the dominant compound of nitrogen in all batches, and the concentration of ammonia-nitrogen remained constant. It can be assumed that the influence of nitrate-nitrogen can be ignored in this test. According to the figure, a positive correlation between the sensor reading and the concentration of ammonia-nitrogen was found in this study. It can be seen from the chart that higher ammonia-nitrogen concentration results in higher sensor reading. The potential explanation for the trend of sensor output along with the ammonia-nitrogen concentration can be from the prospective of the impedance change. In biofilter, ammonia-nitrogen can be in forms of dissolved ammonia-nitrogen and free ammonia. The dissolved ammonia-nitrogen can be divided into two species: ionized ammonia (NH_4^+) and un-ionized ammonia ($NH_3 \cdot H_2O$). Both the dominant component, free ammonia and un-ionized ammonia, decreased the impedance of media and caused increase of sensor reading. To sum up, the introduction of ammonia-nitrogen decreased the impedance of the biofilter media, and lower impedance led to higher sensor reading.

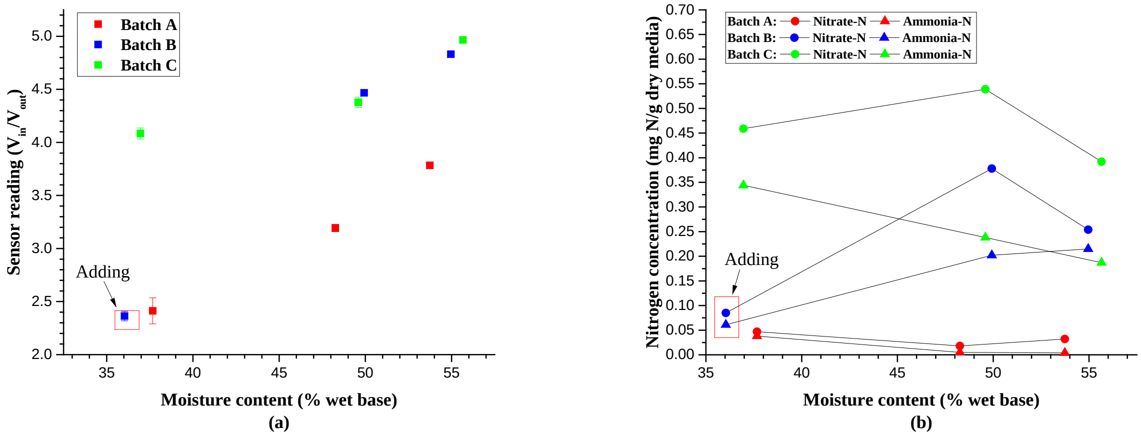

Figure 6. Results regarding ammonium nitrate enriching: (a) averages and standard deviation of sensor readings at varied moisture contents, and (b) nitrogen concentrations of biofilter media at varied moisture contents (biofilter batch A, B, C were treated with nitrate-nitrogen associate with the same ammonia-nitrogen at the concentration of 0.0625, 0.125, 0.5 mg per gram dry biofilter media, respectively, "Adding" represents a second ammonia nitrate enriching).

The Figure 6 illustrated the sensor output of different biofilter batches and the profiles of different nitrogen treated by ammonium nitrate enriching. Unlike the previous test, several slight adjustments were made in this test. 1) During the operation of increasing moisture content from 35% to 50%, a second ammonium-nitrate enriching was implemented as a special scenario. 2) The interval for moisture content between each operation were enlarged to diminish the influence of other factors (e.g., microbial activities, aging of the woodchips). With the same ammonia-nitrogen but different nitrate-nitrogen, the sensor readings at 50% and 55% moisture content of biofilter batch B and batch C behaved very similar to each other. It indicated that the impedance of biofilter media had been less affected by the nitrate-nitrogen than ammonia-nitrogen.

3.3 Mathematical model

The following mathematical model is established to demonstrate the relationship between sensor reading and moisture content merely.

Theoretical assumptions and validation

The following assumptions were made to simplify the modeling process.

1). Assume the fraction volume of nitrogen is negligible compared with water.

The unit of the nitrogen concentration in this investigation was mg N per g dry media, with the ratio of one-in-one-thousand in mass. And the powder dissolved in the water and can be regarded as negligible.

2). Consider the impedance of biofilter media as a simple parallel connection of a resistor and a capacitor, the contribution of resistor to the impedance is little compared with capacitor.

The validation was based on the results of experiments. The impedance of the reference capacitor $\left|Z_{ref}\right|$ was

$$\left|Z_{ref}\right| = \left|\frac{1}{j\omega C_{ref}}\right| = \left|\frac{1}{j2\pi f C_{ref}}\right| = \left|\frac{1}{2\pi \times 10^{5}\,Hz \times 10^{-9}\,F}\right| = 1591.5\Omega$$

The sensor readings were ranging from 2 (35% MC) to 20 (55% MC), corresponding to the impedance of biofilter media ranging from 1591.5 Ω to 83.7 Ω. While the resistance of the biofilter media was calculated based on the conductivity (Zelinka et al., 2008) and the equation (4).

$$R = \rho \frac{\ell}{A} \tag{4}$$

Where

R is the resistance, ℓ is the length of the conductor, A is the cross-sectional area of the conductor measured, and ρ is the electrical resistivity.

The resistances of woodchips were decreased with the increasing moisture content. However, for moisture content of 35%, the resistance was $10^4\,\Omega$; and the for moisture content of 65%, the resistance was $10^3\,\Omega$. Both the value of resistances were larger than the impedance. Since the equivalent impedance of a parallel-connection circuit was determined by the contributor with smaller value. It is thus clear that

$$Z_{biofilter} \approx \frac{1}{j\omega C_{biofilter}} \tag{5}$$

Mathematical formulation for correlation of sensor reading and moisture content

$$reading = 1 + \frac{|Z_{ref}|}{|Z_{biofilter}|} = 1 + \frac{\left|\frac{1}{j\omega C_{ref}}\right|}{\left|\frac{1}{j\omega C_{biofilter}}\right|} = 1 + \left|\frac{C_{biofilter}}{C_{ref}}\right| \tag{6}$$

$$C_{biofilter} = \frac{\varepsilon_{biofilter} A}{d} = b\varepsilon_{biofilter} \tag{7}$$

$$reading = 1 + \left|\frac{C_{biofilter}}{C_{ref}}\right| = 1 + \left|\frac{b\varepsilon_{biofilter}}{C_{ref}}\right| = 1 + |c\varepsilon_{biofilter}| \tag{8}$$

Where

C_{ref} : Capacitance of reference capacitor (constant)

$C_{biofilter}$: Capacitance of biofilter media in Farads,

ε : Dielectric constant (absolute, not relative)

A : Area of plate overlap (constant)

d : Distance between plates (constant)

$b = \frac{A}{d}$: Constant

$c = \frac{b}{C_{ref}}$: Constant

According to previous literature (Heimovaara et al., 1994),

$$\varepsilon_m^a = \Sigma \varepsilon_i^a v_i \tag{9}$$

Where ε_m is the dielectric constant of the medium, i represents each component (air, organic material, inorganic material, and water), v is the volume fraction of each component, and constant a is close to 0.5.

$$\varepsilon_{biofilter}^{0.5} = \varepsilon_{water}^{0.5} v_{water} + \varepsilon_{woodchips}^{0.5} v_{woodchips} + \varepsilon_{nitrogen}^{0.5} v_{nitrogen} = \varepsilon_{solution}^{0.5} v_{solution} + \varepsilon_{woodchips}^{0.5} v_{woodchips} \tag{10}$$

$$(\varepsilon_{biofilter}^{0.5})^2 = (\varepsilon_{solution}^{0.5} v_{solution} + \varepsilon_{woodchips}^{0.5} v_{woodchips})^2 \Leftrightarrow$$

$$\varepsilon_{biofilter} = \varepsilon_{solution} v_{solution}^2 + \underline{\varepsilon_{solution}^{0.5} \varepsilon_{woodchips}^{0.5} v_{solution} v_{woodchips}} + \underline{\varepsilon_{woochips} v_{woodchips}^2} = e v_{solution}^2 + f v_{solution} + g \tag{11}$$

Where e, f, g are constants.

$$\text{Since } MC = \frac{m_{water}}{m_{total}} \tag{12}$$

$$v_{solution} = \frac{\frac{m_{solution}}{\rho_{solution}}}{\frac{m_{total}}{\rho_{total}}} = \frac{\frac{m_{water}}{\rho_{water}}}{\frac{m_{total}}{\rho_{total}}} = hMC\rho_{total} \tag{13}$$

Where ρ_{total} is the density of the biofilter media, which is a linear function of moisture content when the moisture content ranges from 35% to 65% (Simpson, 1993).

$$\begin{aligned} &\rho_{total} = kMC \\ &reading = 1 + \left| c\varepsilon_{biofilter} \right| = 1 + \left| cev_{solution}^2 + cfv_{solution} + cg \right| \\ &= 1 + \left| ce(hkMC^2)^2 + cf(hkMC^2) + cg \right| = lMC^4 + mMC^2 + n \end{aligned} \quad (14)$$

Where h, k, l, m, and n are constants.

Then the sensor reading can be express as a function of moisture content.

3.4 Statistical model

The relationship between sensor reading and moisture content has been built, but the extent of the influence of different nitrogen as well as the concentration is far from uncertain. Limited research mentioned the correlation between the nitrogen concentration and impedance of biofilter media.

A multiple linear regression associated with the fourth-degree polynomial regression was applied to determine the relationships among sensor reading, moisture content, and different forms of nitrogen as well as their concentration. The coefficients of the fourth-degree polynomial function and the statistical significance of coefficients were shown in Table 3 and equation (15).

Table 3. Coefficients of fourth-degree polynomial and their statistics significance

	Estimate	Std. Error	t value	Pr (>|t|)	
(Intercept)	3.398e+00	8.348e-01	4.070	0.000137	***
Ammonia-N conc.	4.737e+00	7.401e-01	6.400	2.46e-08	***
Nitrate-N conc.	-2.758e+00	1.203e+00	-2.293	0.025325	*
MC^2	-2.867e-03	7.884e-04	-3.636	0.000570	***
MC^4	1.196e-06	1.621e-07	7.380	5.15e-10	***
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1					
Multiple R-squared: 0.8727					

$$reading = (1.196e-6) \times MC^4 - (2.867e-3) \times MC^2 + 4.737C_{ammonia-N} - 2.758C_{nitrate-N} + 3.398 \quad (15)$$

The coefficients showed that both the increase of the ammonia-nitrogen and moisture content significantly results in higher sensor reading, while the loading of nitrate-nitrogen decreases the sensor reading, but not very significantly. Based on the above function, the predicted sensor reading and the observed sensor reading were shown in Figure 7. For sensor reading smaller than 8, the predicted sensor reading fitted well with the observed sensor reading, which indicated that this fourth-degree polynomial function was accurate to build up the relationships among sensor reading, moisture content, and different forms of nitrogen as well as their concentrations.

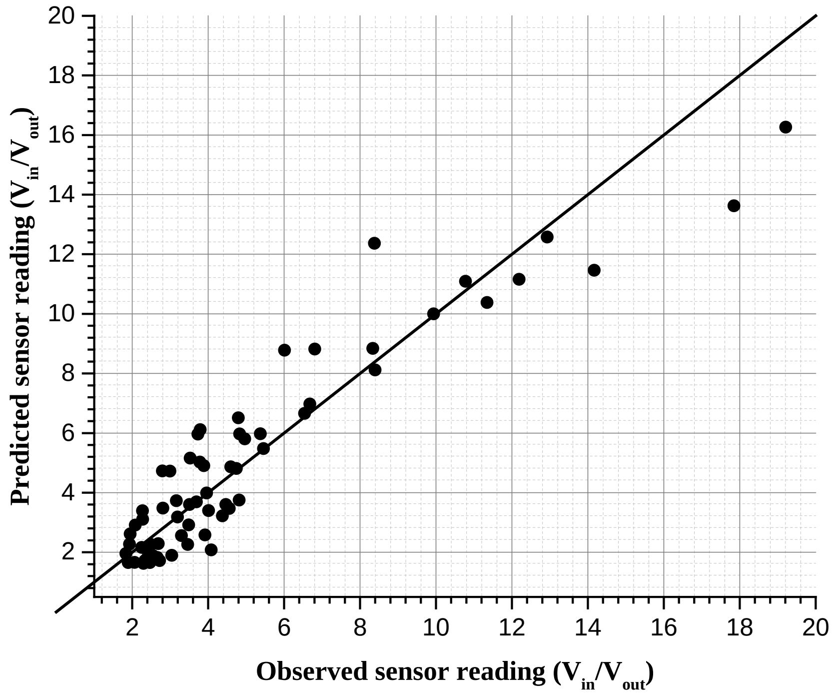

Figure 7. Comparison of predicted sensor reading and observed sensor reading

4. CONCLUSION

The impedance-based moisture sensor was applied as an indicator of impedance of biofilter media. Qualitative analysis showed that the particle size distribution has direct effects on impedance-based moisture sensing. The change of impedance of biofilter media can be attributed to 1) the contact area between biofilter media and sensing unit, and 2) uneven moisture content distribution due to compaction. This means the sensor may require re-calibration based on the particle size distribution of the biofilter media caused by compaction effect. Both qualitative and quantitative analysis showed that the concentration of different forms of nitrogen (ammonia-nitrogen, nitrate-nitrogen) have significant impact on the impedance of biofilter media. The mathematical model was established to correlate the sensor reading with moisture content. And the statistical model verified that the moisture content, ammonia-nitrogen, and nitrate-nitrogen determine the sensor reading of the impedance-based moisture sensor. These results are useful to design a better biofilter moisture monitor and control system to keep the biofilter working in good condition. Further studies are needed to improve the performance of the sensor considering other potential factors.

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