An Evaluation of the Use of Sensors for the Detection of Emissions in Slurry Management

Abimbola Y. Ikoyi, Jacqueline Humphries
Technological University of the Shannon (Midwest)
Thurles, Co. Tipperary, Ireland
Email: abimbola.ikoyi@tus.ie; jacqueline.humphries@tus.ie

***Abstract*— The minimization of ammonia and greenhouse gas emissions from slurry management is crucial in meeting emission reduction targets and ensuring the sustainability of the agricultural sector. Whilst there are gains to be made across the wide range of manure management approaches, there is considerable interest in technological advancements, in particular sensors, to add further value. In this paper, an evaluation of existing sensor research in the detection and determination of ammonia and greenhouse gases is conducted. The advantages and disadvantages of the use of sensors are summarized. It is found that while sensors are useful tools in smart agriculture, their use remains largely focused on measurement and descriptive analytics, with limitations still present in their application for predictive analytics for efficient slurry management. This paper emphasizes the need for further research into the application of sensors for minimization of emissions in slurry management for sustainable agriculture.**

Keywords- Sensors; Precision Agriculture; Ammonia; Greenhouse Gas; Emissions; AgriTech.

I. INTRODUCTION

Livestock slurry, while a valuable agricultural resource, poses significant environmental challenges if mismanaged. Slurry contains valuable nutrients like nitrogen and phosphorus, but improper management can lead to significant losses through runoff, leaching, and volatilization. This can cause water pollution (e.g., eutrophication) and air pollution (e.g., ammonia emissions).

There is immense pressure on the agricultural sector in Ireland to minimize Ammonia (NH_3) and Greenhouse Gas (GHG) emissions [1]. This is because the sector accounts for the majority of Irish national NH_3 (99%) and GHG (37.8%) emissions [1]-[3]. Methane (CH_4) emissions from slurry management represent 10.6% of agricultural GHG in Ireland (EPA, 2024). Therefore, minimization of Irish national NH_3 and GHG emissions, especially from agriculture, is crucial in meeting emission reduction targets and ensuring the sustainability of the agricultural sector.

Efforts to reduce emissions occur within the many processes involved in the management of slurry, such as removal and storage management, treatment adjustments, slurry application rates, soil uptake, and so on. However, these are not without challenges. For example, the storage of slurry is accompanied by the release of pollutant gases, such as NH_3 and CH_4 emissions [1][4]. Several manure management approaches have been proposed with the possibility of reducing these dangerous gases associated with slurry management. Ambrose et al. (2023) found that the use of additives, which encourage acidification, reduces CH_4 and NH_3 emissions from slurry storages [5]. Guidance from the United Nations Economic Commission for Europe (UNECE) Task Force on Reactive Nitrogen: Ammonia Guidance Document [6] sets out emission abatement measures in the nitrogen lifecycle from livestock feeding strategies, animal housing techniques, manure storage techniques, through to manure application techniques. Also, research conducted by Buckley et al., (2020) in which the impact, potential, and costs associated with abating national NH_3 emissions up to 2030 also sets out common mitigation strategies [7].

Since the UNECE and Teagasc guidance documents [6][7] were published, there have been exponential advancements in technology. Sensor technology enables the Internet of Things (IoT). Big data is gathered from sensors, hosted on cloud platforms, and analyzed using statistical methods or artificial intelligence to enable real-time predictions - driving the Industrial Revolution known as Industry 4.0 [8]. Agriculture 4.0, using the nomenclature of Industry 4.0, promises the same revolution in smart farming. Indeed, many industry consortia, fora and solution providers propose slurry management solutions which use sensors, and make claims that emissions are reduced. A rigorous journal review process is necessary to substantiate claims and conclusions made in these channels [9]. In this research, the application of advanced sensor technologies for real-time monitoring and control of slurry management processes are investigated. The research questions posed are (1) How can sensors be used in the reduction or mitigation of ammonia or greenhouse gas emissions in slurry management? (2) What are the advantages and disadvantages of the use of advanced sensor technologies when used for this purpose?

The rest of this paper is organized as follows. Section II outlines the research method undertaken. In Section III, the literature is analyzed. In Sections IV and V the findings from the literature are set out, and summarized. The conclusions close the article.

II. RESEARCH METHOD

Narrative literature reviews are a critical tool for theoretical exploration, in that they provide a comprehensive

Courtesy of IARIA Board and IARIA Press. Original source: ThinkMind Digital Library https://www.thinkmind.org

Copyright (c) IARIA, 2025. **ISBN: 978-1-68558-327-9**

overview of the available knowledge on a particular topic [9], and as such, a narrative literature review is chosen in this research. Journal papers, conference articles and book chapters available on Web of Science, and Scopus databases were chosen as sources for relevant research.

The search query situated the research within the context of modern agriculture which is identified using the terms ("smart farm*" OR "AgriTech" OR "Agriculture 4*" OR "precision agriculture"). The papers were constrained to ammonia and methane emissions using the terms ("ammonia" OR "NH_3" OR "greenhouse gas" OR "GHG") AND ("slurry" OR "manure")). The term Agriculture 4.0 has been around for the last ten years, and so for that reason, papers published in the timeline 2015 to 2025 are considered. The inclusion criteria also indicated English as the publication language. 1,037,423 papers were returned.

The first round of elimination included reading the title, abstract, and conclusions leaving 11,584 papers.

The second round of elimination involved reading the full text of all articles and retaining articles that focus on the research objective, and classifying the papers. 101 papers were retained. In addition to the initial database search, backward citation tracking was employed by screening the reference lists of the included studies to identify further potentially relevant publications.

III. LITERATURE REVIEW

As previously mentioned, the emergence of smart farming and precision agriculture is due to advancements in technology. There has been an increase in the applications of such technologies for sustainable agriculture, and an emerging area is the mitigation of emissions in agriculture. An example is the use of IoT technology for the improvement of slurry management on farms. These field-based IoT sensors record and monitor soil and weather-related conditions targeted at helping farmers make better decisions on best timing for slurry application to minimize losses and maximize nutrient use. However, these sensors were unable to measure key slurry parameters (such as pH, dry matter, temperature, and nutrient content), perform in situ and online monitoring, or provide data for comprehensive slurry management [28].

Several authors [12][14][21][23][26][27] have reported on the application of sensors for determination of nutrient components of slurry. However, few reports have been published on the use of sensors for the quantification of gas emissions, such as ammonia and greenhouse gases (methane, nitrous oxide and CO_2). This review covers the three major stages in the traditional management of slurry: slurry production in animal houses, slurry storage and field application.

A. Slurry Production

Livestock production results in the generation of animal waste. Housing of animals comes with the challenge of handling and management of slurry. Efficient manure management reduces environmental impact, thus maintaining animal health. Environmental sensors measuring factors like air quality and humidity, generate vast amounts of data providing crucial insights into the well-being of the herd and the optimization of the farm environment [19].

Air quality in farmhouses is linked with ammonia, CO_2, Particulate Matter (PM) and Hydrogen Sulphide (H_2S) concentrations. These gases have negative effects on animals and human health in the environment. The quality of air is affected by some other factors, such as frequency of slurry removal and floor type [17]. A 21-day study which utilized an IoT gas and environmental sensors for continuous detection of NH_3, CO_2, H_2S and PM concentrations in two piggeries revealed that housing structures and slurry management systems had a huge impact on the gas emissions in the piggeries. Specifically, slurry management resulted in increased H_2S up to 1.9 ppm and increased NH_3 concentration of 63%. In addition, the structure of housings resulted in accumulation of gases, CO_2 and NH_3 increasing up to 52% and 34% than daily average value respectively [17]. The use of sensors at different times of the day, further confirms the need for advanced technology for the mitigation of environmental impacts of agriculture.

Optimum environmental conditions (temperature, moisture, air quality, etc.) must be maintained in livestock houses. The maintenance of these conditions results in huge electrical energy consumption particularly in poultry houses (broiler house - 75.5%, laying hen house - 58.9%) due to the use of various equipment [29]. This is predicted to increase in the future due to technological advancement which indirectly leads to increased GHG emissions. Consequently, for improved efficiency and sustainability, the prediction of the energy consumption of the indoor environmental condition for intensive poultry farming is expedient [13].

In order to minimize reliance on additional equipment, [13] developed a customized hourly model for the interpretation and analysis of electronically collected data. In this study, gas sensors were utilised for the measurement of CO_2 (Model 336, Huakong Xingye Technology, Beijing, China) and ammonia gas concentration (Model 458, Zhize, Jinan, China) emitted in a poultry house. The average CO_2 and ammonia concentration detected by the sensors were similar to the average predicted data using the developed model [13]. On the other hand, there is need for improvement in the sensitivity levels for the gas sensors to enable accurate detection at extremely low concentrations.

As indicated previously, NH_3 is typically an odorous compound produced from the decomposition of organic nitrogen and is a precursor of secondary inorganic aerosols. Similarly, H_2S, a strong odorous and toxic compound that affects animal and human health, is mainly produced from anaerobic digestion of organic sulphur [15]. These gases are usually at high concentrations in animal houses. A study evaluated the use of Electrochemical (EC) gas sensors for the quantification of odours from ammonia (Model #SO1198 Senko LTD. Korea) and hydrogen sulphide (Model #SO1N8 Senko LTD Korea) in a piggeries' manure treatment facility. Acceptable values were obtained for linearity, accuracy, repeatability, lowest detection limit and response time for the sensors, thus confirming their suitability for on-field testing. However, a longer sampling time of at least 15 minutes might

Courtesy of IARIA Board and IARIA Press. Original source: ThinkMind Digital Library https://www.thinkmind.org

be necessary for ammonia monitoring to reach target concentration point [15].

B. Slurry Storage

Upon generation of faeces from animals in the animal houses, the slurry (manure) is usually stored for a specific amount of time. Sensor networks that monitor real-time changes in ammonia concentrations assist in minimizing losses of plant-available nitrogen during manure storage [25]. The duration of storage varies and is affected by several factors, such as time of the year, regulation governing spreading as organic fertilizer, farm slurry storage capacity and so on. Sensors were used in a study for the development of a prediction model for methane and ammonia gas emissions in piggeries with two different types of manure management systems: Long Storage (LS) in deep pits and Short Storage (SS) by daily flushing of a shallow pit with sloped walls and partial manure dilution [20]. The study revealed a positive correlation between calculated and measured CH_4 and NH_3 emissions on an annual basis. This confirms the reduction potential of the studied measures for CH_4 and NH_3 emissions from pig houses. In addition, the developed model provides a possibility for the assessment of mitigation measures on CH_4 and NH_3 emissions. This provides a robust basis for assessing the impact of management and housing strategies on CH_4 and NH_3 emissions from pig houses, which in turn, helps support more sustainable practices in pig farming [20].

In a similar study, manure management and sensor location played a huge role in the determination of gas concentration [10]. Higher ammonia concentration was recorded for open slurry pit compared to the slurry management system with daily removal of slurry. Meanwhile, electro-chemical DOL53 ammonia sensors (DOL Sensors, Aarhus, Denmark) located at 1.0m above floor level recorded approximated ammonia concentrations and were more vulnerable to local fluctuations in comparison to those located at 1.8 m above floor level [10].

In contrast to the previous studies where electro-chemical sensors were used for gas concentration determination, a Fourier-Transform Infrared (FTIR) spectroscopy monitor was used to measure gas transport and concentrations of greenhouses gases (methane, carbon dioxide, and nitrous oxide) and ammonia inside manure piles at various depths. Results showed that carbon dioxide dominated the greenhouse gas emissions. An interesting observation in this study was the reduction of gas emissions with increased moisture content in manure with high water holding capacity [11]. Results obtained using FTIR Spectroscopy monitor provided insights into management strategies for emission reduction from solid dairy manure [11] .

Drones are used as platforms to carry and deploy sensors**,** such as RGB cameras, multispectral, hyperspectral, and thermal sensors for aerial imaging and mapping, multispectral or LiDAR sensors for soil and field analysis, and gas sensors (e.g., methane, ammonia), infrared or laser-based detectors sensors to detect and map emission. Drones are effective in counting animal populations and detecting methane leaks in natural gas infrastructure. These techniques have been applied on a small scale to assess and determine livestock-related methane emissions on farms [16].

Electrochemical sensors were found to have several advantages, such as multi-gas non-specific detection, high sensitivity and precision, making them the preferred alternative for emission detection, albeit they have a long response time and short service life. Similarly, FTIR spectroscopy have the advantage of multi-gas non-specific detection but have higher operating cost in comparison with electrochemical sensors [16].

A UAV-based active AirCore system for the estimation of CH_4 emissions from dairy cow farms is outlined in [25]. The inclusion of local wind speed and direction measurement would result in increased accuracy of methane estimation [25]. In addition, there is need for further research in the use of aerial technology for the assessment of emissions from livestock farming.

C. Field Application of Slurry

The application of fertilizers and manure on fields is the largest source of NH_3 in the atmosphere. Ammonia emission from agriculture has negative environmental consequences and is largely controlled by the chemical microenvironment and the respective biological activity of the soil [18]. While gas phase and bulk measurements can describe the emission on a large scale, those measurements fail to unravel the local processes and spatial heterogeneity at the soil air interface [18].

For better understanding of some of these processes, a two-dimensional (2D) imaging approach which visualized three of the most important chemical parameters associated with NH_3 emission from soil was developed by [8]. Ammonia, O_2 and pH microenvironments were imaged using reversible optodes in real-time with a spatial resolution of $<100\mu m$. This NH_3 optode enhanced the understanding of microscale factors influencing NH_3 emissions, allowing for visualization of the soil's chemical microenvironment following manure application [18].

Though there is a surge in the incorporation of precision agriculture tools, these systems often operate in isolation, focusing on specific parameters without providing a holistic view of the agricultural environment [22]. There is a need to bridge this gap by integrating multiple sensors and data sources into a unified monitoring system. In [22] a comprehensive monitoring system using sensors was developed for the measurement of gases, such as CO_2, methane, and ammonia. This system known as Agri-Guard consists of two sets of devices: the IoT based Agri-cones and a centralized camera stand. The Agri-cones consisted of an array of sensors including temperature, humidity, moisture, CO_2 and methane gas sensors. Upon manure application to the soil, substantial increase in sensor readings were observed in the CO_2 and methane gas sensor (MQ9), due to the organic matter decomposition in the manure. Similarly, as microbial decay progressed, the ammonia sensor (MQ135), showed a slight increase, signifying the breakdown of organic nitrogen compounds in the manure [22].

Courtesy of IARIA Board and IARIA Press. Original source: ThinkMind Digital Library https://www.thinkmind.org

Copyright (c) IARIA, 2025. ISBN: 978-1-68558-327-9

TABLE 1. SUMMARY OF APPLICATION OF SENSORS FOR THE MITIGATION OF EMISSIONS IN SLURRY MANAGEMENT

	Summary of application of sensors for the mitigation of emissions from slurry		
	Purpose of Study	***Sensor***	***Monitored animal/slurry source***
1	Evaluation of slurry management in two different housing structures	Environmental Sensor	Pigs
2	Development of energy consumption model for animal houses	Gas Sensors	Pigs
3	Emission monitoring and odour intensity estimation	Electrochemical Sensor	Pigs
4	Development of prediction models for emissions from various slurry storage systems	Gas Sensors	Pigs
5	Effect of manure management and sensor location on emission concentration	Electrochemical	Piggeries
6	Evaluation of compaction effects on emissions from dairy manure	FTIR	Cattle
7	Estimation of emissions from dairy cows manure	UAV	Cattle
8	Visualization of emissions from soil upon manure application	Optical sensors	Livestock (unspecified)
9	Monitoring of gaseous emissions from manure in farms	Gas sensors	Livestock(Unspecified)

TABLE 2. ADVANTAGES AND DISAVANTAGES OF SENSORS TECHNOLOGY FOR EMISSION REDUCTION IN SLURRY MANAGEMENT

	Advantages and disadvantages associated with use of sensors in slurry management	
	Advantages	**Disadvantages**
1	Real time monitoring and decision support [17] [22]	Limited capabilities for slurry characterization [28]
2	Enhanced detection capabilities [11] [13]	Variation in sensor sensitivity and accuracy [13] [15]
3	Improved emision quantification [20]	Operational constraint [10] [16]
4	Spatial temporal precisions [18] [24]	High cost and maintenance [11]
5	Support and sustainable practices [19]	Fragmented system design [22]

IV. RESULTS

The applications of sensors in slurry management are outlined in Table 1, covering housing, storage, and field use. Their advantages and disadvantages are summarized in Table 2, showing benefits for monitoring and quantification alongside limitations in sensitivity, cost, and integration.

V. DISCUSSION

In this section, the findings are discussed in relation to the two central research questions: firstly, how sensors can be employed to reduce or mitigate ammonia and greenhouse gas emissions in slurry management, and secondly, to summarize the advantages and disadvantages associated with the use of advanced sensor technologies for this purpose.

A. How can sensors be employed to reduce or mitigate ammonia and greenhouse gas emissions in slurry management?

The aim of employing sensors is to minimize negative environmental impacts while optimizing nutrient recovery and beneficial use. Data-driven management facilitated by sensors enables more efficient and environmentally friendly slurry handling. Observations reported in this review present the various types of sensors utilized for monitoring and quantification of hazardous gases (H_2S and NH_3), and GHG, such as CO_2 and methane. There seemed to be few experiments conducted on the use of sensors for the quantification of NO_2. This could be due to the presence of NO_2 in lower concentrations in the various stages of slurry management in comparison to all the other gases. This would require the development of highly sensitive equipment with increased lower detection limit for measurement. Similarly, the use of FTIR was reported once in this review for the monitoring of ammonia, CO_2, NO_2 and CH_4. This contrasts with most of the other experiments where electrochemical sensors were used for emission detection and quantification.

The majority of studies primarily use descriptive analytics on the data captured from sensors. In these studies, focus is on reporting sensor measurements, conditions, or observed effects [11][15]-[18][22][25]. However, a few studies incorporate predictive elements, particularly those that develop or validate models for estimating gas emissions, use data to build or validate models, or attempt forecasting or scenario analysis [13][20].

B. Advantages and Disadvantages Associated with the Use of Sensor Technologies in slurry management

1) Advantages

a) Real-Time Monitoring and Decision Support: IoT-based sensors allow real-time measurement of environmental parameters, such as temperature, humidity, and gas concentrations (e.g., NH_3, CO_2, H_2S), which support better

Courtesy of IARIA Board and IARIA Press. Original source: ThinkMind Digital Library https://www.thinkmind.org

decision-making regarding optimal slurry application timing to reduce emissions [17][22].

b) Enhanced Detection Capabilities: EC sensors and FTIR spectroscopy can detect multiple gases, including ammonia and greenhouse gases, such as methane and CO_2, providing valuable insights across different stages of slurry management—from housing to field application [11][13].

c) Improved Emission Quantification: Sensors facilitate accurate quantification of gaseous emissions, which is critical for developing predictive models and validating mitigation strategies [20].

d) Spatial and Temporal Precision: Technologies, such as optode-based imaging and UAV-mounted sensors, provide high-resolution spatial and temporal data, enabling precise mapping of emission hotspots and variability [18][24].

e) Support for Sustainable Practices: Sensor integration into farm management systems contributes to more efficient nutrient use and helps meet regulatory and sustainability goals through emission reduction [19].

2) *Disadvantages*

a) Limited Capability for Slurry Characterization: Despite their usefulness, many current sensors do not measure key slurry properties, such as pH, dry matter content, and nutrient composition in-situ, thus limiting their utility for comprehensive slurry management [28].

b) Sensor Sensitivity and Accuracy: Certain sensors, especially for gas detection, require improvements in sensitivity to accurately detect low-concentration gases, such as nitrous oxide, which was underrepresented in the literature [13][15].

c) Operational Constraints: Some sensors, particularly electrochemical types, have drawbacks including long response times, vulnerability to environmental fluctuations, had implementation constraints, such as the specific distances they had to be placed in relation to the slurry source, and relatively short operational life [10][16].

d) High Cost and Maintenance: Advanced technologies, such as FTIR, are costly to operate and maintain, which may limit their adoption on smaller farms or in developing regions [11].

e) Fragmented System Design: Many precision agriculture tools, including gas sensors, are not integrated into unified platforms, which limits their ability to provide a holistic understanding of the slurry management system [22].

VI. CONCLUSION

Traditional slurry management practices often lead to pollution and greenhouse gas emissions. There is potential within slurry management to reduce these emissions and have a positive impact on national emissions targets. Significant efforts to reduce emissions occur within the lifecycle of slurry, from livestock feed selection through manure spreading or the alternative pathway of biomethane production. In the past ten years there have been exponential developments in technology that have fuelled Smart Agriculture.

At the core of these developments are the use of sensors which capture and, in some instances, analyze data at source. In this narrative review an overview of the various applications of sensors for the monitoring of emissions in slurry management is provided, and as such provides an insight to the reduction of emissions in the slurry life cycle in livestock farming.

This review found that sensors add value in smart agriculture. Currently they are used largely for the purpose of measurement and descriptive analysis which provide benefits in slurry management around real-time monitoring and decision support, enhanced detection capabilities, improved emission quantification, spatial and temporal precision, and support for sustainable practices. There are currently limitations in their application, such as limited capability for slurry characterization, sensor sensitivity and accuracy, operational constraints, high cost and maintenance, and fragmented system design.

A. Further Research

This review has shown that there is limited research conducted on the use of sensors for the quantification of greenhouse gases emissions from slurry particularly at the field application stage. Therefore, there is a need for further research to develop, calibrate, and validate robust and reliable sensor systems for measurement of greenhouse gases during all stages of the slurry life cycle. This includes addressing challenges related to sensor fouling, durability, and data accuracy in harsh, slurry environments.

Furthermore, the majority of studies use descriptive analytics on sensor data, which although they provide valuable insights into current and past conditions, help identify emission patterns, hotspots, and the effectiveness of management practices in real time, they are not useful for proactive decision-making. Future studies should incorporate predictive and prescriptive analytics, which allow forecasting future emissions or simulated scenarios, such as extreme weather events. Predictive and prescriptive analytics are more useful for proactive decision-making and long-term mitigation planning, helping to avoid emissions before they happen.

B. Limitations

This narrative review is conducted on a search of two databases, in English, and on the last ten years. This will have limited the results. It is therefore probable that some relevant research has not been included. The results could be repeated on other databases, other languages, different timeframes, and through the use of alternative synonyms.

There is the saying that 'research follows industry', and that the period for rigorous research to be conducted, and published, is slower than that which may be occurring in the field and industry. Thus, there may be many advances in technology that haven't yet been reported in research databases.

Courtesy of IARIA Board and IARIA Press. Original source: ThinkMind Digital Library https://www.thinkmind.org

REFERENCES

[1] Environmental Protection Agency (EPA), "Ireland's National Inventory Report" available at: https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/Ireland's-NIR-2024_cov.pdf, 2024a. [retrieved: February 2025].

[2] Environmental Protection Agency (EPA), "Latest emissions data", available at: https://www.epa.ie/our-services/monitoring–assessment/climate-change/ghg/latest-emissions-data/, 2024c. [retrieved: February 2025]

[3] Teagasc, "Alternative slurry amendments for cattle slurry storage" available at: https://www.teagasc.ie/news--events/daily/dairy/alternative-slurry-amendments-for cattleslurrystorage.php, 2023.

[4] Environmental Protection Agency (EPA) "Ireland's Informative Inventory Report 2023", available at: https://www.epa.ie/publications/ monitoring--assessment/climate-change/air-emissions/IIR_Ireland_2024v1.pdf, 2024b. [retrieved: February 2025].

[5] H. W. Ambrose, F. R. Dalby, A. Feilberg, and M. Kofoed, "Additives and methods for the mitigation of methane emission from stored liquid manure", Biosystems Engineering 229: 209–245, 2023.

[6] S. Bittman, M. Dedina, C. M. Howard, O. Oenema, and M. A. Sutton, "Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen", NERC/Centre for Ecology & Hydrology, 2014.

[7] C. Buckley et al., "An Analysis of the Cost of the Abatement of Ammonia Emissions in Irish Agriculture to 2030", Teagasc, 2020

[8] J. Humphries, A. Ryan, and P. Van de Ven, "A New Model for Quality 4.0" in: J. Reis et al. "Driving Quality Management and Sustainability in VUCA Environments", ICQUIS, Springer Proceedings in Business and Economics. Springer, Cham doi.org/10.1007/978-3-031-52723-4_15, 2024.

[9] M. N. Ahmad, "Narrative Literature Reviews in Scientific Research: Pros and Cons", Jordan Journal of Agricultural Sciences, 21(1), pp. 1–4, doi.org/10.35516/jjas.v21i1.4143, 2025.

[10] J. Bus et al., "Short-term associations between ambient ammonia concentrations and growing-finishing pig performance and health", Preventive Veterinary Medicine, 242, doi.org/10.1016/j.prevetmed.2025.106555, 2025.

[11] F. Chang, E. Fabian-Wheeler, T. L. Richard, and M. Hile, "Compaction effects on greenhouse gas and ammonia emissions from solid dairy manure", Journal of Environmental Management, 332. doi.org/10.1016/j.jenvman.2023. 117399, 2023

[12] B. Chugh et al., "Electrochemical sensors for agricultural application", Nanosensors for Smart Agriculture, pp. 147–164. doi.org/10.1016/B978-0-12-824554-5.00018-5, 2022.

[13] L. Du et al., "Development and Validation of an Energy Consumption Model for Animal Houses Achieving Precision Livestock Farming", Animals, 12(19). doi.org/10.3390/ani12192580, 2022.

[14] X. Feng, R. A. Larson, and M. F. Digman, "Evaluation of Near-Infrared Reflectance and Transflectance Sensing System for Predicting Manure Nutrients", Remote Sensing, 14(4), doi.org/10.3390/rs14040963, 2022.

[15] H. Joo et al., "Field application of cost-effective sensors for the monitoring of NH3, H2S, and TVOC in environmental treatment facilities and the estimation of odor intensity", Journal of the Air and Waste Management Assoc., 73(1), pp. 50–64, doi.org/10.1080/10962247.2022.2131652, 2023

[16] W. Ma et al., "Automatic Monitoring Methods for Greenhouse and Hazardous Gases Emitted from Ruminant Production Systems: A Review", Sensors (Vol. 24, Issue 13), Multidisciplinary Digital Publishing Institute (MDPI), doi.org/10.3390/s24134423, 2024.

[17] A. Mautone and A. Finzi, "Air quality monitoring in piggeries through an IoT gas and environmental sensors device", 11th European Conference on Precision Livestock Farming, pp. 1728–1736, 2024.

[18] T. Merl and K. Koren, "Visualizing NH3 emission and the local O2 and pH microenvironment of soil upon manure application using optical sensors", Environment International, 144. doi.org/10.1016/j.envint.2020.106080, 2020.

[19] S. Neethirajan, "Net Zero Dairy Farming—Advancing Climate Goals with Big Data and Artificial Intelligence", Climate (Vol. 12, Issue 2). Multidisciplinary Digital Publishing Institute (MDPI), doi.org/10.3390/cli12020015, 2024.

[20] P. Sefeedpari, S. H. Pishgar-Komleh, and A. J. A. Aarnink "Model Adaptation and Validation for Estimating Methane and Ammonia Emissions from Fattening Pig Houses: Effect of Manure Management System", Animals, 14(6), doi.org/10.3390/ani14060964, 2024

[21] F. M. Silva et al., "Precision Fertilization: A critical review analysis on sensing technologies for nitrogen, phosphorous and potassium quantification", Computers and Electronics in Agriculture, 224. doi.org/10.1016/j.compag.2024/109220, 2024.

[22] K. Singh, K. A. Momin, M. Nishal, C. Sultania, and M. Rao, "Agri-Guard: IoT-Based Network for Agricultural Health Monitoring with Fault Detection", International Conference on Internet of Things, Big Data and Security, IoTBDS - Proceedings, pp. 223–230. doi.org/10.5220/ 0013209500003944, 2025.

[23] M. K. Sørensen, O. Jensen, O. N. Bakharev, T. Nyord, and N. C. Nielsen, "NPK NMR Sensor: Online Monitoring of Nitrogen, Phosphorus, and Potassium in Animal Slurry", Analytical Chemistry, 87(13), pp. 6446–6450. doi.org/10.1021/acs.analchem.5b01924, 2015.

[24] K. Vinković et al., "Evaluating the use of an Unmanned Aerial Vehicle-based active AirCore system to quantify methane emissions from dairy cows", Science of the Total Environment, 831. doi.org/10.1016/j.scitotenv.2022.154898, 2022.

[25] J. K. Whalen, B. W. Thomas, and M. Sharifi, "Novel Practices and Smart Technologies to Maximize the Nitrogen Fertilizer Value of Manure for Crop Production in Cold Humid Temperate Regions" pp. 1–85, doi.org/10.1016/bs.agron. 2018.09.002, 2019.

[26] A. Y. Ikoyi and B. A. Younge, "Impact of Sample Volume and Wavelength Region on the Near Infrared Spectroscopy (NIRS) Prediction of Inorganic Nutrient in Equine Faeces", National Symposium on NIR Spectroscopy - Proceedings, 2021.

[27] A. Y. Ikoyi and B. A. Younge, "Faecal near-infrared reflectance spectroscopy profiling for the prediction of dietary nutritional characteristics for equines", Animal Feed Science and Technology, 290. doi.org/10.1016/j.anifeedsci. 2022.115363, 2022.

[28] J. Hughes, "European Innovation Partnership Using Internet of Things technology to improve slurry management on farms - Year 2 Report", buisnesswales.gov.wales/farmingconnect/ sites/farmingconnect/files/documents/EIP%20Wales_IoT%20 Management_Final%20Report.pdf, 2023.

[29] A. Costantino, E. Fabrizio, A. Biglia, P. Cornale, and L. Battaglini, "Energy Use for Climate Control of Animal Houses: The State of the Art in Europe", Energy Procedia, 101, pp. 184–191. doi.org/10.1016/j.egypro.2016.11.024, 2016.

Courtesy of IARIA Board and IARIA Press. Original source: ThinkMind Digital Library https://www.thinkmind.org