Smart Agricultural Technology 14 (2026) 102156

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology

# A case study to test an early warning technology to detect enteric dysbiosis in broiler production and to reduce the use of antibiotics

F. Borgonovo [a], M. Guarino [a], F. Leone [a,*], C. Brandolese [b], M. Grotto [c], A. Canidio [c], C. Mazzi [d], V. Ferrante [a]

[a] Department of Environmental Science and Policy, Università degli Studi di Milano, Via G. Celoria 2, 20133, Milan, via Ponzio 34, 20133, Milan, Italy
[b] Department of Electronics, Information and Bioengineering, Politecnico di Milano, via Ponzio 34, 20133, Milan, Italy
[c] IBT Systems, Viale Lombardia 217, 20900, Monza, Italy
[d] Agronomist, Technical Service Broiler Chain, Verona, Italy

ARTICLE INFO

*Keywords:*
Broiler
*Eimeria* spp.
Enteric diseases
Volatile organic compounds
Organic acids

ABSTRACT

This study presents a case study of a novel early-warning system for detecting enteric dysbiosis in broiler chickens using Volatile Organic Compounds (VOCs) analysis. The system combines metal oxide semiconductor (MOS) sensors with PCA–KNN algorithms to identify metabolic air-profile changes associated with enteric diseases. Field validation was conducted in two broiler houses in Northern Italy using oocyst counts as the diagnostic gold standard. The monitoring system issued alerts up to four days before clinical signs appeared, enabling timely intervention with organic acids instead of antibiotics. Early treatment reduced mortality, maintained feed conversion efficiency, and preserved antibiotic-free certification. The model achieved over 80% accuracy in early detection, while organic acid intervention (€88) was substantially more cost-effective than antibiotic treatment (€180). Overall, this technology offers a non-invasive, real-time tool to support antimicrobial reduction strategies in poultry production, aligning with EU objectives to minimize antibiotic use. Limitations of the study include reliance on oocyst count alone, and need for IoT connection. Nonetheless, this approach represents a scalable and sustainable alternative to antibiotics in broiler production systems.

## 1. Introduction

In response to the increasing demand for high-quality food, the global poultry industry has undergone several changes, including advancements in farm management, genetics, and feed formulation. Among these, genetic selection played a key role, resulting in fast-growing birds with better feed conversion ratio (FCR) and higher meat yields [1]. Because gut health is closely linked to mortality rates and overall performance, maintaining optimal intestinal integrity has become a major priority for modern poultry production [2]. Intestinal disorders negatively affect broiler chickens' performance by causing higher morbidity and mortality, a reduced body weight gain, a poor FCR, increasing costs for farmers [2,3]. These disorders may arise from bacteria, viruses, or parasites (individually or in synergy), and can be exacerbated by suboptimal management or environmental conditions. Among enteric pathogens, *Clostridium perfringens* is an anaerobic, spore forming enteric pathogen recognized as the primary causative agent of clinical and subclinical enteric disease in chickens. The most severe clinical form of enteric disease is necrotic enteritis (NE), a disease driven by rapid bacterial proliferation and toxin release in the gastrointestinal tract. The NE is characterized by a distended and fragile intestine, with necrosis of the intestinal mucosa typically covered by a yellow to light brown pseudomembrane. The clinical form of NE is associated with substantial economic losses, whereas the subclinical form significantly negatively affects growth performance in chickens by causing extensive damage to the intestinal epithelium [4].

One of the main predisposing factors for NE is coccidiosis, a parasitic disease caused by protozoa of the family *Eimeriidae*, which are widespread in poultry houses [5]. Coccidiosis-induced damage to the intestinal epithelium increases gut permeability and facilitates secondary infections [6]. Intestinal infections associated with clinical or subclinical coccidiosis can significantly promote the proliferation of *C. perfringens* [4].

Control strategies for coccidiosis rely mainly on the use of anticoccidial drugs (coccidiostats) and vaccination. Coccidiostats are veterinary medicines used to treat and prevent coccidiosis [7]. However,

---

* Corresponding author.
*E-mail address:* francesca.leone@unimi.it (F. Leone).

https://doi.org/10.1016/j.atech.2026.102156
Received 27 February 2026; Received in revised form 16 April 2026; Accepted 24 April 2026
Available online 25 April 2026

their efficacy has been increasingly compromised by the development of drug resistance [8]. According to the Regulation (EC) No 1831/2003 [9] coccidiostats differ from antibiotics due to their specific mode of action on parasites rather than intestinal microbiota. However, both ionophore and synthetic coccidiostats may lose efficacy over time [10], due to the development of drug resistance [8]. Vaccination with live Eimeria oocysts represent an alternative control strategy, although its effectiveness may be limited by strain specificity and the need for adequate parasite exposure in the litter to introduce full protective immunity. In addition, vaccines can be costly and may show inconsistent efficacy under field conditions [8,11]. In the past, sub-therapeutic doses of antibiotics were widely used as growth promoters (AGPs), supporting digestive efficiency, nutrient absorption, and microbiota stability [12]. However, extensive AGP usage has contributed to the emergence of antibiotic-resistant bacteria, raising major public health concerns [13].

Antimicrobial resistance (AMR) is now considered one of the leading global health threats. A recent study reported that AMR prevalence continues to rise, a trend further intensified by the COVID-19 pandemic [14]. Despite reductions in veterinary antibiotic use across the EU since 2014, coordinated One Health strategies remain essential to curb AMR spread in humans, animals, and the environment (Fig. 1) [15,16]. Similarly, the extensive use of anticoccidial drugs in poultry production has led to the development of drug resistance in Eimeria species, highlighting the urgent need for alternative control strategies such as vaccination and non-antibiotic approaches [6].

In response to these challenges, the European Union prohibited the use of antibiotics as growth promoters from 1 January 2006, in accordance with Regulation (EC) No 1831/2003 [9]. In addition, the Regulation (EU) 2024/1973 was published with the aim of strengthening the control over the use of antimicrobials in veterinary medicine [17]. This approach involves the use of antibiotics only in specific cases, and other treatment options have been ruled out. Under these regulatory constraints, prevention and early diagnosis have become crucial. Biosecurity, environmental management, and nutritional strategies can support gut health [18,19]. In this context, feed additives such as prebiotics, probiotics, essential oils, organic acids, and enzymes have emerged as promising alternatives to antibiotics, contributing to the maintenance of intestinal microbial balance and supporting animal performance. These additives have shown beneficial effects on gut taxonomy, immune modulation, inflammatory processes and intestinal morphology, while limiting the colonization of pathogenic bacteria. In particular, their beneficial effects are associated with their ability to modulate the intestinal microbiota, promote the growth of beneficial bacterial populations, and enhance digestive efficiency, ultimately resulting in improved performance [2,20].

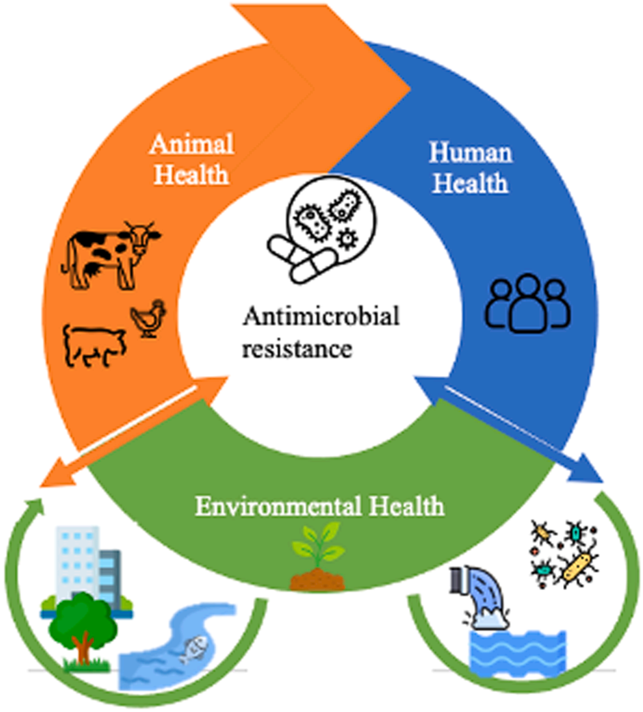

**Fig. 1.** Schematic overview of the One Health approach to antimicrobial resistance (AMR). The model highlights the interconnected nature of human, animal, and environmental health, emphasizing their collective contribution to the selection, amplification, and transmission of antimicrobial-resistant microorganisms.

Despite their potential, the widespread adoption of these alternatives is hindered by high costs, management complexity, and an indirect mechanism of action that limits their efficacy in treating acute infections compared to direct action of antibiotics, as their implementation in commercial poultry systems is strongly influenced by economic constraints, product availability, and farm management practices. Furthermore, their performance is highly influenced by animal-specific and environmental factors, including species, age, health status, and farm management [20], suggesting that the prophylactic administration would be an optimal strategy.

Diagnostic methods for enteric diseases are traditionally invasive, *post-mortem*, and slow. Histopathology, bacteriology, necropsy, and PCR can require up to 8 days and are costly (€200–400 per case), allowing disease progression across entire flocks of 20,000–40,000 birds [21–23]. Although molecular tools and microbiome sequencing have improved pathogen characterization [24], these methods still require animal sacrifice and cannot support real-time decision-making. Consequently, there is a growing need for rapid and non-invasive tools able to detect early intestinal dysbiosis before clinical signs appear [25]. In this context, recent studies suggest that endogenous metabolic alterations and host–pathogen interactions influence the profile of volatile organic compounds (VOCs) emitted from animals [26]. VOC analysis has been explored as a diagnostic strategy in livestock and human medicine [27], and in poultry it has mainly been used to assess air quality inside houses [28]. Furthermore, MOS-based gas sensing systems allow real-time, non-invasive monitoring of VOC emissions, with changes in sensor resistance closely correlated with microbial proliferation and metabolic processes, thereby enabling early detection of biological alterations before visible signs of deterioration appear. Moreover, these sensors demonstrate high sensitivity and reliability through gas adsorption–induced changes in electrical resistance, supporting their application in environmental, food, and biological monitoring systems [29–32]. However, their potential for detecting enteric diseases in broilers remains unexplored.

Given the limitations of current diagnostic approaches and the increasing pressure to reduce antibiotic use, there is a clear need for innovative, non-invasive, and real-time monitoring tools capable of identifying early alterations in gut health before clinical signs emerge. So, the aim of this case study was to evaluate a novel technology for the early detection of enteric dysbiosis in a poultry farm by monitoring variations in VOCs, prior to the onset of clinical signs. Specifically, the authors aimed to determine whether an early warning system for enteric dysbiosis could reduce the use of antibiotics by enabling timely intervention with organic acids instead, thereby improving economic benefit.

## 2. Materials and methods

### 2.1. Birds and housing

This case study was conducted in a poultry farm located in Northern Italy. It consisted of two sheds (120 m long by 12 m wide, each shed covering 1440 $m^2$), equipped with forced ventilation by negative-pressure systems and wood shavings as litter. A total of 20.660 fast-growing broiler chicken ROSS 308 (mixed sexes) were reared in each shed at the stocking density of 33 kg/$m^2$ [33]. Feed and water were provided ad libitum. A nutritional program was followed as standard practice, in accordance with the guidelines of the hybrid [34]: starter phase from day 1 to 10, grower phase from day 11 to 28, and finisher phase from day 29 until the end of the cycle. Broilers received standard hatchery vaccination during the incubation phase. Acidified drinking water containing formic and propionic acids was provided ad libitum from day 18 to day 22. The schedule of vaccination and supportive treatment in broilers is summarized in Table 1

Environmental parameters (temperature, relative humidity, and ventilation rate) were automatically regulated according to the ROSS 308 management guidelines, under a standard 16L:8D lighting programme [34]. Climate control in the sheds was completely automated, and climate variables were continuously monitored (24/7), including indoor air temperature and relative humidity. The calibrated sensors for relative humidity (RHM.2-RHO/2 Sensor) and air temperature (SF.7 Temp Sensor) were installed by Fancom BV. Raw data were recorded every 10 min, resulting in a total of 5705 observations, and were collected using FarmManager (Fancom BV, Panningen, The Netherlands), then automatically uploaded and stored on an online data server. Wet-bulb temperature was subsequently calculated using Stull Formula [35]. Table 2 reports the mean (± SD) environmental parameters over the entire production cycle in the two sheds, including dry-bulb temperature and relative humidity, as well as the wet-bulb temperature. The temperature–humidity index (THI) was calculated as $THI_{broilers} = 0.85\ T_{db} + 0.15\ T_{wb}$

### 2.2. Performance

Feed conversion ratio (FCR) and the total mortality rate were assessed throughout the production cycle. Instead, average body weight at slaughter (aBW), carcass rejections rate, and dead-on-arrival (DOA) birds were recorded at the thinning (32 days of age) and at the end of the cycle.

### 2.3. Installation of the new technology and VOCs analysis

The new technology tested consisted in an integrated IoT device protected by patented technology (International Publication Number: WO2017/212,437). The validation of this technology was based on the oocyst count, used as gold standard [36].

The device operates measures VOCs with semiconductor metal oxide gas sensors (MOS), and through of a mathematical model it is capable to detect the variation of chemical composition in the air. MOS sensors react to the presence of different VOCs by changing their resistance, which is then converted in a voltage through a voltage divider and converted into a digital measure by an ADC (Analog to Digital Converter) sampled every 10 min. The resulting measure is correlated with the concentration of different volatile compounds in the air [37]. This sensing principle is based on gas adsorption processes occurring at the sensor surface, which induce measurable changes in electrical resistance and have been shown to correlate with microbial activity and VOC emissions in real-time monitoring applications [38]. The timeseries resulting from the measurements of six different VOCs sensors are then fed to a processing pipeline capable of detecting variations associated to environmental changes. The mathematical model was trained to correlate environmental changes to the potential presence of intestinal disorders in poultry farms at early stage, when the pathology is not evident yet. Deeper understanding of these variations should be facilitating the veterinarian in the development of effective disease-control measures to treat. Enteric disorders, outlined by the system and associated with VOCs, could be both of a pathological (viral or bacterial agents and parasites) and metabolic (feed, management practices, and environmental factors) origin.

The device was installed in both sheds and placed in the middle of each building (Fig. 2), 80–90 cm above the floor.

**Table 1**
Schedule of vaccination and treatment in broilers.

| Intervention | Timing | Details |
|---|---|---|
| Standard hatchery vaccination | Hatchery | |
| Formic + Propionic acids | Days 18–22 | Provided ad libitum via drinking water |

**Table 2**
Environmental parameters in the two sheds.

| SHEDS | Tdb ( °C) | RH ( %) | Twb ( °C) | THI ( °C)[a] |
|---|---|---|---|---|
| 1 | 25.6 ± 2.76 | 67.4 ± 5.09 | 21.5 | 24.99 |
| 2 | 25.4 ± 2.81 | 67.5 ± 5,16 | 21 | 24.7 |

[a] THIbroilers = 0.85 Tdb + 0.15 Twb
Tdb = dry-bulb temperature, °C
Twb = wet-bulb temperature, °C.

### 2.4. Data collected

Faeces samples were weekly collected in five different zones of each shed (Fig. 2) to perform the count in laboratory with the Mc Master chamber method expressed in oocysts per gram of faeces (OPG) [39]. This number was used by the algorithm as the basis for classification of VOCs measurements over time. More precisely, previous studies [40–42] have demonstrated 1000 oocyst per gram can be defined as the threshold value that may allow the veterinarian to intervene with alternative products upon receiving an alert. Considering this threshold, the prediction approach has been simplified from a continuous domain to a discrete classification problem.

### 2.5. The predictive model and data processing analysis

Several key methods have been adopted in the processing chain to maximize the prediction capabilities of the overall system. First of all, temperature and humidity compensation have been applied to raw data to account for the conditions in different farms and the daily and seasonal throughout the whole broiler production cycle (Fig. 3). Compensated data is then normalized based on the measures of the first 3–5 days of the farming cycle and detrended to account for the periodic daily variations by considering sliding windows of 24-hours. On such windows, a set of six features is extracted for each sensor every 60 min, obtaining a total of 36 features (Fig. 4).

Features are then reduced using PCA (Principal Component Analysis) to an orthonormal set of 7 components explaining 98 % of the variance of the model. The dataset used consists of 22,286 datapoints (approximately 600–700 data points per farming cycle), partitioned in a training set consisting of 80 % of the data and a test set consisting of the remaining 20 %. Several binary (critical/non-critical) classifiers have

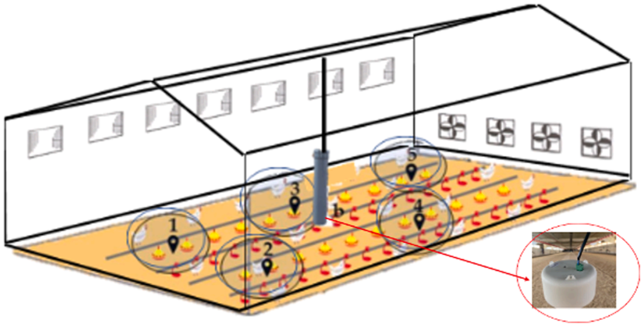

**Fig. 2.** Device installation and the five-sampling zone (1–5).

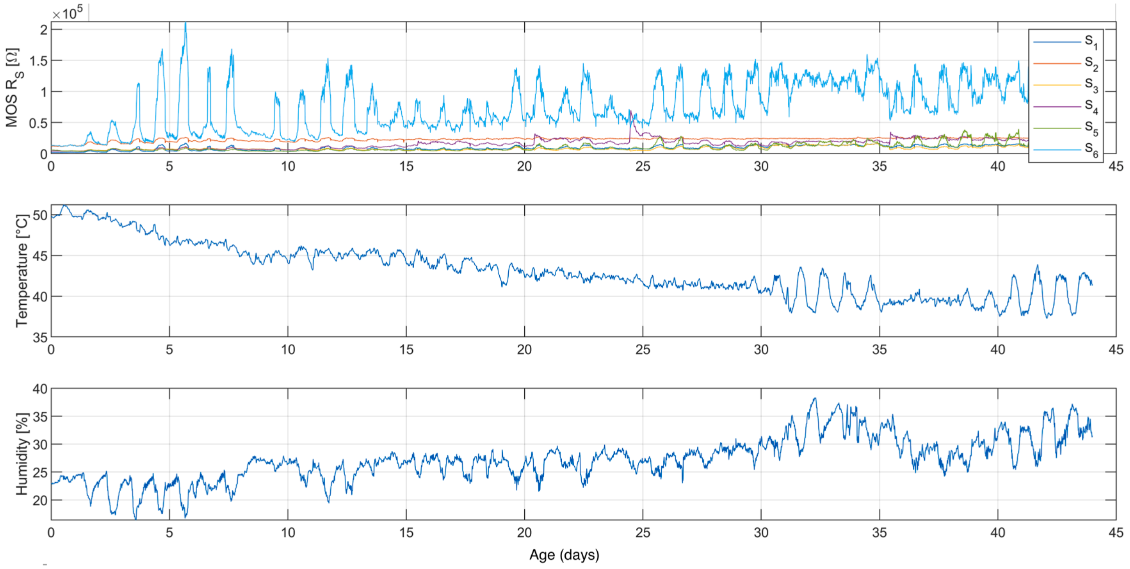

**Fig. 3.** Trend of MOS sensors activity during the whole broiler production cycle monitored. (a) Raw data; (b, c) Temperature and humidity compensation applied to raw data.

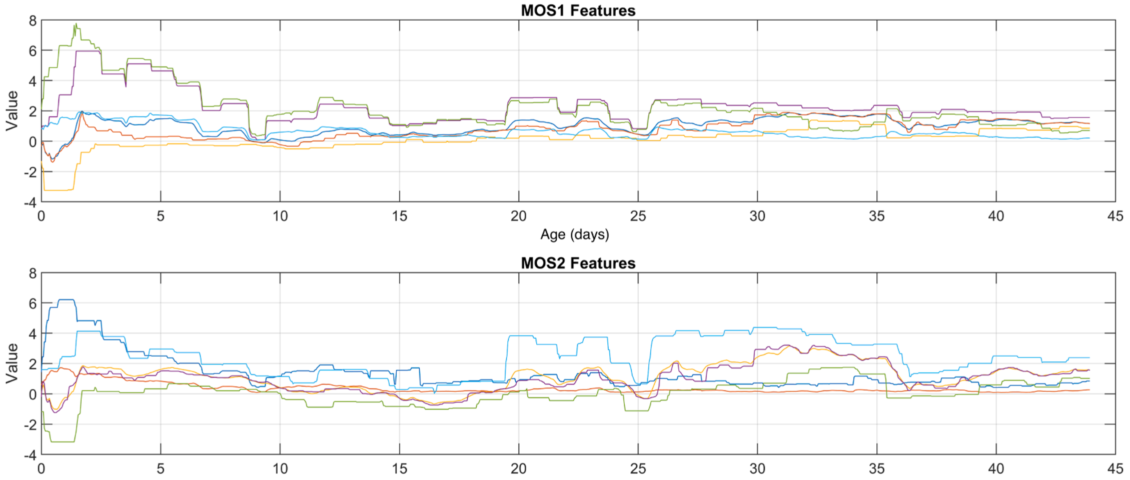

**Fig. 4.** Example illustrating the extraction of six features for two MOS sensors.

been trained (trees, random forest, KNN, linear SVM, logistic regression, neural networks) and the best performance was obtained with a KNN classifier, which achieved an accuracy of 82.7 % (see confusion matrix Table 3) [43].

The model shows good overall performance, with solid accuracy (82.7 % on the test set and test, 90.0 % on the training set) and balanced precision–recall behaviour, as the F1 score indicates (Tab 4). Generalization capability is acceptable, though performance drops from training to test (especially sensitivity), suggesting mild overfitting, which mainly depends on the imbalance between the size of critical and non-critical sets. Finally, the low FPR (∼8 %) and high specificity (∼0.92) indicate few false alarms, but the higher FNR (∼30 %) means some positives are still being missed. Analysing the predictions over time for the different farming cycles, though, it can be observed that in most of the cases, the overall effect is a delay in the prediction of a critical situation. On the other hand, spurious false positives have been mitigated by filtering the raw prediction of the KNN classifier through a deterministic finite state machine.

**Table 3**
Confusion matrix.

| | | Prediction | |
|---|---|---|---|
| | | True | False |
| Actual | True | 28.9 %<br>(1010) | 12.3 %<br>(429) |
| | False | 5.0 %<br>(173) | 53.8 %<br>(1879) |

**Table 4**
Statistical characterization of the results.

| Index | Value | Confidence interval (95 %) |
|---|---|---|
| Sensitivity | 0.702 | 0.677 – 0.725 |
| Specificity | 0.916 | 0.903 – 0.927 |
| Precision | 0.854 | 0.832 – 0.073 |
| False Positive Rate | 0.084 | 0.073 – 0.097 |
| False Negative Rate | 0.298 | 0.275 – 0.322 |
| F1 Score | 0.770 | N/A |

The model shows good overall performance, with solid accuracy (82.7 % on the test set and test, 90.0 % on the training set) and balanced precision–recall behaviour, as the F1 score indicates. Generalization capability is acceptable, though performance drops from training to test (especially sensitivity), suggesting mild overfitting, which mainly depends on the imbalance between the size of critical and non-critical sets. Finally, the low FPR (∼8 %) and high specificity (∼0.92) indicate few false alarms, but the higher FNR (∼30 %) means some positives are still being missed. Analysing the predictions over time for the different farming cycles, though, it can be observed that in most of the cases, the overall effect is a delay in the prediction of a critical situation. On the other hand, spurious false positives have been mitigated by filtering the raw prediction of the KNN classifier through a deterministic finite state machine.

Such alerts are finally filtered through a deterministic finite state machine with the goal of minimizing spurious alerts. Alerts (Fig. 5) are shown on the system dashboard and notified via email or SMS to the farmer.

## 3. Results and discussion

### 3.1. Performance

The performance, collected at the slaughterhouse, was similar in the two sheds: mortality rate was pointed at 4.88 % and the overall FCR of 1.60. In Table 5 are reported at day 32 (thinning) and 46 (end of the cycle) the aBW, the carcass rejection rate, and the DOA, although was not possible to performe a statistical analysis, due to the lack of standard deviation, the differences between the two sheds for the carcass rejections at the thinning period were 25 % higher in shed 2 compared to shed 1.

The performance results observed in both sheds were consistent with those typically recorded in this farm under disease-free conditions. The average body weight (aBW) at 32 days was 1.60 kg in Shed 1 and 1.56 kg in Shed 2, increasing to 2.7 kg at final slaughter in both sheds, which aligns with expected growth curves for ROSS 308 hybrids [34]. These values indicate that the treatment allowed to not compromise growth performance in a substantial way. Carcass rejection rates remained low at both thinning and final slaughter, suggesting that the prompt treatment succeeded in minimising the side effects of the enteric challenge. Such values fall well within the normal variability of commercial slaughterhouse and are typically observed when enteric lesions remain mild or are managed early, preventing progression to severe necrotic forms [21]. The DOA values reported are also compatible with standard commercial ranges and likely reflect common pre-transport and handling stressors rather than acute pathology [25]. The total mortality recorded across the production cycle (4.88 %) remained below the 5 % threshold generally considered acceptable in intensive broiler production systems [44]. The maintenance of mortality within physiological limits suggests that the enteric dysbiosis did not evolve into a clinically severe outbreak, likely due to the timely intervention with organic acids in water applied after the early warning. Similarly, the final FCR of 1.60 reflects good feed efficiency, especially considering that the final body weight reached 2.7 kg. Enteric diseases are well known to impair nutrient absorption and increase feed conversion due to villus damage and lower digestive efficiency [2,21]. The preservation of a competitive FCR, even during a confirmed enteric challenge, supports the interpretation that early intervention contributed to stabilize intestinal functionality before performance impairment became evident. Overall, the consistency of growth performance, low carcass rejection rates, acceptable mortality, and preserved feed efficiency indicate that the enteric imbalance detected by the sensor system did not translate into severe production losses thanks to the prompt intervention with the organic acids.

**Table 5**
Broiler chickens' performance.

| Performance | *Thinning* | | *End* | |
|---|---|---|---|---|
| | *Shed 1* | *Shed 2* | *Shed 1* | *Shed 2* |
| *aBW (kg)* | 1.6 | 1.56 | 2.7 | 2.7 |
| *Carcass rejections ( %)* | 0.48 | 0.6 | 0.8 | 0.8 |
| *DOA (n)* | 3 | 3 | 27 | 28 |

### 3.2. Data analysis and prediction plot calculated by the algorithm

The device installed in shed 2 had an early warning at day 14. Following the early warning, an inspection was conducted by the veterinarian that did not observe any clinical symptoms, but he collected faecal samples and carried out *post-mortem* examinations on the dead animals.

Following the alert at day 14, daily mortality increased to approximately 30 birds in shed 2. The veterinarian, in agreement with the authors, although at that time no overt clinical signs of pathology were observed, decided to intervene in both sheds by administering from the 18th day to the 22nd day acidified drinking water containing formic and propionic acids, aimed at lowering gut pH and creating a less favourable environment for pathogens [3].

A week after the start of the acidification treatment, the veterinarian lab could confirmed that the deceased birds revealed enteritis, characterized by thinning the intestinal membrane. This diagnosis was further supported by the detection of *Eimeria* oocysts in the lab (see Table 3). In fact the faecal samples were collected throughout the production cycle to monitor the presence and intensity of *Eimeria* infection, that analysis revealed a progressive increase in oocyst shedding over time. In shed 1, a rise was observed from the third week, whereas in shed 2 the increase began earlier, during the second week. The highest counts were recorded in week 3 in both sheds, reaching over 33,000 oocysts/g in shed 1 and 32,200 oocysts/g in shed 2 (Table 6).

Data collected showed that the device was triggered approximately seven days before the highest oocyst levels were recorded (Fig. 5). To explain better the time-line of the alert, the oocyst count in the two sheds, the day mortality trend, the necroscopy findings and when the treatment was administered, is reported in Table 7.

The importance of this time frame lies in the fact that it enables non-antibiotic treatment interventions and lowers both health and economic

**Table 6**
Oocyst count (oocysts/g) in the two sheds during the production cycle.

| Shed | Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6 |
|---|---|---|---|---|---|---|
| 1 | 600 | 500 | >33,000 | 23,300 | 300 | 0 |
| 2 | 600 | 3200 | 32,200 | 20,000 | 800 | 800 |

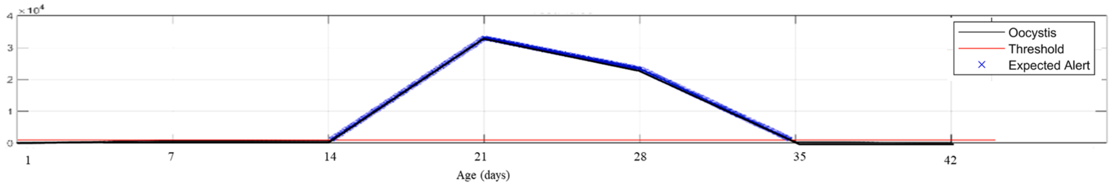

**Fig. 5.** Oocyst count over time in broilers. The black line represents oocyst counts, the red line indicates the threshold level, and the blue line represents the alert level. An alert was triggered when oocyst counts exceeded the threshold.

**Table 7**
time-aligned of activities carried out over the birds production cycle.

| Cycle day | Alert | Oocyst count Shed 1 | Oocyst count Shed 2 | Day mortality trend | Necroscopy findings | Treatment |
|---|---|---|---|---|---|---|
| **7** | No | Low | Low | Normal | NC | NC |
| **14** | Yes | Low | Moderate | Normal | NC | NC |
| **15** | Yes | NC | NC | Normal | NC | NC |
| **18** | Yes | NC | NC | Slight increase | NC | Treatment started |
| **21** | Yes | High | High | Slight increase | NC | Treatment in progress |
| **22** | Yes | NC | NC | Slight increase | NC | Treatment end |
| **24** | Yes | NC | NC | Normal | Enteritis characterized by thinning the intestinal membrane | NC |
| **28** | Yes | Medium | Medium | Normal | NC | NC |
| **35** | No | Low | Low | Normal | NC | NC |
| **42** | NO | Absent | Low | Normal | NC | NC |

NC= not carried out.

risks. This case study has therefore demonstrated the effectiveness of organic acids that can be given after VOCs alert detection as a viable alternative to antibiotics, contributing to the reduction in the use of antibiotics in livestock farming, in line with AMR mitigation strategies. Organic acids can also improve water quality by reducing microbial load and promoting intestinal health [45]. The complex interactions among gut microbiota, immune responses, and intestinal bacterial metabolic wastes are depicted in VOCs. This confirms what was described by Martynova-Van Kley et al. [46] reported that *Eimeria* infections lead to microbial fermentation and epithelial degradation, which is likely the cause of the VOC variation detected by the sensor system. The results are consistent with previous research that connects air composition in poultry houses to flock health status [27,47].

### 3.3. Economic impact of timely intervention

This technology has shown a significant economic benefit by reducing mortality, avoiding antibiotic use and preserving compliance with antibiotic-free policies, which could prevent a 10–20 % loss in profits for poultry farms. Moreover, the early warning enabled prompt treatment with organic acids to be started. Timely intervention was crucial in this case, as it allowed the farmer to successfully implement water acidification and avoid the use of antibiotics. This strategy ensured satisfactory health outcomes and resulted in a substantially lower treatment cost (see Table 5), highlighting the economic and management value of early non-antibiotic intervention. The acidifier product used cost €4.40 per litre, and 20 litres were administered over the 5-day treatment period, for a total cost of €88. In comparison, an antibiotic treatment with amoxicillin would have cost €180. These results emphasize that timely intervention enables effective non-antibiotic management while generating substantial cost savings. Early intervention improved flock uniformity, reduced feed conversion ratio (FCR), and decreased carcass rejections at slaughterhouses. Conversely, non-compliance with antibiotic-free requirements could result in an additional 10–20 % loss of profit for poultry farms, while high mortality rates translate into a loss of approximately €0.063 per tonne in premium payments (Table 8).

This paper presents a case study showing how the economic benefits derived from early warning signals underscore the importance of prompt intervention. A broader adoption of these devices would allow the generation of larger datasets, thereby enabling increasingly robust economic evaluations. It is also important to remember that the significance of these findings is amplified by the current economic and regulatory context as Regulations (EC) 1831/2003 [9] and (EU) 2024/1973 [17] aim to phase out routine antibiotic use in animal production within the European Union. By providing actionable and real-time insights, technologies such as those used in this case study can serve as key enablers of this transition. In contrast to vaccination or coccidiostat inclusion, which can be costly or lose effectiveness in the future [10,11], real-time monitoring systems can adapt to farm-specific conditions and are scalable, flexible, and adaptive. The results obtained from this case study appear to be promising.

**Table 8**
Economic impact of organic acid vs antibiotic treatment.

| Parameter | Organic Acid Treatment | Antibiotic Treatment (Amoxicillin) |
|---|---|---|
| Treatment Cost (€) | €88 | €180 |
| Product Used | Acidifiers | Amoxicillin |
| Product Cost per Unit | €4.4 / litre | €56 / 1000 g |
| Dosage | 20 litres over 5 days | 20 g per 100 litres for 5 days |
| Total Quantity Used | 20 litres | Calculated based on flock water consumption |
| Cost Impact on Agistment Contract Farmers | | €0.063 / tonne (due to mortality penalties) |
| Impact on Flock Performance | Improved uniformity<br>Reduced FCR<br>Fewer carcass rejections | Not specified |
| Profit Loss (Antibiotic-Free Label Violation) | None | Estimated 10–20 % loss in profit |

## 4. Conclusions and implications

The application of VOC-based sensing technologies for the early detection of enteric diseases in broiler chickens can be strongly supported by the findings of this case study. This study, even if only a case study, demonstrates the effectiveness of a novel VOCs-based monitoring system, integrated with signal processing and advanced machine learning algorithms, for an early detection of enteric dysbiosis in broiler chickens. By capturing air composition changes associated with intestinal disorders, the system provided timely alerts up to several days before the appearance of clinical symptoms, thereby enabling preventive interventions. From a production perspective, these findings indicate that the integration of this technology with organic acid administration can enhance animal health management and overall performance, ensuring production stability while minimizing potential losses.

From a production perspective, these findings indicate that the integration of this technology with organic acid administration can enhance animal health management and overall performance, ensuring production stability while minimizing potential losses. This approach was associated with reduced mortality, improved feed conversion ratio (FCR), maintained flock uniformity, and minimized carcass rejections at slaughter in the present paper. Within routine farm management practices, which require rigorous and methodical organization to ensure animal welfare, production efficiency, and biosecurity, visual inspection represents an essential component of the monitoring activity. In this context, the device may serve as a complementary decision-support tool by providing continuous and objective early warnings, thereby facilitating more targeted and efficient on-farm interventions.

From an economic perspective, the cost of acid-based intervention was significantly lower than that of conventional antibiotic treatments, while also preserving the antibiotic-free certification critical for market positioning and premium contracts, with farmers cooperation more case studies will be performed to strengthen these results. Failure to maintain such certification could result in financial losses estimated at 10–20 % per production cycle. The use of this technology therefore allows poultry producers to benefit in terms of prevention, animal welfare, and economic performance, and it aligns with the growing regulatory and societal demand to reduce antimicrobial use in livestock. By providing an early, non-invasive, and automated diagnostic tool, it supports the transition toward more sustainable, precision-based poultry production systems.

This case study also presents some limitations, such as the reliance on oocyst counts alone, and the need for IoT connection. Nevertheless, the approach remains a scalable and sustainable alternative to conventional antibiotics, providing an effective tool for early dysbiosis detection, improved animal welfare, and enhanced production efficiency in broiler systems.

## Data availability

The data that support the findings of this study are available from the corresponding author upon request.

## Statement

The authors declare that the ethical approval was not necessary as the devices work without any direct contact with poultry and it was installed before the entrance of birds. Faecal samples were collected by the farmer during the normal routine. No birds were manipulated nor sacrificed.

## CRediT authorship contribution statement

**F. Borgonovo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Data curation. **M. Guarino:** Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **F. Leone:** Writing – review & editing, Writing – original draft, Validation, Data curation. **C. Brandolese:** Supervision, Formal analysis. **M. Grotto:** Software. **A. Canidio:** Software. **C. Mazzi:** Investigation. **V. Ferrante:** Project administration, Methodology.

## Declaration of competing interest

The authors declare that they have no competing financial interests.

## Acknowledgements

The authors would like to thank the farm owner and staff for their collaboration and for allowing the installation and testing of the monitoring system under commercial farming conditions. We also acknowledge the support of the attending veterinarian for clinical inspections and diagnostic activities, and the laboratory technicians for their assistance with the analyses.

## References

[1] K.K. Cooper, J.G. Songer, F.A. Uzal, Diagnosing clostridial enteric disease in poultry, J. Vet. Diagn. Invest. 25 (2013) 314–327, https://doi.org/10.1177/1040638713483468.

[2] S.A. M'Sadeq, S. Wu, R.A. Swick, M. Choct, Towards the control of necrotic enteritis in broiler chickens with in-feed antibiotics phasing-out worldwide, Anim. Nutr. 1 (2015) 1–11, https://doi.org/10.1016/j.aninu.2015.02.004.

[3] M.A. Ali, H. Mostafa El Agrab, M. Mamdouh Hamoud, A. Mohamed Gamal, M. Refat Mousa, S. Abo Elsoud Nasr, M. Ahmed Hassan El Shater, S. Elsaeed Laban, O. Kamel Zahran, M. Mohamed Ali, Effect of acidified drinking water by organic acids on broiler performance and gut health, AAVS 8 (2020), https://doi.org/10.17582/journal.aavs/2020/8.12.1301.1309.

[4] E.A. Rana, T.A. Nizami, M.S. Islam, H. Barua, M.Z. Islam, Phenotypical identification and toxinotyping of *Clostridium perfringens* isolates from healthy and enteric disease-affected chickens, Vet. Med. Int. 2023 (2023) 2584171, https://doi.org/10.1155/2023/2584171.

[5] F.A. Uzal, C.G. Sentíes-Cué, G. Rimoldi, H.L. Shivaprasad, Non- *Clostridium perfringens* infectious agents producing necrotic enteritis-like lesions in poultry, Avian Pathol. 45 (2016) 326–333, https://doi.org/10.1080/03079457.2016.1159282.

[6] R. Ahmad, Y.-H. Yu, K.-F. Hua, W.-J. Chen, D. Zaborski, A. Dybus, F.S.-H. Hsiao, Y.-H. Cheng, Management and control of coccidiosis in poultry — a review, Anim. Biosci. 37 (2024) 1–15, https://doi.org/10.5713/ab.23.0189.

[7] M. Rybicki, Coccidiostats in treating coccidiosis, Zntj 125 (2020) 127–137, https://doi.org/10.15193/zntj/2020/125/364.

[8] H.D. Chapman, Applied strategies for the control of coccidiosis in poultry, CABI Rev. (2018) 1–11, https://doi.org/10.1079/PAVSNNR201813026.

[9] European Parliament, Regulation (EC) No 1831/2003 of the European parliament and of the council on additives for use in animal nutrition, Off. J. Eur. Union (2003). https://eur-lex.europa.eu/legal-content/it/ALL/?uri=CELEX%3A32003R1831.

[10] R.R. Martins, L.J.G. Silva, A.M.P.T. Pereira, A. Esteves, S.C. Duarte, A. Pena, Coccidiostats and poultry: a comprehensive review and current legislation, Foods. 11 (2022) 2738, https://doi.org/10.3390/foods11182738.

[11] E. Barbour, D. Ayyash, A. Iyer, S. Harakeh, T. Kumosani, A review of approaches targeting the replacement of coccidiostat application in poultry production, Rev Bras Cienc. Avic. 17 (2015) 405–418, https://doi.org/10.1590/1516-635x1704405-418.

[12] M. Rahman, I. Fliss, E. Biron, Insights in the development and uses of alternatives to antibiotic growth promoters in poultry and swine production, Antibiotics 11 (2022) 766, https://doi.org/10.3390/antibiotics11060766.

[13] H.M. Hafez, Enteric diseases of poultry with special attention to clostridium perfringens, Pak. Vet. J. (2011).

[14] N.A. George, D. Pan, L. Silva, R.F. Baggaley, P. Irizar, P. Divall, A. Al-Oraibi, D. P. Khan, C.A. Martin, J. Nazareth, I. Collins, S.L. Chew, L.B. Nellums, M. Pareek, The prevalence and risk of mortality associated with antimicrobial resistance within nosocomial settings—A global systematic review and meta-analysis of over 20,000 patients, EClinicalMedicine 87 (2025) 103384, https://doi.org/10.1016/j.eclinm.2025.103384.

[15] M. Cecchini, D. Monnet, E. Liebana, B. Freischem, R. Botgros, Antimicrobial Resistance in the EU/EEA: a one health response., OECD, ECDC, EFSA and EMA, 2022.

[16] M.E. Velazquez-Meza, M. Galarde-López, B. Carrillo-Quiróz, C.M. Alpuche-Aranda, Antimicrobial resistance: one health approach, Vet. World (2022) 743–749, https://doi.org/10.14202/vetworld.2022.743-749.

[17] European Commission, Commission implementing Regulation (EU) 2024/1973 establishing a list of antimicrobials which shall not be used in accordance with articles 112 and 113 of regulation (EU) 2019/6 of the European parliament and of the council or which shall only be used in accordance with those articles subject to certain conditions, Off. J. Eur. Union (2024).

[18] T. Morishita, Enterococcosis in poultry - poultry, Merck Veterinary Manual (2025). https://www.merckvetmanual.com/poultry/enterococcosis/enterococcosis-in-poultry (accessed February 26, 2026).

[19] Y. Mehdi, M.-P. Létourneau-Montminy, M.-L. Gaucher, Y. Chorfi, G. Suresh, T. Rouissi, S.K. Brar, C. Côté, A.A. Ramirez, S. Godbout, Use of antibiotics in broiler production: global impacts and alternatives, Anim. Nutr. 4 (2018) 170–178, https://doi.org/10.1016/j.aninu.2018.03.002.

[20] H. Ayalew, H. Zhang, J. Wang, S. Wu, K. Qiu, G. Qi, A. Tekeste, T. Wassie, D. Chanie, Potential feed additives as antibiotic alternatives in broiler production, Front. Vet. Sci. 9 (2022) 916473, https://doi.org/10.3389/fvets.2022.916473.

[21] S. Fathima, W.G.A. Hakeem, R. Shanmugasundaram, R.K. Selvaraj, Necrotic enteritis in broiler chickens: a review on the pathogen, pathogenesis, and prevention, Microorganisms 10 (2022) 1958, https://doi.org/10.3390/microorganisms10101958.

[22] W. He, E.C. Goes, J. Wakaruk, D.R. Barreda, D.R. Korver, A poultry subclinical necrotic enteritis disease model based on natural Clostridium perfringens uptake, Front. Physiol. 13 (2022) 788592, https://doi.org/10.3389/fphys.2022.788592.

[23] M.M. Suyemoto, G.K. Walker, U. Taldo, K.R. Diveley, L.B. Borst, Development and application of optimized isolation methods and diagnostic PCR protocols for the detection of pathogenic Enterococcus cecorum isolated from broiler chickens, Avian Dis. 68 (2025), https://doi.org/10.1637/aviandiseases-D-24-00067.

[24] K.-W. Lee, H.S. Lillehoj, Role of Clostridium perfringens necrotic enteritis B-like toxin in disease pathogenesis, Vaccines 10 (2021) 61, https://doi.org/10.3390/vaccines10010061.

[25] G. Vasdal, E.G. Granquist, E. Skjerve, I.C. De Jong, C. Berg, V. Michel, R.O. Moe, Associations between carcass weight uniformity and production measures on farm and at slaughter in commercial broiler flocks, Poult. Sci. 98 (2019) 4261–4268, https://doi.org/10.3382/ps/pez252.

[26] C.K. Ellis, R.S. Stahl, P. Nol, W.R. Waters, M.V. Palmer, J.C. Rhyan, K. C. VerCauteren, M. McCollum, M.D. Salman, A pilot study exploring the use of breath analysis to differentiate healthy cattle from cattle experimentally infected with mycobacterium bovis, PLoS One 9 (2014) e89280, https://doi.org/10.1371/journal.pone.0089280.

[27] P. Guffanti, V. Pifferi, L. Falciola, V. Ferrante, Analyses of odours from concentrated animal feeding operations: a review, Atmos. Environ. 175 (2018) 100–108, https://doi.org/10.1016/j.atmosenv.2017.12.007.

[28] S. Trabue, K. Scoggin, H. Li, R. Burns, H. Xin, J. Hatfield, Speciation of volatile organic compounds from poultry production, Atmos Environ. 44 (2010) 3538–3546, https://doi.org/10.1016/j.atmosenv.2010.06.009.

[29] Azerbaijan State Oil and Industry University, Baku, Azerbaijan, R.G. Abaszade, A. G. Mammadov, Azerbaijan State Oil and Industry University, Baku, Azerbaijan, E. A. Khanmamedova, Azerbaijan State Oil and Industry University, Baku, Azerbaijan, F.G. Aliyev, Azerbaijan University of Architecture and Construction, Baku, Azerbaijan, V.O. Kotsyubynsky, Vasyl Stefanyk Precarpathian National University, Ivano-Frankivsk, Kyiv, Ukraine, E. Gür, Eskisehir Osmangazi University, Eskisehir 26040, Turkey, B.D. Soltabayev, Nazarbayev University, Nur-Sultan 010000, Astana, Kazakstan, T.O. Margitich, Kyiv Institute for Nuclear Research, National Academy of Sciences of Ukraine, 03680, Kyiv, Ukraine, M.O. Stetsenko, Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen University, 518060, Shenzhen, PR China, A. Singh, Department of Physics, University of Jammu, Jammu 180006, India, S. Arya, Department of Physics, University of Jammu, Jammu 180006, India, Photoconductivity of functionalized carbon nanotubes, DJNB 19 (2024) 837–843, https://doi.org/10.15251/DJNB.2024.192.837.

[30] B. Soltabayev, A.O. Çağırtekin, A. Mentbayeva, M.A. Yıldırım, S. Acar, Investigation of indium insertion effects on morphological, optical, electrical impedance and modulus properties of ZnO thin films, Thin. Solid. Films. 734 (2021) 138846, https://doi.org/10.1016/j.tsf.2021.138846.

[31] B. Soltabayev, Y. Raiymbekov, A. Nuftolla, A. Turlybekuly, G. Yergaliuly, A. Mentbayeva, Sensitivity enhancement of $CO_2$ sensors at room temperature based on the CZO nanorod architecture, ACS. Sens. 9 (2024) 1227–1238, https://doi.org/10.1021/acssensors.3c02059.

[32] A. Tangirbergen, G. Yergaliuly, Y. Wang, L. Tsoukalas, A. Mentbayeva, B. Soltabayev, Multiscale design of metal oxide semiconductor gas sensors: a DFT-driven perspective on structure–property–function relationships, Mater. Des. 258 (2025) 114647, https://doi.org/10.1016/j.matdes.2025.114647.

[33] Council Directive, Council Directive 2007/43/EC Laying Down Minimum Rules For the Protection of Chickens Kept For Meat Production, Official Journal of the European Union, 2007.

[34] Aviagen, ROSS management handbook, (2025). https://aviagen.com//.

[35] R. Stull, Wet-bulb temperature from relative humidity and air temperature, J. Appl. Meteorol. Climatol. 50 (2011) 2267–2269, https://doi.org/10.1175/JAMC-D-11-0143.1.

[36] E. Tullo, I. Fontana, A. Diana, T. Norton, D. Berckmans, M. Guarino, Application note: labelling, a methodology to develop reliable algorithm in PLF, Comput. Electron. Agric. 142 (2017) 424–428, https://doi.org/10.1016/j.compag.2017.09.030.

[37] A. Szczurek, M. Maciejewska, B. Bąk, J. Wilde, M. Siuda, Semiconductor gas sensor as a detector of Varroa destructor infestation of honey bee colonies – Statistical evaluation, Comput. Electron. Agric. 162 (2019) 405–411, https://doi.org/10.1016/j.compag.2019.04.033.

[38] A. Tangirbergen, A. Tleubekova, G. Yergaliuly, A. Kurmanbayeva, B. Soltabayev, A. Soltabayeva, Real-time detection of potato spoilage by gas sensor array coupled with microbiological analysis, LWT 239 (2026) 118926, https://doi.org/10.1016/j.lwt.2025.118926.

[39] P.A. Holdsworth, D.P. Conway, M.E. McKenzie, A.D. Dayton, H.D. Chapman, G. F. Mathis, J.T. Skinner, H.-C. Mundt, R.B. Williams, World Association for the Advancement of Veterinary Parasitology (WAAVP) guidelines for evaluating the efficacy of anticoccidial drugs in chickens and turkeys, Vet. Parasitol. 121 (2004) 189–212, https://doi.org/10.1016/j.vetpar.2004.03.006.

[40] G. Grilli, F. Borgonovo, E. Tullo, I. Fontana, M. Guarino, V. Ferrante, A pilot study to detect coccidiosis in poultry farms at early stage from air analysis, Biosyst. Eng. 173 (2018) 64–70, https://doi.org/10.1016/j.biosystemseng.2018.02.004.

[41] F. Borgonovo, V. Ferrante, G. Grilli, R. Pascuzzo, S. Vantini, M. Guarino, A data-driven prediction method for an early warning of coccidiosis in intensive livestock systems: a preliminary study, Animals 10 (2020) 747, https://doi.org/10.3390/ani10040747.

[42] F. Borgonovo, V. Ferrante, G. Grilli, M. Guarino, An innovative approach for analysing and evaluating enteric diseases in poultry farm, Acta IMEKO 13 (2024) 1–5, https://doi.org/10.21014/actaimeko.v13i1.1627.

[43] Z. Zhang, Introduction to machine learning: k-nearest neighbors, Ann. Transl. Med. 4 (2016) 218, https://doi.org/10.21037/atm.2016.03.37.

[44] L. Manning, S.A. Chadd, R.N. Baines, Key health and welfare indicators for broiler production, World 19s Poult. Sci. J. 63 (2007) 46–62, https://doi.org/10.1017/S0043933907001262.

[45] A. Eftekhari, V. Rezaeipour, R. Abdullahpour, Effects of acidified drinking water on performance, carcass, immune response, jejunum morphology, and microbiota activity of broiler chickens fed diets containing graded levels of threonine, Livest. Sci. 180 (2015) 158–163, https://doi.org/10.1016/j.livsci.2015.07.010.

[46] M. Martynova-Van Kley, E.O. Oviedo Rondon, S.E. Dowd, M. Hume, A. Nalian, Effect of Eimeria Infection on cecal microbiome of broilers fed essential oils, Int. J. Poult. Sci. 11 (2012) 747–755, https://doi.org/10.3923/ijps.2012.747.755.

[47] M.W. Dunlop, P.J. Blackall, R.M. Stuetz, Odour emissions from poultry litter – a review litter properties, odour formation and odorant emissions from porous materials, J Env Manag. 177 (2016) 306–319, https://doi.org/10.1016/j.jenvman.2016.04.009.