IMPEDANCE-BASED MOISTURE CONTENT SENSOR ASSESSMENT FOR GAS-PHASE BIOFILTER MEDIA

Z. Zheng, L. Yang, R. S. Gates, J. Wu, X. Wang

ABSTRACT. *A woodchip-based gas-phase biofilter is capable of mitigating livestock airborne ammonia efficiently with low cost. Control of the moisture content (MC) of biofilter media is critical for ammonia mitigation and limiting nitrous oxide generation. It is important to monitor the real-time biofilter MC to maintain biofilter performance. The objectives of this study were to further develop and evaluate impedance-based MC measurement and to improve methodologies to monitor the MC of gas-phase biofilters. A sensor consisting of a sensing unit (three perforated parallel plates) and a circuit generating DC voltage output was used to measure MC. The sensor readings changed significantly with stepwise MC increases, particle size distribution, and nitrogen (ammonia-nitrogen, nitrate-nitrogen) concentrations in biofilter media. A mathematical model was developed for the relationship between the sensor reading and MC. A statistical model was established to predict the MC in biofilter media based on the sensor reading, ammonia-nitrogen concentration, and nitrate-nitrogen concentration.*

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

Ammonia emissions contribute to a variety of environmental problems related to reactive nitrogen cascade, a phenomenon that describes multiple sequence effects of ammonia on ecosystems (atmosphere, terrestrial ecosystems, and freshwater and marine systems) caused by reactive nitrogen (Galloway, 1998, 2003, 2013). Reactive nitrogen cascade causes eutrophication, which leads to depletion of dissolved oxygen and detrimental impacts on aquatic life and vegetation (Erisman et al., 2007; Hong et al., 2013). Additionally, ammonia emissions pose negative impacts on human health through particulate matter formation and deposition (Galloway et al., 2003; Pope, 2000; Pope and Dockery, 2006). Ammonia emissions from agricultural sources are dominant over other natural emissions and are the largest contributors to the global inventory (Allen et al., 2011; Bouwman et al., 2002), with a range of 27 to 38 Tg (1 Tg = 10^{12} g) per year. Livestock production accounts for 59% to 71% of global agricultural ammonia emission (Beusen et al., 2008). In the U.S., ammonia arises from agricultural sources, with concentrated animal feeding operations (CAFOs) as the dominant source (Balasubramanian et al., 2015, 2017). Research related to the control of livestock-derived airborne ammonia emission is crucially needed.

Gas-phase biofiltration has been designated by the Illinois State Office of the Natural Resource Conservation Service as a candidate technology for livestock ammonia emissions control (Delhoménie and Heitz, 2005; Yang, 2013). During biofilter operation, air is forced through the biofilter media continuously, and ammonia can be retained in the media (la Pagans et al., 2005; Nicolai et al., 2006). Previous research suggested that woodchip-based biofiltration was capable of mitigating livestock airborne ammonia efficiently with a low cost (Chen et al., 2009). The moisture content (MC) of the biofilter media was regarded as the key determinant for biofilter performance (Maia et al., 2012a). Nitrous oxide (N_2O), a potent greenhouse gas, can be produced primarily under incomplete denitrification processes within a biofilter (Melse and Hol, 2017). The generation of N_2O is closely related to media MC, especially at high MC conditions (Maia et al., 2011a, 2012a). There is no precise MC setting for biofilter operation, but a recommended MC range of 35% to 65% has been suggested (Chen and Hoff, 2009; Maia et al., 2012b). In addition to MC, particle size also affects the performance of a biofilter. Yang et al. (2011) and Maia et al. (2011b) tested the airflow resistances of numerous biofilter media and their mixtures and suggested that particle size distribution and media compaction were significant in determining pressure drop during biofilter operation, and that the MC relation for a given media strongly depended on particle size distribution.

Maintaining the MC within a desired range requires precise and robust moisture measurement. However, because woodchips have a larger and more varied particle size com-

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pared to soil (Yang et al., 2011), regular soil sensors are inapplicable for moisture measurement in biofilter media. Even if the probe successfully contacted the biofilter media, the local measurements are not suitable for global MC measurement. Reyes et al. (2000) suggested using a time domain reflectometry (TDR) probe to monitor mixed biofilter media consisting of 60% compost and 40% pearlite, but such a biofilter media mixture was not ideal for practical application due to excessive pressure drop. D'Amico et al. (2010) successfully stimulated a wire probe with pulse signals to measure the round-trip time to indicate MC, but the measurement variation increased significantly when the MC exceeded 40%. Hultnäs and Fernandez-Cano (2012) tested and evaluated a Mantex Desktop Scanner based on dual energy X-ray with pine woodchips; however, this method required hospital instruments, which can be expensive. To date, none of the methods developed have been perfected enough to be put into field practice. More research on moisture sensors is needed, especially for low-cost real-time continuous measurement in livestock facilities.

The use of impedance, rather than electrical conductivity (EC) or electrical resistance (R), in the prior study was selected because the impedance sensor was driven by alternating current. Impedance in AC systems is equivalent to resistance in DC systems, and the corresponding analog for EC in an AC system is admittance. Using impedance allows generalization of the key controlling factors in gas-phase ammonia biofiltration. Recently, an impedance-based moisture sensor was developed that performed better than a capacitive parallel-plate moisture sensor (Yang et al., 2013a, 2013b). The principle of this sensing method takes advantage of the dielectric characteristic of the biofilter media. In a biofiltration system, the dielectric constant (an important index for the dielectric properties) of liquid water (80.1 at 20°C) is much higher than that of air (1 at 20°C) and woodchips (1 to 5 at 20°C). However, the dielectric constant of ammonia is 16.61 at 20°C (Billaud and Demortier, 1975), which may influence the sensing results. Large amounts of ammonium and nitrate ions may accumulate in biofilter media, but the previous research did not evaluate their effects on the impedance of the biofilter media. In fact, a woodchip-based biofilter is comprised of multiple components, including woodchips of varying size, free water, trapped air, and different forms of nitrogen. Ammonia-nitrogen and nitrate-nitrogen are the two major nitrogen compounds, which account for 50% to 100% of total nitrogen in the biofilter (Yang et al., 2012), and they arise from the building ventilation air stream. During operation, the maximum accumulating concentrations of ammonia-nitrogen and nitrate-nitrogen were 78.9 and 249.7 mg kg^{-1} (dry basis), respectively (Hood et al., 2015), although this will vary with loading rate and other factors, such as media age. Particle size distribution is another key issue, as it affects the contact area between the sensing probe and the biofilter media. To the best of our knowledge, previous studies failed to consider the influences of particle size and nitrogen accumulation on sensor performance.

This study sought to improve the moisture sensing methods of Yang et al. (2013a, 2013b). The objectives were to: (1) examine the effects of particle size and nitrogen loading on moisture sensing, and (2) develop models to facilitate real-time moisture monitoring of a gas-phase biofilter. The actual pH of the biofilter media was not determined. The influences of pH and microbial activity on biofilter media impedance were not investigated in this study. Other factors, such as ionization of ammonia, partitioning of ammonia/ammonium between liquid and solid phases, and ionization effects on dielectric constant, were not considered in this study because they may be determined or affected by the pH value.

Materials and Methods

Overview

Figure 1 shows the schematic of this study. To understand the impacts of particle size distribution (PSD) on the impedance of the biofilter media, two PSD scenarios were considered. To study the impacts of nitrogen loading on the impedance of biofilter media, a four-step procedure was followed. The first step compared the impedance of biofilter media with the same ammonia-nitrogen concentration but different nitrate-nitrogen concentrations. The second step investigated ammonium hydroxide enriching and ammonium nitrate enriching. In the third step, a mathematical model was developed to describe the relationship between sensor reading and MC, which served as a precursor for a statistical model. Finally, the statistical model was developed to quantitatively correlate the ammonia-nitrogen concentration, nitrate-nitrogen concentration, and MC with the sensor reading.

Media Selection

Woodchips, consisting of shredded and chipped mixed wood stock, were obtained from a landscape recycling center in Urbana, Illinois. They were naturally dried to 10% to 15% MC (wet basis). Two media groups (PSDs of 0.2 to 0.8 cm and 0.8 to 1.9 cm) were sorted from the mixture using a Penn State Forage Particle Separator (Product No. C24682N, Nasco, Fort Atkinson, Wisc.). Wood chips were not reused in this test.

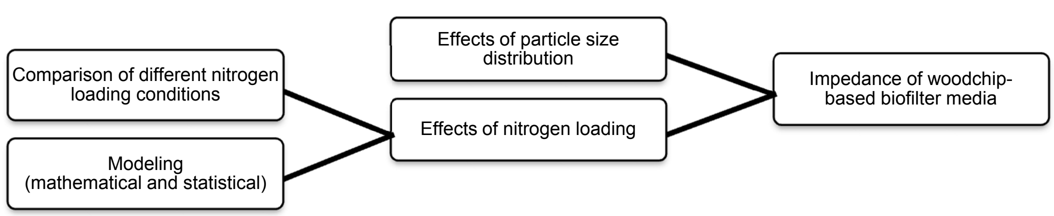

Figure 1. Schematic of procedures and methods.

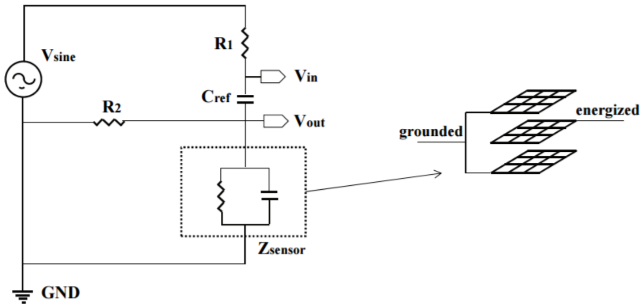

Figure 2. Simplified schematic of the sensor circuit and parallel plates (adopted from Yang et al., 2013a).

Sensor Construction

The sensor design (fig. 2) was composed of a conditioning circuit and a sensing unit (Yang et al., 2013a, 2013b). The circuitry consisted of a voltage-divider circuit and a peak-detector circuit. The principle of the circuitry is to compare the impedance of the biofilter media mounted between sensor plates ($Z_{biofilter}$) to a reference capacitor (Z_{ref}). Sine-wave AC voltages with ±2.0 V P-P were generated, then converted to two DC voltages (V_{in} and V_{out}) by a voltage divider circuit and integrated circuits, and finally recorded using a data acquisition system (Personal Daq/56, Measurement Computing, Norton, Mass.). The acquired signals were applied to the following equation to calculate the voltage ratio as the sensor reading:

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

Previous tests on the sensor showed that the impedance was distinguishable at a high frequency of 100 kHz. The sensor reading was a function of the media impedance, which was related to the media MC. The sensing unit consisted of three parallel coated steel plates (80% perforated with 2.54 mm holes), separated by three sets of plastic bars. The top and bottom plates were grounded, while the middle plate was energized. The size of each plate was 30 cm × 30 cm, while the distance between the center and side plates was 7.5 cm. The sensing plates were installed in the center of a sealed plastic test chamber (62.5 cm × 47.6 cm × 35.2 cm, L × W ×H) and filled with biofilter media. The height between the lowest plate and the bottom of the chamber was 5 cm, while height between the highest plate and the top of the biofilter media was also 5 cm. A total of three sets of sensors were fabricated and used in this study.

Particle Size and Moisture Content

To control the PSD of the biofilter media, two groups of media (PSD of 0.2 to 0.8 cm and PSD of 0.8 to 1.9 cm) were re-mixed at volume ratios of 1:1 and 1:4. The MC of the woodchips was increased gradually by adding DI water manually with a 5% increment of the MC. The time interval between water additions was 3 to 4 days. For each operation, the biofilter media was taken out of the test chamber and mixed with water on a tray. Water was added as a spray. The biofilter media was then placed back into the chamber as soon as possible. The sensor outputs (V_{in} and V_{out}) were recorded every 10 min for 2 to 3 days. For each batch, the biofilter media was sealed in the test chamber, and the biofilter was operated at a normal room temperature (22°C). Normally, biofilters are subjected to airflow. However, to reduce water loss, no airflow was applied in this study.

Nitrogen Enriching

Biofilter media with a 1:4 particle size mixture ratio was used for this study. Nitrogen enriching was carried out by adding ammonium hydroxide and ammonium nitrate. The objective of adding ammonium hydroxide was to introduce ammonia-nitrogen only into the biofilter media and to determine the influence of ammonia-nitrogen on the impedance of the biofilter media. The objective of adding ammonium nitrate was to introduce both ammonia-nitrogen and nitrate-nitrogen at a ratio of 1:1 (stoichiometric ratio of ammonium and nitrate) into the biofilter. The biggest challenge of this test was that neither the ammonia-nitrogen nor the nitrate-nitrogen could be completely absorbed/adsorbed by the biofilter media. Nitrogen might be lost in the form of ammonia gas during the mixing and measuring steps.

The ammonium hydroxide or ammonium nitrate was added to the media when the MC was 30%. Sensor outputs V_{in} and V_{out} were recorded every 10 min for 2 to 3 days. As limited by the experimental setup, three batches at most were available for each scenario. There was no replication for the batch treatments. For the purpose of covering wider ranges of nitrogen concentrations and some special scenarios, the parameters of each biofilter batch, as well as the procedure of each experiment, are shown in table 1.

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

Scenario 2: To analyze the change in impedance of the biofilter media caused by ammonia-nitrogen, two concentration levels of ammonia hydroxide enriching were used: batch A was treated with 0.25 mg of ammonia-nitrogen per gram dry biofilter media, and batch B was treated with 0.50 mg of ammonia-nitrogen per gram dry biofilter media. The MC of these batches ranged from 30% to 65%.

Scenario 3: To analyze the influence of the nitrate-nitrogen associated with ammonia-nitrogen on the impedance of the biofilter media, two concentration levels of ammonium nitrate enriching were used for the test: batches A and B were treated with nitrate-nitrogen associated with the same ammonia-nitrogen at concentrations of 0.0625 and 0.5 mg per gram dry biofilter media, respectively. A slight adjustment regarding this series of experiments was that the increment for MC was uneven. The starting MC for measurement was 35%, and then all MC values were immediately increased to 50%.

Scenario 4: To analyze the influence of a high concentration of nitrate-nitrogen associated with ammonia-nitrogen on the impedance of the biofilter media, two concentration levels of ammonium nitrate enriching were tested: batches A and B were treated with nitrate-nitrogen associated with the

Table 1. Summary of nitrogen-enriching treatments (nitrogen concentration = mg ammonia-N or nitrate-N per gram dry media).

Testing Batch	Scenario 1: Nitrogen Loading	Scenario 2: Ammonium Hydroxide	Scenario 3: Ammonium Nitrate	Scenario 4: Ammonium Nitrate
Batch A	Control group	0.25 ammonia-N	0.0625 nitrate-N + 0.0625 ammonia-N	1.25 nitrate-N + 1.25 ammonia-N
Batch B	0.75 ammonia-N	0.50 ammonia-N	0.50 nitrate-N + 0.50 ammonia-N	1.75 nitrate-N + 1.75 ammonia-N
Batch C	0.75 nitrate-N + 0.75 ammonia-N	-	-	-

same concentration of ammonia-nitrogen at 1.25 and 1.75 mg per gram dry biofilter media, respectively. In this scenario, MC ranged from 35% to 65%.

SAMPLING AND ANALYSIS

Samples were taken from the upper (two samples), middle (two samples), and lower layers (two samples) of the test chambers. The weight of each sample was 30 g. The samples were then re-mixed for a composite moisture measurement. MC was measured 2 h after each operation, while the nitrogen concentrations and the pH of the biofilter media were measured 36 h after each operation. A 30 g sample was dried in a 105°C oven for 24 h to determine the wet basis MC. Triplicate subsamples were analyzed and averaged. Nitrogen concentrations were measured based on modified TMECC 04.02 standards (Thompson et al., 2001). Samples with 4 g woodchips were extracted by 40 mL of DI water. Each sample was mixed using a mixer for 5 min to dissolve the molecules, ions, and gasses. The mixture was centrifuged (3000 rpm for 30 min), and then the pH value of the supernatant was measured with a pH meter (PH1100 Series, Oakton Instruments, Vernon Hills, Ill.). In this study, the exact pH value of the biofilter media was not determined because the measured supernatant pH value based on the protocols may not have indicated the actual pH of the biofilter media (e.g., the MC of the biofilter media changed when introducing water for extraction) (Sullivan and Miller, 2001). The nitrogen concentrations of the filtrate were analyzed with a spectrophotometer (model DR/2010, Hach Co., Loveland, Colo.). Ammonia-nitrogen (the sum of NH_4^+-N and NH_4OH-N) was measured using Method 8155 (0 to 0.50 mg L^{-1}), and nitrate-nitrogen (NO_3^--N) was measured using Method 8171 (0 to 4.50 mg L^{-1}). The effects of NH_4^+-N and NH_4OH-N on impedance were not explored in this study because of the lack of pH data.

MATHEMATICAL AND STATISTICAL MODEL CONSTRUCTION

The relationship between sensor reading and MC can be established by a mathematical model. Because the causation between nitrogen concentrations and sensor reading is far from certain, to make use of the data, statistical models were used to explore correlation patterns.

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

$$Z_{ref} = \frac{1}{j\omega C_{ref}} \tag{2}$$

where the unit of impedance (Z) is Ω. Because the impedance of the biofilter media can be regarded as a parallel connection of a resistor and capacitor, its impedance can be calculated as:

$$Z_{biofilter} = R_{biofilter} // \frac{1}{j\omega C_{biofilter}} = \frac{R_{biofilter} \times \frac{1}{j\omega C_{biofilter}}}{R_{biofilter} + \frac{1}{j\omega C_{biofilter}}} \tag{3}$$

where

C_{ref} = capacitance of reference capacitor (constant)

ω = angular frequency

$R_{biofilter}$ = resistance of biofilter media

f = frequency of imposed alternating field

j = index of imaginary part (the square root of -1)

// = symbol of parallel connection.

A paired t-test was applied to the sensor readings to determine the influence of the PSD of the biofilter media. Multiple linear regression (MLR) was used to model the relationship among sensor reading, MC, and nitrogen concentration. Linear regression was also used to evaluate the predictive model. Data analysis was carried out in the R statistical environment (R-Studio, Boston, Mass.) and Origin 2016 (OriginLab Corp., Northampton, Mass.). Package "forecast" in R was applied for data treatment, which generated the predicted value of the sensor reading.

RESULTS AND DISCUSSION

SENSOR RESPONSE TO PARTICLE SIZE AND MOISTURE CONTENT

Differences in sensor readings (V_{in}/V_{out}) were noticed between the two batches with different PSDs (fig. 3). The differences increased with the MC. At each moisture measurement, the sensor reading remained steady, as indicated by the small standard deviations. For MC ranging from 40% to 60%, the sensor reading of the testing batch with 1:1 volume ratio was higher than that with 1:4 volume ratio. Paired t-tests confirmed that the PSD made a significant difference in moisture sensing ($p < 2.2e\text{-}16$).

One possible reason for the differences between sensor readings for the two particle size batches could be the contact area between the woodchip particles and the sensing units. When the volume percentage of small particles decreased from 50% (1:1 volume ratio) to 20% (1:4 volume ratio), the small particles had fewer chances to contact with the sensor plates, which led to a decrease in the total contact area and

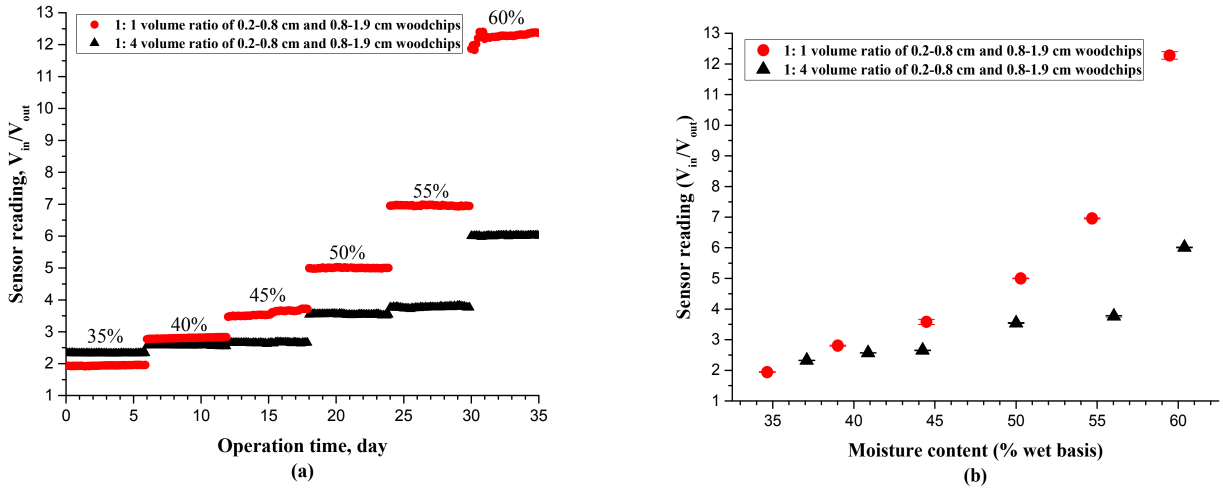

Figure 3. Sensor response to changing particle size: (a) real-time sensor readings at varied moisture contents and (b) means and standard deviations of sensor readings at varied moisture contents.

resulted in higher impedance, thus the lower sensor reading. Another possible reason may be due to the compaction effect (Yang et al., 2013a). A volume with small particles has more surface area and thus can adsorb more water than larger particles. Smaller particle mixtures also tend to settle due to gravitational force; the smaller particles the biofilter contained, the more compressed the biofilter media could be, resulting in more water within the sensing unit. Smaller particles also reduced the void space in the testing batch, which minimized the air space. Because the water and the woodchips had lower impedance compared to air, the impedance of the biofilter media with many smaller particles would decrease, thus increasing the sensor reading.

Sensor Response to Nitrogen Concentration with Changing Moisture Content

Influence of Different Nitrogen Loadings

The sensor response (V_{in}/V_{out}) to nitrogen-enriching scenario 1 is shown in figure 4. The sensor readings of the control group were in the range of 2.3 to 8.5 during the test, while the sensor readings of the nitrogen loading batches were in the ranges of 3.6 to 10.8 for ammonia nitrate enriching and 3.5 to 19.3 for ammonia hydroxide enriching. Distinct differences appeared between the nitrogen loading batches and the control group. The most rapid increase was in the batch with ammonium hydroxide enriching when the MC exceeded 50%. For the batch with ammonium nitrate enriching, the increase in sensor output with MC was also significant. The disparities in sensor readings between groups were increased along with increasing MC. The contribution of MC to an increase in sensor readings has been demonstrated by previous research (Yang et al., 2013a, 2013b). These results show that nitrogen loading significantly affected sensor readings along with the changing MC.

Figure 5 explores the relationship between sensor reading and nitrogen loading. With respect to ammonium hydroxide enriching, the most impressive feature was that the ammonia-nitrogen concentration remained constant, which was also the dominant form of nitrogen within the biofilter media during the test. There was no significant difference in the ni-

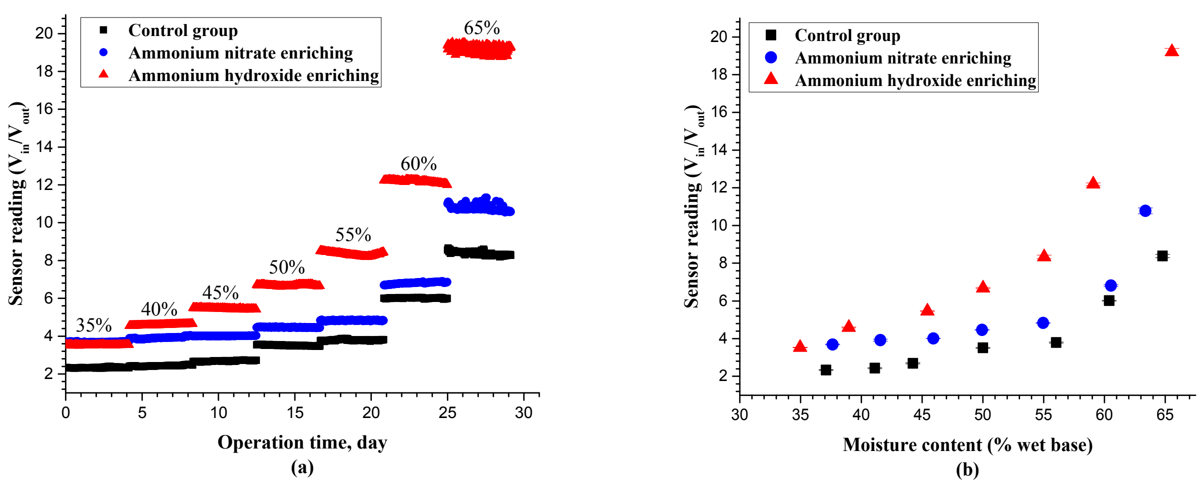

Figure 4. Sensor response to nitrogen enriching: (a) real-time recording of sensor readings at each moisture step and (b) means and standard deviations of sensor readings at varied moisture contents (no nitrogen enriching for the control batch, 0.75 mg of nitrate-nitrogen per gram of dry biofilter media for ammonium nitrate enriching, and 0.75 mg of ammonia-nitrogen associated with 0.75 mg of nitrate-nitrogen per gram of dry biofilter media for ammonium hydroxide enriching).

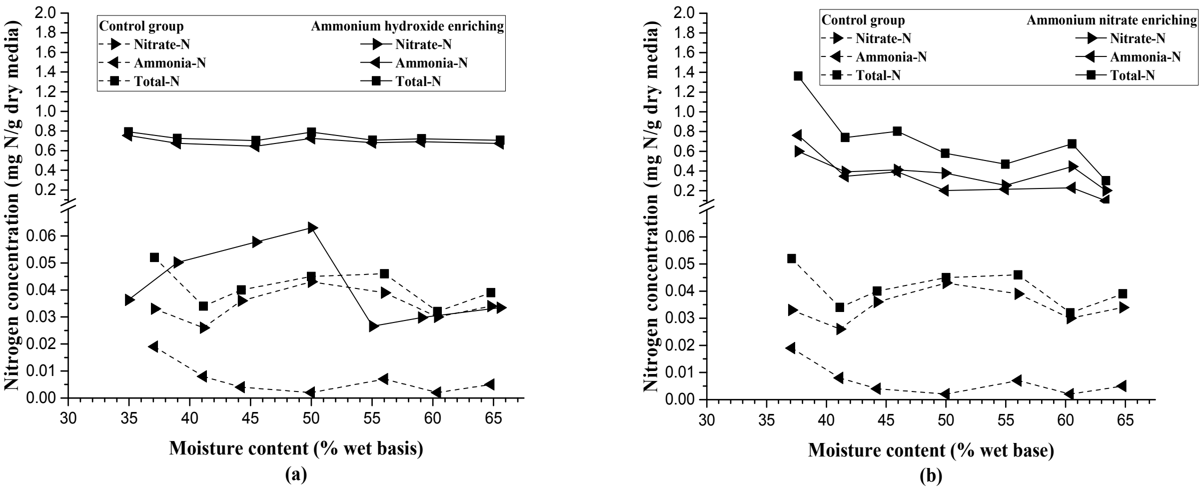

Figure 5. Profiles of nitrogen concentrations for different methods of nitrogen enrichment: (a) 0.75 mg of ammonia-nitrogen per gram of dry biofilter media for ammonium hydroxide enriching and (b) 0.75 mg of ammonia-nitrogen associated with 0.75 mg of nitrate-nitrogen per gram of dry biofilter media for ammonium nitrate enriching.

trate-nitrogen concentration between the control group and the ammonium hydroxide enriching group. With respect to ammonium nitrate enriching, the concentrations of nitrate-nitrogen and ammonia-nitrogen were both higher than those in the control group. Another noticeable trend was that both forms of nitrogen decayed over time.

The difference in sensor responses may be explained by the introduction of nitrogen, which changed the impedance of the biofilter media. The lower sensor reading for ammonium nitrate enriching compared to ammonium hydroxide enriching might be attributed to the introduction of nitrate-nitrogen, which increased the impedance of the biofilter media, resulting in the decreased sensor reading. Because the impedance of the biofilter media is determined by the dielectric constant, the smaller the dielectric constant, the lower the capacitance, and thus the higher the impedance would be. In this test, the introduction of nitrate-nitrogen reduced to nitrate ions, which decreased the dielectric constant of the media. This result is consistent with the study carried out by Lileev et al. (2003), who found that the values of the dielectric constant of a solution containing nitrate ions decreased with the increase in salt concentration, and the stronger the ion hydration, the less the dielectric constant.

Influence of Ammonium-Hydroxide and Ammonium-Nitrate

Biofilter media with a 1:4 particle size mixture ratio was used for all the scenarios. To determine the influence of ammonia-nitrogen on sensor performance, figure 6 shows the sensor outputs for two tests with different nitrogen loading concentration along with increased MC (scenario 2). Ammonia-nitrogen was the dominant nitrogen compound in all batches, and its concentration remained stable. It can be assumed that there was little influence of nitrate-nitrogen in this test because its concentration was far lower than that of ammonia-nitrogen. A positive correlation between the sensor reading and ammonia-nitrogen concentration was found. A potential explanation for the trend of sensor output with ammonia-nitrogen concentration could be the impedance change. In the biofilter, ammonia-nitrogen can be in the form

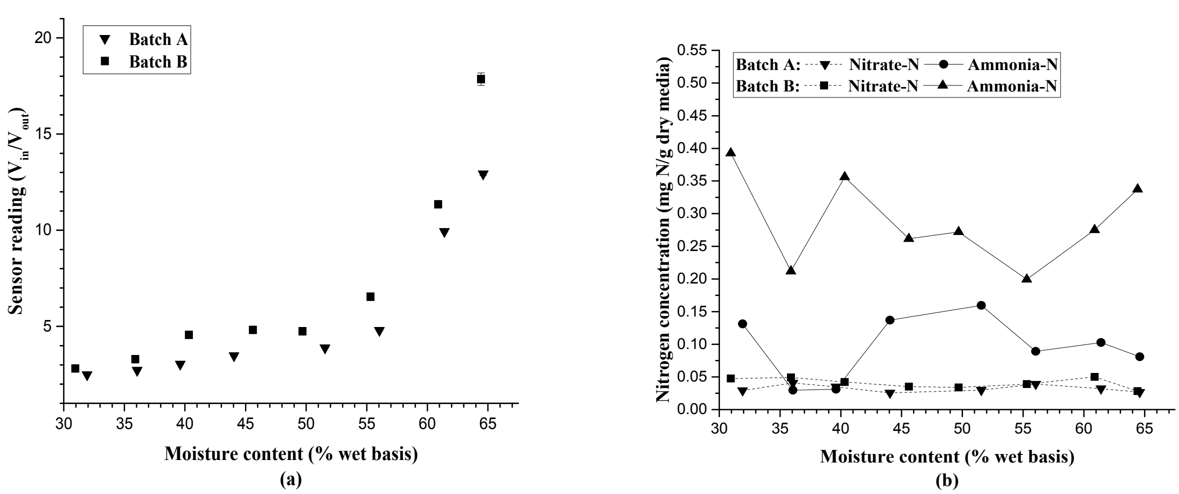

Figure 6. Results of ammonium hydroxide enriching: (a) means and standard deviations of sensor readings at varied moisture contents and (b) nitrogen concentrations of biofilter media at varied moisture contents (batches A and B were treated with 0.25 and 0.50 mg of ammonia-nitrogen per gram of dry biofilter media, respectively).

of dissolved ammonia-nitrogen and free ammonia. The dissolved ammonia-nitrogen can be divided into two species: ionized ammonium (NH_4^+) and un-ionized ammonia ($NH_3 \cdot H_2O$). Both dominant components, free ammonia and un-ionized ammonia, decreased the impedance of the media and caused an increase in the sensor reading. In summary, the introduction of ammonia-nitrogen decreased the impedance of the biofilter media, and the lower impedance led to a higher sensor reading.

To evaluate the influence of ammonia-nitrogen and nitrate-nitrogen at comparable concentrations on sensor performance, an ammonium nitrate enriching test (scenario 3) was carried out (fig. 7). In this test, to diminish the influence of other variables (e.g., microbial activity, aging of the woodchips), the MC interval between each operation was increased. Figure 7 suggests that a higher ammonium-nitrate concentration resulted in a higher sensor reading. It indicates that the impedance of the biofilter media was influenced by the combined effects of ammonia-nitrogen and nitrate-nitrogen. However, at this point, the individual contributions of ammonia-nitrogen and nitrate-nitrogen are not clear. This will be determined using statistical analysis.

As a special case, to consider the influence of high nitrogen concentration on the impedance of the biofilter media (scenario 4), biofilter batches were treated with ammonium nitrate enriching at extremely high concentrations (fig. 8). What should be noted is that the pH in figure 8 was the corresponding pH value of the supernatant when measuring the nitrogen concentration, which did not represent the pH value of the biofilter media (solid) during operation. The sensor readings ranged from 4.6 to 28.6. The higher sensor readings compared to those obtained in previous studies indicate that the introduction of nitrogen at a high concentration had a significant impact on the sensor reading. However, there was no significant difference in sensor readings between batch A and batch B. This observation reinforces the importance of considering all the potential variables (MC, ammonia-nitrogen, and nitrate-nitrogen) for sensor readings. In addition, there might be interactions between nitrogen enriching and MC. The pH value is another potential factor because it affects the total ammonia present as un-ionized ammonia and the phase partitioning of ammonia and ammonium (Bower and Bidwell, 1978; Emerson et al., 1975; Jaeschke et al., 1998).

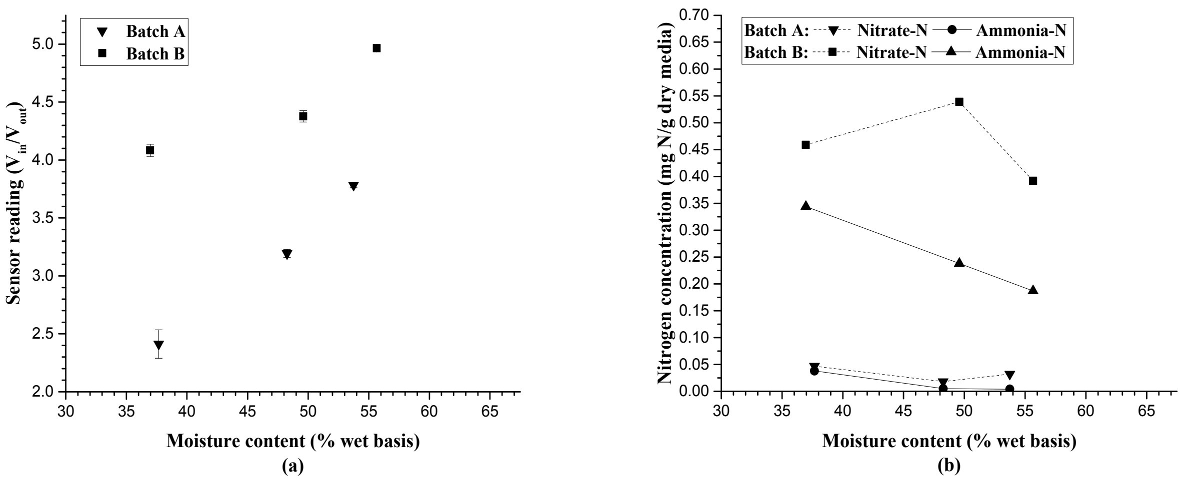

Figure 7. Results of ammonium nitrate enriching: (a) means and standards deviation of sensor readings at varied moisture contents and (b) nitrogen concentrations of biofilter media at varied moisture contents (biofilter batches A and B were treated with nitrate-nitrogen associated with the same ammonia-nitrogen at concentrations of 0.0625 and 0.5 mg per gram of dry biofilter media, respectively).

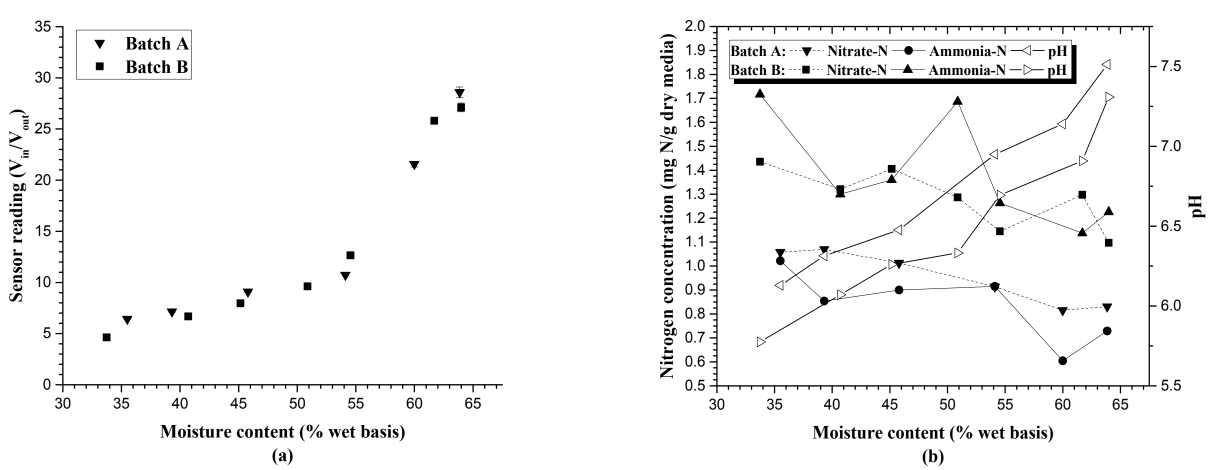

Figure 8. Results of ammonium nitrate enriching: (a) means and standard deviations of sensor readings at varied moisture contents and (b) nitrogen concentrations and pH of biofilter media at varied moisture contents (biofilter batches A and B were treated with nitrate-nitrogen associated with the same ammonia-nitrogen at concentrations of 1.25 and 1.75 mg per gram of dry biofilter media, respectively).

MATHEMATICAL MODEL

The following mathematical model was established to demonstrate the relationship between sensor reading and MC.

Theoretical Assumptions and Validation

The following assumptions were made to simplify the modeling process:

1. The volume fraction of nitrogen was assumed negligible compared to water. The unit of nitrogen concentration in this study was mg N per g dry media. The chemical powder dissolved in the water were negligible.
2. The impedance of the biofilter media was considered as a simple parallel connection of a resistor and a capacitor, and the contribution of the resistor to the impedance was little compared to a capacitor.

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

$$\left|Z_{ref}\right| = \left|\frac{1}{j\omega C_{ref}}\right| = \left|\frac{1}{2\pi\times 10^5\,\text{Hz}\times 10^{-9}\,F}\right| = 1591.5\,\Omega \tag{4}$$

The sensor readings ranged from 2 (35% MC) to 20 (55% MC), corresponding to the impedance of the biofilter media ranging from 1591.5 to 83.7 Ω. The resistance of the biofilter media was calculated based on the conductivity (Zelinka et al., 2008) and equation 5:

$$R = \rho\frac{\lambda}{A} \tag{5}$$

where R is the resistance (Ω), λ is the length of the conductor (m), A is the cross-sectional area of the conductor (m^2), and ρ is the electrical resistivity (Ω·m).

Based on the calculation, the resistance of the woodchips decreased with increasing MC. However, for MC of 35%, the resistance was 10^4 Ω, and for MC of 55%, the resistance was 10^3 Ω. Both values were much higher than the impedance. Because the equivalent impedance of a parallel-connection circuit is determined by the contributor with the smaller value, we may neglect the contribution of resistance. Thus:

$$Z_{biofilter} \approx \frac{1}{j\omega C_{biofilter}} \tag{6}$$

Mathematical Formulation for Correlation of Sensor Reading and Moisture Content

The following equations and their derivation are given:

$$\begin{aligned} reading &= 1+\frac{\left|Z_{ref}\right|}{\left|Z_{biofilter}\right|} \\ &= 1+\frac{\left|\dfrac{1}{j\omega C_{ref}}\right|}{\left|\dfrac{1}{j\omega C_{biofilter}}\right|} = 1+\left|\frac{C_{biofilter}}{C_{ref}}\right| \end{aligned} \tag{7}$$

$$C_{biofilter} = \frac{\varepsilon_{biofilter}A}{d} = b\varepsilon_{biofilter} \tag{8}$$

$$reading = 1+\left|\frac{C_{biofilter}}{C_{ref}}\right| = 1+\left|\frac{b\varepsilon_{biofilter}}{C_{ref}}\right| = 1+\left|c\varepsilon_{biofilter}\right| \tag{9}$$

where

C_{ref} = capacitance of reference capacitor (1 nF in this study, constant)

$C_{biofilter}$ = capacitance of biofilter media

ε = dielectric constant (absolute, not relative)

A = area of plate overlap (constant)

$b = A/d$ (constant)

$c = b/C_{ref}$ (constant)

d = distance between plates (constant).

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

$$\varepsilon_m^a = \Sigma\varepsilon_i^a v_i \tag{10}$$

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.

$$\varepsilon_{biofilter}^{0.5} = \varepsilon_{solution}^{0.5}v_{solution} + \varepsilon_{woodchips}^{0.5}v_{woodchips} \tag{11}$$

$$\begin{aligned} \varepsilon_{biofilter} &= \varepsilon_{solution}v_{solution}^2 \\ &\quad + \varepsilon_{solution}^{0.5}\varepsilon_{woodchips}^{0.5}v_{woodchips}v_{solution} \\ &\quad + \varepsilon_{woodchips}v_{woodchips}^2 \end{aligned} \tag{12}$$

$$\varepsilon_{biofilter} = ev_{solution}^2 + gv_{solution} + h \tag{13}$$

where e, g, and h are constants.

Because

$$\text{MC} = \frac{M_{water}}{M_{total}} \tag{14}$$

$$v_{solution} = \frac{\dfrac{M_{solution}}{\rho_{solution}}}{\dfrac{M_{total}}{\rho_{total}}} = \frac{\dfrac{M_{water}}{\rho_{water}}}{\dfrac{M_{total}}{\rho_{total}}} = i\text{MC}\rho_{total} \tag{15}$$

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

$$\rho_{total} = k\text{MC} \tag{16}$$

$$\begin{aligned} reading &= 1+\left|c\varepsilon_{biofilter}\right| \\ &= 1+\left|cev_{solution}^2 + cgv_{solution} + ch\right| \end{aligned} \tag{17}$$

$$\begin{aligned} reading &= 1+\left|ce\left(ik\text{MC}^2\right)^2 + cg\left(ik\text{MC}^2\right) + ch\right| \\ &= l\text{MC}^4 + m\text{MC}^2 + n + \delta \end{aligned} \tag{18}$$

where i, k, l, m, and n are constants, and δ refers to potential factors other than the MC of the biofilter media.

The sensor reading can be expressed as a function of MC (eq. 18). This is the first demonstration of the relationship between sensor reading and MC. Moisture content can be determined directly from equation 18 based on the sensor reading if the effects of nitrogen content are ignored.

Statistical Analysis

With the measured data, a multiple linear regression statistical method was employed to determine the relationship among sensor reading, MC, and nitrogen loading. Two approaches were tested to explore the influence of ammonia-nitrogen and nitrate-nitrogen on the sensor reading.

The first approach was to identify the respective influences of ammonia-nitrogen and nitrate-nitrogen. The independent variables were ammonia-nitrogen concentration (ANC), nitrate-nitrogen concentration (NNC), the square of the moisture content (MC^2), and the fourth order of the moisture content (MC^4). The dependent variable was the sensor reading (SR). The second approach was to identify the influence of total nitrogen concentration as well as the dominant nitrogen form. The independent variables were the sum of the ammonia-nitrogen concentration and nitrate-nitrogen concentration (TNC), the ratio of nitrate-nitrogen to ammonia-nitrogen (RNC), the square of the moisture content (MC^2), and the fourth order of the moisture content (MC^4). The dependent variable was sensor reading (SR). These statistical approaches can be expressed as:

$$SR = o\text{ANC} + p\text{NNC} + q\text{MC}^2 + r\text{MC}^4 + s \tag{19}$$

$$SR = o\text{TNC} + p\text{RNC} + q\text{MC}^2 + r\text{MC}^4 + s \tag{20}$$

where o, p, q, r, and s are constants. The coefficients of the fourth-degree polynomial function and the statistical significance of the coefficients are shown in tables 2 and 3.

For approach 1, the coefficients show that increased ANC and MC resulted in a significantly higher sensor reading, while loading with NNC slightly decreased the sensor reading. Based on this model, the predicted and observed sensor readings are plotted in figure 9a. For sensor readings less than 13, the predicted sensor reading agreed with the observed sensor reading, which indicated that this fourth-degree polynomial function was accurate and can estimate the relationship among sensor reading, MC, and the two forms of nitrogen as well as their concentrations. For approach 2, the coefficients show that increases in both MC and total nitrogen concentration resulted in a significantly higher sensor reading, but the ratio of different nitrogen forms did not have any significant impact on the sensor reading. Figure 9b shows the predicted sensor reading and observed sensor

Table 2. Coefficients of fourth-degree polynomial and statistics significance for approach 1 (multiple R^2 = 0.873).

Parameter	Estimate	SE	t-Value	Pr (>|t|)	Significance
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	***

Table 3. Coefficients of fourth-degree polynomial and statistics significance for approach 2 (multiple R^2 = 0.837).

Parameter	Estimate	SE	t-Value	Pr (>|t|)	Significance
Intercept	4.091e+00	9.314e-01	4.393	4.54e-05	***
Total N conc.	1.692e+00	6.476e-01	2.612	0.011307	*
Ratio N conc.	-6.431e-02	3.799e-02	-1.693	0.095551	
MC^2	-3.131e-03	9.044e-04	-3.462	0.000986	***
MC^4	1.254e-06	1.852e-07	6.771	5.73e-09	***

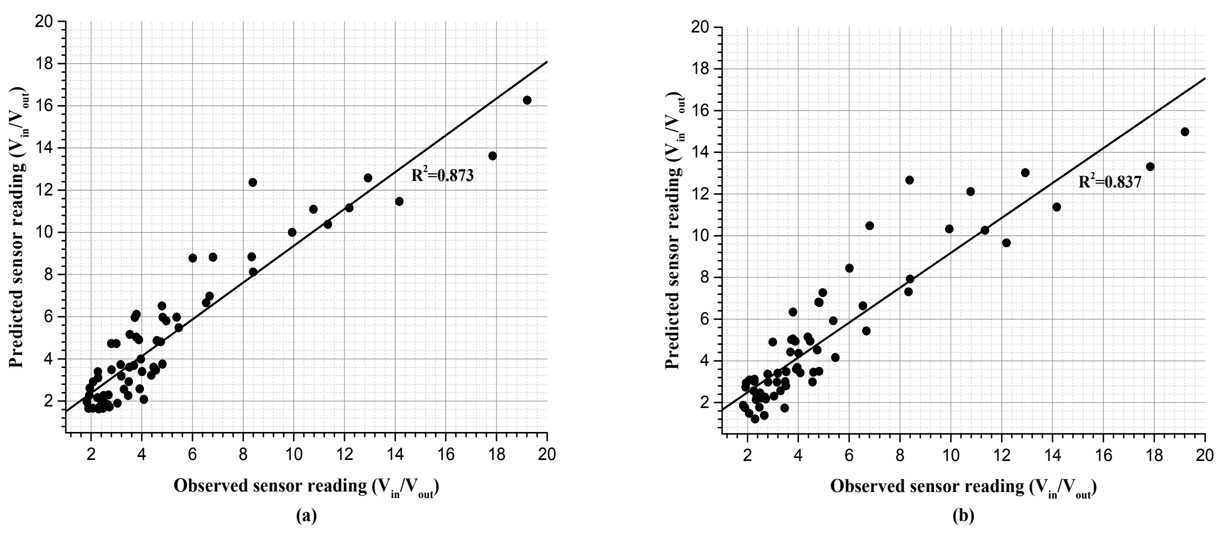

Figure 9. Comparison of predicted sensor readings and obtained sensor readings: (a) approach 1, which correlated moisture content, ammonia-nitrogen concentration, and nitrate-nitrogen concentration; and (b) approach 2, which correlated moisture content, the sum of ammonia-nitrogen and nitrate-nitrogen concentrations, and the ratio of nitrate-nitrogen to ammonia-nitrogen concentrations.

reading based on the above regression. Overall, the results of the statistical regression suggest that all the sensor readings in this investigation were influenced by MC and different forms of nitrogen. Approach 1, which correlated sensor reading with MC, ammonia-nitrogen concentration, and nitrate-nitrogen concentration with high multiple R^2 (R^2 = 0.873), was the better approach for the calibration of sensor performance.

Conclusion

Particle size distribution of the biofilter media was shown to directly affect impedance-based moisture sensing. The concentration of different forms of nitrogen (ammonia-nitrogen and nitrate-nitrogen) in the biofilter media was found to significantly impact the biofilter media impedance. Impedance of the biofilter media was negatively related to increased ammonia-nitrogen concentration but positively related to increased nitrate-nitrogen concentration. A mathematical model was established to couple the sensor reading with the moisture content (MC). This is the first time that a model has been developed to describe the relationships among these variables. A statistical model showed that MC, ammonia-nitrogen, and nitrate-nitrogen determined the sensor reading with an acceptable predictive power (R^2 = 0.873). These results are useful for designing accurate biofilter moisture monitoring and control systems to keep biofilters in a good working condition.

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