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Development and validation of a rapid-prototyping IoT-based sensor system for poultry house microclimate monitoring

Glauber da Rocha Balthazar [a,b], Robson Mateus Freitas Silveira [a,*], José Tadeu Aldrigue [a], Iran José Oliveira da Silva [a]

[a] Ambience Research Center. Department of Biosystems Engineering - Luiz de Queiroz College of Agriculture, University of São Paulo (ESALQ/USP), Av. Pádua Dias, 11- São Dimas 13418-900, Piracicaba, São Paulo, Brazil

[b] Federal Institute of Education, Science and Technology of São Paulo (IFSP) R. Heitor Lacerda Guedes, 1000 - Cidade Satélite Íris 13059-581, Campinas, São Paulo, Brazil

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ABSTRACT

The industrial production system for broiler chickens involves raising the animals in an artificial environment (aviary) that must provide all necessary conditions to generate a suitable microclimate. This microclimate ensures optimal development of the animals based on their productive indices and genetic potential. Monitoring this environment requires careful attention to environmental variables that directly influence animal performance. This study presents the development of an electronic module, termed the Environmental Sensor, that captures key microclimate variables in broiler poultry houses using microcontrollers and rapid-prototyping sensors. Specifically, the device was built around a Wemos Mega R3 (ESP8266/ATmega2560) microcontroller and employed rapid-prototyping sensors (MQ-137 for NH_3, MH-Z19E for CO_2, MQ-7 for CO, BME280 for temperature and humidity, DSM501A for dust, and TEMT6000 for luminosity). The construction method involved selecting electronic components via an iterative prototyping process, and each sensor was calibrated against industrial-grade references following Technical Standard NBR 14,610. Statistical analysis of the calibration data yielded linear regression equations for each variable (e.g., for NH_3: $y = 0.602x + 501.86$). Performance metrics demonstrated high agreement with certified and calibrated reference instruments: the MQ-137 NH_3 sensor exhibited a correlation of $R = 0.82$ ($R^2 = 0.64$) with the industrial benchmark (standard error = 0.41 ppm), and the BME280 temperature sensor achieved $R = 0.95$ ($R^2 = 0.91$) (standard error = 0.07 °C). These results indicate the system's accuracy and suitability for monitoring broiler house conditions. Subsequent field experiments in a commercial poultry farm confirmed the sensors' compatibility with each measured variable and demonstrated that the calibrated prototyping sensors can reliably estimate the microclimate parameters under practical production conditions.

1. Introduction

The production of modern broiler chickens is conducted in an artificial environment where all environmental variables are monitored and controlled to optimize zootechnical development at each phase of breeding. These variables, are documented in the literature, include air temperature and relative humidity, air speed, thermal radiation, presence of harmful gases (ammonia, carbon monoxide and carbon dioxide) and dust levels [1–4].

Controlling these variables directly influences the animals' homeostasis, especially during the initial stages of breeding, as animals at this stage do not yet have a fully developed thermoregulatory system, requiring total control of the microclimate in which they are inserted [[5,6]. However, maintaining precise control of environmental variables is crucial at all stages, as achieving the best production rates necessitates raising the animals under specific environmental conditions tailored to each week of breeding. Failure to maintain this control results in scrapping, low feed conversion, disease development, batch non-uniformity and higher mortality rates [7–12].

Thus, modern aviaries have the presence of various sensors and

* Corresponding author at: Luiz de Queiroz College of Agriculture (ESALQ), University of Sao Paulo (USP), *Av.* Pádua Dias, 11- São Dimas 13418-900; Piracicaba, São Paulo, Brazil.

E-mail addresses: robsonsilveira@usp.br, robsonmateusfs1994@gmail.com (R.M.F. Silveira).

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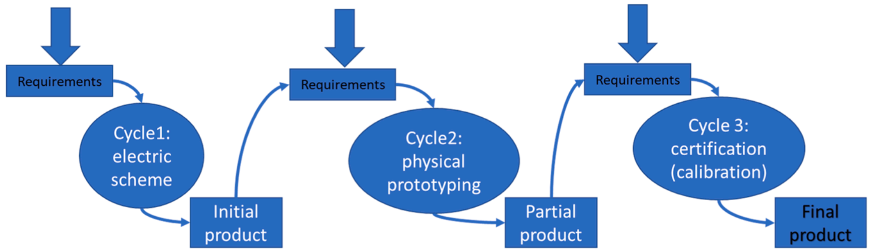


Fig. 1. Iterative and incremental cycle of Environmental Sensor development.

electronic and automated equipment that both monitor and control the environmental conditions, providing an ideal artificial environment for the animals [13,14]. In line with this, our Environmental Sensor monitors temperature, humidity, NH_3, CO, CO_2, dust (PM_{10}) and luminosity — each parameter having a recognized impact on broiler welfare and productivity. Temperature and humidity govern birds' thermal comfort and metabolic balance; gaseous pollutants (NH_3 from litter and CO/CO_2 from combustion) at high concentrations can irritate the respiratory tract and reduce growth. Dust particles carry pathogens and exacerbate respiratory distress, while appropriate light intensity regulates feeding behavior and physiological rhythms, thereby affecting feed intake and growth. Monitoring these parameters ensures that the poultry house microclimate remains within optimal ranges for healthy, efficient broiler production [13].

Several studies have emerged aiming to combine existing monitoring systems with technologies to enhance the reliability and accuracy of the monitoring process [15–17]. The research involves the use of IoT (Internet of Things) and cloud computing to develop electronic equipment that can capture variables in the poultry house's microclimate, enabling the visualization of production index data for precise decision-making in production. However, the accurate capture of environmental variables is strongly dependent on sensors that present reliable and accurate data reflecting the current microclimate conditions. This study proposes to validate the hypothesis that it is possible to construct an electronic device module that can monitor the environmental variables of a broiler house using rapid prototyping sensors and microcontrollers, provided they are calibrated with industrial-grade sensors to ensure accuracy in their readings.

The objective is to construct an electronic environmental sensing module, referred to as Environmental Sensor, employing rapid prototyping sensors and microcontrollers to monitor the microclimate of a broiler poultry house. The specific objectives are to: (1) develop the electronic device using electronic prototyping equipment; (2) perform environmental data readings and store them in permanent memory; and (3) validate the data collected by rapid prototyping sensors against industrial sensors using appropriate statistical methods.

2. Materials and methods

The construction process of the Environmental Sensor was guided by the iterative and incremental method [18]. Consequently, three development cycles were created where each one generated software artifacts (products) as productive results (Fig. 1).

Below, each development cycle is detailed:

- **Cycle 1:** Electrical Scheme: responsible for designing the electronic and electrical architecture of the environmental sensor, as well as the arrangement of sensors, organization and asymmetry of components within a container; initial product generated: a set of diagrams and 3D modeling of the sensor;
- **Cycle 2:** Physical Prototyping: responsible for constructing and physically implementing the sensors and microcontroller within the container; partial product generated: a physical device incorporating the previously generated diagrams and the electronic components manipulation algorithm (in *C++*);
- **Cycle 3:** Certification (Calibration): the method used for calibration was designed based on an adaptation of Technical Standard NBR 14,610 [19], which established the following premises:
  - all rapid prototyping sensors are hereinafter identified simply as "sensors" and industrial sensors as "standard instruments";
  - the thermal medium used for the experimentation (laboratory analysis) was a hermetically sealed box and later (field analysis) the microclimate of a commercial broiler aviary with data collection in the geometric center of the aviary;
  - Laboratory analysis: the test execution time and the number of collection samples are not determined by ABNT 14,610. However, Freitas [20] and Eurachem [21] determine that the minimum value must be 10 records; Therefore, a minimum collection time of 300 min (5 h) was specified for this project, with a 2-minute interval between collections, thus generating 150 reference values for each sensor and its respective standard instrument;
  - Field analysis (in the poultry house): a period of 180 min (3 h) was set, with a 2-minute interval between collections, generating 90 reference values for each sensor. The objective was to assess how well the model fit the observed data by verifying whether the underlying assumptions of linear regression are met;
  - Statistical methods were used to calibrate the Sensors with the Standard Instruments through the following steps: 1. data collection in the laboratory for each of the sensors in parallel to their respective standard instruments; 2. statistical analysis that quantified a linear relationship between sensor and standard instrument, evaluating the degree of association between them using Pearson's correlation; 3. Adopted the following standard: understand the level of correlation by adopting the "high" standard above 0.8 for certification [22] and significance level of 95 %;

Finally, the product generated in this cycle (Final Product) was: a degree of confidence for the data collected by the Environmental Sensor when they had the same graduation and their respective curve adjustment reference value (Linear Regression, using the least squares method) for the data collected by the Environmental Sensor.

3. Execution and analysis

To carry out this cycle, a partnership was established with a producer of broiler chickens from the Cobb lineage located in the city of Itatiba, São Paulo, Brazil, approximately 64 km from the capital São Paulo, located Latitude: −23.0068, Longitude: −46.8387, 23° 0′ 24″ South, 46° 50′ 19″ West; altitude of 771 m; and characterized by a humid subtropical climate with Köppen-Geiger climate classification: Cfa. The aviary used was negative pressure with dimensions of 135 m long, 14 m wide, ceiling height of 3 m, consisting of evaporative plates and exhaust fans. The aviary was also equipped with an electronic system for monitoring relative humidity and dry air temperature (inoBram brand, model SMAAI 3 PE) which functioned automatically. Furthermore, this work was submitted, analyzed and approved by the Ethics Committee on the Use of Animals of the Luiz de Queiroz College of Agriculture of the

Table 1
Electronic components used in the Environmental Sensor.

Type	Model
Microcontroller	Wemos Mega R3 ESP8266 and ATmega2560
Battery (power)	Li-Ion Battery JWS 6 × 18,650 rechargeable, 8.4 V and 28,800 mAh
Temperature and Humidity Sensor	BME/P 280
Carbon Monoxide Sensor	MQ-7
Ammonia Sensor	MQ137
Dust Sensor	DSM501A
Brightness Sensor	TEMT6000
DataLogger	MicroSDCard
Clock	Rtc Ds3231
Relay Sensor	Module 5 V, 10 A and 2 channels
Carbon Dioxide Sensor	MH-Z19E

University of São Paulo, under protocol number 7364,090,322.

The process of acquiring both the sensors and the standard instruments was funded by the São Paulo State Research Support Foundation (FAPESP) under process number 2022/07,442–8.

The microcontroller chosen for the project was the Wemos Mega R3 ESP8266/ATmega2560. This microcontroller is a hybrid with two processors (ATMega 2560 and ESP8266), featuring a clock speed of 16 MHz and 32 MB flash memory; In addition, it has the following Input/Output (I/O) configurations: 54 digital ports, 13 Pulse Width Modulation (PWM) ports, 16 analog ports, 2 serial pins (Tx/Rx) and 2 SPI and DAS/SCL ports. The battery chosen was a 28,800 mAh Li-Ion battery with 8.4 V voltage. The sensors selected were compatible with the project's requirements. These components are presented in Table 1.

3.1. Cycle 1: electrical diagram

The electrical and electronic diagram of the sensor (Fig. 2) and its

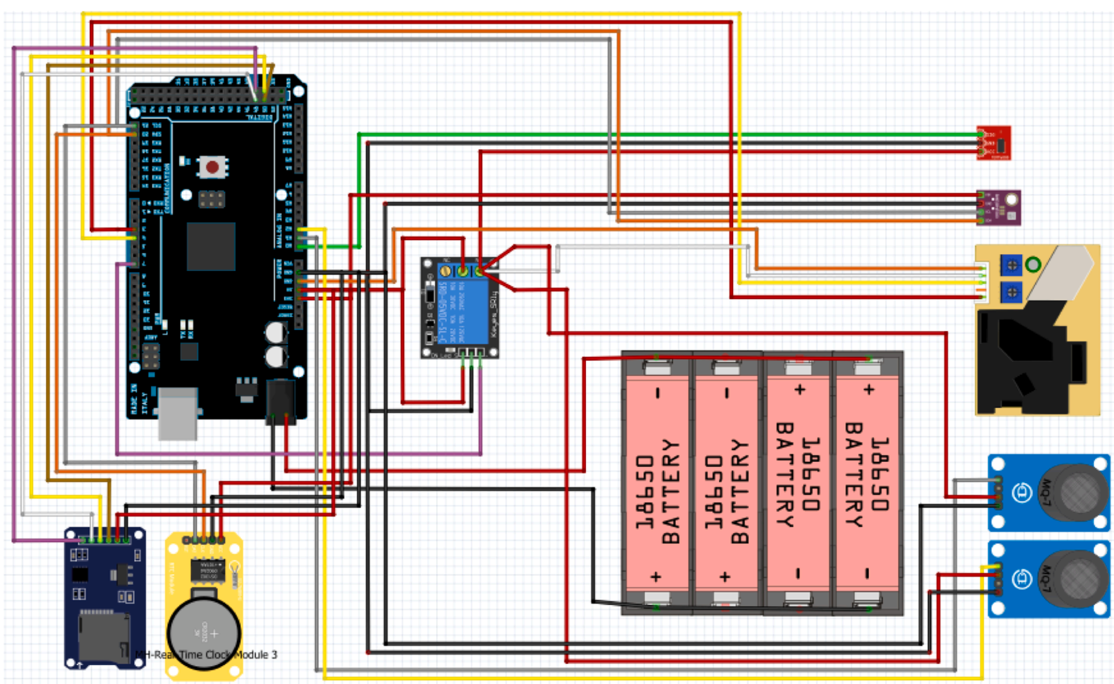
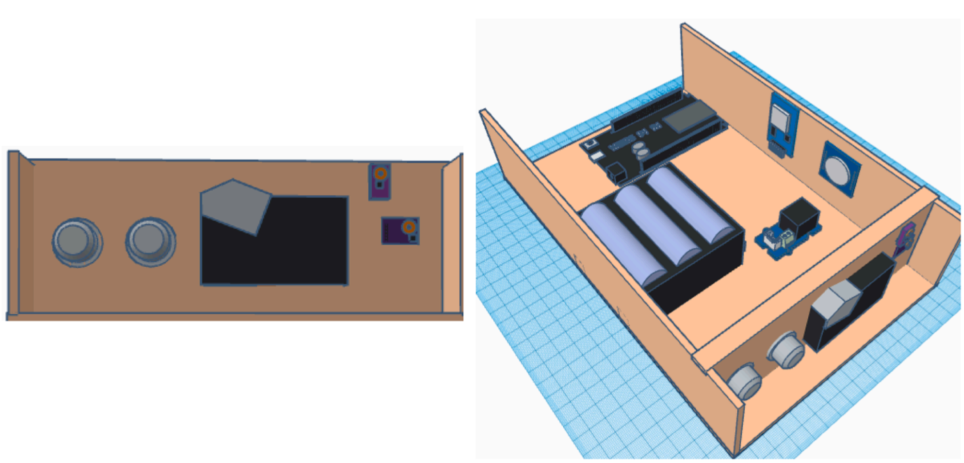


Fig. 2. Electrical diagram of the environmental sensor.

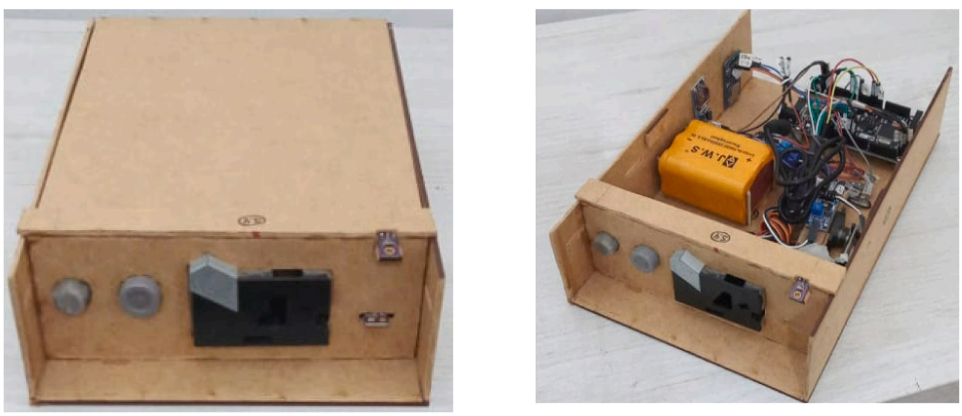


A	B

Fig. 3. 3D modeling of the environmental sensor. A) Front View; B) Top View.

A B

Fig. 4. Physical prototyping of the environmental sensor. A: exterior view; B: interior view.



A B

Fig. 5. Physical prototyping of the environmental sensor. A: exterior view; B: interior view.

Table 2
Standard instruments used for sensor calibration.

Sensor	Model	Description
Temperature and Humidity	HOBO U12–013Vectus	Measurement: Temperature from −20 °C to 70 °C and RH from 5 % to 95 %. Resolution: temperature 0.03 °C and RH 0.03 % Accuracy: temperature ± 0.35 °C and RH ± 2.5 %
Ammonia (NH^3)	AKSO SGTP-NH3	Measurement: 0 to 100 ppm Resolution: 1 ppm Accuracy: ±5 %
Carbon dioxide (CO^2)	AZ 7755	Measurement: 0 to 2000 ppm Resolution: 1 ppm Accuracy: ±50 ppm or ± %
Carbon monoxide (CO)	AZ EB 7701	Measurement: 0 to 999 ppm Resolution: 1 ppm Accuracy: ± 20 % at 0~100 ppm and ± 15 % at 100~500 ppm
Dust Levels	Airing-1000 Temtop	Measurements: PM 10 from 0 to 999 μg/m³ Precisions: PM 10 of 0.1 μg/m³
Luminosity	AKROM KR832	Measurements: 0 to 40,000 lx Resolution: 1 lx Accuracy: ± 3 %

respective three-dimensional (3D) modeling (Fig. 3) were produced as outcomes of this cycle.

3.2. *Cycle 2: physical prototyping*

Two versions of the Environmental Sensor were built in 3 mm thick MDF (Medium Density Fiberboard). The first version was powered by a 117/220 V alternating current source converted to 9 V and 2 A direct current. The objective of this version was to capture the microclimate variables from a fixed point (geometric center) of the poultry house. The dimensions of this prototype were: 15.5 cm long, 15 cm wide and 10 cm high (Fig. 4).

The second version was powered by an 8.4 V and 28,800 mAh Li-Ion battery. The objective of this version was to capture the microclimate variables at variable points, serving this prototype as a portable sensor, which can be fitted to a mobile robotic system (sensing module for the biosensing agent). The dimensions of the prototype were: 26 cm long, 16.5 cm wide and 6.5 cm high (Fig. 5).

3.3. *Cycle 3: certification (calibration)*

The standard instruments used were industrial sensors acquired with respective calibration certificates. The standard instruments used for calibration are listed in Table 2.

Following the guidelines of Technical Standard NBR 14,610 [19], the calibration process (laboratory analysis) was individualized for each sensor, in which each one was subjected to the presence of its respective

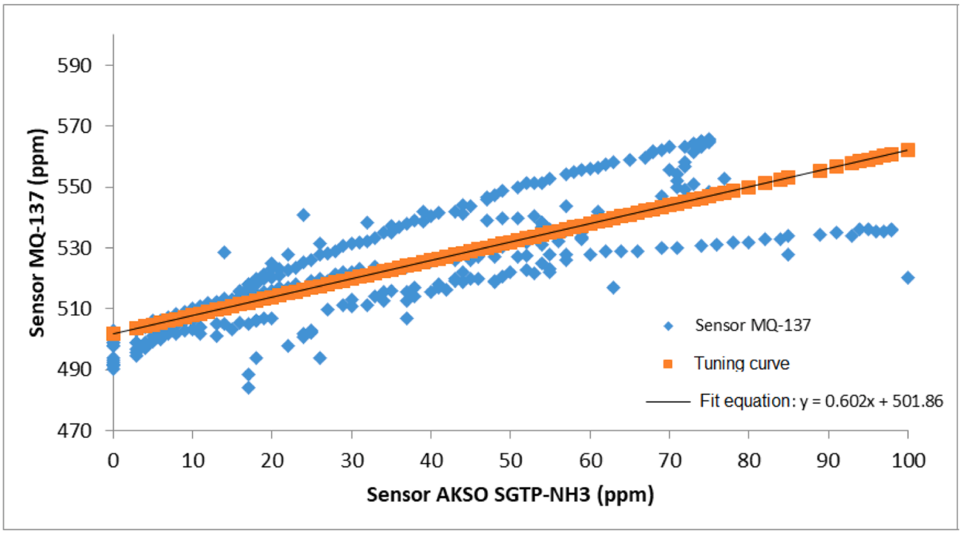


Fig. 6. Calibration equation for ammonia.

Table 3
Result of individual sensor analyses.

Assessment elements	Sensors	Correlation	R^2
Ammonia	MQ-135	0.43	0.19
	MICS-6814	0.17	0.04
	MQ-137	0.82	0.64
Carbon dioxide	MG-811	0.57	0.33
	MHZ-19E	0.93	0.84
Carbon monoxide	MQ-7	0.77	0.59
	MICS-5524	0.55	0.30
	CJMCU-6814	0.32	0.11
Luminosity	TEMT-6000	0.95	0.90
	BH-1750	0.94	0.85
Temperature	DHT-22	0.89	0.80
	BME-280	0.95	0.91
Moisture	DHT-22	0.78	0.61
	BME-280	0.84	0.71
Dust	DSM-501A	0.74	0.52
	GP2Y1014AU0F	0.41	0.24

detectable elements. However, several sensors performed the same measurement, raising doubts about which was the most accurate. To understand the precision of these sensors, the experiment was conducted with at least two different sensor models, though similar, comparing their statistical data (dispersion measures). The sensor that presented the best results at a high significance level of correlation (above or equal to 0.80) at a 95 % confidence level was chosen. Subsequently, each of these sensors was placed in a hermetically sealed box. The microclimate of this box was then saturated until the Standard Instrument reached the maximum reading peak and stabilized.

Figs. 6–12 show each equation generated and Table 3 displays the results of this process. (Fig. 7, Fig. 8, Fig. 9, Fgiure 10, Fig. 11, Fig. 12)

The determining factor for choosing each sensor was the highest correlation ($\geq$ 0.80). The sensors that met these requirements were: ammonia (NH^3) MQ-137, carbon dioxide (CO^2) MHZ-19E, carbon monoxide (CO) MQ-7, temperature BME-280, humidity BME-280 and dust DSM501A (the latter did not reach a correlation above 0.80; however, it was the highest value among the other sensors). The calibration curve equations are presented in Table 4.

The calibration equations were evaluated through statistical analyses that checked how well each model fit a set of real data in a commercial

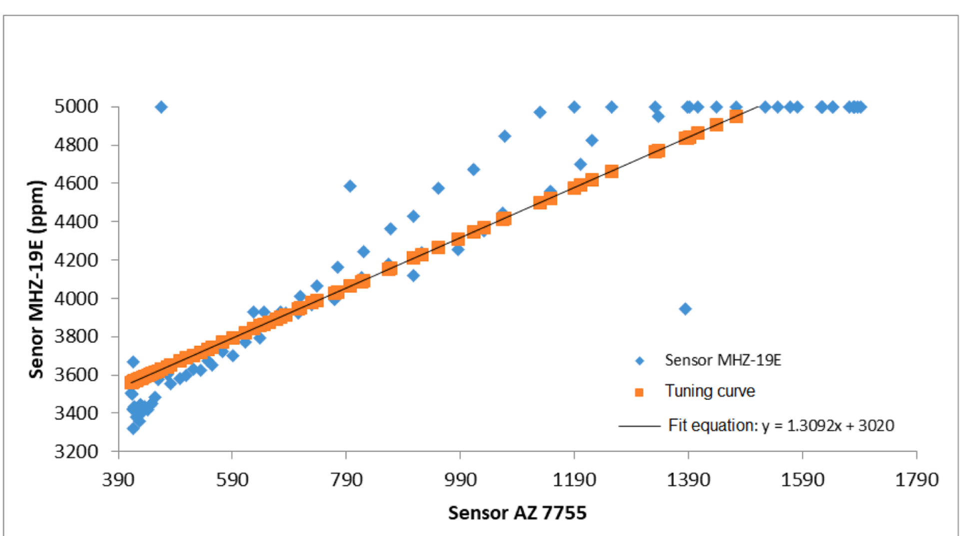


Fig. 7. Calibration equation for carbon dioxide.

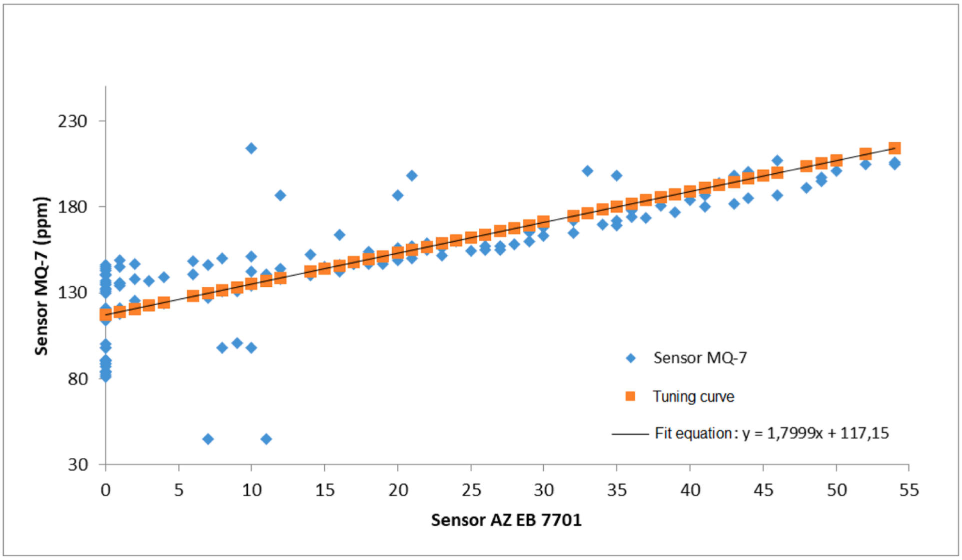


Fig. 8. Calibration equation for carbon monoxide.

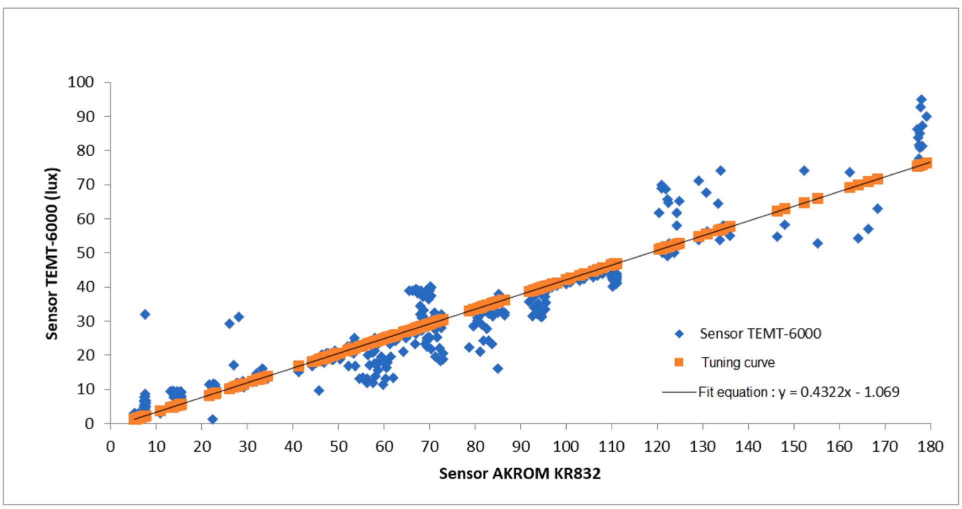


Fig. 9. Brightness calibration equation.

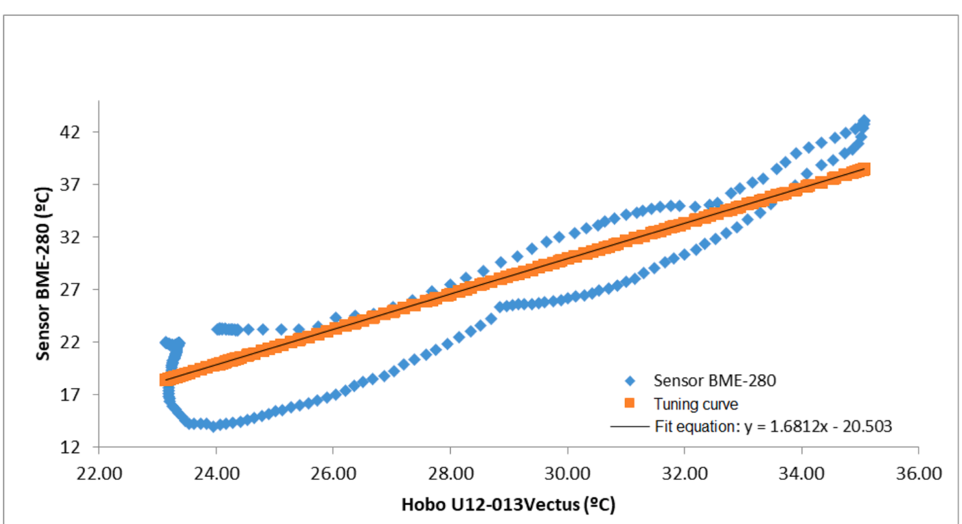


Fig. 10. Calibration equation for temperature.

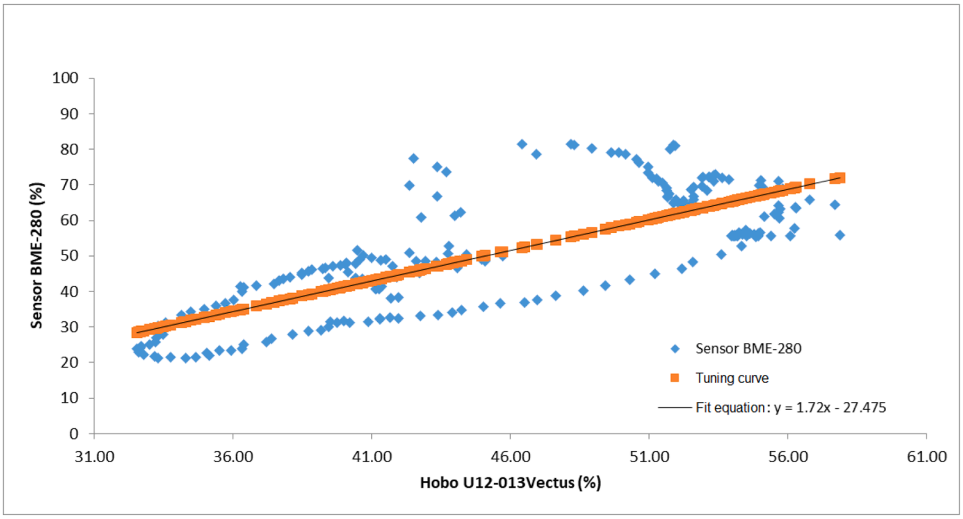


Fig. 11. Calibration equation for humidity.

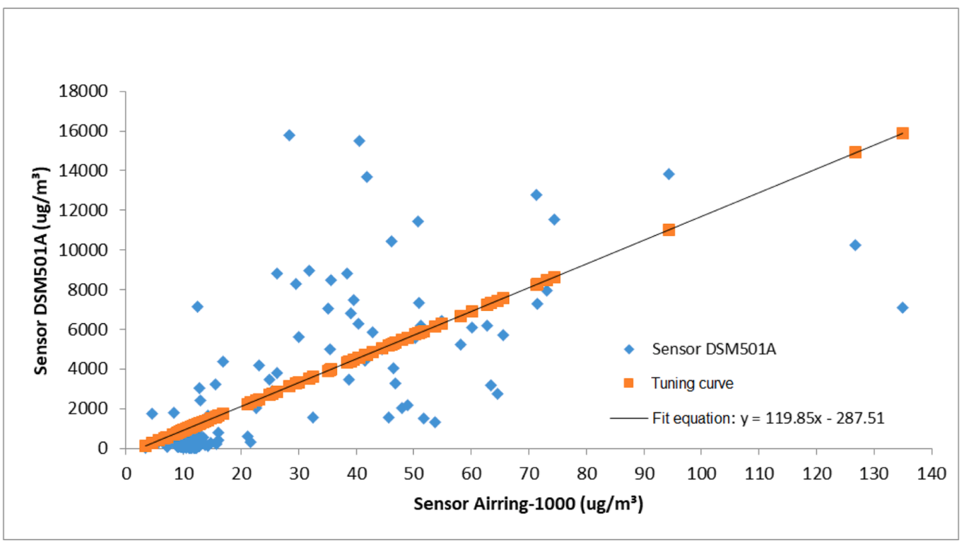


Fig. 12. Calibration equation for dust.

Table 4
Calibration equations for each sensor.

Assessment elements	Sensor	Fitting Equation
Ammonia	MQ-137	$y = 0.602x + 501.86$
Carbon dioxide	MHZ-19E	$y = 1.3092x + 3020$
Carbon monoxide	MQ-7	$y = 1.7999x + 117.15$
Luminosity	TEMT-6000	$y = 0.4322x + 1.069$
Temperature	BME-280	$y = 1.6812x - 20.503$
Moisture	BME-280	$y = 1.72x - 27.475$
Dust PM 10	DSM-501A	$y = 125.32x - 365.27$

poultry farm (field analysis). The Environmental Sensor was taken to the partner aviary along with the standard instruments. Data collection was conducted in a commercial aviary during the fifth week of breeding on November 15, 2023.

This comparative study was carried out by placing all equipment in parallel, at the same time, with the data recorded in the database. Data acquisition lasted for 5 h with records taken every 2 min, totaling 150 records. Different statistical metrics were used to ensure the accuracy and fit of the linear regression equation to the real values of the poultry

Table 5
Statistical metrics on the accuracy of the linear regression equation.

Assessment Elements	Average of Residuals	Standard Error of the Estimate	Estimated Value Found	Average Expected Range
Ammonia	0.3193	0.41	2.16 ppm	Max. 15 ppm
Carbon dioxide	−1.1671	20.08	1041 ppm	Max. 3000 ppm
Carbon monoxide	7.9492	8.05	1.25 ppm	Max.16.09 ppm
Luminosity	3.3425	1.31	26.28 lx	Between 10 and 20 lx
Temperature	0.2541	0.07	26.76 °C	Between 19.5 and 24.6 °C
Moisture	3.2544	1.27	74.18 %	Between 54 and 65 %.
Dust PM 10	54.35	28.32	1290.24 μg/m^3	Between 1280 and 3362 μg/m^3

house. Table 5 presents the final summary of the metrics used.

The Dust (PM 10) and Carbon Dioxide sensors exhibited larger standard error in estimating the value. This is due to the difficulty of generating an equation that reliably predicts the measured value based on the industrial sensor. The other sensors presented low values for both average of residuals and standard error of the estimate, thus ensuring high reliability in predicting the estimated value.

4. Conclusions and final considerations

The Environmental Sensor module was constructed and functioned correctly for data collection. The rapid prototyping sensors integrated into the module were calibrated with industrial sensors. The result of this calibration yielded equations that predicted the estimated values. These values were analyzed using statistical methods, presenting the residual rate and the relationship to the standard error of the estimate in relation to the estimated value found, thereby determining the reliability of the predicted response. Furthermore, the estimated value was compared to the expected average value, indicating the condition of the microclimate where the sensor was positioned in the aviary. The results of each sensor were consistent with the conditions observed during the fifth week of breeding. It is concluded that the module is reliable and ready for use.

CRediT authorship contribution statement

Glauber da Rocha Balthazar: Writing – review & editing, Visualization, Validation, Supervision, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Robson Mateus Freitas Silveira:** Writing – review & editing, Visualization, Validation, Investigation, Conceptualization. **José Tadeu Aldrigue:** Writing – review & editing, Visualization, Validation, Investigation. **Iran José Oliveira da Silva:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

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Data availability

Data will be made available on request.

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