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Review

Gas Sensing for Poultry Farm Air Quality Monitoring to Enhance Welfare and Sustainability

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Abstract

This investigation highlights the importance of adopting ethical and sustainable practices in chicken farming, in response to the increasing global demand for poultry products driven by the expanding world population. How ambient gases, such as hydrogen sulfide (H_2S), nitrous oxide (N_2O), ammonia (NH_3), carbon dioxide (CO_2), and methane (CH_4), affect the welfare of farm workers and poultry is investigated. The use of various gas sensor technologies is crucial for effective management and monitoring of these gases. The research emphasizes the vital importance of precise gas concentration measurements in mitigating environmental impact. It is noteworthy that there is a closely intertwined relationship between CO_2 levels and chicken health, requiring vigilant monitoring and care. There are potential risks associated with NH_3 exposure, and waste management and ventilation practices are necessary. Furthermore, the contribution of CH_4 sensors to environmental sustainability and safety is addressed. The review also examines H_2S emissions, providing mitigation strategies to safeguard avian health. This study identifies an important gap between the limited use of commercially available Metal Oxide Semiconductor (MOS) sensors in the commercial Internet of Things (IoT) systems for poultry farms and their potential to detect a wider range of chemical gases. The pivotal role played by gas sensors in these sustainable efforts is highlighted.

Keywords: metal oxide semiconductor (MOS); parts per million (ppm); parts per billion (ppb); volatile organic compounds (VOC); room temperature (RT); response/recovery (res/rec); Internet of Things (IoT); Global Livestock Environmental Assessment Model (GLEAM); Food and Agriculture Organization of the United Nations (FAO)

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Received: 30 July 2025
Revised: 3 September 2025
Accepted: 9 September 2025
Published: 10 September 2025

Citation: Abbas, I.e.; Comin, E. Gas Sensing for Poultry Farm Air Quality Monitoring to Enhance Welfare and Sustainability. *Chemosensors* **2025**, *13*, 347. https://doi.org/10.3390/chemosensors13090347

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1. Introduction

Nowadays, poultry products have become a prominent source of nutrition in the daily diet of a significant portion of the population around the globe. The global population is expected to surpass nine billion by 2050, driving a corresponding increase in food demand. Chicken production offers an efficient solution to feed this expanding population due to its comparatively lower environmental footprint and shorter production cycle, as shown in Figure 1. Meeting the rising demand for chicken products presents an opportunity for the poultry industry to contribute to global food security, economic growth, and improved nutrition. By adopting sustainable and responsible practices, chicken production can minimize its environmental impact and promote animal welfare. To overcome this demand, we must build healthier environments within existing and future poultry farms. However, currently, there is minimal information available regarding the monitoring of environmental

factors that significantly affect growth. Poultry farmers are facing challenges related to the health issues of poultry birds, which are directly linked to the gaseous emissions produced in poultry farms. For instance, ammonia NH_3, nitrous oxide N_2O, methane CH_4, carbon dioxide CO_2, and hydrogen sulfide H_2S are the major gaseous byproducts in poultry farms. Therefore, the role of gas sensors in poultry farming is crucial for monitoring air quality, detecting harmful gases, and ensuring a healthy and safe environment for the animals. Poultry farms can have elevated levels of various gases due to factors such as manure decomposition, waste management practices, and ventilation systems. Gas sensors may help farmers maintain optimal conditions, preventing health issues and promoting overall farm productivity. Chemical gas sensors, in particular, play a vital role in monitoring these compounds. A shed's interior relative humidity should typically range from 50 to 70%. A decrease in relative humidity accelerates heat loss through evaporation, leading to dryness of mucous membranes and airways. Conversely, elevated temperatures and humidity can negatively impact the performance of broiler chickens. In recent years, the use of nanomaterials has become increasingly popular due to advancements in technology and processing methods. Various techniques, including sol-gel, thermal oxidation, hydrothermal processing, sputtering, electrospinning, and Atomic Layer Deposition (ALD), have been successfully employed to fabricate metal oxides with diverse morphologies, such as nanosheets, nanoparticles, nanowires, nanorods, nanofibers, nanocages, and nanoflowers [1,2]. It was demonstrated by Yamazoe in 1991 that a drop in crystal size significantly enhances sensor performance [3]. Nanosized metal oxide grains have a lower conductivity in the presence of air due to a higher number of depleted carriers compared to microsized grains. When exposed to the target gas, nanosized metal oxide exhibits a substantial change in conductance as more carriers transition from trapped states to the conduction band. Various technologies, such as Metal Oxide Semiconductor (MOS) [4], polymer [5], optical [6], surface acoustic wave [7], and electrochemical [8] methods, are employed to detect the target gases. Among these, metal oxide gas sensors have gained significant attention in recent years due to their affordability, ease of production, excellent sensor response, and rapid reaction/recovery times. Metal oxides are the predominant material used in both academic and industrial chemi-resistive gas sensors [9]. For the recognition of toxic and dangerous gases. The MOS sensors identify chemical components through oxidation-reduction reactions between the MOS and the target gas. The two categories of metal oxide semiconductor (MOS) sensors, namely n-type and p-type, exhibit distinct behaviors when sensing the same gas. Oxidizing gases, such as NOx, function as electron acceptors when they are present. As a consequence, the resistance of n-type semiconductors increases, whereas the resistance of p-type semiconductors decreases. The operational temperature plays a critical role in influencing the rates of oxygen ion adsorption and desorption on the surface of the metal oxide semiconductor. The MOS gas sensors utilize shifts in the equilibrium of surface chemisorbed oxygen processes to measure gas concentrations in the presence of target gases. Consequently, resistance is determined relative to the concentration of the target gas when it is present. The concentration of the target gas is determined by the alteration in electrical resistance resulting from the absorption of the target gas by the active sensing layer. The MOS sensors are economical, lighter, and more robust than other sensor technologies and are adopted in many applications. MOS sensors are also generally long-lasting and composed of non-toxic materials [10]. MOS sensors integrate with the other sensor technologies to form modern IoT systems for agriculture monitoring. An IoT platform integrates multiple sensors, wireless communication, data processing, and an automated control system to provide comprehensive farm management solutions, as depicted in Figure 2.

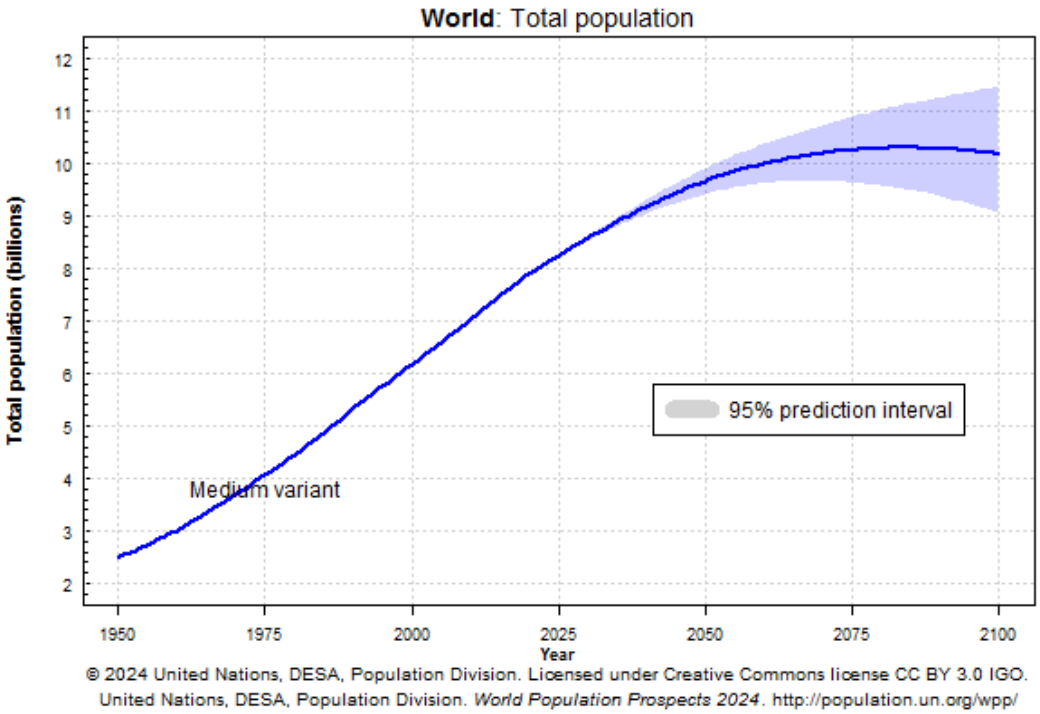


Figure 1. Observed world population and expected growth over years 1950–2100 [11].

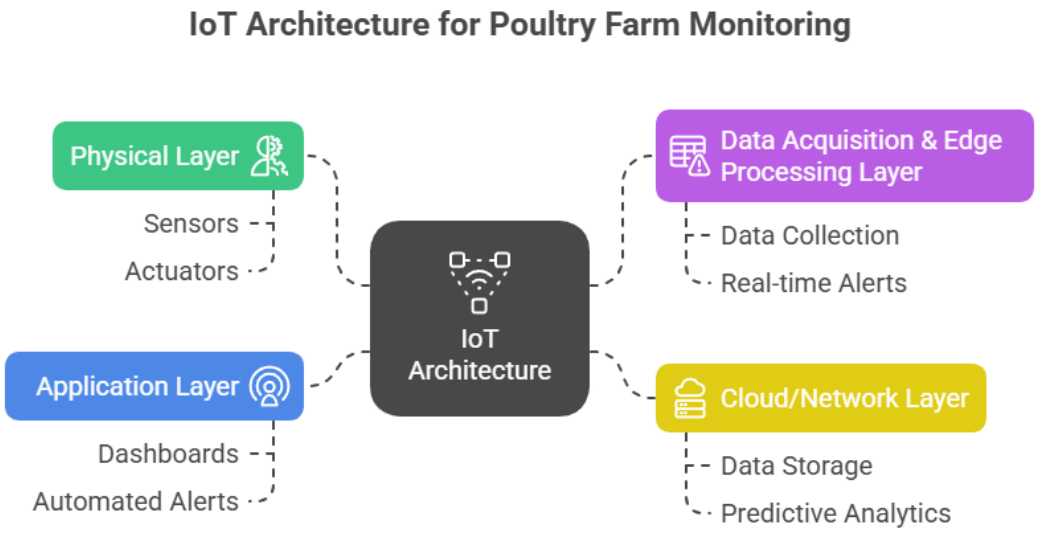


Figure 2. IoT architecture for poultry farm monitoring.

The IoT systems used in poultry farms typically include NH_3 and CO_2 sensors, as well as humidity and temperature sensors, to enable smart farming that can adjust ventilation, heating, and other farming parameters, as shown in Table 1.

A critical limitation was observed between the capabilities of individual sensor technologies and their implementation in current commercial IoT systems for poultry. MOS can technically detect various gases, including H_2S, N_2O, and CH_4, which are missing in commercial agriculture IoT systems. This problem poses a significant risk to poultry health, worker safety, and environmental sustainability, which remain largely unmonitored in practical applications. Our study highlights the gap between the available MOS sensor capabilities and practical implementations of IoT, demonstrating the need for more comprehensive monitoring systems in poultry farming.

Table 1. Comparison of key IoT poultry farm systems.

Feature/System	Monitored Parameters	Sensors Used	Actuators	Communication Protocol	Field-Tested	Advanced Features	Ref.
WiMoCoSPH	Temperature, relative humidity, CO_2, NH_3	HDC1080, CCS811, MQ-135	Fans, heaters, sprinklers, curtains	Wi-Fi (HTTP)	Yes	Distributed architecture, web dashboard, curtain control	[11]
Smart Poultry Farm	Temperature, humidity, NH_3, water level	DHT11, MQ6, ultrasonic sensor	cooling fan, heater, sprayer, water motor	Wi-Fi (Blynk cloud/App)	Yes	Automated water refill, lighting strategy	[12]
Smart Sensors and AI-based PLM	T, H, NH_3, weight, behavior	DHT22, MQ-135, HX711, camera	Actuators for environmental control	MQTT	Yes	AI for health prediction, image processing for behavior	[13]
Low-Cost IoT-based IS	T, H, weight, feed consumption, mortality	SHT20, JARM ESP32 board	Fans, heating lamps	LoRa/Wi-Fi	Yes	Controlled experiment on weight gain, low-cost design	[14]

2. Environmental Gases

In this section, each gas released by chicken farms will be individually examined, together with its impact on both humans and birds.

2.1. Ammonia (NH_3)

Ammonia is a common byproduct of poultry waste and can be harmful to both birds and humans at high concentrations. Humans can only tolerate a concentration of 100 parts per million (ppm) for eight hours [12]. Humans can detect it when present at concentrations of 25 ppm or higher. As per the Health and Safety Executive, the threshold limit value for ammonia is 25 ppm for an eight-hour exposure and 35 ppm for exposure lasting up to fifteen minutes. Nevertheless, continuous exposure to concentrations as low as 25 ppm can lead to various diseases in chickens and also in humans [13]. Ammonia sensors are crucial to monitor and control ammonia levels in poultry houses. Elevated (NH_3) levels (e.g., >25 ppm) result in compromised production efficiency, diminished welfare, and deteriorating health in poultry. This includes respiratory disorders, reduced food intake, slower growth rates, decreased egg production, inefficient feed utilization, increased susceptibility to infectious diseases, and increased mortality. Moreover, laying hens subjected to prolonged exposure to elevated (NH_3) levels exhibit inferior egg quality, characterized by factors like albumen height, pH, and condensation. Because (NH_3) is toxic to the eyes, skin, and respiratory system, it can irritate the throat, nose, eyes, and lungs; hence, the increased concentration of (NH_3) adversely affects the health of agricultural workers. By maintaining appropriate ventilation and waste management, farmers can minimize ammonia levels, promoting healthier conditions for the birds. Chemical gas sensors for the detection of ammonia use a variety of sensing materials that, when exposed to the target gas, undergo particular chemical processes. Changes in electrical or optical properties brought on by these reactions can be detected and quantified to ascertain the ammonia concentration. The sensitivity, selectivity, and overall performance of these sensors have been significantly enhanced over time through developments in nanotechnology and materials science. Different gas sensing methods for ammonia detection are shown in Figure 3. Metal oxide gas sensors are widely favored for detecting ammonia, constituting one of the most popular types of gas sensors for this purpose. Tin dioxide (SnO_2), tungsten oxide (WO_3), or zinc oxide (ZnO) are some examples of metal oxide thin films used as active materials. These metal oxides experience a redox reaction when exposed to ammonia, which alters their electrical resistance. The concentration of ammonia is then calculated with the resistance change.

Since the 1950s, significant advancements have been made in reducing the operational temperatures of MOS-based gas sensors, accompanied by simultaneous enhancements in sensitivity and selectivity for these devices. There are numerous ways to improve these sensors' ability to detect gases. To enhance gas sensing properties, catalysts such as noble metals, including silver (Ag), platinum (Pt), gold (Au), palladium (Pd), and aluminum (Al), have been employed. This strategy improves performance while reducing operating temperatures and the interfering effects of relative humidity. A depletion layer is also formed at the interface of various materials when metal oxide nanocomposites are created, which controls surface conductivity and ultimately enhances gas sensing capability. Many publications on undoped and noble metal-doped MOS sensors have been published, exhibiting various cutting-edge synthesis, design, and fabrication techniques.

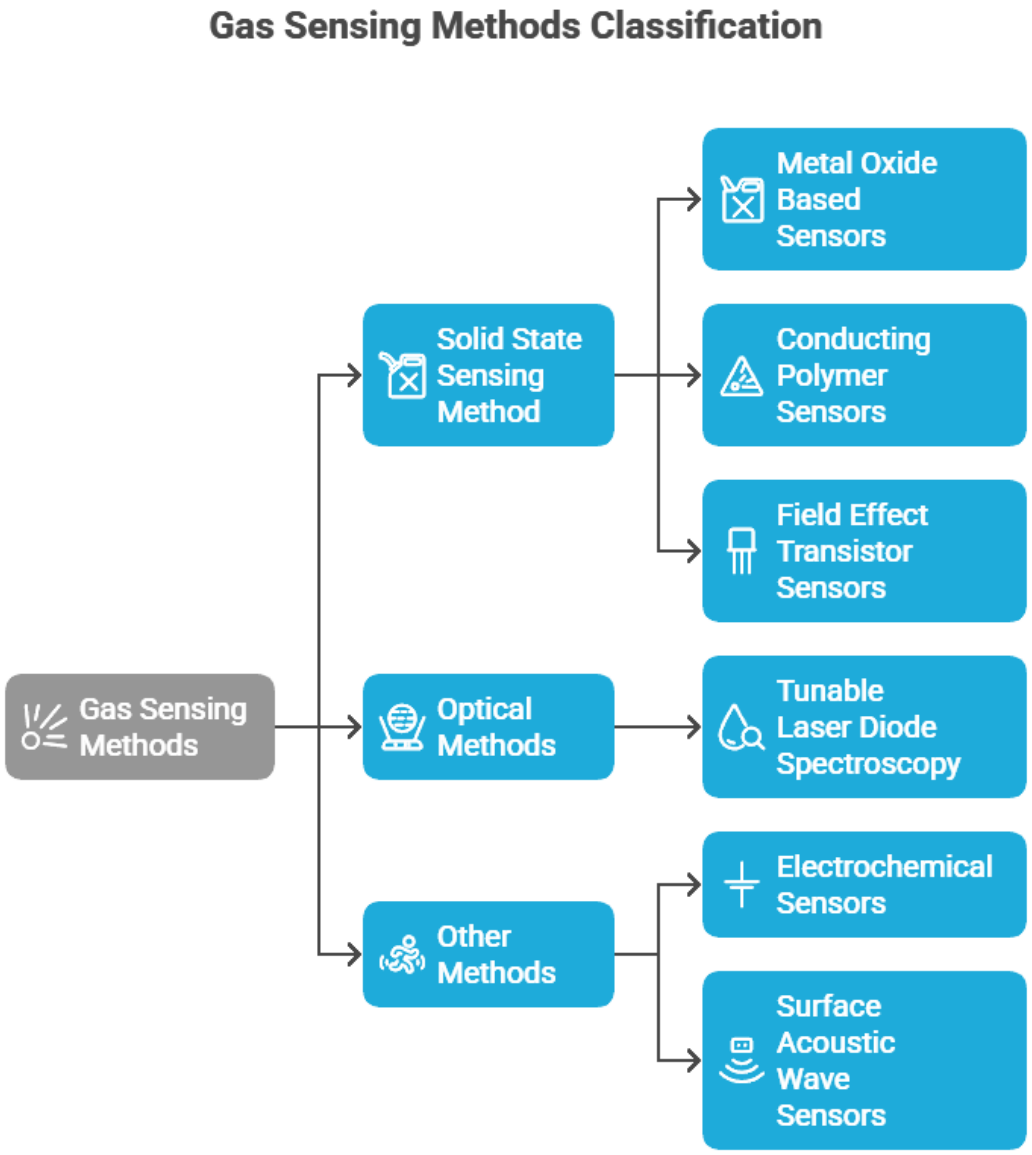


Figure 3. Different gas sensing methods for ammonia detection.

Usually, MOS are beneficial in determining (NH_3) concentration, but these sensitivities are severely affected by volatile organic compounds (VOC) and carbon monoxide. By altering the structures and morphologies of the materials, researchers have consistently worked to increase the sensitivity of metal oxide sensors. For instance, to improve the active surface area and enhance gas adsorption and sensitivity, nanostructured metal oxide thin films and nanoparticles have been created [14]. Furthermore, it has been demonstrated that

the addition of noble metal nanoparticles, such as gold or palladium, to metal oxide surfaces can enhance sensing capabilities due to their catalytic effects [15]. For (NH_3) gas sensing applications, conducting polymers such as polyaniline, polypyrrole, and polythiophene have also been investigated for potential applications. When these polymers are exposed to ammonia, their conductivity changes as a result of the protonation or deprotonation of their functional groups. Researchers have attempted to make conducting polymer sensors more stable and selective. The response and selectivity of ammonia gas sensors can be improved using techniques such as functionalizing the polymer surfaces with particular receptors or using composites containing carbon nanotubes or metal oxides [16]. Due to their large surface area and superior electrical characteristics, carbon nanotubes (CNTs) have gained a great deal of interest as materials for gas detection. When exposed to NH_3 gas, single or multi-walled carbon nanotubes can be employed as sensing elements, with the resistance changing accordingly. Metal nanoparticles or metal oxides were functionalized onto CNTs to increase sensitivity. This increases (NH_3) molecule adsorption and strengthens electrical reactions. The use of hybrid materials, such as CNT–polymer composites, has also been investigated by researchers as a way to combine the benefits of the two types of materials, resulting in increased selectivity and stability [17]. A family of porous materials known as metal-organic frameworks (MOFs) consists of metal ions bonded to organic ligands. The large surface areas and customizable characteristics of MOFs make them attractive options for gas-sensing applications. As they can be tuned to interact with (NH_3) molecules only, researchers have created MOFs with specialized pore diameters and functional groups. To increase their sensitivity and responsiveness to (NH_3) gas, post-synthetic alteration methods, including the introduction of flaws in MOF structures, have been investigated [18]. Figure 4 presents the trend in academic interest in ammonia gas sensors, as measured by the number of publications retrieved from Google Scholar up to September 2025. The results demonstrate a consistent increase in research activity during this period. In recent years, substantial research has been done on MOS-based gas sensors to enhance their ability to detect different gases. Knowing the fundamentals of designing and making improved gas-sensing materials and sensors requires an understanding of the principles and working mechanisms of MOS sensors. Table 2 summarizes the studies conducted using different types of ammonia sensors with the primary performance metric, the sensing materials, and the limit of detection.

Table 2. Comparison of various chemical gas sensors for NH_3, their synthesis methods, operating conditions, and performance.

Materials	Method	Op. Temp (°C)	Concentration	Response (Ra/Rg, Rg/Ra, $\Delta R/R$)	Year	Res/Rec Time (s)	Morphology	Ref.
Co-doped NiO	SILAR method	27	50 ppm	–	2025	20/16	Thin film	[19]
NiO	Solvothermal	27	100 ppm	–	2025	40/44	Nanoflower	[20]
Ca-doped ZnO	Sol-gel	300	4000 ppm	33 for 4000 ppm	2024	5/221	–	[21]
Ti_2C-T_x/Ti_3AlC_2	Drop coating	27	50 ppb	1.2	2023	–	–	[22]
Al-doped ZnO	Co-precipitation method	27	1 ppm	–	2023	26/18	Nanoflowers	[23]
PANI/MoS_2/SnO_2	Hydrothermal + in situ polymerization	27	100 ppm–200 ppb	10.9% for 100 ppm	2021	–	–	[24]
$CoSe_2$@NC/MWCNTs	Reaction	27	10 ppm	–	2021	4/27	–	[25]
Pt-decorated WO_3	RF sputtering	250	1–1000 ppm	3.37 for 1 ppm	2019	26	–	[26]
TiO_2	Sol-gel + Hydrothermal	350	43 ppm	–	2011	–	–	[27]
PANI-TiO_2	Spin Coating	27	20–100 ppm	72% for 20 ppm	2011	–	–	[28]

Table 2. *Cont.*

Materials	Method	Op. Temp (°C)	Concentration	Response (Ra/Rg, Rg/Ra, Δ*R*/*R*)	Year	Res/Rec Time (s)	Morphology	Ref.
Mn-doped ZnO	Hydrothermal method	150	20–100 ppm	28.584	2017	4/10	Wurtzite	[29]
Ni-doped ZnO	Spray pyrolysis	27	25–1000 ppm	2.52 for 100 ppm	2014	–	Thin film	[30]
Cr_2O_3–ZnO	Dipping technique	27	100 ppm	1.37	2007	25/75	Thin film	[31]
ZnO nanorods	Hydrothermal method	27	100 ppm	22.8	2014	–	Thin film	[32]
ZnO	Dipping technique	27	100 ppm	13	2012	–	Thin film	[33]
Carbon nanotubes	Plasma-enhanced CVD	27	100 ppm	25	2017	–	–	[34]
MnO_2	Chemical route	27	100 ppm	20	2016	70/85	Thin film	[35]
ZnO	Sol-gel method	150	50–600 ppm	57 for 600 ppm	2014	160/660	Thin film	[36]
ZnO	RF sputtering	250	1000 ppm	289 for 1000 ppm	2015	31/78	Thin film	[37]
ZnO nanorods	Hydrothermal growth	300	10–1000 ppm	80.6 for 1000 ppm	2012	–	Nanorods	[38]
ZnO nanowires	AAO template method		50 ppm	28/29	2014	–	Nanowires	[39]
ZnO Nanostructures	RF sputtering	26	25 ppm	49/19	2015	–	Nanorods	[40]
ZnO	Carbothermal + Hummer's method	26	0.1 ppm	7.2	2015	50/200	–	[41]

Note: ppm = Parts Per Million, ppb = Parts Per Billion.

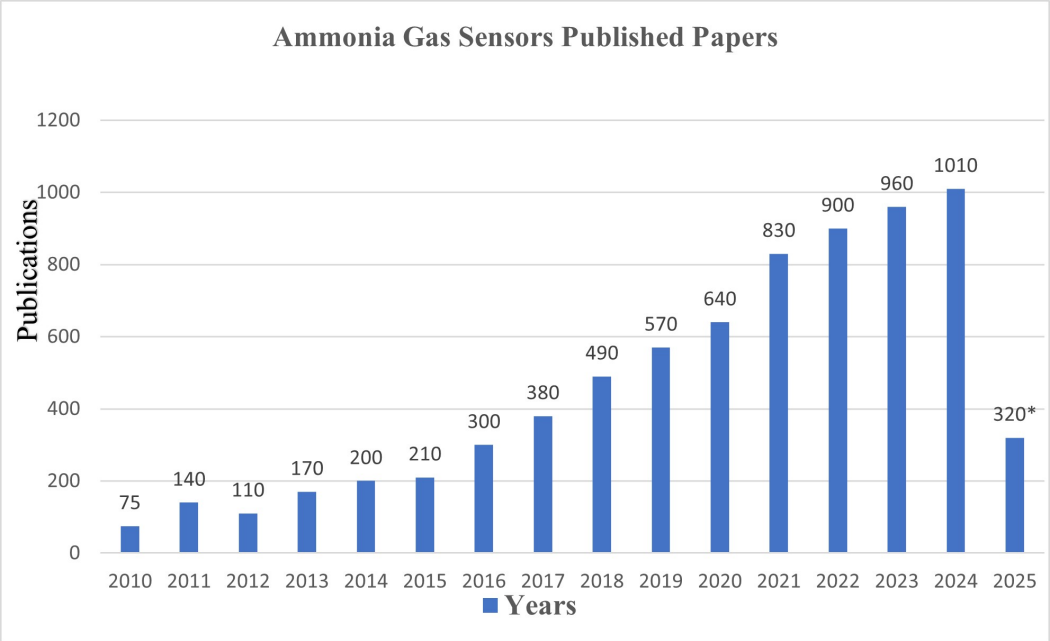


Figure 4. Number of publications retrieved from Google Scholar using the keyword "Ammonia gas sensor" up to September 2025. Note: * Indicates that the publication count is expected to increase further, as data collection is ongoing.

2.2. Nitrous Oxide N_2O

Nitrous oxide N_2O gas levels in poultry housing are intricately linked to the management practices employed for poultry manure. Poultry manure decomposition can occur in two ways: aerobic and anaerobic [42]. Aerobic decomposition of poultry manure occurs in the presence of oxygen. This process is relatively odorless and results in the production of stabilized organic matter, water, and carbon dioxide. When poultry manure is exposed to oxygen, beneficial microorganisms break down the organic matter, resulting in a less odorous and less hazardous environment. Many manure management methods rely on anaerobic decomposition, a process prevalent in systems like liquid manure handling, collection pits, holding tanks, and storage lagoons, where oxygen is limited or absent. Anaerobic decomposition is characterized by the production of noxious odors and elevated amounts of hazardous gases that can be harmful to

both humans and livestock. Various factors in the manure management process influence the characteristics of poultry manure, including collection, storage, transfer, treatment, and utilization. The type of bedding material used in poultry houses plays a significant role in managing manure and gas emissions. Bedding materials need to be absorbent to limit ammonia production and the growth of harmful pathogens, while also providing adequate drying time to prevent excessive moisture [43]. Poultry manure constitutes an intricate blend comprising bedding materials, feathers, spilled water and feed, process-generated wastewater, and deceased birds. The characteristics of the manure exhibit variations not only among different poultry species but also within various types of poultry birds. The organic content of manure affects soil metabolism, oxygen levels, and the emission of gases such as N_2O. Gaseous nitrogen compounds, specifically nitrogen oxides (NOx) and N_2O, are widely recognized for their detrimental impact on the environment. The N_2O is a greenhouse gas that contributes to ozone depletion in the stratosphere by breaking down into nitric oxide (NO) through a photochemical process. The resulting NOx further accelerates the ozone destruction, which is why nitric oxide (NO) gas sensors are also included in the table given below [44,45]. Efficient manure management practices, such as separating manure solids from liquid, can help to reduce the liquid manure that leads to lower emissions of N_2O gas. Implementing strategies to manage manure effectively can help minimize the environmental impact of poultry farming, reduce odors and hazardous gas emissions, and improve overall air quality in poultry housing environments [46]. The N_2O gas can be detected using chemical gas sensors, which operate on various principles, including resistive, capacitive, and optical sensing. To increase the execution of N_2O gas sensors, their sensitivity, selectivity, stability, and reaction time must be improved. Among the most widely utilized types of resistive gas sensors used for N_2O detection are the metal oxide-based resistive gas sensors. Investigations into the sensing capabilities of metal oxides for N_2O have been conducted on tungsten oxide (WO_3), tin oxide (SnO_2), and other metal oxides. Researchers have been focusing on enhancing the sensing capability by modifying materials, nano-structuring them, and doping them with various metal ions. For instance, Umar et al. reported the production of ZnO-doped CeO_2 nanoparticles, which demonstrated enhanced sensing performance and selectivity towards N_2O [47]. By using a specific catalyst material to catalyze the gas reaction, catalytic gas sensors can detect N_2O [48]. An electrical signal that may be measured is produced when the catalytic activity changes [49]. For instance, to increase the sensitivity for N_2O detection, researchers have explored the use of Pt, Pd, and Au on a support matrix [50,51]. Alternative N_2O detection methods include optical gas sensors, which have benefits including real-time measurements, high sensitivity, and potential downsizing. These sensors are based on the idea that when a substance is exposed to gas, its optical characteristics change [52]. Table 3 summarizes the studies conducted using different types of NO and N_2O sensors with the primary performance metric, sensing materials, and the limit of detection.

Table 3. Nitrous (N_2O) gas sensors.

Materials	Method	Op. Temp (°C)	Concentration	Response (Ra/Rg, Rg/Ra, $\Delta R/R$)	Year	Res/Rec Time (s)	Morphology	Ref.
CuO:TiO_2	GLAD	27	5 ppm	–	2023	36/50	Nanorod	[53]
MoS_2–Au NPs	Facile solution-mixing		30 ppm	7.6	2023	406/516	Nanoparticles	[54]
SnO_2	Hydrolysis method	500	300 ppm	90	2001	20/60	–	[55]
InO_3	Thermal evaporation	150	10 ppm	60	2006	20/20	Nanowires	[56]
WO_3	Solvothermal method	–	10 ppm	20–25	2006	10/60	Nanowires	[56]
SnO_2	L-MOCVD	210	100 ppm	11.5	2005	–	Thin film	[57]

Note: ppm = Parts Per Million, ppb = Parts Per Billion.

2.3. Methane (CH_4)

Natural gas primarily consists of methane. Methane is the simplest element in the series of paraffin hydrocarbons, as indicated by its chemical formula CH_4. It is one of the strongest colorless and odorless gases. Anaerobic digestion, which results in the formation of CH_4 and CO_2 from the breakdown of complex and simple organic matter, is the most significant process at the organic level [58]. The analysis based on the Global Livestock Environmental Assessment Model (GLEAM), a tool made by the Food and Agriculture Organization of the United Nations (FAO), evaluates greenhouse gas emissions and resource use in livestock systems and shows that enteric fermentation of chicken reared all over the world is a major contributor to greenhouse gas emissions. According to the study, 34% of CH_4 in manure storage comes from poultry [59]. Research on the direct effects of methane on poultry health is limited, and, in general, there is a scarcity of studies on this topic. However, the available findings suggest that the symptoms associated with methane exposure in poultry are primarily based on increased stress and respiratory problems [60]. Gastric methane emissions are typically regarded as extremely tiny and fall below the first level of emissions [61]. For instance, but not alone, in their work to calculate intestinal methane emissions from Irish chickens, Al-Kerwi et al. [58] discovered that the emissions are concentrated at the second and third levels. To provide a clear overview of the existing emission data, we have standardized the reported values from various studies. Table 4 presents the summary of these findings, with emissions converted into milligrams per hour (mg/h) where possible, along with their original context.

Table 4. Summary of methane emission data.

Emission Rate	Unit	Context	Ref.
0.44	mg/h per bird	Summer	[62]
1.87	mg/h per bird	Winter	[62]
13	mg/day	Daily average	[63]
82.63	mg/kg·h	Mean body mass of 1.92 kg	[64]

Methane sensors are believed to be a practical and affordable solution to issues with fugitive emissions, service distribution, and pipeline leaks. CH_4, as a significant greenhouse gas, has considerable importance in various industrial applications, including energy production and transportation. Hence, the enhancement of methane chemical gas sensors is crucial for environmental monitoring, safety, and process control. The sensors aim to accurately detect methane leaks, emissions, and concentrations. The solution is to reduce methane gas emissions caused by poultry waste and various activities related to gas and oil production. Reliable and practical methane sensors should be developed to detect gaseous fuel leaks. Different methane sensors were developed: optical sensors, capacitive sensors, thermal sensors, flash sensors, acoustic sensors, pyroelectric sensors, MOS sensors, and electrochemical sensors. Numerous studies have been conducted to design various types of gas sensors to monitor the CH_4; Zhu et al. [65] describe the advantages, limitations, and sensor performance, providing a detailed correlation between MOS gas sensors and different ones. SnO_2 is widely used to detect methane due to its stability and high response. However, because methane is the most stable hydrocarbon, it is difficult to operate at low temperatures. Pd-loaded SnO2 nanoparticles are used as a sensing layer to overcome this issue [24]. Mitra and Mukhopadhyay [66] reported the response of the ZnO thin films to methane gas. A wet chemical process deposits a layer of palladium chloride $PdCl_2$ to increase its efficiency. As a result, a response of 86% is observed in less than a minute, and a fast recovery is observed at 200 °C. The MOS surface absorbs gas molecules and lowers the potential barrier of the sensing layer when exposed to an

atmosphere containing reducing gases such as methane. This increases the concentration of electrons on the surface, thereby reducing the electrical resistance. However, MOS sensors have disadvantages, including low selectivity, a limited operating temperature range, slow recovery speed, and high insertion force. In addition, the sensor and its sensitivity depend on temperature and are also sensitive to degradation and changes in humidity [67]. For industrial applications, the energy consumption of gas sensors must be further reduced [68]. Hence, there is a demand for the development of a highly responsive (CH_4) sensor capable of operating at lower temperatures than conventional sensors, which typically function at 400 °C. Various types of (CH_4) sensors have been created to detect methane at different concentrations [69–71]. Among these, methane sensors based on metal oxide semiconductors have garnered significant attention. This is attributed to their remarkable features, including cost-effectiveness, wide detection limits, rapid response, durability, swift recovery, and ease of fabrication [69]. Given that the metal oxide semiconductor plays a crucial role in CH_4 sensor composition, its physical and chemical properties directly influence the device's performance and its ability to detect gases. Table 5 summarizes the studies conducted using different types of CH_4 sensors with the primary performance metric, sensing materials, and the limit of detection.

Table 5. Methane (CH_4) gas sensors.

Materials	Method	Op. Temp (°C)	Concentration	Response (Ra/Rg, Rg/Ra, $\Delta R/R$)	Year	Res/Rec Time (s)	Morphology	Ref.
NiO/ZnO	Hydrothermal method		5000	8.6	2024	32/182	Nanospheres	[72]
ZnO-Pd@ZIF-8	Self-templated method	210	100	20.6	2023	9.9/3.3	Nanorods	[73]
CQDs@NiO	Hydrothermal method	150	30	77	2020	10/14	–	[74]
Pt-doped SnO_2	Hydrothermal method	100	500	1.98	2019	–	Flower-like	[75]
NiO/SnO_2	Hydrothermal method	250	1000	15	2016	18/20	–	[76]
RGO/ZnO	Electrochemical anodization	250	500	1.67	2016	–	–	[77]
ZnO/SnO_2	Hydrothermal method	190	500	8	2015	–	Nanorods	[78]
Pd/Al_2O_3	Colloidal method	400	1	–	–	–	–	[70]
SnO_2–NiO	DC sputtering	400	200	127	2014	–	Thin films	[79]
SnO_2–Pd	RF sputtering	220	200	97.2	2012	–	Thin film	[80]
Ag-doped ZnO	Solvothermal method	200	5000	20.15	2021	118/119	Flower-like microsphere	[81]
ZnO	PE-CVD	300	500	1.70	2010	60/120–180	–	[82]
Pd-doped SnO_2	Chemical method	600	6500	21	2011	–	–	[83]

Note: ppm = Parts Per Million, ppb = Parts Per Billion.

2.4. Carbon Dioxide (CO_2)

One of the prominent gases generated in livestock farms is carbon dioxide CO_2, a byproduct of the breakdown of uric acid present in poultry manure [84]. Within poultry houses, there is a noticeable elevation of CO_2 levels, primarily influenced by factors such as bird quantity, size, ventilation rate, and manure handling conditions. Specific practices, like the use of flame heaters and low-aeration management techniques, can contribute to elevated CO_2 levels, particularly during the brooding stage of production [62,85]. Beyond the mentioned factors, CO_2 concentrations within poultry facilities are also affected by variables such as consumption rates, food components, activity level, and bird age [86]. Past studies have explored the mechanisms through which elevated CO_2 levels can negatively impact poultry farms. Notably, the modern poultry farms aim to maintain a concentration level below 3000 ppm, while some sources can indicate a maximum of 5000 ppm is also

acceptable [87]. Laying hens, exposed to concentrations ranging from 20,000 to 50,000 ppm for 12 to 54 h, exhibited respiratory discomfort, gasping, reduced appetite, and a decrease in eggshell thickness, accompanied by an increase in Haugh unit values [88]. Some findings also emerged in a study by Frank and Burger in 1965 [89], which indicated a decrease in egg weight and production levels. However, a reduction in eggshell thickness to less than 12% was observed at 25,000 ppm for a duration of 21 days. These studies collectively emphasize the intricate relationship between CO_2 levels and poultry well-being, shedding light on the various factors that influence gas concentrations within poultry farming environments. In the initial phases of production, the chicken house emitted 247 kg/h of CO_2, a value that increased to 459 kg/h in the later stages. A continuously operating electric heater contributed approximately 39 kg of CO_2 per hour to the emissions. Notably, the aeration rate plays a significant role in influencing CO_2 emissions within the facility, and these emissions remain relatively consistent during the fattening phases [90]. Specifically, during the fattening stage, the average CO_2 release per bird was 10.4 kg, resulting in an annual CO_2 rate of 73.11 kg. Calvet et al. [62] reported that the average emission rate per bird in summer was 3.84 g, whereas in winter it slightly increased to 4.06 g. These findings highlight the variations in CO_2 emissions throughout different production stages and seasons, emphasizing the importance of considering factors such as aeration rates and environmental conditions in poultry houses. The need for CO_2 sensors with high accuracy, quick reaction times, and affordable prices has grown over the past years as a result of the necessity for CO_2 monitoring in the locations mentioned earlier. The modern concern about the greenhouse effect, which is caused by both human and industrial activities, is that it contributes to global warming, altering climatic patterns and having an impact on several industries, including agricultural and marine life. Among the primary greenhouse gases, CO_2 is notably produced in substantial quantities due to fossil fuel usage. The excessive presence of CO_2 disrupts the Earth's energy equilibrium by absorbing short wavelengths reflected from the planet into space, contributing to temperature elevation. Consequently, alterations in climate patterns lead to phenomena such as floods, droughts, and the melting of polar ice [91]. Moreover, confined spaces with elevated CO_2 concentrations pose respiratory risks, diminishing available oxygen and resulting in conditions such as allergies, asthma, and vertigo [92]. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has established recommended maximum CO_2 concentrations for indoor and outdoor spaces, emphasizing the importance of adherence to limits—350–800 ppm and 1000 ppm, respectively. Failure to comply with these guidelines can cause discomfort, manifesting as headaches, sore throats, and nasal irritation [93]. Given these considerations, it becomes crucial to control, monitor, and detect carbon dioxide concentrations in diverse settings, including factories (producing chemicals or cooling systems), the food industry (especially in carbonated beverage production) [94,95], agro-industries linked with fertilizer manufacturing, medical facilities employing incubators, as well as indoor spaces like offices, schools, and other locations [96]. In response to the increasing demand for precise, rapidly responsive, and cost-effective CO_2 sensors, their necessity has become more pronounced in recent years, especially in the mentioned sectors requiring vigilant CO_2 monitoring. As the primary contributor to 76% of the enhanced greenhouse effect, CO_2 is considered the leading factor behind global warming [97]. Human-induced CO_2 emissions have led to a more than 30% increase in outdoor CO_2 concentrations since pre-industrial times, with an annual growth rate of approximately 1.5 ppm [98]. In June 2019, global land and ocean temperatures experienced the most significant deviation from the average since 1880. Notably, regions in eastern and central Europe, northeastern Canada, northern Russia, and southern South America recorded temperatures 2.0 °C or more above the average [99]. Moreover, elevated indoor CO_2 levels may result in adverse health effects,

including headaches, fatigue, ocular symptoms, long-term asthma, bronchitis, sore throat, and respiratory tract problems [100]. Installing a CO_2 sensor on the farm is a prudent decision, prioritizing the health of the chicks and paving the way for future energy and financial sustainability. This specially designed sensor is tailored for large spaces, making it well-suited for chicken farms. It enables accurate measurement of CO_2 concentrations in the air, facilitating timely adjustments if needed. Moreover, the sensor designed for poultry enables vigilant monitoring of any gas concentration changes that may pose a risk to the birds' well-being [101]. Numerous sensors, such as optical [102], polymer-based [103], field-effect transistors [52], and MOS [104], have been developed based on various sensing concepts. Conventional CO_2 sensors, however, have some drawbacks, including more expense, greater weight, greater size, and lower durability [105]. For CO_2 sensors to be widely used in many facets of contemporary life, low-cost, mass-producible devices with ultralow power consumption, resilience, and simplicity are required. Additionally, a precise and dependable sensor that can function under extreme temperatures and pressures, like those found in nuclear reactors or deep oil wells, is required. Due to their affordability, stability, and resilience in challenging environments, nanomaterial-based CO_2 sensors have garnered growing interest in recent times as a means of fulfilling these demands [106]. Table 6 summarizes the studies conducted using different types of CO_2 sensors with the primary performance metric, sensing materials, and the limit of detection.

Table 6. Carbon dioxide (CO_2) gas sensors.

Materials	Method	Op. Temp (°C)	Concentration	Response (Ra/Rg, Rg/Ra, $\Delta R/R$)	Year	Res/Rec Time (s)	Morphology	Ref.
SnO_2	Electron beam evaporation	20	5000	–	2025	01/120	Thin film	[107]
$BaTiO_3$	Co-precipitation method	27	50	–	2024	23/20	Nanospheres	[108]
SnO_2	Co-precipitation	240	20,000	1.185	2016	31/47	Nanoparticles	[109]
ZnO	Precipitation	250	1000	0.125	2019	9/9	Nanoflakes	[110]
ZnO	DC sputtering	300	500–10,000	1.13	2014	20/20 for 1000 ppm	Thin film	[111]
Ca-doped ZnO	Sol-gel	450	0–10,000	1.13	2015	10/10	Nanoparticles	[112]
Ba-doped Co_3O_4	Solvothermal method	200	500	–	2017	227/245	Hexagonal	[113]
Pd@MoO_3/NiO	Hydrothermal	150	1000	96.1	2019	30/20	Nanoparticles	[114]
$ZnSnO_3$	Hydrothermal		400	4.65	–	73/79	Nano powders	[5]
ZnO	Spray pyrolysis	350	400	2.86	–	75/108	Thin film	[115]

Note: ppm = Parts Per Million, ppb = Parts Per Billion.

2.5. Hydrogen Sulfide (H_2S)

Exposure to high concentrations of H_2S can have immediate and severe effects on poultry. For instance, birds exposed to 4000 ppm of H_2S experienced an increase in respiratory frequency and rapid death within a short time (15 min), a direct and acute effect on the respiratory system [116]. Elevated H_2S concentrations (12 mg/kg) were found to reduce carcass weight, increase water loss, and raise pH levels in breast and thigh tissues. Studies presented by Kendall et al. [117] suggest that gas concentrations should be limited to 2 mg/kg for birds aged zero to three weeks and 6 mg/kg for birds aged four to six weeks to ensure their resistance to H_2S. Reducing the basic protein content to 8.5% by the sixth week of life resulted in a 48% reduction in H_2S and ammonia levels [117]. Efforts have been made to mitigate gas emissions, both pre- and post-excretion. Pre-excretion techniques have

revealed that byproducts like distillers dried grain plus solubles can significantly reduce emissions by up to 20% [118]. Adding chlorine dioxide to feed mixtures at rates between 0.05% and 0.1% reduced H_2S emissions by about 0.05% [119]. Phytobiotics such as Punica granatum contributed to lowering emissions to a range of 0.5% to 1% 138. Post-excretion techniques have also been explored, with the addition of probiotics like species of Candida, Lactobacillus, Streptococcus, Bacillus, and Clostridium, resulting in varying degrees of emission reduction [120]. These measures aim to address the critical issue of H_2S emissions in poultry farming. In the realm of poultry farming, the release of hydrogen sulfide (H_2S), a sulfur-based compound, is a topic of significant concern. This gas is generated when sulfur-containing components like methionine and cysteine are introduced into feed mixes. The primary source of H_2S within poultry facilities originates from the anaerobic degradation of amino acids present in accumulated poultry manure. Notably, the poultry industry stands out among livestock sectors, including dairy and swine, for its substantial H_2S emissions, reaching levels of 0.33 ppm [121]. Furthermore, the amount of H_2S released can be influenced by the specific type of fat incorporated into chicken diets [122]. Hydrogen sulfide (H_2S) is a highly toxic, colorless, and combustible gas, known for its high toxicity. Researchers and organizations dedicated to gas monitoring place great emphasis on developing effective methods to detect toxic gases. The MOS, such as CuO, ZnO, H_2S, NiO, and others, are widely utilized materials for creating chemi-resistive gas sensors due to their strong conductivity across a wide temperature range. As research in this field progresses, the aim is to enhance safety and environmental monitoring by continuously improving sensor materials and numerous techniques are available for monitoring hydrogen sulfide gas, but only a few can effectively measure concentrations lower than parts per billion (ppb) [4,123,124]. Au-doped SnO_2 nanofibers were synthesized to detect H_2S, which was nearly independent of humidity at 370 °C. It shows an excellent response and selectivity compared to pristine SnO_2 [125]. The Pt-functionalized α-Fe_2O3 nanowires used as a sensing material to detect H_2S gas, which shows an outstanding selectivity and response of 10s for 100 ppm at 175 °C. The maximum response value ranges from 150 to 10 ppm for H_2S [126]. Table 7 summarizes the studies conducted using different types of H_2S sensors with the main performance metric, sensing materials, and the limit of detection.

Table 7. Hydrogen sulfide (H_2S) gas sensors.

Materials	Method	Op. Temp (°C)	Concentration	Response (Ra/Rg, Rg/Ra, $\Delta R/R$)	Year	Res/Rec Time (s)	Morphology	Ref.
Ag/ZnO	Hydrothermal	120	1 ppm	–	2025	190/120	Nanoparticles	[127]
Fe-doped SnO_2	Co-precipitation	275	100 ppm	92	2025	–	Nanoparticles	[128]
In_2O_3	Thermal oxidation	27	5 ppm	–	2024	36/18	Thin film	[129]
CuO	Magnetron Sputtering	150	10 ppm	76.5	2021	92/196	Needle array	[130]
La-doped ZnO	Electrospinning	175	90 ppm	6485	2019	53.7/20.7	Nanofibers	[131]
PANI–PEO	Electrospinning	26	1 ppm	5	2016	120/250	Nanofibers	[132]
Cr_2O_3	Air calcination (scallion roots)	170	100 ppm	42.81	2022	73/192	Nanosized cylinders, ellipsoids	[133]
In_2O_3	Electrospinning	25	50 ppm	320.14	2017	45/12	Nanotubes	[134]
SnO_2	HCH	150	10 ppm	25	2014	0.5/3	Nanowires	[135]
SnO_2	Electrospinning	350	1 ppm	15.2	2014	15/230	Porous nanofibers	[136]
SnO_2	Electrospinning	300	5 ppm	154.8	2017	99.5/111	Nanotubes	[137]

Table 7. *Cont.*

Materials	Method	Op. Temp (°C)	Concentration	Response (Ra/Rg, Rg/Ra, $\Delta R/R$)	Year	Res/Rec Time (s)	Morphology	Ref.
P–CuO_x–TiO_2	Electrochemical anodization	26	100 ppm	1.88	2021	41/92	Nanochannels	[138]
ZnO	CVD method	27	4 ppm	6	2017	22/540	Comb-like	[48]
ZnO	CVD	30	100 ppm	17.3	2008	20/50	ZnO dendrites	[139]

Note: ppm = Parts Per Million, ppb = Parts Per Billion.

3. Discussion

In this review, we examine the critical role of gas sensors in monitoring environmental conditions during poultry farming operations. This analysis reveals that MOS sensors present the most promising technology for detecting the five primary gaseous byproducts of poultry farms, such as NH_3, N_2O, CH_4, CO_2, and H_2S. Ammonia is the most immediate threat to both poultry health and farm worker safety. Concentrations above 25 ppm can cause respiratory disorders, reduce growth rates, and increase the mortality of poultry birds. The relationship between CO_2 level and poultry welfare is particularly noteworthy, as high concentrations can cause respiratory distress and reduced egg production. Although methane emissions from poultry are relatively lower compared to other livestock, they still contribute significantly to greenhouse gas emissions. Studies show that 34% of CH_4 in manure storage originates from poultry operations. A comparative analysis of sensor technologies reveals that MOS sensors offer a distinct advantage, including cost-effectiveness, rapid response times, and operational stability. However, there are still some challenges to achieving optimal selectivity, particularly for NH_3 sensors, which are affected by volatile organic compounds and CO interference. The incorporation of noble metal dopants (Au, Pd, Pt) and engineered nanostructured morphologies has led to significant enhancements in sensor performance, including improved sensitivity, selectivity, and response time. The performance of MOS sensors is highly susceptible to environmental factors, including temperature and humidity. These factors can cause sensor drift and alter baseline resistance, leading to inaccurate readings [15,140,141]. To overcome these limitations, IoT systems often use software algorithms for temperature and humidity compensation [142]. Furthermore, data from an array of MOS sensors can be combined with machine learning to create unique "fingerprints" for different gas mixtures [143]. This approach significantly improves the selectivity of the sensors, enabling more accurate analysis and reliable performance in real-world applications. The integration of IoT systems with chemical gas sensors presents a transformation opportunity for automated poultry farm management. Real-time monitoring capabilities enable immediate response to harmful gas concentrations, potentially preventing health problems. The configuration of an IoT system that considers all environmental factors remains a technical challenge and requires further advancement.

4. Future Directions

The future of IoT in poultry farming depends on integrated multi-gas sensor platforms that can detect critical gases currently absent from existing IoT systems. Hydrogen sulfide poses a threat to both poultry and workers, while nitrous oxide and methane are significant greenhouse gases associated with poultry farming and contribute to climate change. These platforms should integrate diverse sensor technologies on a single platform to identify these neglected gases alongside established metrics while ensuring low power usage and minimal costs. Future systems must incorporate artificial intelligence and machine learning

for advanced predictive modeling that leverages thorough gas monitoring. By analyzing data on hydrogen sulfide, nitrous oxide, and methane in conjunction with environmental variables, AI systems can predict acute health hazards and ecological consequences, allowing earlier intervention to protect animal health and reduce agricultural emissions. Success requires open-source modular architectures with integrated sensing for these previously ignored gases. This design enables farmers to enhance monitoring, promoting both animal health and environmental sustainability while scaling across diverse farm settings.

5. Conclusions

This investigation has highlighted the pivotal role of gas sensors in the surveillance and enhancement of the well-being of farm-raised chickens. The growing global demand for poultry products requires sustainable practices that protect both animal welfare and environmental health. We have discussed how environmental gases from poultry farms, such as NH_3, N_2O, CH_4, CO_2, and H_2S, directly affect the growth and health of poultry as well as the welfare of farm laborers. Methane contributes less to poultry compared to other gases, yet its environmental impact is significantly greater. Various types of MOS sensors have been discussed for detecting these gases. The development of advanced sensors has facilitated the collection of extensive data on poultry production, allowing a deeper understanding of environmental factors. To further enhance productivity in chicken farms, the implementation of automation processes is essential. This can be achieved by IoT monitoring systems, which use these chemical gas sensors. There is a significant limitation in commercial gas sensors, which often do not detect essential gases such as N_2O, CH_4, and H_2S. To overcome this limitation, future IoT systems should focus on developing multi-gas monitoring platforms that can reliably detect all these gases. Advanced AI-driven gas monitoring systems with modular designs offer farmers a means to predict and prevent health hazards through scalable technology. The adoption of these methods promises greater transparency in farm operations and aids in the effective monitoring of infectious diseases, ultimately contributing to the advancement of sustainable and efficient chicken farming practices. To support environmental sustainability and enhance animal welfare throughout the agricultural sector, the concepts and methods presented in this review can be applied to other livestock industries, such as swine and dairy production. Realizing the full potential of gas monitoring systems in livestock management will require ongoing improvements in sensor technologies, as well as initiatives to overcome the difficulties associated with industrialization and mass production. Farms can improve productivity, increase transparency, and support more sustainable farming methods by implementing these technologies.

Author Contributions: Conceptualization, I.e.A. and E.C.; investigation, I.e.A.; writing—original draft preparation, I.e.A.; data curation: I.e.A. and E.C.; writing—review and editing, I.e.A. and E.C.; supervision, E.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Sarcopenia-on-chip: an integrated platform based on chemical sensors, microfluidic devices, and machine learning algorithms for the development and testing of personalized treatment for sarcopenia disease (SELENE).

Conflicts of Interest: The authors declare no conflicts of interest.

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