Construction and Validation of a Low-Cost System for Indoor Air Quality Measurements in Livestock Facilities

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Abstract. In recent years, there has been an increase in demand for food of animal origin. The number of intensive production systems such as pig and poultry farming has been increasing more and more and exerting great impacts on the environment, due to a large amount of particulate material and gaseous pollutants that are generated within these facilities. Thus, low-cost devices emerge as a cheap alternative that provides farmers with information on indoor air quality in its facilities. However, it is important that these devices make precise and accurate measurements, providing reliable concentration readings. Therefore, the objective of this study is the construction and validation of a low-cost system capable of measuring, storing and sending, via the mobile network, the concentrations of hydrogen sulfide, ammonia, carbon dioxide, $PM_{2.5}$, PM_{10}, temperature, and relative humidity. Preliminary inter-comparison tests showed that the built system had a reliable behavior in relation to all variables, even though the CO_2 sensor was the one with the highest determination coefficient. The built device is able to provide continuous monitoring of atmospheric pollutants concentrations, at low cost and with simple handling.

Keywords: Livestock, Sensors, Indoor Air Quality.

1 Introduction

In spite of the large adaptation of the intensive production, many livestock buildings such as those adopted successfully in monogastric species (e.g., pigs and poultries) are concentrated in a single point [1]. Between 1961 and 2017, there was a worldwide increase in pig production from 400 million to almost 1 billion heads per year, while poultry production rose from 3.9 to 22.8 billion annually [2].

These intensive production systems have increasingly impacted the environment, with the emission of greenhouse gases (GHG's) [3], as well as contributing to the contamination of the outdoor and indoor air, due to the emission of pollutants as ammonia (NH_3) [4], particulate matter less than 10 μm ($PM_{2.5}$, PM_{10}) [5], hydrogen sulfide (H_2S) [6] and carbon dioxide (CO_2) [7].

Long-term exposures to these substances within these livestock facilities can cause respiratory complications in agricultural workers as well as in the animals living there, which can result in severe diseases [8]. Many studies report the importance of the use of indoor air quality (IAQ) measurement and control devices, in order to determine the concentrations of pollutants and to develop mitigation measures and technologies [9].

Despite the importance of monitoring indoor levels of those pollutants, the conventional solutions (e.g., gas analyzers, dust monitors) can often reach acquisition costs, routine calibration and maintenance exceeding tens of thousands of euros, requiring also large spaces for their installation as well as skilled labor, which dissuades facilities managers to perform regular monitoring [10][11].

In this context, the use of low-cost devices can bring with them innovative contributions, such as the integration of these systems into a wide network of sensors and computational technologies, and, therefore, facilitating the detection of pollutants present in the indoor air of livestock facilities [10][12]. One of the great advantages of low-cost gas sensors is the wide variety of options available on the market, being catalytic, thermal, electrochemical, optical, infrared, semiconductors and surface acoustic wave type sensors, and its different performance characteristics, such as sensitivity, selectivity, detection limit, response time, among others aspects [13].

An important feature that must be considered when constructing indoor air pollutant monitoring systems with low-cost sensors is the cross-sensitivity between interfering gases and the gas of interest. As shown in the literature [14], the development of many gas detection systems is limited because the sensors are susceptible to undergo interferences from other gases. Therefore, because they are low-cost devices, inadequate values of pollutants can be measured, deceiving system users and limiting their use in higher precision applications. In such cases it is necessary to validate the sensors, performing calibrations in the laboratory and in the facilities, using statistical procedures to guarantee product quality [15].

Therefore, the objective of this work is the construction and validation of a system composed of a network of low-cost integrated sensors for pig and poultry facilities capable of remotely registering, storing and sending data to a server of the concentrations of pollutants obtained over time.

2 Device architecture

For the construction and development of the low-cost monitoring system, semiconductor, electrochemical and optical sensors were integrated to detect the gases of interest and to measure the temperature and relative humidity of the indoor air of the livestock facilities. Along with the sensors, the system integrates modules for visualization, storage, and data transmission over GSM/GPRS network to a data server.

All the sensors used, with the exception of the NH_3 sensor, are digital. This means that the interface between the processing board and the sensors is easier to make, since they have a pre-calibration and do not require analog to digital conversion procedures. For the NH_3 sensor the Arduino internal Analog to Digital Converter (ADC) was used to obtain the digital value of the ammonia concentration.

An Arduino Mega 2560 board was used for processing and converting the data with perceptible responses to the user. It is possible to have an overview of the system in Fig. 1. The modules and sensors used will be detailed below.

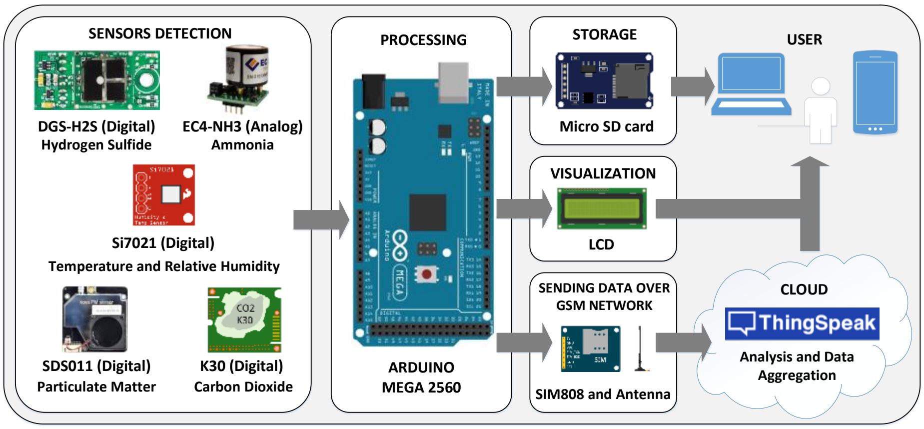

Fig. 1. Overview of the prototype architecture.

2.1 Modules and Sensors Used

All gas sensors chosen were based on the concentration ranges reported in different studies, performed by other authors, conducted in pig and poultry facilities. It is possible to observe in Table 1 the limits found in the indoor air of these facilities and the limit of operation of the chosen sensors.

Hydrogen sulfide sensor DGS-H_2S is an electrochemical sensor from Spec Sensors, with a measurement range of 0 to 10 ppm and a resolution of 10 ppb. The lifetime of the sensor depends on the operating conditions and can vary from 5 to 10 years. It is a sensor little affected by cross-sensitivity caused by other gases.

Ammonia sensor EC4-NH_3-100 is an electrochemical sensor from Pewatron. It has a measuring range of 100 ppm and a resolution of 0.1 ppm, with a life expectancy of 24 months. As a great benefit, it does not show cross-sensitivity to other gases. To facilitate the connection of the sensor to the system, an Easyboard was used, in which the sensor is connected. This module offers a stable voltage, digital results, and temperature measurement which the user can select as the measurement channel.

Carbon dioxide sensor K30 is an optical sensor of CO2meter, has an operating range of 0 to 10,000 ppm, with a resolution of 30 ppm. It is a sensor that comes with an integrated algorithm capable of self-correcting over a period of time. The principle of operation of this device is Non-dispersive Infrared (NDIR), therefore it does not present cross-sensitivity since only the ideal wavelength to absorb the molecules of CO_2 is deviated (band 4.28 μm) [23].

Table 1. Concentration range of pollutants in pig and poultry housing found in the literature.

Air Pollutant and Environmental Parameters	**Sensor (Operation range)**	**Range of indoor air pollutant at pig housing**	**Range of indoor air pollutant at poultry housing**	**Unit**
Hydrogen Sulfide	DGS-H_2S (0 – 10,000)	15 – 6,180[16]	30 – 2,240[16]	ppb
Ammonia	EC4-NH_3-100 (0 – 100)	2 – 87[16, 17]	1 – 50[16, 18]	ppm
Carbon Dioxide	K30 (0 – 10,000)	1,000 – 5,000[16]	500 – 3,000[16, 18]	ppm
$PM_{2,5}$	SDS011 (0 – 1,000)	15.2 – 415[17, 19]	81 – 380[18]	$\mu g.m^{-3}$
PM_{10}		116 – 1,746[17, 19]	135 – 5,003[18, 20]	
Temperature	Si7021-A20 (-40 – 125)	18.1 – 29.4[21, 22]	16.2 – 29.1[22]	°C
Relative Humidity	Si7021-A20 (0 – 100)	41.0 – 84.0[21, 22]	41.2 – 92.9[22]	%

SDS011 particulate sensor, also an optical sensor and manufactured by Nova Fitness Co. Ltd, has detection range from 0 – 1,000 $\mu g.m^{-3}$ and a resolution of 0.3 $\mu g.m^{-3}$. It detects both $PM_{2.5}$ and PM_{10} and the lifetime of this sensor is 8,000 hours. In the lower region of the sensor, there is a coupled fan that assists in the passage of the particles.

Temperature (T) and relative humidity (RH) Si7021-A20 sensor, is a semiconductor sensor from Sparkfun, operates with a measuring range of 0 to 100% for RH and 3% resolution, and from -40 °C to 125 °C with a resolution of 0.4 °C. This device comes with factory calibration data stored in non-volatile memory, so it is not necessary to recalibrate or make changes to its operating code.

In conjunction with the sensors, three modules have been installed: a liquid crystal display for local visualization of the detected gases, particulate matter, temperature and relative humidity values; a micro SD card module that communicates through a file system to record all measured values locally (operates as backup system); and a GPRS/GSM Quad-band SIM808 module that allows sending data to a remote server (ThingSpeak), via mobile network using a SIM card, and that can operate in the frequency bands 850/900/1,800/1,900 MHz which allows its use worldwide.

2.2 Cross-Sensitivity

As the most relevant devices in this study, the EC4-NH_3-100 ammonia sensor and DGS-H_2S hydrogen sulfide sensor were chosen because of little or no typical response to other gases that may be present at the site of study. According to manufacturers of the sensors Spec Sensors [24] and Pewatron [25], concentrations of some pollutants on the H_2S and NH_3 sensors were applied with the purpose of verifying the reading for each gaseous substance that may interfere with the reading of the gas of interest. The measurements observed for both sensors in the presence of other compounds, is shown in Table 2.

Table 2. DGS-H_2S and EC4-NH_3-100 cross-sensitivity.

Compounds (molecular formula)	**Applied Concentration H_2S[24] sensor (ppm)**	**Typical Response H_2S sensor[24] (ppm H_2S)**	**Applied Concentration NH_3[25] sensor (ppm)**	**Typical Response NH_3[25] sensor (ppm NH_3)**
Hydrogen Sulfide (H_2S)	10	10	50	0
Chlorine (Cl_2)	10	-2.2	1	0
Nitrogen Dioxide (NO_2)	10	-2	-	-
Sulfur Dioxide (SO_2)	20	1.7	-	-
Nitric Oxide (NO)	50	1.2	-	-
Carbon Monoxide (CO)	400	1.1	100	0
Carbon Dioxide (CO_2)	-	-	5,000	0
Ozone (O_3)	5	-0.9	-	-
Methane (CH_4)	500	0.1	-	-
Ammonia (NH_3)	100	0.1	100	100
N-Heptane (C_7H_{16})	500	<0.5	-	-
Hydrogen (H_2)	-	-	100	0
Isopropanol (C_3H_5OH)	-	-	1,000	0

3 Validation of the low-cost monitoring system

For a preliminary validation of the prototype, the equipment was submitted to a controlled environment in which it was possible to have greater control of the gases generated by the manure. The variables controlled in the test were ammonia, carbon dioxide, temperature and relative humidity.

Manure was placed inside a smaller box that contained holes and, in turn, this box was placed inside a larger box along with the built prototype (collecting data from 1 in

1 minute) and with other commercially available equipment used as 'reference' instruments – the multi-gas analyzer Gasera One and the DirectSense® IQ-610 probe.

The multi-gas analyzer Gasera One was coupled to the box through a hose, by using a ¼'' Teflon tubing. After the gas is drawn by the pump into the instrument, concentrations are measured by means of acoustic detection, based on the cantilever-enhanced photoacoustic. Concentrations are obtained and readings are shown to the user through a display [26]. Gasera was programmed to collect data in 3 minute periods and to measure the concentration of substances of interest, such as NH_3.

The DirectSense® IQ-610 probe was placed inside the box and it operates through the Non-dispersive Infrared principle. This probe is connected to the PDA Socket® SoMo 650-DX.

Despite not having been performed the analysis in a livestock facility, these environments are very dynamic due to the animals it contains, therefore, many factors influence the variation of the concentrations of pollutants, such as the flow of ventilation, the movements, breaths and digestive processes of these animals. Thus, it was chosen sampling periods of 1 minute. All the experiment built can be visualized in Fig. 2.

Fig. 2. Controlled environment built for data validation.

All data obtained from the 'reference' equipment and prototype were worked on the Microsoft Excel 2016 spreadsheet. This way, it is possible to make comparisons of the sensitivity of low-cost sensors by comparing them with the detection of 'reference' equipment as a function of time. Arithmetic averages were also performed every 10 minutes, and thus, the best range was chosen to determine the equation of the line and the coefficient of determination R^2, and therefore to use this correction in the algorithm of the low-cost system developed.

4 Results and Discussion

The indoor air quality monitoring system for pig and poultry housing was built to meet two needs: low-cost sensors and modules and minimal interference with reactive gases that can be found in these facilities. Fig. 3 shows the constructed prototype.

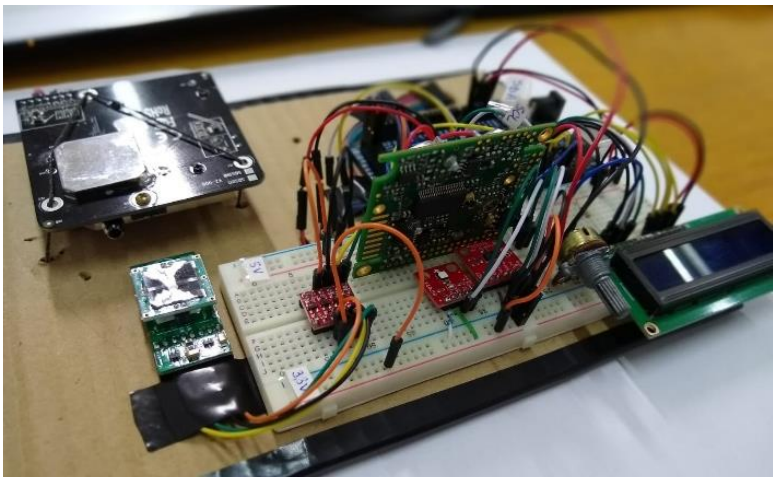

Fig. 3. IAQ system built for pig and poultry facilities.

Thus, the values detected by the sensors are processed by the Arduino Mega board and stored on the 4 Gb micro SD card in a period of 1 minute in the CSV format to facilitate the editing of the data in spreadsheets. The obtained concentrations can be viewed on the LCD in real time. However, the collected data is also sent over a mobile data network using General Packet Radio Service (GPRS) technology to a cloud. These values are sent to the Internet of Things (IoT) platform, called ThingSpeak. Therefore, the values can be aggregated, viewed, analyzed and downloaded by the user.

The operating conditions of the prototype are based on the conditions under which the installed sensors and modules can operate. Therefore, the system operates well between temperatures of 0 to 40 °C, a relative humidity of 15 to 90% and atmospheric pressure between 86 and 110 kPa.

The system power is supplied by an AC/DC power supply, with an input of 100 to 240 V AC 50/60 Hz and an output that is 9 V - 2 A. The typical measured average current consumed by the board with all sensors and modules is 710 mA, with consumption peaks of 2.25 A. The peaks are associated with the high-power consumption at startup of the SIM808 module.

The total cost for the purchase of the components and production of the prototype was €467.80. However, the cost could reach €371.38 if the cheaper sellers are selected. The maintenance of the system is based on the lifetime of the sensors. In the case of large-scale production, the circuit used in the prototype must be completely redesigned to become a single printed circuit board (PCB). Therefore, as soon as the microcontroller is integrated into the board, the rest of the components are easily incorporated and the production cost is further minimized, while remaining a well-finished and professional job.

Often the ‘reference’ equipment is characterized by a high price, due to its innovative technology employed and robustness. Typically, a ‘reference’ equipment used to analyze indoor pollutants can cost from €5,000 to €30,000 or more.

In some cases, it can be built using low cost sensors integrated into a PCB and sold at a high price (€5,000), but there is still an interfering pollutant. In other cases, there may be a patented technology that differentiates the gas and particle analyzer from other products on the market, plus great reliability, support, and removal of interfering pollutants, which will characterize the equipment at an even higher price (> €30,000).

Thus, the prototype built in this study is characterized as low-cost because the set of sensors and components used is 10 to 60 times cheaper than the ‘reference’ equipment.

The time spent learning on system construction and on code developing were 44 days, as shown in Table 3. The sensors chosen comply with Directive 2015/863/EU of the European Parliament and of the Council of the European Union [26], also known as RoHS 3, which deals with the restriction of the use of certain dangerous substances, such as lead, mercury, cadmium, etc., for the manufacture of electrical and electronic components.

Table 3. Expenses of the built system and time used for construction.

Components and Sensors	Acquired price (€)	Lowest price available (€)	Time spent (days)
DGS-H_2S	63.55	63.55	4
K30	74.70	74.70	3
EC4-NH_3-100	90.00	90.00	6
SDS011	43.20	13.89	3
Si7021	9.95	1.22	2
SIM808 module	34.42	22.87	15
Arduino Mega 2560 + LCD and micro SD card modules	51.45	7.65	8
Other components[a]	100.53	97.50	3
Total	467.80	371.38	44

[a] Wire jumper, resistors, capacitors, BOB-12009, Easyboard adapter.

4.1 Data validation

The process of validating data when designing a device is very important because it allows to verify the accuracy of the equipment. From the validation, it is also possible to carry out the calibration. In this way, the system built can delivery precise and reliable readings to the meat producers.

The two tests performed on the K30 CO_2 sensor, Fig. 4, even at different times of 8h and 4h30min, show us behavior similar to Graywolf, used as the 'reference' equipment. It is also verified in Fig. 4 (a), that greater intensification occurred in the anaerobic digestion, due to the greater light exposure between 3h and 5h and near 7h, as a consequence there was a higher CO_2 production, causing the sensor reaches its 10,000 ppm threshold during the test. However, in Fig. 4 (b), due to less light exposure, smaller amounts of CO_2 were produced, peaking at 9,528 ppm with the 'reference' equipment.

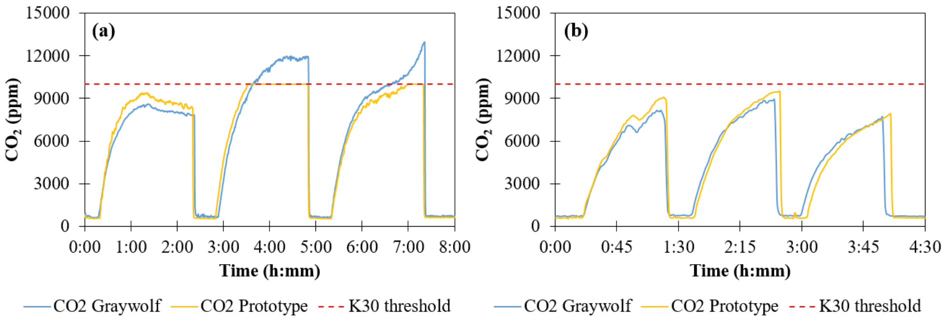

Fig. 4. Behavior of the K30 sensor and IQ-610 Graywolf equipment during (a) 8h and (b) 4h30min.

Based on the Graywolf and Prototype concentrations, it was possible to find the line equation, which will be used for correcting the prototype sensor reading, so that the detected values are closer to the equipment used as 'reference'. As shown in the Fig. 5 (a) and (b) the coefficient of determination R^2 reached values higher than 0.998 in both cases. Even tested in different time periods, the line equation resembles in both experiments. The selected time range for performing the arithmetic mean in Figure 5 (a) was 0 to 2h15min and in Fig. 5 (b) from 0 to 1h20min. However, the best linear fit was in the second test, with in R^2 of 0.9985.

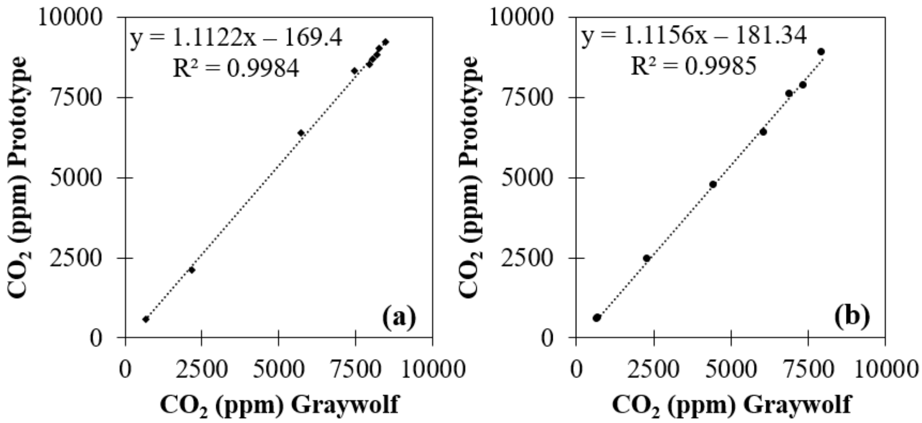

Fig. 5. Linear equation and coefficient of determination R^2 performed in (a) first test and (b) second test of the CO_2 sensor and Graywolf.

During the first 8h assay, the Si7021 air temperature sensor proved to be promising well, because the temperature ranged from 22 to 27 °C, while the Graywolf temperature ranged from 22 °C to 27 °C, Fig. 6 (a). On contrary, for the relative humidity, there were a large deviation between both sensors, with the low-cost sensor ranging from 38 to 60% and the 'reference' equipment ranged from 29 to 49%, Fig. 6 (b). It is possible to verify in the first test that the Si7021 sensor presents coarse signals because the *int* data type was used to determine the T and RH variables, so the detected values are represented in their entire format.

For the second 4h30min test, the *int* data type was changed to *float*, improving the representation precision of the Si7021 obtained measurements. The detected temperature of the prototype varied from 27 °C to 28 °C, and that of the reference equipment from 28 to 30 °C, with a variation of 2 °C, this variation can happen due to the error of the sensor itself, not being significant (Fig. 6 (c)). With regard to the relative humidity it ranged from 35% to 51% in the prototype, and from 24 to 39% in IQ-610 Graywolf (Fig. 6 (d)).

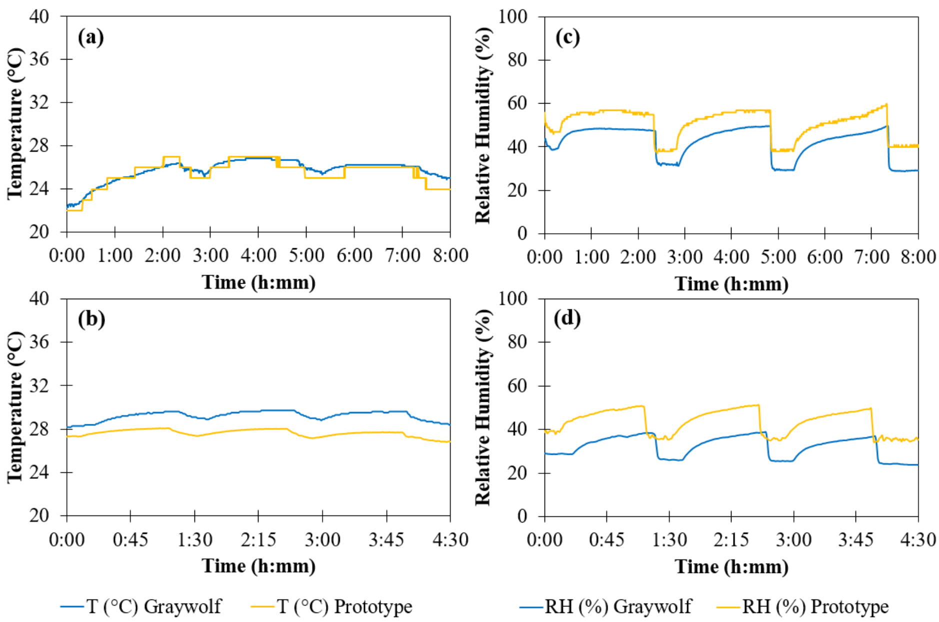

Fig. 6. Behavior of the Si7021 and reference equipment to (a) T and (b) HR in 8h and (c) T and (d) RH in 4h30min.

From the second test, the linear equation was generated in order to adjust the temperature and relative humidity of the prototype Si7021 sensor, causing the adjusted values to approximate the values detected by the Graywolf equipment. Good coefficient of linear determination values were also generated, for T (R^2 = 0.9692, Fig. 7 (a)) and for RH (R^2 = 0.9296, Fig. 7 (b)). The range that best fit the data pairs X and Y in the linear regression for T was between 3h and 4h30min and for HR between 2h50min and 3h50min.

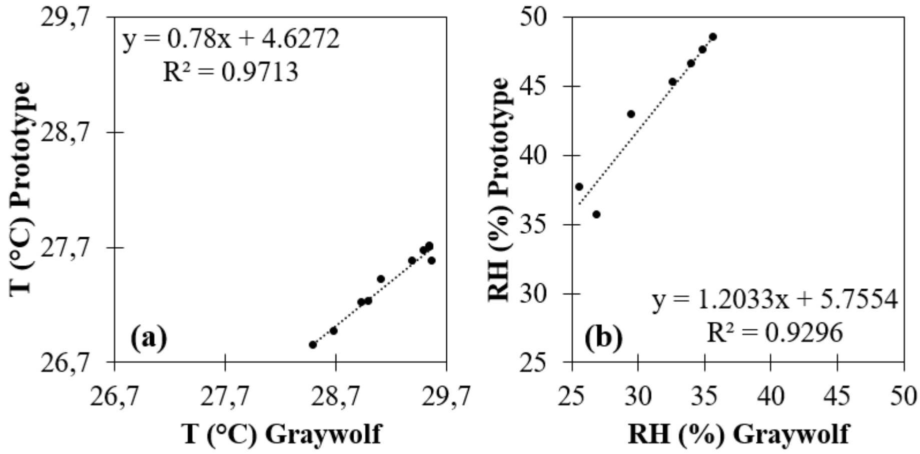

Fig. 7. Linear equation and coefficient of determination R^2 performed in second test to (a) T and (b) RH.

It is worth mentioning that the analysis only mirrors the values found for T between 23 to 29 °C and HR between 31 to 49%. Therefore, it will be necessary to subject the system built to regimes with large amplitudes of relative humidity and temperature to obtain an improved linear regression.

Concerning the NH_3, the EC4-NH_3-100 sensor, during the 8h test, showed maximum peaks of 12 ppm and minimum values close to zero, while the readings Gasera One reached much higher values, ranging from 2 to 154 ppm, Fig. 8 (a). Theses higher values were expected as the test being carried out in the daytime period, with a great amount of sun light, causing a greater release of ammonia during the acidogenesis phase of a very intensified anaerobic digestion process [27][28].

In the second test, the NH_3 sensor gain was adjusted to improved detection. Thus, according to Fig. 8 (b), a promising improving in the detection of ammonia was observed, even with small abrupt variations. Because the second test was performed in an area of low light exposure, the low-cost sensor detection range was 1 to 21 ppm and the Gasera One varied from 1 to 23 ppm.

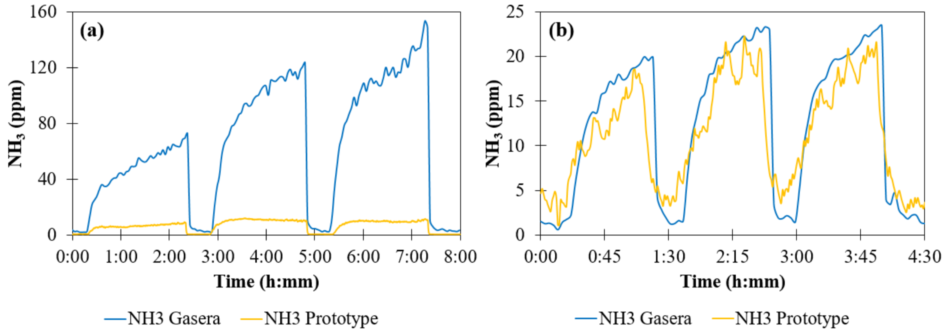

Fig. 8. Behavior of the EC4-NH_3-100 sensor relative to the reference equipment for the (a) first test and (b) second test.

Linear regression was also used to find the equation that best fit the values acquired by the low-cost sensor. It is possible to observe an improvement in the coefficient of determination. In the first experiment R^2 = 0.9573, (Fig. 9 (a)) and in the second R^2 = 0.9805, (Fig. 9 (b)), demonstrating a better performance of the EC4-NH_3-100 sensor.

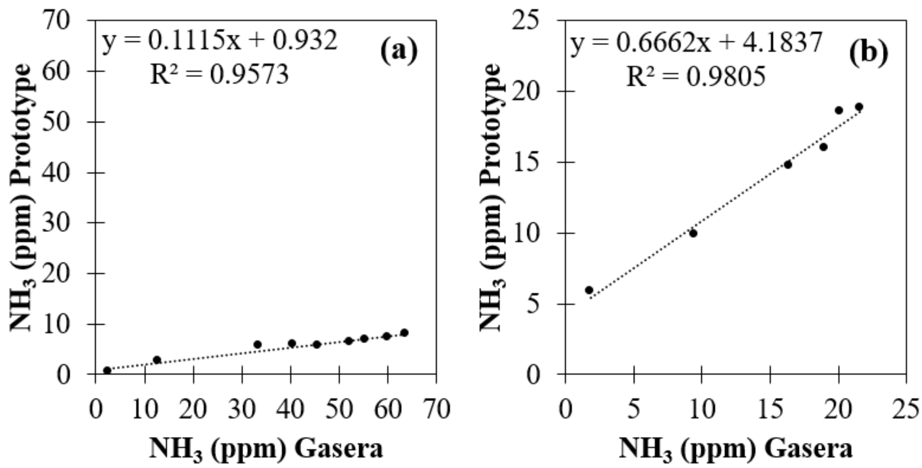

Fig. 9. Linear equation and coefficient of determination R^2 performed in (a) first test and (b) second test of the NH_3 sensor and Gasera.

The SDS011 particulate sensor has not yet been validated due to the construction of a suitable environment to perform a reliable inter-comparison experiment.

The hydrogen sulfide sensor DGS-H_2S will also be validated in a very near future by performing a multipoint calibration against a standard bottle of H_2S.

No tests were performed on livestock facilities because the equipment was only in the construction, validation, calibration phase. Subsequently, the prototyping phase will be carried out and then tests will be carried out on pig and poultry farms.

5 Conclusion

With the scientific and technological evolution, new possibilities have arisen to build more compact and low-cost gas detection systems, which consequently improve the management of the internal air quality of livestock installations. These devices provide the farmer with more efficient control of the concentrations of gaseous and particulate contaminants that are formed and released within these facilities, enabling the development of mitigating solutions to reduce environmental and health impacts.

The monitoring system built is capable of detecting particulate matter ($PM_{2.5}$ and PM_{10}), and gaseous pollutants such as hydrogen sulfide, ammonia, carbon dioxide, in addition to measuring environmental parameters such as temperature and relative humidity.

Through the process of data validation, it was possible to visualize a great similarity between prototype and 'reference' equipment readings, as shown by the coefficient of determination of each sensor. The carbon dioxide sensor is the one that presents the best coefficient of determination $R^2 = 0.9985$, the other sensors presented accurate results. From the line equation, corrections will be made to the algorithm in all sensors. The objective is to approximate the detected values of the built equipment to the values of the reference equipment.

Future work will focus on calibrating the sensors so that the prototype readings provide accurate and precise responses. It will also be encapsulated, bringing robustness and durability to the system. Finally, a case study will be carried out, in which the concentrations of pollutants and environmental parameters of indoor air quality of pig and poultry farms in Brazil and Portugal will be analyzed.

Acknowledgments

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References

1. Robinson, T.P., Thornton P.K., Franceschini, G., Kruska, R.L., Chiozza, F., Notenbaert, A., Cecchi, G., Herrero, M., Epprecht, M., Fritz, S., You, L., Conchedda, G. & See, L.: Global livestock production systems. FAO, Rome (2011).
2. Food and Agriculture Organization of the United Nations Statistics Database, http://www.fao.org/faostat/en/#home, last accessed 2019/02/07.
3. Arrieta, E. M.; & González, A. D.: Energy and carbon footprints of chicken and pork from intensive production systems in Argentina. Science of The Total Environment 673, 20-28 (2019).

4. Leip, A.; Billen, G.; Garnier, J.; Grizzetti, B.; Lassaletta, L.; Reis, S.; Westhoek, H.: Impacts of European livestock production: Nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. Environmental Research Letters 10(11), 1-13 (2015).
5. Cambra-López, M.; Aarnink, A. J.; Zhao, Y.; Calvet, S.; & Torres, A. G.: Airborne particulate matter from livestock production systems: A review of an air pollution problem. Environmental Pollution 158(1), 1-17 (2010).
6. Zheng, S.; Jin, X.; Chen, M.; Shi, Q.; Zhang, H.; & Xu, S.: Hydrogen sulfide exposure induces jejunum injury via CYP450s/ROS pathway in broilers. Chemosphere 214(2019), 25-34 (2019).
7. Ecim-Djuric, O.; & Topisirovic, G.: Energy efficiency optimization of combined ventilation systems in livestock buildings. Energy and Buildings 42(8), 1165-1171 (2010).
8. Banhazi, T.; Aland, A.; & Hartung, J.: Air quality and livestock farming. Taylor & Francis Group, London, UK (2018).
9. Ni, J.; Heber, A. J.; Darr, M. J.; Lim, T. T.; Diehl, C. A.; & Bogan, B. W.: Air Quality Monitoring and On-Site Computer System for Livestock and Poultry Environment Studies. Transactions of the ASABE 52(3), 937-947 (2009).
10. Bamodu, O.; Osebor, F.; Xia, L.; Cheshmehzangi, A.; & Tang, L.: Indoor environment monitoring based on humidity conditions using a low-cost sensor network. Energy Procedia 145, 464-471 (2018).
11. Ropkins, K.; Colvile, R. N. Critical Review of Air Quality Monitoring Technologies for Urban Traffic Management and Control (UTMC) Systems. Urban Traffic Management & Control (UK) (2000).
12. Ni, J.; Heber, A. J.; Darr, M. J.; Lim, T. T.; Diehl, C. A.; & Bogan, B. W. Air Quality Monitoring and Data Acquisition for Livestock and Poultry Environment Studies. Iowa State University Digital Repository (eds). Livestock Environment VIII - Proceedings of the 8th International Symposium, pp. 1021–1028 (2008).
13. Yunusa, Z.; Hamidon, M. N.; Kaiser, A.; Awang, Z. Gas sensors: a review. Sensors and Transducers. 168(4), 61-75 (2014).
14. Manap, H.; Muda, R.; O'Keeffe, S.; Lewis, E.: Ammonia sensing and cross sensitivity evaluation with atmosphere gases using optical fiber sensor. Procedia Chemistry. 1(1) 959-962 (2009).
15. Rai, A. C.; Kumar, P.; Pilla, F.; Skouloudis, A. N.; Sabatino, S. D.; Ratti, C.; Yasar, A.; Rickerby, D.: End-user perspective of low-cost sensors for outdoor air pollution monitoring. Science of The Total Environment,607-608, 691-705 (2017).
16. Heyden, C. V.; Demeyer, P.; & Volcke, E. I.: Mitigating emissions from pig and poultry housing facilities through air scrubbers and biofilters: State-of-the-art and perspectives. Biosystems Engineering 134, 74-93 (2015).
17. Shen, D.; Wu, S.; Li, Z.; Tang, Q.; Dai, P.; Li, Y.; & Li, C.: Distribution and physicochemical properties of particulate matter in swine confinement barns. Environmental Pollution 250, 746-753 (2019).
18. Winkel, A.; Mosquera, J.; Aarnink, A. J.; Koerkamp, P. W.; & Ogink, N. W.: Evaluation of oil spraying systems and air ionisation systems for abatement of particulate matter emission in commercial poultry houses. Biosystems Engineering 150, 104-122 (2016).
19. Ransbeeck, N. V.; Langenhove, H. V.; & Demeyer, P.: Indoor concentrations and emissions factors of particulate matter, ammonia and greenhouse gases for pig fattening facilities. Biosystems Engineering 116(4), 518-528 (2013).
20. Melse, R. W.; & Hol, J. M.: Measures to reduce fine dust emission from poultry houses: Biofiltration of exhaust air of a manure drying system at a barn for laying hens (in Dutch).

Report No. 498. Livestock Research, Wageningen University & Research, Netherlands. (2012).

21. Chmielowiec-Korzeniowska, A.: The concentration of volatile organic compound (VOCs) in pig farm air. Ann Agric Environ Med 16, 249-256 (2009).
22. Cambra-López, M.; Winkel, A.; Mosquera, J.; Ogink, N. W.; & Aarnink, A. J. (2015). Comparison between light scattering and gravimetric samplers for PM10 mass concentration in poultry and pig houses. Atmospheric Environment 111, 20-27 (2015)
23. Kwon, J.; Ahn, G.; Kim, G.; Kim, J.; & Kim, H.: A study on NDIR-based CO_2 sensor to apply remote air quality monitoring system. *2009 ICCAS-SICE*. Fukuoka, Japan, pp. 1683-1687 (2009).
24. SPEC Sensors, https://www.spec-sensors.com/wp-content/uploads/2017/01/DGS-H2S-968-036.pdf, last accessed 2019/02/15.
25. Pewatron, https://www.pewatron.com/fileadmin/products/datasheets/188/EC4-NH3-1_1620-21570-0019-E-0217.pdf, last accessed 2019/02/15.
26. European Parliament and of the Council of the European Union, Directive 2015/863 / EU - List of substances subject to restriction, Official Journal of the European Communities, Brussels, 31 March 2015.
27. Cheng, J. (2018). *Biomass to renewable energy processes*. Boca Raton: CRC Press, Taylor & Francis Group.
28. Horan, N. J., Yaser, A. Z., & Wid, N. (2018). *Anaerobic digestion processes: Applications and effluent treatment*. Singapore: Springer.