Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Scientific Paper
Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v43n4e20230062/2023

EVALUATION OF AMMONIA SENSOR MODULES IN A COMPOST BARN SYSTEM DURING WINTER IN BRAZIL

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KEYWORDS

Intensive system, dairy cattle, ammonia concentration, characterization, electrochemical sensors.

ABSTRACT

This study aimed to characterize the performance of three electrochemical ammonia sensor modules (MQ137, FECS44-100, and MIX2801) in comparison to standard equipment (iPMU) under atmospheric conditions of an open Compost Barn (CB) during the winter period in Brazil. The study was conducted in Cajuri (MG) over three days, collecting data from 06 am to 05 pm on ammonia concentration, temperature, relative humidity, and air velocity in the CB, specifically at the center of the bedding area. The evaluation period was divided into three parts: Period 1 (06 to 09 am); Period 2 (10 am to 01 pm); and Period 3 (02 pm to 05 pm). Recorded data were analyzed using descriptive statistics. It was observed that the greatest discrepancy among the readings occurred in Period 1 (for all sensor modules and the iPMU), due to air saturation conditions. In Periods 2 and 3, readings from the sensor modules closely matched those recorded by the iPMU. Throughout all periods, the MIX2801 showed the most significant discrepancies compared to the iPMU, whereas the MQ137 was the closest to the standard equipment. This finding suggests that the MQ137 is a viable option for use in CB facilities.

INTRODUCTION

The Brazilian agricultural sector is a cornerstone for food security both within the nation and globally, playing a crucial role in the country's efforts to address climate change and fulfill its commitments to the United Nations Framework Convention on Climate Change (MMA, 2021). As per the Food and Agriculture Organization, in 2022, Brazil produced approximately 34.801 billion liters of milk, positioning the nation as one of the top global milk producers (FAO, 2022).

To achieve this level of milk production, Brazil had to make significant advancements in genetics, nutrition, management, and the overall production environment by embracing new technologies. Among these technologies, intensive confinement systems for livestock have emerged as a primary strategy to enhance productivity, milk quality, and the health of the confined animals (Perissinotto & Moura, 2007; Passetti et al., 2016; EMBRAPA, 2020).

Over the past decades, the Compost Barn (CB) system, initially designed for temperate climates, has gained traction among Brazilian producers (Eckelkamp et al., 2016; Damasceno, 2020; Leso et al., 2020). Given its origin, its application in Brazilian tropical and subtropical climates warrants further research to better understand its functionality and adaptability to the open-shelter typology commonly found in the country (Damasceno, 2020).

Facilities used for intensive animal production are significant sources of ammonia (NH_3) emissions. With increased confinement, there is a higher deposition of excreta due to a larger number of animals per area unit (Drewry et al., 2018; Ngwabie et al., 2009; Owen & Silver, 2015). Animal excreta contains ammoniacal nitrogen, with typically around 20% of the total volume being volatilized as NH_3 within confinement facilities (EEA, 2016; Sommer et al., 2019).

Ammonia is a hazardous air pollutant linked to the formation of inhalable particulate matter ($IPM_{2,5}$), soil

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Area Editor: Héliton Pandorfi
Received in: 4-13-2023
Accepted in: 9-14-2023

acidification, eutrophication and degradation of water resources, and potential irritations and lesions to the mucous membranes of animals and workers (Koerkamp, 1994; Pushkarsky et al., 2003; Wu et al., 2016; Naseem & King, 2018; Liu et al., 2020). Therefore, it is crucial to measure its concentrations and emissions within animal confinement facilities. This helps in compiling emission inventories for the dairy sector and in devising mitigation strategies (Hassouna et al., 2016; Insausti et al., 2020).

Ammonia concentration can be gauged using sensor modules operating on various principles (chemiluminescence, photoacoustic, and electrochemical). Sensors should be chosen based on environmental characteristics since each device has specific measurement ranges. Other technical aspects, such as operational speed, measurement range, precision, reliability, selectivity, dimensions, and acquisition costs, should also be considered (Insausti et al., 2020; Bielecki et al., 2020).

Given this background, determining the right sensor module for a CB facility must consider the environmental variables it will be exposed to, like dry bulb temperature, relative air humidity, and ammonia concentration. Accordingly, this study aims to characterize the performance of different electrochemical ammonia sensor modules (MQ137, FECS44-100, and MIX2801) compared to standard equipment (iPMU) in the atmospheric conditions of an open CB during the Brazilian winter.

MATERIAL AND METHODS

Description and characterization of the Compost Barn (CB) facility

The experiment was conducted in an open CB-type dairy cattle confinement facility with positive pressure ventilation. The facility is in the *Zona da Mata Mineira* in the municipality of Cajuri (MG), at latitude 20° 46’ 41” S, longitude 42° 48’ 51” W, and an altitude of 670 m. According to Köppen's climate classification, the local climate is *Cwa* — mesothermal subtropical climate (Sá Júnior et al., 2012). As per the records from the nearest meteorological station (83648) by the National Institute of Meteorology (INMET) from 1991 to 2020, the following were noted: minimum, average, and maximum dry bulb air temperatures of 2.0°C (July), 20.3°C, and 38.0°C (October) respectively; minimum, average, and maximum relative air humidity of 15.0% (October), 79.4%, and 100.0% (January) respectively; and minimum, average, and maximum monthly accumulated rainfall of 8 mm (July), 105 mm, and 266 mm (December) respectively (INMET, 2023).

The CB facility where the study was conducted has its ridge oriented in the Southeast-Northwest direction and features the following characteristics: 60.0 m length; 27.6 m width; 5.0 m eave height; 2.2 m eave depth; 33 reinforced concrete pillars; double-sloped metal roof with a central opening, covered with metal tiles (slope of 22%); bedding area of 14.4 x 60.0 m; feeding alley of 4.2 x 60.0 m; drive-through alley of 4.6 x 60.0 m; service alley of 2.2 x 39.0 m; feeding area consisting of a continuous trapezoidal feed bunk (ceramic-coated) spanning the entire length of the barn in the feeding alley; and four tipper drinkers installed on walls opposite the feed bunk, each measuring 0.5 x 2.0 m (Figure 1a).

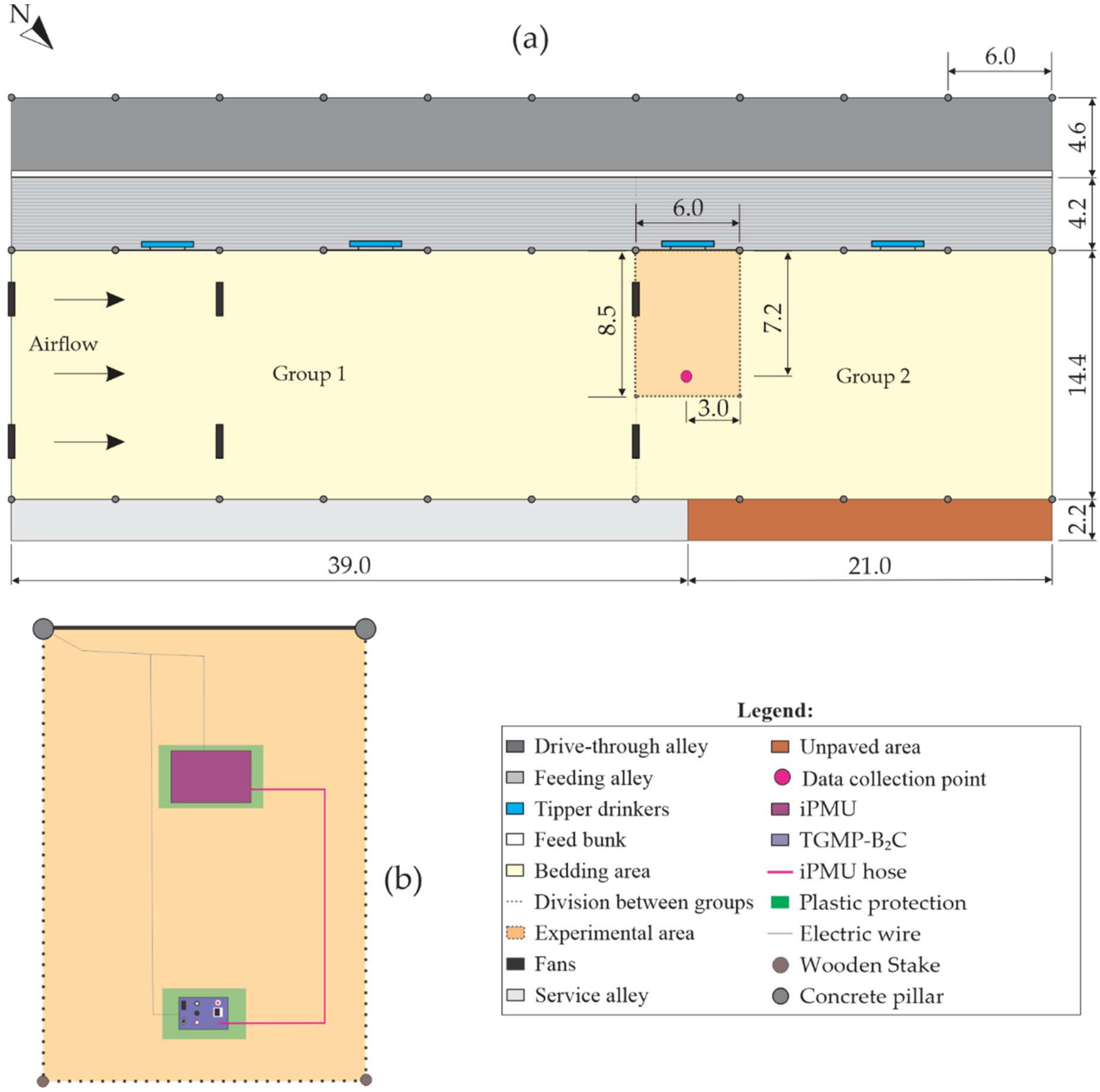

FIGURE 1. Schematic representation of the (a) floor plan of the Compost Barn facility and location of data collection point (measurements in meters) and (b) detail of the experimental area focusing on equipment arrangement (off scale).
Source: The Authors (2023).

The material used for the bedding in the CB system was a mixture of wood shavings (particle diameter from 8.0 to 25.0 mm) and sawdust (particle diameter less than 8.0 mm) from *Eucalyptus*, in equal proportions. The replenishment of this material was based on the moisture content of the bedding, following the regular management of the facility without interfering in the process. The average depth of the bedding was 0.60 m. A scarifier combined with a clod-breaking roller was used for the turning process. This operation was performed twice a day, starting at 05 am and 06 pm, and lasting fifteen minutes each time.

The barn was ventilated by positive pressure using six low-volume and high-rotation fans (Figure 1a), which were continuously turned on. These fans were installed 3.0 m above the bedding and tilted at 45° to the horizontal. Two three-blade fans (1.52 m in diameter, 1.5 hp, and an airflow of 86000 $m^3 \cdot h^{-1}$) were aligned with the first row of pillars (Southeast face), and the other four six-blade fans (1.53 m in diameter, 2.0 hp, and an airflow of 55000 $m^3 \cdot h^{-1}$) were installed on the third and seventh rows of pillars, as illustrated in Figure 1. The average prevailing wind direction in the region was 15° relative to the North (INMET, 2023).

In total, 80 Holstein cows (purebred, average weight of 600 kg, in the lactation phase) were confined in the facility. These animals were divided into two groups. In Group 1, the higher-producing animals were housed, and in Group 2, the lower-producing animals. The animals had free access to the feed bunk and the tipper drinkers. The complete diet was provided to the cows three times a day (08 am, 12 pm, and 02 pm), totaling 46.20 $kg.animal^{-1} \cdot day^{-1}$ for Group 1 and 43.20 $kg.animal^{-1} \cdot day^{-1}$ for Group 2. The diet was formulated by the farm's zootechnician and consisted of corn silage, cornmeal, soy, and cottonseed. Milking was performed twice a day (05 am and 05 pm) with an average total duration of two and a half hours for each milking session.

The research was submitted and approved by the Ethics Committee of the Federal University of Viçosa (Process 04/2021). All experimental procedures were based on the guidelines established by the mentioned committee.

Development of the thermal and aerial monitoring platform

Air dry-bulb temperature (T_{bs_i}), relative humidity ($UR_{\_i}$), air velocity (V_{ar_i}), and ammonia concentration ($C_{\_NH3\_i}$) were measured inside the CB facility using the Thermal-Gas Monitoring Platform Brazil-Colombia (TGMP-B_2C). This platform monitors thermal and aerial variables in animal production facilities. The TGMP-B_2C had sensor modules attached to record the following environmental variables:

• Air dry-bulb temperature and relative humidity: STH31 (Sensiron Co., Switzerland) – 2.2-5.5V, 0-90°C (±0.2) & 0-100% humidity (±0.2);

• Air velocity: Rev. P (Modern Device, USA) – 9.0-12.0V, 0-67 $m \cdot s^{-1}$ (±0.1);

• Ammonia concentration (three sensors): MQ137 (Hanwei Co., China) – Electrochemical, 5V (±0.1), 1-200 ppm (±3%); MIX2801 (Mixsen, China) – Electrochemical, 5V (±0.1), 0-30 ppm (±0.01); and FECS44-100 (Figaro Engineering Inc., Japan) – Electrochemical, 5V (±0.2), 0-100 ppm (±1).

Data collection

The experiment was conducted in July 2022, during winter, at the CB facility over three days. Its goal was to assess the three ammonia sensors of TGMP-B_2C under the conditions of the facility. We used the iPMU (Intelligent Portable Monitoring Unit), equipped with the Honeywell EC-FX-NH_3 sensor, as a reference for ammonia concentration. This device is a renowned global standard in animal housing facilities.

Figure 1b shows the positioning of both TGMP-B_2C and iPMU within the facility. The study area, similar to other bedding zones, was fenced to keep animals out. TGMP-B_2C recorded T_{bs_i}, UR_i, Var_i, and NH_3 levels, while iPMU measured the standard ammonia concentration.

Data points were strategically placed for accuracy, as depicted in Figure 1a. Collections occurred from 06 am to 05 pm for three days. Both devices, positioned at bedding height, were activated at 05:30 am. TGMP-B_2C logged data every 10 seconds, while iPMU followed an hour-long cycle of sampling, purging, and resting. During purging, the hose of iPMU was placed 25 meters outside the facility, ensuring clean air intake.

Data analysis

In the TGMP-B_2C, data collection was conducted every 10 seconds. The obtained data were then filtered, selecting only those recorded at times when data was also collected by the iPMU (which collected data every 10 minutes). The data were organized into three different periods throughout the day: Period 1 (06 to 09 am), Period 2 (10 am to 01 pm), and Period 3 (02 pm to 05 pm).

Descriptive statistics, including maximum, minimum, average values, and standard deviation, were employed for comparative analysis, visualized through boxplot graphs (Cooksey, 2020). The analyses were performed using the Python language, through the interactive literary programming interface tool Jupyter Notebook from Anaconda Navigator (Jupyter, 2022). In this tool, functions from the Pandas (Numfocus Inc., 2022) and Matplotlib (Matplotlib Org., 2022) libraries were used to manipulate, investigate, and extract statistical information of interest. For the creation of the boxplot graphs, the Seaborn library (Waskom, 2022) was used.

RESULTS AND DISCUSSION

Characterization of the environmental variables in the CB facility to which sensor modules were exposed

Figure 2 presents the curves corresponding to hourly averages of internal dry-bulb temperature in the cow housing facility (T_{bs_i}), internal relative humidity ($UR_{\_i}$), and internal air velocity (V_{ar_i}). These values indicate the conditions the equipment was exposed to throughout the experimental period.

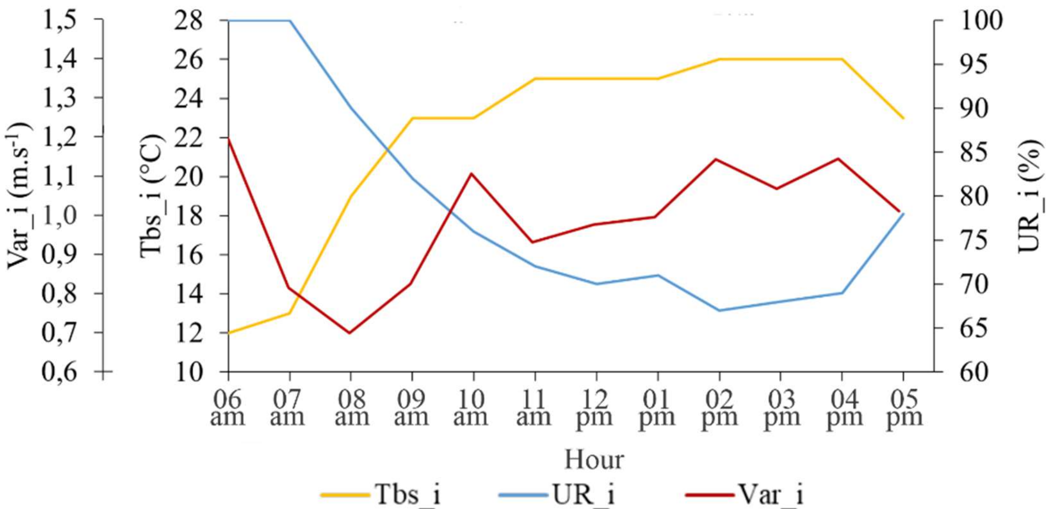

FIGURE 2. Distribution curves of hourly averages during the experiment for dry-bulb temperature (T_{bs_i}), relative air humidity ($UR_{\_i}$), and air velocity (V_{ar_i}) inside the facility.
*Data collected using TGMP-B_2C (T_{bs_i}, $UR_{\_i}$, and V_{ar_i}).

As depicted in Figure 2, throughout the evaluated period, the variation of T_{bs_i} was 14.0°C. The lowest value was recorded at 06 am (12.0°C), and the peak occurred between 02 pm and 04 pm (26.0°C). The early monitoring hours saw a rapid increase in T_{bs_i}. By 07 am, the average temperature was recorded at 13.0°C, and by 09 am, the sensors registered 23.0°C (a thermal amplitude of 10.0°C). After reaching 23.0°C at 09 am, T_{bs_i} remained stable until the end of the data collection at 05 pm, during which the thermal amplitude was 3.0°C. It is noteworthy that the hottest period was between 12 pm and 04 pm, with T_{bs_i} fluctuating between 25.0°C and 26.0°C. Conversely, the coolest interval was between 06 am and 08 am, with T_{bs_i} ranging from 13.0°C to 19.0°C (Figure 2).

As seen in Figure 2, the behavior of $UR_{\_i}$ during the assessment period was decreasing. It reached saturation (100.0%) in the early hours and gradually decreased to an average minimum of 67.0% by 02 pm. This means the $UR_{\_i}$ amplitude was 33.0% during the assessed period. Importantly, $UR_{\_i}$ values throughout the day displayed an inverse pattern to T_{bs_i}, that is, as T_{bs_i} rose, $UR_{\_i}$ declined.

From Figure 2, V_{ar_i} during the assessment period ranged from 0.70 to 1.20 $m \cdot s^{-1}$, with a daily average of 0.95 ± 0.22 $m \cdot s^{-1}$. Notably, the lowest V_{ar_i} values were recorded between 08 and 9 am, during which there was a significant drop in V_{ar_i} compared to other times of the day.

Hourly behavior of ammonia sensor modules

Figure 3 illustrates the behavior of the ammonia sensors throughout the experimental day.

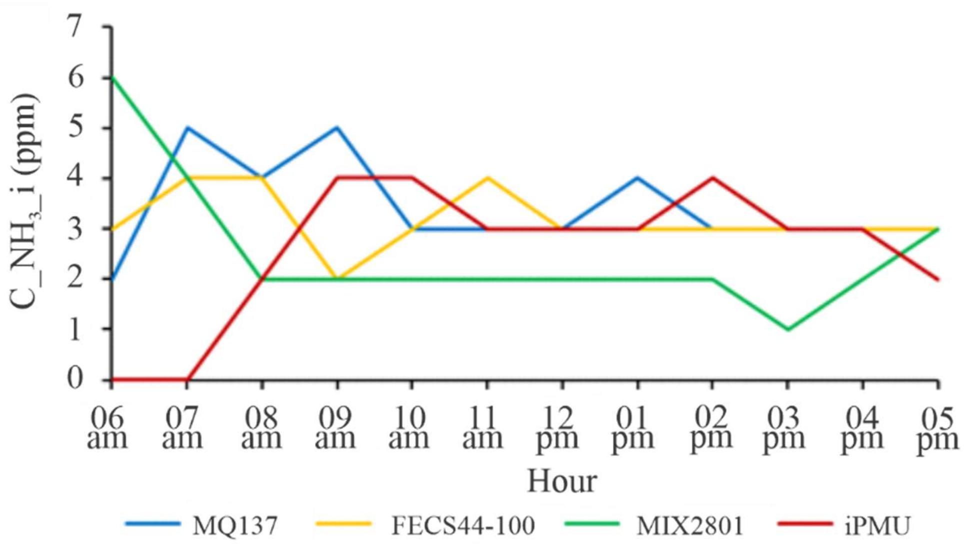

FIGURE 3. Hourly curves of ammonia concentration ($C_{\_NH3\_i}$) determined by the MQ137, FECS44-100, MIX2801, and iPMU sensor modules.

As shown in Figure 3, during the early evaluation hours (06 to 07 am), the MQ137, FECS44-100, and MIX2801 sensor modules displayed measurements differing from the iPMU (standard equipment). This variation was evident in the distancing of the three sensor curves from the iPMU curve. During this period, $UR_{\_i}$ (Figure 2) was at the saturation point (100%), therefore, the ammonia sensor modules might have been influenced by this condition, as it is deemed as inadequate by technical manuals for the tested equipment (Winsen, 2015, Ji et al., 2016, Figaro, 2021, Mixsen, S.D.). These guidelines define a maximum operational limit of 90% for humidity.

This influence of $UR_{\_i}$ on the sensor measurements became more pronounced as the day progressed. As hours went by, $UR_{\_i}$ decreased, a T_{bs_i} increased, and under these changing conditions, the ammonia sensor module readings became more stable and closer to each other (after 09 am), which is highlighted by the convergence of curves (Figure 3).

Notably, iPMU did not record any ammonia concentration (0.0 ppm) from 06 to 07 am. This was unexpected since ammonia emissions inside animal facilities are constant (Damasceno, 2020); yet the other sensor modules detected the gas. Therefore, iPMU might not have responded adequately under high humidity conditions inside the CB facility. Nonetheless, this behavior has not been reported in other literature-based studies conducted in poultry houses (Ji et al., 2015, Ji et al., 2016, Xiong, 2019, Zheng et al., 2020, Dotto et al., 2022).

Comparing the responses of MQ137 with those of the iPMU, we observed that the largest differences in $C_{\_NH3\_i}$ measurements were between 06 am and 09 am (Figure 3). After 09 am, the readings from these two sensors became closer, with a maximum difference of 1.0 ppm until the end of data collection at 05 pm. This indicates that the MQ137 could potentially be recommended for use in the TGMP-B_2C, especially given its cost-effectiveness. However, further tests are needed to study its responses to different environmental conditions, such as across diverse temperatures and humidity. These tests can be conducted using climate chambers or field tests across seasons. Overall, although current results show MQ137 works well under field conditions at CB facilities, more tests are required for wider environmental ranges.

Similarly, when comparing the results from FECS44-100 with those of the iPMU, it demonstrated a behavior similar to the MQ137. During the early hours (06 to 09 am, Figure 3), there was a notable difference between FECS44-100 and iPMU readings. However, after 10 am, both devices showed closer measurements, with a difference no greater than 1.0 ppm until 05 pm. Therefore, the FECS44-100 sensor performed similarly to the standard device and may be a good alternative for TGMP-B_2C. The main concern is its cost, around $1000 in 2022, including shipping fees.

On the other hand, the MIX2801 sensor showed the most significant discrepancies in its readings throughout the day when compared to the iPMU (Figure 3). The largest differences were observed between 6 and 11 am, whereas between 11 am and 01 pm it was reduced (1 ppm). These initial findings suggest that this sensor might not be the most suitable for the TGMP-B_2C. Further testing and experiments are still recommended to evaluate its performance under varying conditions.

The behavior of ammonia sensor modules over the experimental period

Figure 4 illustrates the performance of the three ammonia sensor modules (MQ137, FECS44-100, and MIX2801) attached to TGMP-B_2C, compared to the iPMU (standard) during the experiment.

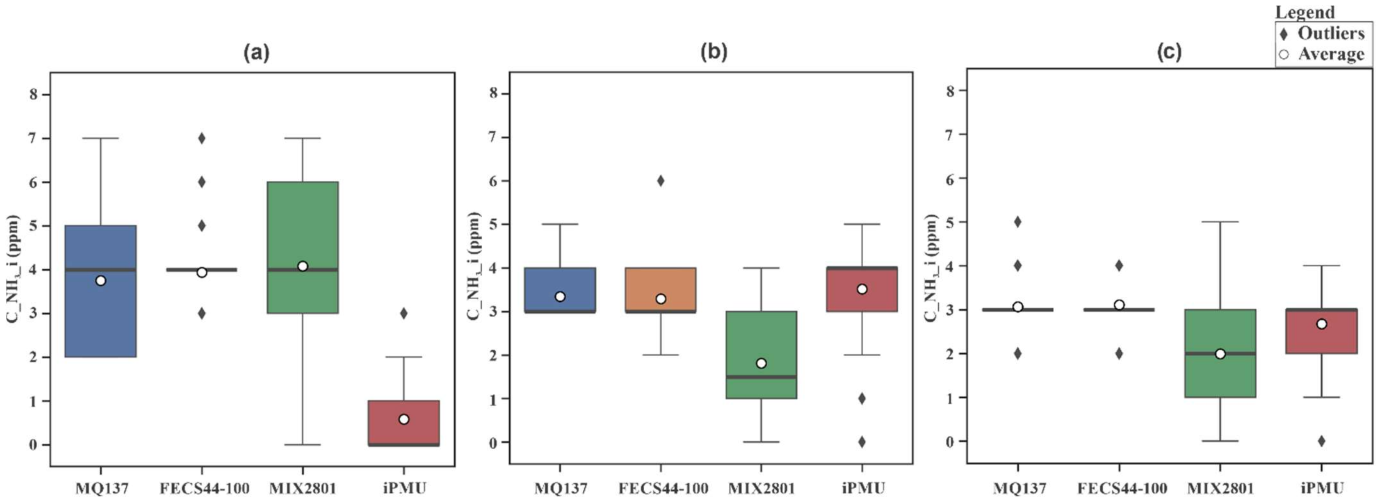

FIGURE 4. Boxplot charts illustrating the behavior of sensor modules throughout the experimental period [ammonia concentration ($C_{\_NH3\_i}$) versus ammonia sensor modules] for the following time slots: (a) 1 (06 am to 09 am), (b) 2 (10 am to 01 pm), and (c) 3 (02 pm to 05 pm).

For Period 1 (06 am to 09 am, Figure 4a), the MQ137, MIX2801, FECS44-100 sensors, and the iPMU showed similar results with average ammonia concentrations of 3.9 ppm, 4.0 ppm, 4.1 ppm, and 0.6 ppm, respectively. The FECS44-100 sensor data did not vary (Figure 4a), recording a value of 4.0 ppm. This could suggest the sensor did not adequately detect ammonia concentration fluctuations in the environment. However, this was unexpected given its technical specifications tout better accuracy and sensitivity.

Comparing the three sensors attached to TGMP-B_2C (MQ137, MIX2801, FECS44-100) with the iPMU results, discrepancies were found. The iPMU reported lower values, averaging 0.6 ppm. This divergence might relate to a technical issue with the iPMU during times when relative humidity exceeded 90%. It is worth noting this pattern persisted throughout the data collection days. Whenever $UR_{\_i}$ approached saturation, the iPMU readings deviated from the other sensor readings. Surprisingly, this outcome was not anticipated since all technical specifications for dry bulb temperature and relative humidity were met by the ammonia sensor in the iPMU throughout the experiment, and no previous study has reported such behavior.

In Period 1, the MQ137 and MIX2801 sensors behaved most similarly (Figure 4a), with average readings (3.9 and 4.1 ppm, respectively) and reading ranges (7.0 to 2.0 ppm and 7.0 to 0.0 ppm, respectively) close to each other. However, since their values differed from the iPMU readings (average of 0.6 ppm and reading range from 2.0 to 0.0 ppm), their accuracy for this period could not be confirmed. Hence, new tests and experiments must be conducted under high humidity conditions.

During Period 2 (10 am to 01 pm, Figure 4b), the sensors experienced less environmental variation (Figure 2) with reduced value ranges. Tbs_i and UR_i in Period 1 varied at 11°C and 18%, while in Period 2 variations were 2°C and 6%, respectively. As observed in Figure 4, the sensor readings were more consistent during this period, in which recorded average data and reading intervals were 3.3 ppm and from 5.0 to 3.0 ppm for MQ137, 3.3 ppm, and from 4.0 to 2.0 ppm for FECS44-100, of 1.9 ppm and from 4.0 to 0.0 ppm for MIX2801, and of 3.5 ppm and from 5.0 to 2.0 ppm for iPMU. Therefore, the iPMU readings were similar to the FECS44-100 and MQ137 readings. However, the MIX2801 sensor exhibited more variation (Figure 4b), indicating potentially poorer performance.

In Period 3 (01 pm to 05 pm, Figure 4c), environmental conditions resembled those of Period 2 (T_{bs_i} and $UR_{\_i}$ ranging in 3°C and 11%). This reflected the behavior of the sensors since the result in Period 3 was like that in Period 2.

According to Figure 4c, the MIX2801 sensor showed the most considerable reading range (5.0 to 0.0 ppm) and the lowest ammonia concentration reading (2.0 ppm). These results differed the most from the other sensors. MQ137, FECS44-100, and iPMU showed reading ranges of 3.0 to 3.0 ppm, 3.0 to 3.0 ppm, and 4.0 to 1.0 ppm, and readings of 3.0, 3.0, and 2.8 ppm, respectively. Such a significant difference could indicate less accurate results from MIX2801. Still, its readings fell within the measurement range of iPMU. Therefore, new tests under varying conditions using different comparison methods are needed to fully characterize this sensor module.

It is essential to note that the MQ137 and FECS44-100 sensors did not vary in Period 3 (Figure 4c) since outliers were discarded, both recording 3.0 ppm. This behavior was also observed in Period 1 for FECS44-10 data. The measurement intervals and averages from the MQ137 and FECS44-100 sensor modules in Period 3 were close to the values and ranges determined by the iPMU, unlike what occurred in Period 1 (Figure 4a). Despite their readings being close to those of iPMU during Period 3, they did not capture the variation noted by the iPMU. This could be attributed to technological differences between the devices.

In Period 3 (Figure 4c), the MQ137 and FECS44-100 sensors matched the iPMU (standard) results more closely than MIX2801. This suggests that, of the three sensors evaluated, MIX2801 was less accurate under these conditions. New tests are recommended, as environmental factors can significantly impact sensor performance (Gates et al., 2005, Li et al., 2005, Casey et al., 2010, Saraz et al., 2013, Winsen, 2015, Ji et al., 2016, Figaro, 2021, Mixsen, S.D.).

Price-wise, the MQ137 was cheaper than the other sensors, ranging from \$10 to \$40 in 2022, depending on quantity, manufacturer, and supplier. The MIX2801 was pricier at around \$100 in 2022, considering import and shipping costs. The FECS44-100 was the most expensive, sold at \$1000 in 2022.

Comparing the three sensors with iPMU results, the FECS44-100 and MQ137 were closest to the iPMU readings throughout the day. Thus, under the experimental conditions, the MQ137, given its performance and lower cost, appears more viable than the FECS44-100. However, potential users should be aware of its complex handling, installation, and programming, requiring more specialized labor.

Considering the microclimatic conditions evaluated, our findings highlighted that the MQ137 sensor is the most suitable for TGMP-B_2C. However, clarity is lacking for other atmospheric conditions, underscoring the need for more research. Future experiments should expose sensors to different environments, which can be done using climate chambers. Field exposure is also crucial, as contact with other gases or dust can influence results (Winsen, 2015, Ji et al., 2016, Figaro, 2021, Mixsen, S.D.).

CONCLUSIONS

This study enabled characterizing the functioning of three different ammonia sensor modules (MQ137, FECS44-100, and MIX2801), in comparison with a standard equipment (iPMU), under atmospheric conditions of a Compost Barn (CB) facility during the winter season in Brazil.

Relative humidity can impact the results shown by electrochemical sensor modules, and situations, where environmental variables exceed the recommendations stated in technical manuals, may lead to undesirable behaviors, as observed during Period 1. In this regard, it is essential to emphasize the importance of tailoring the equipment type to the specific environment in which it will be deployed.

The ammonia sensor module that proved most viable for use in CB facilities during winter was the MQ137. It displayed results close to those recorded by the iPMU and comes at a significantly lower cost, roughly 5% of those of FECS44-100 (\$1000). However, it is worth noting that, despite the recommendation for the MQ137, this suggestion is based on specific conditions. Therefore, further studies should be conducted covering different dry bulb temperatures, relative humidity, and air velocity, as well as exposure to various gases.

ACKNOWLEDGMENTS

The authors express their gratitude to the Federal University of Viçosa and AMBIAGRO (Research Center on Ambience and Agro-industrial Systems Engineering) for their support in the development of this study. Additionally, we thank CNPq (National Council for Scientific and Technological Development) and CAPES (Coordination for Improvement of Higher Education Personnel – Finance code 001) for their financial support and for granting research scholarships.

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