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Review

E-Nose-Driven Advancements in Ammonia Gas Detection: A Comprehensive Review from Traditional to Cutting-Edge Systems in Indoor to Outdoor Agriculture

Ata Jahangir Moshayedi [1], Amir Sohail Khan [1], Jiandong Hu [2], Abdullah Nawaz [3] and Jianxiong Zhu [4,*]

[1] School of Information Engineering, Jiangxi University of Science and Technology, No. 86, Hongqi Ave., Ganzhou 341000, China; ajm@jxust.edu.cn (A.J.M.); mrsohail21@gmail.com (A.S.K.)
[2] Key Laboratory of Wheat and Maize Crop Science, Henan Agricultural University, Zhengzhou 450002, China; jdhu@henau.edu.cn
[3] Department of Advance Study in Energy, University of Engineering and Technology, Peshawar 25120, Pakistan; kabdullahnawaz@gmail.com
[4] School of Mechanical Engineering, Southeast University, Nanjing 211189, China
* Correspondence: mezhujx@seu.edu.cn

Abstract: Ammonia (NH_3) represents a perilous gas that poses a substantial hazard to both human well-being and the environment, particularly within agricultural regions. Agricultural activities constitute a primary source of ammonia emissions. Thus, effective monitoring and measurement of ammonia sources in agriculture are imperative for mitigating its adverse impact. However, not all existing ammonia detection methods are suitable for discerning the low concentrations typically encountered in agricultural ammonia volatilizing (ranging from 0.01 to 5 parts per million). Consequently, curtailing ammonia volatilization from farmland assumes paramount importance, with real-time monitoring serving as a crucial mechanism for assessing environmental contamination and minimizing agricultural ammonia losses. Deploying appropriate detection methodologies ensures that requisite measures are taken to safeguard human health and the environment from the deleterious repercussions of ammonia exposure. The present paper introduces a comprehensive approach to detecting and analyzing ammonia in agricultural settings. It elucidates the merits and demerits of conventional indoor and outdoor ammonia detection methods, juxtaposing them with the innovative technology of Electronic nose (E-nose). Within the paper, seven widely employed ammonia detection methods in farmland are scrutinized and compared against traditional techniques. Additionally, the constructional aspects and distinct components of E-nose are meticulously delineated and appraised. Ultimately, the paper culminates in a comprehensive comparative analysis encompassing all the aforementioned methodologies, elucidating the potential and limitations of E-nose in facilitating ammonia detection endeavors within agricultural contexts.

Keywords: ammonia gas detection; agriculture gas; synthetic fertilizers; indoor and outdoor ammonia detection; Electronic nose (E-nose)

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1. Introduction

Ammonia (NH_3) is a gas with a potent odor, despite being colourless, and is classified by the United States Environmental Protection Agency (EPA) as one of the 366 extremely hazardous substances [1]. NH_3 plays a role in the creation of fine particulate matter that is 2.5 micrometers or less in size: (PM2.5) particles [2], which are known as pollution that significantly reduce the health index of residents and increase the incidence of chronic diseases and depression [3]. The majority of ammonia utilized as a fertilizer is composed of key components such as ammonium nitrate and urea. These components are also used to produce ammonium and nitrate salts in agricultural areas and require accurate diagnosis and measurement of ammonia levels within fertilizer elements [4]. On the other side It is important to note that these are general effects, and the actual symptoms and severity may vary depending on various factors such as the level and duration of exposure, individual susceptibility and preexisting health conditions.

Ammonia can contribute to air pollution, which can have negative impacts on both the environment and human health. It can also contribute to eutrophication, which can harm aquatic ecosystems [5]. NH_3 is a hazardous gas that presents significant risks to human health and the environment, particularly in agricultural areas where it is a byproduct of production. Based on declared values, the outdoor air quality standard for ammonia is set at 50 parts per billion (ppb) over a one-hour period [6]. However, the actual effects and symptoms caused by exposure to ammonia depend on a number of factors, including the level and duration of exposure, individual sensitivity, and pre-existing health conditions. Figure 1 gives a thorough overview of the possible impacts of ammonia gas emissions, focusing on how they may affect humans, animals, the ecosystem, and the atmosphere through things like water contamination, air pollution, soil pollution, and changes in the climate.

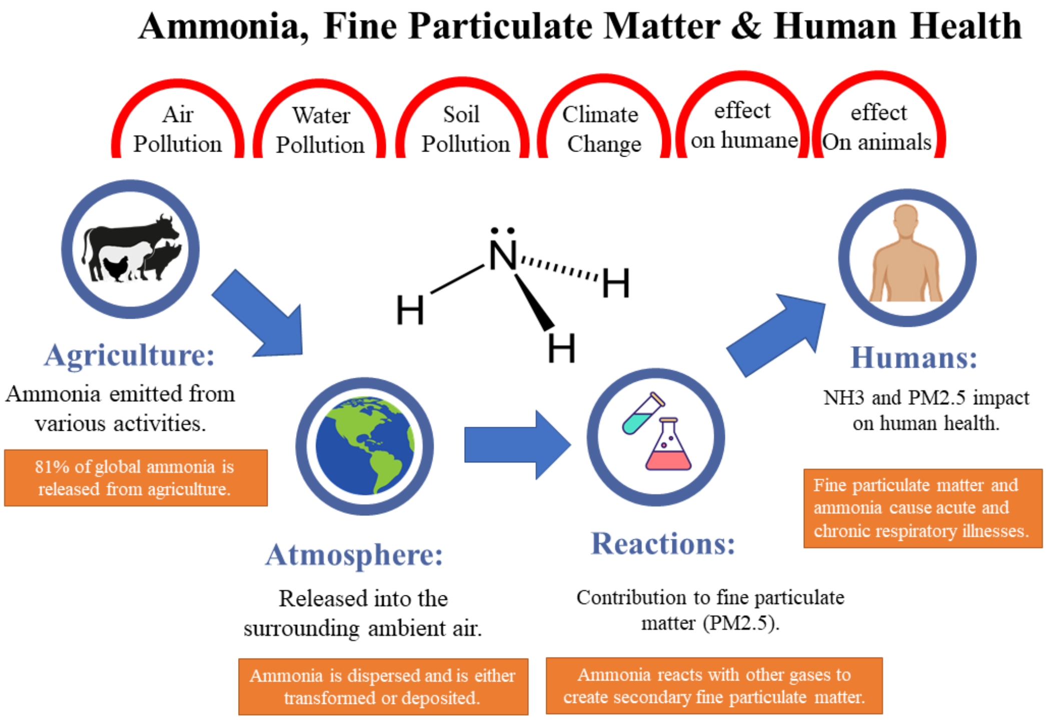

Figure 1. Ammonia gas effect in agriculture, humans, and the atmosphere [7].

The influence of ammonia gas emissions on several elements, including animals, people, the atmosphere, and the environment, is depicted in Figure 1. It demonstrates how ammonia gas emissions can have a variety of negative consequences. The picture also depicts the consequences on animals and people, suggesting that ammonia exposure can be hazardous to their health and well-being. This may include breathing problems, eye and skin irritation, and long-term health implications. Furthermore, the image emphasises the impact on the environment, illustrating that ammonia gas emissions lead to air, water, and soil contamination. In general, exposure to ammonia can be harmful to the human body, as it readily dissolves in water and can interact with moist mucous membranes, potentially leading to eye, respiratory, lung, and skin diseases [8–10]. Furthermore, some studies have reported that high levels of ammonia exposure can cause neurological symptoms, such as headaches, dizziness, and confusion. In this state, ammonia can cause liquefaction necrosis. Therefore, even there is no single policy regarding the control of ammonia gas, numerous countries have established regulations and policies to address the release of ammonia into the environment and minimize its impacts on human health and the environment [11].

Ammonia is a ubiquitous chemical compound that is generated from both anthropogenic and natural sources. The Figure 2 shown the ammonia source emission and their effect on human and animals.

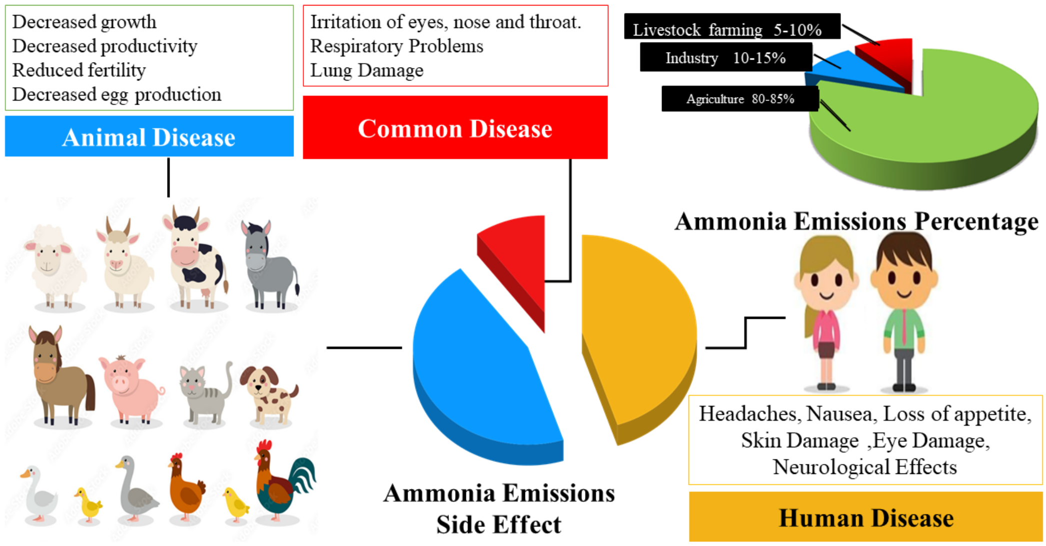

Figure 2. Ammonia Effect On Humans And Animals.

Figure 2 represents that agriculture stands out as the most significant contributor to ammonia emissions, accounting for approximately 80–85% of the total. This is due to the widespread use of nitrogen-rich fertilizers and animal manure in agriculture, which can release large amounts of ammonia into the atmosphere [12]. The emissions stem from various agricultural practices, including the management of livestock waste and the use of fertilizers and crop residues [13]. The research conducted by various researchers demonstrates the correlation of the diets of chickens, turkeys, ducks, meat pigs, cows, sheep, and goats with ammonia production. Four species (cattle, poultry, goats, and pigs) and three crops (wheat, maize, and rice) accounted for more than 70% of all ammonia emissions. This is because animal waste, including urine and feces, can release ammonia into the environment [14]. Additionally, industrial activities, such as the production of fertilizers, plastics, and explosives, release ammonia into the environment, albeit to a lesser extent, contributing to around 10–15% of total emissions. Although ammonia is also emitted naturally from soil, water bodies, and vegetation, these natural sources generally account for less than 5–10% of the total [15].

It is important to note that the exact proportion of ammonia emissions from different sources can vary depending on the country and the specific agricultural and industrial practices in use. As depicted in the visual representation presented in Figure 2, even ammonia is an essential part of plant nutrition because it gives plants the nitrogen they need for vigorous, healthy growth. However, too much ammonia may be harmful to both plants and animals since it raises the amount of acidity in the environment, which can cause health problems including respiratory illnesses or even death if not controlled for an extended period [16].

High levels of ammonia can cause respiratory problems in humans and animals, including irritation of the eyes, nose [17], and throat. It can also cause respiratory problems, as well as damage to the lungs [18,19]. Chronic exposure to high levels of ammonia can also lead to decreased growth and productivity [20], reduced fertility and decreased egg production [21]. Then monitoring ammonia levels can help farmers ensure compliance with environmental regulations and promote sustainable agricultural practices for example for good crop production because it enables growers to foresee possible issues with soil fertility before planting.

Finally, reducing ammonia emissions can help farmers reduce their environmental footprint and promote more sustainable agricultural practices. However, detecting low concentrations of agricultural ammonia volatilization (0.01–5 ppm) can be challenging, and not all ammonia detection methods are suitable for this task [22–24]. The ammonia effect range is based on parts per million (ppm) as shown in Figure 3.

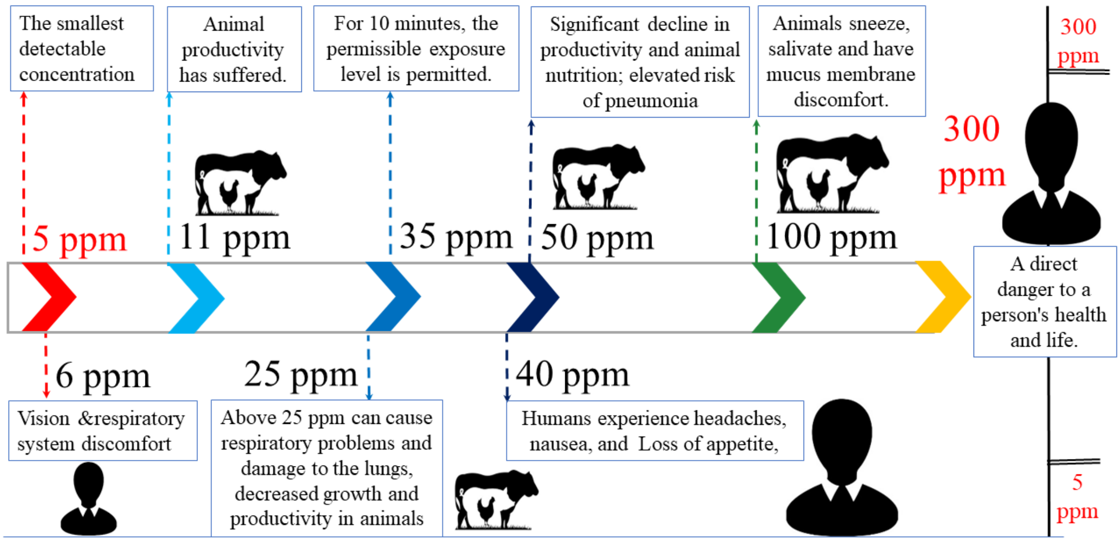

Figure 3. The ammonia level and its effect on humans and animals.

Figure 3 shows that the ammonia concentration suitable for agriculture is 0.01–100 ppm and the regional ammonia concentration after manure or synthetic fertilizer application was 0.01–5 ppm [25]. Different concentrations of ammonia can have severe consequences for poultry and humans. The smallest detectable level of ammonia is 5 ppm, but even 6 ppm can cause discomfort in the respiratory and visual systems. Animal productivity can be affected at concentrations as low as 11 ppm. Although the United States Environmental Protection Agency (EPA) considered 25 ppm of ammonia safe for human exposure for one hour, exposure to 35 ppm is limited to just 10 min. Concentrations of 40–50 ppm of ammonia can result in headaches, nausea, loss of appetite, and decreased productivity in humans. Exposure to 100 ppm of ammonia can cause sneezing, salivation, and discomfort in the mucus membranes in animals. The most hazardous levels of ammonia concentration are 300 ppm or higher, which pose a direct threat to human health and life [26]. Agricultural sources should be thoroughly examined from both the source and its side effects and appropriate measures should be implemented to decrease the concentration of tropospheric NH_3, as noted in reference [7]. There are many methods for detecting ammonia concentration, but due to ammonia's nature to react with water and its strong adsorption few methods are applicable for detecting volatile ammonia in agriculture. Furthermore, the inherent environmental complexity in agriculture with small changes make this task difficult.

This paper describes the different methods for the detection of ammonia in agriculture. Also, one of the main contributions of the paper is the ammonia detection methods in deep with a focus on the Electronic nose (E-nose) as the solution for better measurement.

- Classifying the efficacy of various techniques for determining ammonia levels in agricultural settings, specifically analyzing indoor and outdoor methodologies and weighing the pros and cons of each.
- Investigating and comparing the performance of Electronic nose (E-nose) structures in agriculture, measuring the amount of ammonia in indoor and outdoor space and classifying advantages and disadvantages.
- Comprehensive review of indoor and outdoor ammonia detection methods in agricultural environments.

- Analysis of the advantages and disadvantages of each method for detecting low concentrations of agricultural ammonia volatilization (0.01–5 ppm).
- Emphasis on the importance of monitoring and measuring sources of ammonia in agriculture to mitigate negative health and environmental impacts.
- Discussion of the need for real-time monitoring of ammonia volatilization in agriculture for environmental pollution control and loss prevention.
- Highlight the importance of selecting the right detection method to ensure the protection of human health and the environment from the harmful effects of ammonia.
- Highlight the potential for combining E-nose technology with recent algorithms like deep learning to improve the accuracy of detection.
- A valuable resource for understanding the methods and considerations involved in detecting and reducing ammonia volatilization in agriculture.

Data Collection

To evaluate the existing literature on ammonia detection, a comprehensive search was conducted in relevant databases. The principal sources encompassed scholarly articles and conference papers that had undergone rigorous peer review, as well as online resources, published technical reports, and market analyses pertaining to ammonia detection employing diverse technological approaches. The temporal scope of this investigation spanned from 1995 to 2023, resulting in a cumulative total of 113 papers. Among these, the conference papers appraised for the purposes of this study accounted for 27 documents, constituting 23.9 % of the articles under review, while the remaining 86 papers consisted of journal articles, thereby representing 76.1% of the articles surveyed in this scholarly endeavor. Figure 4 presents the main publishes of the journal articles used in this review.

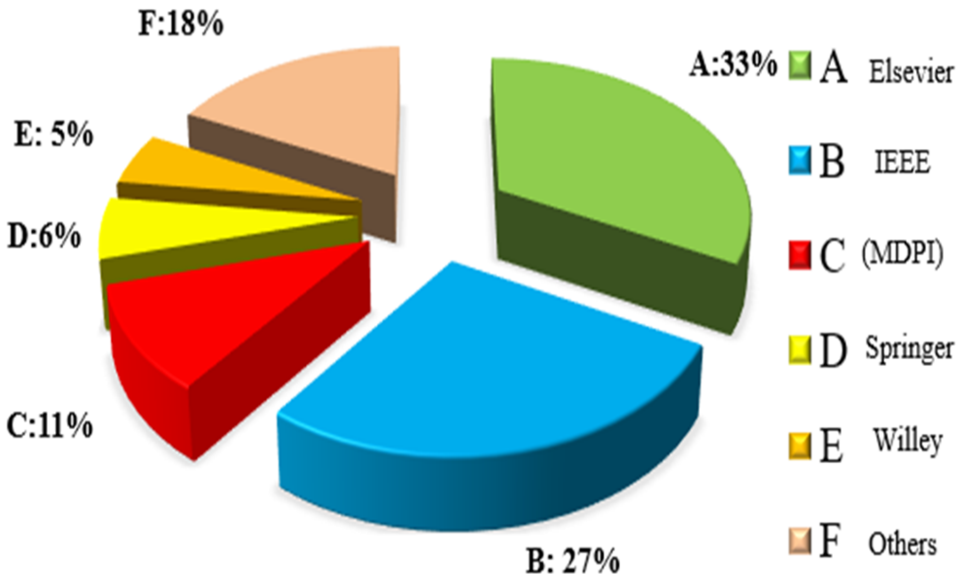

Figure 4. Journal publishers used for the review, including A: Elsevier 33%, B: IEEE 27%, C: MDPI (Sensors) 11%, D: Springer 6%, E: Wiley Online 5%, and F: Other Databases (e.g., EAI, Journal of the transportation research board, Semantic Scholar, etc.) 18%.

In Figure 4, Elsevier journals have been the primary source for this review with a consistently high number of published papers in recent years. The paper is structured as follows: Section 2 explores seven renowned ammonia detection methods in agricultural areas, providing insights into their respective structures and functionalities. In this section, we also delve into the E-nose framework, which represents a recent approach for ammonia measurement, covering its sensor components and various sections of implementation. Section 3 presents a comprehensive comparison between traditional methods and E-nose, shedding light on their relative strengths and weaknesses. Finally, in Section 4, the paper concludes with a summary and comparative analysis of the discussed methodologies.

2. Methodology

The method for the detection of ammonia consists of traditional detection method and the modern smart sensing method known as Electronic nose (E-nose). These methods are discussed in detail as below:

2.1. Traditional Ammonia Detection Method

Traditional methods used in agriculture for ammonia detection typically rely on manual or chemical-based approaches. The most commonly used methods are shown in Figure 5.

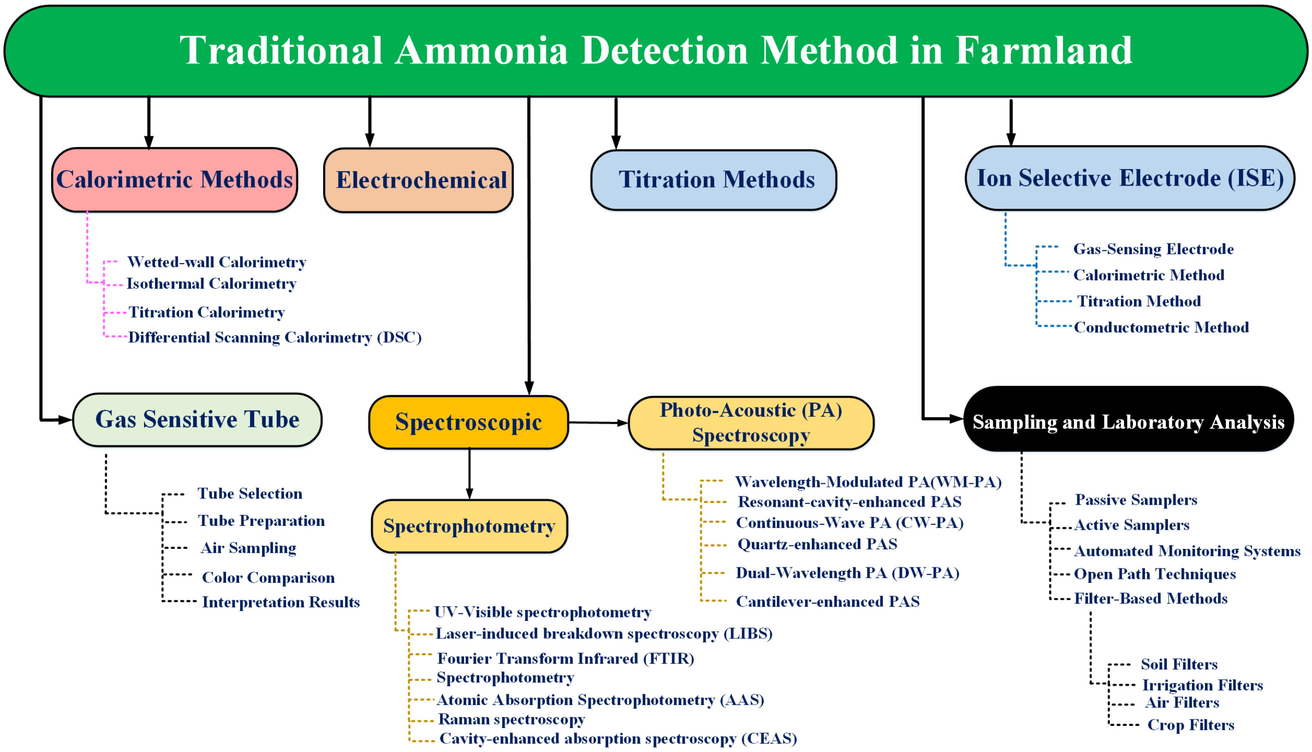

Figure 5. Traditional Ammonia Detection Methods Used in Farmland.

As illustrated in Figure 5, the preeminent technique employed for ammonia detection, as an established conventional approach, encompasses a range of methods, namely Calorimetric Methods, Electrochemical, Triation Method, Ion Selective Electrodes (ISE), Gas Sensitive Tube, Spectroscopic Methods, and Sampling and Laboratory Analysis [27]. Each of these methods is described below, highlighting their distinctive characteristics and principles of operation.

2.1.1. Calorimetric Methods

Calorimetric methods have been widely used for ammonia gas detection in farmland. Calorimetric methods for ammonia detection are techniques that rely on measuring the heat changes associated with chemical reactions involving ammonia gas in order to determine its concentration in a sample [28]. These methods are based on the principle of calorimetry, which involves measuring heat exchange during a chemical process. These traditional methods rely on the principle of heat exchange to quantify the amount of ammonia present in the air. Figure 5 shows the commonly used calorimetric methods for ammonia gas detection in farmland, these methods are delineated as follows:

- **Wetted-wall calorimetry:** In this method, a wetted wall is exposed to the air sample containing ammonia gas. The ammonia gas reacts with water on the wetted surface, resulting in heat release due to the exothermic nature of the reaction. The change in temperature of the wetted wall is then measured using a temperature sensor, and the amount of ammonia gas present in the air sample is determined based on the heat released [29].
- **Isothermal Calorimetry:** In this method, a sample of air containing ammonia gas is mixed with a known amount of an absorbent solution, such as sulfuric acid or hydrochloric acid, in a calorimeter. The absorption of ammonia gas by the solution is an exothermic reaction, resulting in a change in temperature that is proportional to the amount of ammonia gas present [30].
- **Titration calorimetry:** This method involves reacting an air sample containing ammonia gas with a titrant solution of known concentration in a calorimeter. The titration reaction between the ammonia gas and the titrant is exothermic, resulting in a change in temperature that is proportional to the amount of ammonia gas present [31].
- **Differential scanning calorimetry (DSC):** DSC is a technique used to measure the heat flow associated with chemical reactions. In the context of ammonia gas detection, a DSC instrument can be used to measure the heat flow when an air sample containing ammonia gas is exposed to a reference gas or a reference material. The heat flow is recorded as a function of temperature, and the concentration of ammonia gas in the air sample is determined based on the heat flow and the known properties of the reference gas or material [32].

The calorimetric methods as the traditional methods for ammonia gas detection in farmland have been widely used due to their simplicity and relatively low cost. However, they may require careful control of experimental conditions, such as temperature, humidity, and sample preparation, to obtain accurate results.

2.1.2. Electrochemical

Electrochemical sensors are devices that use an electrical current to detect the presence of a substance. These sensors can be used to detect ammonia by measuring the change in electrical current caused by the presence of the gas. Electrochemical sensors can be used as both indoor and outdoor methods for measuring ammonia concentrations [33]. In a study conducted by [34] showed that the electrochemical method for ammonia detection using a screen-printed electrode (SPE) could be completed within 20 s for a sample with a concentration of 50 ppm. According to the research article "Ammonia Detection in Agricultural Soils using Electrochemical Methods" by [35], the range of electrochemical methods used for detecting ammonia in agricultural soils is between 1 and 100 ppm. The authors utilized various electrode types, such as glassy carbon, gold, and platinum electrodes, to monitor ammonia levels in soil samples. The results showed that electrochemical methods possess high sensitivity and selectivity in detecting ammonia in agricultural soils.

An electrochemical sensor detects the change of electrical signal (resistance, potential, current) caused by the adsorption of NH_3 into different materials. In a research project, ref. [36] described a multi-gas detection system using sensor arrays. The MQ-137 sensor that was used displays the concentration according to the ratio of resistance and is the calibrated resistance value at the known concentration.

$$ppm = A \times pow\left(\frac{R_s}{R_o}, B\right) \tag{1}$$

In Equation (1), A and B are the factory-provided coefficients. R_s/R_o represents the resistance value obtained by the sensor during measurement in term of Part Per Million (ppm). Electrochemical methods offer advantages such as high sensitivity, fast response times, and the potential for miniaturization, making them well-suited for on-site and real-time monitoring of ammonia gas levels in agricultural applications [35,36].

2.1.3. Titration Methods

Titration is a common method used in the laboratory for ammonia measurement. In this method, a known volume of the sample containing ammonia is titrated with a standard solution of acid. The acid reacts with the ammonia in the sample, producing ammonium ions, which can be quantified using a pH meter or indicator. There are several types of sensors that can be used for ammonia measurement, including electrochemical sensors, pH sensors, such as glass electrodes or ion-selective electrodes, which are widely used to monitor the pH changes and provide accurate measurements during the titration of ammonia [27].

2.1.4. Ion Selective Electrodes (ISE)

Ion Selective Electrodes (ISE) are commonly used for the detection of ammonia gas in farmland to monitor the levels of this important compound, which is an essential nutrient for plant growth but can be toxic at elevated concentrations [37].

- **Gas-Sensing Electrode:** One traditional method for ammonia gas detection in farmland involves using a gas-sensing electrode based on ISE technology. The electrode is typically coated with a membrane that is selective to ammonia ions (NH_4^+), allowing only ammonia ions to pass through and interact with the electrode surface. As the ammonia gas from the farmland diffuses into the electrode, it dissolves in water to form ammonium ions, which then interact with the electrode and generate an electrical potential that is proportional to the ammonia concentration. This potential can be measured using a pH meter or a dedicated ion meter, and the concentration of ammonia in the farmland can be calculated based on the Nernst equation [38].
- **Colorimetric Method:** Another traditional method for ammonia gas detection in farmland involves using a colorimetric method with an ISE. In this method, the gas-sensing electrode is coated with a membrane that contains a pH indicator dye, which changes color in the presence of ammonia ions. As the ammonia gas diffuses into the electrode and forms ammonium ions, the pH of the membrane changes, causing the color of the dye to change. The intensity of the color change is proportional to the concentration of ammonia in the farmland, and it can be visually or spectrophotometrically measured to determine the ammonia concentration [39].
- **Titration Method:** The titration method is another traditional method that uses ISE for ammonia gas detection in farmland. In this method, a gas-sensing electrode is immersed in a solution containing the ammonia gas, and a titrant solution of known concentration is added dropwise to the solution. The titrant solution contains a counter ion that reacts with the ammonia ions to form a precipitate or a complex, causing a change in the electrode potential. The titration is continued until the endpoint is reached, which is determined by a sudden change in the electrode potential. The amount of titrant solution required to reach the endpoint is proportional to the concentration of ammonia in the farmland and can be used to calculate the ammonia concentration [40].
- **Conductometric Method:** The conductometric method, a conventional technique for ammonia gas detection in farmland, harnesses the capabilities of Ion Selective Electrodes (ISE) to facilitate accurate measurements. In this method, a gas-sensing electrode is used as one of the two electrodes in a conductometric cell, and the other electrode is a reference electrode. When ammonia gas diffuses into the cell, it dissolves in water to form ammonium ions, which increase the electrical conductivity of the solution. The change in conductivity is proportional to the concentration of ammonia in the farmland and can be measured using a conductivity meter. The conductometric method provides a simple and rapid measurement of ammonia concentration without the need for additional reagents or titration [41].

Figure 5 shows the ion-selective electrode methods for ammonia detection. Ion-Selective Electrodes (ISE) are commonly used in traditional methods for ammonia gas detection in farmland. These methods utilize gas-sensing electrodes coated with a membrane that is selective to ammonia ions, and the changes in electrical potential, color, titrant consumption, or conductivity are measured to determine the ammonia concentration in the farmland. These methods provide valuable information for farmers to manage ammonia levels and optimize fertilization practices for healthy crop growth [42].

2.1.5. Gas-Sensitive Tubes

Gas-sensitive tubes are a traditional method used for detecting ammonia gas in farmland. These tubes are simple, portable, and inexpensive devices that provide a quick and reliable indication of ammonia gas levels in the air [43]. They are widely used in agricultural settings to monitor and manage ammonia emissions from livestock facilities, fertilizer application, and other farm-related activities.

Gas-sensitive tubes work based on the principle of color change. The tubes contain a chemical reagent that reacts with ammonia gas to produce a visible color change. The intensity of the color change is proportional to the concentration of ammonia gas in the air, allowing for semi-quantitative measurements. The tubes typically have a scale printed on them, which allows users to estimate the concentration of ammonia gas by comparing the color of the reagent with the scale.

The procedure for using gas-sensitive tubes for ammonia gas detection in farmland typically involves the following steps:

- **Tube selection:** There are different types of gas-sensitive tubes available, each designed to measure a specific concentration range of ammonia gas. The appropriate tube is selected based on the expected concentration of ammonia in the air.
- **Tube preparation:** The gas-sensitive tube is attached to a hand-operated pump, which is used to draw a known volume of air through the tube. The tube is usually calibrated to a specific flow rate, and the pump is operated accordingly [44].
- **Air sampling:** The pump is used to draw a known volume of air from the farmland area being tested. The air is passed through the gas-sensitive tube, and any ammonia gas present in the air reacts with the reagent in the tube, causing a color change [45].
- **Color comparison:** After the air has been sampled, the gas-sensitive tube is removed from the pump, and the color of the reagent is compared to the scale printed on the tube. The intensity of the color change is used to estimate the concentration of ammonia gas in the air.
- **Interpretation of results:** The concentration of ammonia gas is estimated based on the scale provided on the gas-sensitive tube. The results are typically reported as a range or an approximate value, depending on the accuracy of the tube and the specific application.

As depicted in Figure 5, the gas sensitive tube and the steps it involves for detecting ammonia. It is important to note that gas-sensitive tubes provide only semi-quantitative measurements and are not as precise as modern analytical methods. However, they are still widely used in farmland settings due to their simplicity, portability, and cost-effectiveness. Gas-sensitive tubes are often used as a screening tool to quickly assess ammonia gas levels in different areas of farmland and guide further monitoring or management actions, such as adjusting fertilizer application rates, improving ventilation in livestock facilities, or implementing other mitigation measures to reduce ammonia emissions.

2.1.6. Spectroscopic Methods

Spectroscopic methods comprise two main approaches: photo-acoustic (PA) spectroscopy and spectrophotometry. A thorough exploration of these methods is presented in the subsequent sections, providing detailed insights into their principles and applications.

- **Photo-acoustic (PA) spectroscopy:** This method combines the principles of photonics and acoustics to produce a measurable acoustic signal proportional to the absorption of light by a gas. This method known as a well-established technique for ammonia detection which can be considered an indoor method for measuring ammonia concentrations as a type of direct-reading instrument [46,47]. A variety of PA spectroscopy sensors are employed for ammonia detection, encompassing the following types:

– **Wavelength-Modulated PA (WM-PA) Sensors:** These sensors use a modulated laser source to excite the sample and a detector to measure the PA signal. This type of PA sensor is commonly used for ammonia detection due to its high sensitivity and stability [48].
– **Continuous-Wave PA (CW-PA) Sensors:** These sensors employing a continuous wave laser source and a detector to measure the PA signal. This type of PA sensor is typically used for the detection of low concentrations of ammonia in gas mixtures [49].
– **Dual-Wavelength PA (DW-PA) Sensors:** These sensors utilize two laser sources at different wavelengths to excite the sample and a detector to measure the PA signal. This type of PA sensor is used for the detection of ammonia in the presence of interfering species [50].
– **Resonant-cavity-enhanced PAS:** In this method, the sample gas is contained within a resonant cavity that is designed to enhance the acoustic signal generated by the absorbed light [51].
– **Quartz-enhanced PAS:** In this approach, a quartz tuning fork is utilized both for the generation and detection of the photoacoustic signal [52].
– **Cantilever-enhanced PAS:** This method uses a cantilever to enhance the acoustic signal generated by the absorbed light [53].

In the case of ammonia detection, a laser source is used to provide a short pulse of light that is absorbed by the ammonia molecules. This absorption generates a thermal expansion that results in a pressure wave, which is detected by a microphone or a piezoelectric transducer. The resulting acoustic signal is proportional to the concentration of ammonia in the sample. PA spectroscopy has been used for the detection of ammonia in various applications, including environmental monitoring, industrial process control, and breath analysis for medical diagnostics. The technique offers several advantages over traditional gas sensing methods, including high sensitivity, fast response time, and the ability to detect trace amounts of gas [54]. The use of photoacoustic methods to detect ammonia concentration has been extensively explored by researchers.

In 2003, ref. [55] described the continuous detection of trace levels of ammonia in the air, with the ability to detect concentrations as low as sub-ppb. The experiment was conducted in a 40% carbon dioxide and 40% relative humidity environment. In 2004, the use of photoacoustic spectroscopy for ammonia detection with a detection limit of less than 0.1 ppb was reported [56]. In 2005, ref. [57] demonstrated the use of photoacoustic spectroscopy for detecting ammonia gas in agricultural environments. The results showed good agreement with ion chromatography and were promising for real-time monitoring. A study by [58] reported that the photoacoustic method can detect ammonia concentrations in the range of 0.1 to 20 ppm in laboratory conditions, with high sensitivity and accuracy. Furthermore, a study by [59] found that the photo-acoustic method could detect ammonia in less than 5 s with a detection limit of 2 ppm. These findings suggest that photoacoustic spectroscopy can be an effective and efficient technique for the detection of ammonia in various environments.

- **Spectrophotometry:** Knwon as a common technique that uses light to measure the concentration of a substance. This method can be used to detect ammonia by measuring the absorption of light at specific wavelengths. Spectrophotometry can be considered an indoor method for measuring ammonia concentration in agriculture. Spectrophotometry is a laboratory-based analytical technique that measures the absorption of light by a sample at a specific wavelength [60,61]. A study conducted by [21] found that the range for detecting ammonia using spectrophotometry is typically between 0.1 and 2 ppm, but with proper sample preparation and instrument calibration, it can be extended up to 5 ppm. The diverse range of spectrophotometry sensors are utilized for the detection of ammonia as shown in Figure 5, including:

– **Laser-induced breakdown spectroscopy (LIBS)** This method involves the use of a high-powered laser to create a plasma on the surface of a sample [62].
– **Raman spectroscopy:** This method involves the use of a laser to excite molecules in the sample, which then emit light at a different wavelength [63].
– **Cavity-enhanced absorption spectroscopy (CEAS):** This method involves the use of a high-finesse optical cavity to increase the path length of light passing through the sample [64].
– **UV-Visible spectrophotometry:** This type of spectrophotometry uses ultraviolet (UV) or visible light to measure the absorbance of light by a sample. Ammonia can be detected in solution using this method by measuring the absorbance of light at specific wavelengths [65].
– **Fourier Transform Infrared (FTIR) spectrophotometry:** FTIR spectrophotometry is a type of infrared spectrophotometry that uses interferometry to measure the infrared absorption of a sample. Ammonia can be detected in gas form using this method by measuring the absorbance of light at specific infrared wavelengths [66].
– **Atomic Absorption Spectrophotometry (AAS):** AAS is a type of spectrophotometry that uses the absorption of light by free atoms to determine the concentration of a sample. Ammonia can be detected in solution using this method by measuring the absorbance of light at specific wavelengths [67].

The authors reported that the average time for ammonia detection using spectrophotometry is 10 min, but in the case of complex sample preparation, it can take up to 30 min [68].

2.1.7. Sampling and Laboratory Analysis

This method involves collecting air samples from the agricultural environment using air sampling devices, such as impinges, babblers, or passive samplers. This method holds immense potential to revolutionize crop management practices for farmers. By harnessing the power of data-driven insights, farmers can make well-informed decisions regarding irrigation, fertilization, and pest control. This approach enables them to enhance efficiency, minimize wastage, and elevate yields, all while reducing their environmental footprint. The collected samples are then transported to a laboratory for analysis using sophisticated analytical instruments, such as gas chromatography or mass spectrometry (Figure 5), which can provide accurate and precise measurements of ammonia concentrations.

- **Passive samplers:** Passive samplers are a simple yet efficient tool that relies on the principle of diffusion to collect ammonia gas. They consist of a sorbent material, such as silica gel, that effectively absorbs the ammonia gas from the surrounding air. Passive samplers are a preferred option for long-term monitoring due to their easy usage and durability in the field. These small devices are widely used to measure the levels and presence of contaminants in the environment, including pesticides, herbicides, and other chemicals commonly used in agriculture. The mechanism of passive samplers is based on the process of adsorption and absorption of contaminants from the environment. These devices do not require any external power or pumps to operate, making them convenient to use and maintain. They can be deployed for extended periods, ranging from several days to several months, to collect samples of contaminants in the air, water, or soil [69].
  In farmland, passive samplers play a crucial role in monitoring the levels of pesticides in the air or water that can pose a potential threat to human health and the environment. The information collected by these samplers can be used by farmers and agricultural workers to adjust their practices and reduce the use of harmful chemicals, leading to a safer and healthier farming environment. Passive samplers are also useful in understanding the movement of contaminants within the environment. By deploying samplers at various locations within farmland, it is possible to identify areas that are

more vulnerable to contamination and develop strategies to prevent or reduce the spread of pollutants [70]. This model is known as a valuable tool for monitoring and assessing the health of farmland. By providing accurate and reliable data on the levels of contaminants in the environment, they can help farmers and agricultural workers make informed decisions about their practices and protect the health of the land and the people who work on it [71].

- **Active samplers:** Active samplers are devices that utilize a pump to draw air through a sorbent material actively. Although active samplers are more efficient at gathering ammonia gas than passive samplers, they necessitate a power source and can be more expensive. These devices play a critical role in monitoring soil quality on farmland [72]. They collect soil samples from various depths and locations in a field and analyze them for multiple parameters such as pH levels, organic matter content, and nutrient composition. In recent years, the use of active samplers in farmland has gained importance as farmers and agricultural researchers seek to optimize crop yields and minimize environmental impact. By gaining insights into the soil composition, farmers can make well-informed decisions about management practices like fertilization, irrigation, and more. The active samplers used on farmland come in different types, such as the cone penetrometer and soil corer, which are deployed depending on the specific needs of the farmer or researcher. After collecting the soil samples, they are typically sent to a laboratory for further analysis [73]. The analysis provides critical information on nutrient levels and the presence of any potential contaminants, which can guide farmers to make appropriate decisions on maximizing crop yields while minimizing the environmental impact. In summary, active samplers are essential tools for anyone involved in agriculture, from small-scale farmers to large agricultural corporations. By employing these devices to monitor the quality of soil in their fields, farmers can optimize their yields while taking necessary steps to safeguard the environment.
- **Automated monitoring systems:** These monitoring systems utilize sophisticated sensors to monitor the real-time levels of ammonia gas continously and precisely. These intricately designed systems are interconnected, forming a comprehensive network that enables remote access to the collected data, allowing for in-depth analysis. The use of automated monitoring systems in farmland has gained popularity in recent years, as farmers seek to improve their efficiency and reduce costs. These systems collect data on soil moisture, temperature, humidity, and other environmental factors, as well as data on plant growth and health, using a range of sensors and monitoring tools [74]. The primary advantage of using automated monitoring systems in farmland is that they allow farmers to make data-driven decisions about irrigation, fertilization, and pest control. The system can trigger irrigation to ensure that plants receive the required amount of water to grow, and pesticides can be applied to control the infestation if pests are detected. Furthermore, the use of automated monitoring systems can help farmers to minimize waste and improve sustainability.
  By optimizing irrigation and fertilization, farmers can decrease the quantity of water and chemicals used, resulting in a positive environmental impact. By monitoring plant growth and health, farmers can identify areas that require additional attention, such as areas where plants are not growing as well as they should. Additionally, automated monitoring systems can save farmers time and labor [75]. Instead of manually monitoring every field, farmers can rely on the data collected by the system to make informed decisions about crop management. This is particularly useful for large farms, where manual monitoring may not be practical.
- **Filter-based methods:** Filter-based methods are a fundamental tool in farmland management, aiming to improve crop yields and minimize the risks of plant diseases by eliminating pollutants and impurities from the soil, water, and air. This approach involves using physical and chemical processes to remove contaminants, including gases such as ammonia, from the environment. One common example of a filter-based

method is passing air through a filter to capture particulate matter and gases, followed by laboratory analysis to determine the concentration of the target gas [76].

- **Open-path techniques:** Open-path techniques are a set of remote sensing methods that employ lasers to gauge the concentration of ammonia gas in the air, enabling real-time measurement of ammonia gas concentrations over a vast area. The technique is non-invasive and can measure various environmental parameters such as temperature, humidity, carbon dioxide, and methane concentrations, making it particularly useful in farmland. This technique operates by directing a laser beam across the farmland to gauge the absorption of light by atmospheric gases. One of the key benefits of open-path techniques is their ability to provide real-time measurements of atmospheric conditions over a large area. By continuously monitoring these conditions, farmers can better comprehend the impact of climate change, pests, and diseases on their crops and take appropriate actions to mitigate their effects.
  Moreover, open-path techniques are useful in detecting leaks from agricultural facilities such as animal feedlots or silage storage areas, thus reducing the risk of environmental contamination and greenhouse gas emissions [77]. With open-path techniques, farmers can continuously monitor atmospheric conditions over a large area, which is especially useful in farmland where environmental conditions can fluctuate significantly over short distances [78].
  Several filter-based techniques are employed in farmland management, including soil, irrigation, air, and crop filters.
  - **Soil filters:** use filter media such as activated carbon or sand to remove impurities from the soil, rendering it suitable for farming.
  - **Irrigation filters:** remove sediment and debris from water, improving the efficiency of the water usage and preventing the clogging of irrigation systems.
  - **Air filters:** remove airborne particles from the atmosphere, particularly in areas with high levels of air pollution.
  - **Crop filters:** utilize specific crops to filter out harmful substances from the soil, such as heavy metals, which can be eliminated from the farm system by harvesting and disposing of the crops.

Passive samplers are inexpensive and easy to use in comparison to sampling and laboratory analysis procedures, however they have limited detection capability. Active samplers can take bigger air samples and deliver faster findings, but they must be maintained and trained. Automated monitoring systems provide constant monitoring but are expensive. Filter-based approaches are accurate, but they are costly and time-consuming. Soil, irrigation, air, and crop filters all give information about specific habitats, but they have limits. Open-path approaches provide real-time monitoring but need specialised equipment that can be costly. One common point among all these methods is that all of these approaches seek to measure and monitor pollution levels and offer information on the effects of pollution on various habitats. The difference among them is the cost, ease of use, detection abilities, sampling volume, speed of results, maintenance requirements, and the specific environments they target. Table 1 shows the comparison study of different methods used by the researchers for the detection of ammonia in farmland.

Table 1. A comparison of different detection methods for ammonia gas in farmland.

Method Name	Description	Reference
Calorimetric Methods	*Setup:* Chemical reaction between ammonia and a reagent, produces a measurable change in heat. *Range:* 1–100 ppm or even lower *Sensor:* Rely on the calorimeter or other heat-sensing device to measure the heat change.	[28]

Table 1. *Cont.*

Method Name	Description	Reference
Electrochemical	*Setup:* Different types of electrodes. *Range:* 1 to 100 ppm *Sensor:* Glassy carbon, gold, and platinum electrodes	[35]
Electrochemical	*Setup:* multi-gas detection system using different sensor arrays. *Range:* 0.0904 ppm *Sensor:* MQ-136, MQ-137, TGS-2611	[36]
Electrochemical	*Setup:* screen-printed electrode (SPE). *Range:* 50 ppm	[33]
Titration Methods	*Setup:* Titration methods for ammonia detection typically involve the use of a reagent that reacts with ammonia to produce a visible change in color or pH. *Range:* 0.1 ppm to 100 ppm *Sensor:* Rely on the reagent and titration equipment to measure the change in color or pH resulting from the chemical reaction with ammonia	[27]
Ion Selective Electodes (ISE)	*Setup:* Involve the use of an ammonia-specific membrane. The membrane generates an electrical potential which can be measured using an electrode. *Range:* 1–100 ppm or 10–500 ppm *Sensor:* Ammonia-specific membrane and an electrode to detect and measure the concentration of ammonia ions in a solution.	[37]
Gas Sensitive Tubes	*Setup:* Typically use a tube filled with a reactive substance that changes color or produces a visible reaction in the presence of ammonia. The tube is placed in the path of a gas stream and the concentration of ammonia can be estimated by measuring the length of the tube that has changed color or undergone a reaction. *Range:* 1–100 ppm or 10–500 ppm *Sensor:* Rely on a reactive substance contained within the tube to produce a visible reaction in the presence of ammonia.	[38]
Photo-acoustic	*Setup:* The continuous detection of trace ammonia in the air and the sub-ppb level are realized. *Range:* 32 parts per trillion (ppt) *Sensor:* Photoacoustic spectroscopy, TGA300, TGA310, TGA320	[55]
Photo-acoustic	*Setup:* Depending on laser PAS, a portable ammonium analyzer has been designed and tested.A single-mode CO_2 laser was employed, and for the auditory sensing, a resonant configuration's high sensitivity was completely used. *Range:* 0.1ppb to 3 ppm *Sensor:* Laser Photoacoustic Spectroscopy	[56]
Photo-acoustic	*Setup:* Detection of ammonia gas in the agricultural environment. *Range:* up to 8 ppm *Sensor:* Laser Photoacoustic Spectroscopy, Diode Laser	[57]
Photo-acoustic	*Setup:* Laboratory Conditions *Range:* 0.1 to 20 ppm *Sensor:* Microphone	[58]
Photo-acoustic	*Setup:* Light Source, Sample holder, Acoustic detector, Signal amplifier and processing *Range:* 2 ppm *Sensor:* Interferometer	[59]
Spectrophotometry	*Setup:* Silicone Force Sensor (SXTSC1) *Range:* 0.1 to 2 ppm and extended upto 5 ppm *Sensor:* UV-VIS spectrophotometry	[68]
Sampling and Laboratory analysis	*Setup:* For ammonia detection in air or water, samples are collected and analyzed in a lab using methods like titration or ion selective electrodes. *Range* Ammonia detection ranges vary (0.1–100 ppm) due to different methods and sensors. *Sensor:* pH sensors, Ion selective electrodes (ISEs), Mass spectrometry detectors, Colorimetric sensors, Fluorescence sensors.	[69]

Table 1 presents a comprehensive comparison of various methods used for detecting ammonia gas. The comparison covers several important parameters, such as methods used, setup of the method, concentration range of methods, sensors used by the methods, and the reference study of researchers for the method. By examining the strengths and limitations of each method, researchers can make informed decisions about which approach is most suitable for their specific application. In addition to monitoring environmental conditions, open-path techniques can be used to optimize crop management by identifying areas prone to drought stress or fungal infections. The information gathered can be used to adjust irrigation and fungicide applications, reducing the use of water and pesticides, while improving crop yields. Overall, open-path techniques are an essential tool for farmers looking to improve the efficiency and sustainability of their operations. As technology advances, it is likely that these techniques will become more widely used in agriculture, benefiting farmers and the environment.

2.2. Electronic Nose (E-Nose) Ammonia Detection Method

E-nose is a technology that uses electronic sensors to detect and identify volatile organic compounds (VOCs) in the air. It is also an emerging technology that offers potential advantages for ammonia detection in agriculture. E-nose consists of an array of gas sensors that can detect volatile organic compounds (VOCs) and other gases in the air, including ammonia [79]. E-nose can provide real-time, non-invasive, and automated measurements of ammonia concentrations, without the need for manual sampling or laboratory analysis.

This method is recognised as a type of direct-reading instrument by [80] that can be used for both indoor and outdoor measurements of ammonia. Long-time use of E-nose in agriculture shows it is widely used in agriculture research for various applications such as food quality monitoring, disease detection, and environmental monitoring. However, there is still room for improvement in terms of accuracy and sensitivity in some applications [81,82]. E-nose offers advantages in terms of sensitivity, real-time monitoring, portability, and ease of use, while traditional methods may still be preferred in certain situations where specific regulations, standards, or established methods are required. The choice between E-nose and traditional methods for ammonia detection and measurement would depend on the specific application requirements, budget, and other factors.

2.2.1. E-Nose History Application in Agriculture

The E-nose is a cost-effective solution compared to traditional methods, as it does not require the use of expensive reagents, specialized equipment, or trained personnel. Recent studies demonstrate the potential of E-nose for ammonia detection in various agricultural and environmental settings. This makes it a suitable solution for the detection of ammonia in agriculture, where the cost of analysis is an important consideration. The Figure 6 shows a comprehensive overview of the history of E-nose and traditional ammonia detection in the field of agriculture. With each year passing from 1996 till the current date, the new development in the technology and research work has made it easy to detect the ammonia at agricultural level. As shown in Figure 6, the authors [83], reported the first use of E-nose to detect ammonia emissions from pig housing. The authors of [84] used E-nose technology to detect odors from livestock facilities and to control and reduce ammonia emissions. The study [85] demonstrated that E-nose technology could be used to accurately detect and quantify ammonia in poultry houses, thereby providing a tool for improved environmental control. The authors of [86] demonstrated the feasibility of using an E-nose for continuous monitoring of ammonia levels in dairy barns, which could aid in reducing the negative impact of ammonia emissions on animal health and productivity. Similarly, ref. [87] used E-nose to detect ammonia emissions from composting poultry litter, which is a common practice in many agricultural settings. [88] showed that E-nose technology could be used to detect and differentiate between different sources of ammonia emissions in livestock production, allowing for more targeted management practices. The authors of [89] used an E-nose to detect and monitor ammonia in a pig house. They achieved an accuracy rate of 95% and found that E-nose technology could be used to monitor pig house air quality.

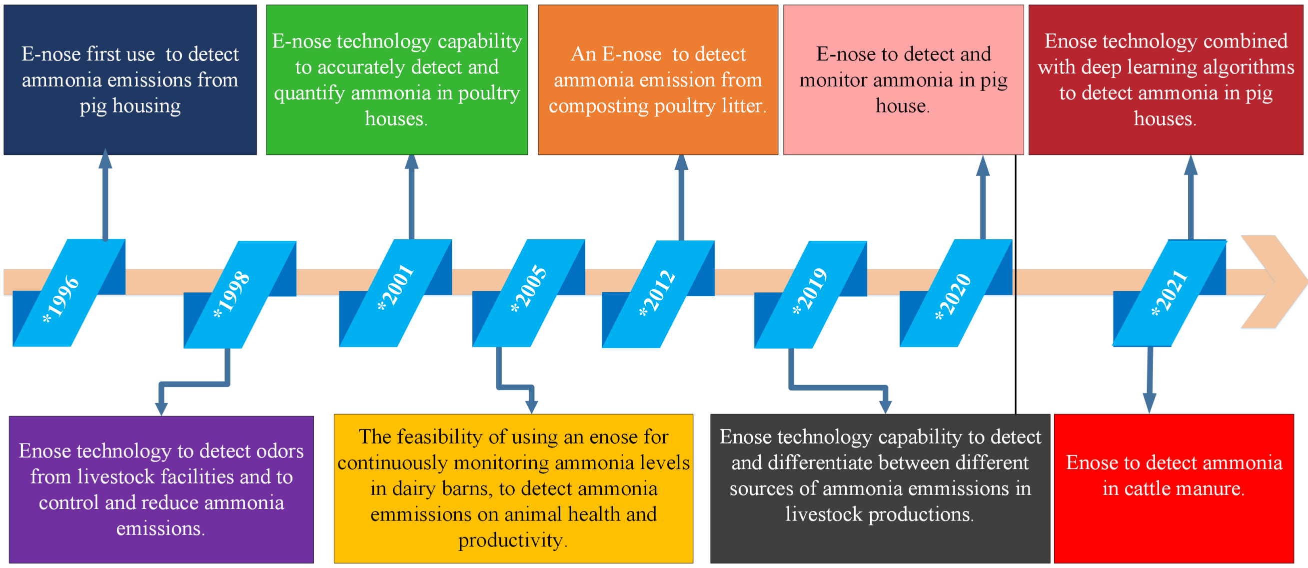

Figure 6. The trend of E-nose and traditional ammonia detection [80–91].

The study [90] used an E-nose to detect ammonia in cattle manure. They found that the E-nose had a high accuracy rate for detecting ammonia in the gas emitted from the cattle manure, and they suggested that this technology could be used to monitor and control the emission of harmful gases in animal husbandry. Furthermore, ref. [91] also used E-nose technology to detect ammonia in pig houses. They proposed a deep learning algorithm to improve the accuracy of E-nose detection and achieved an accuracy rate of 96%. They concluded that E-nose technology combined with deep learning algorithms could be a useful tool for monitoring and controlling ammonia emissions in pig houses [80–91].

2.2.2. E-Nose Structure

An E-nose typically consists of several parts: Sensors, Signal Processing Unit, Power Supply, and Communication Interface that can communicate with other devices such as a computer or a smartphone via a communication interface with wired or wireless-based [92] connection. The sensor and signal processing, as the most important part of E-nose in an ammonia detection apparatus are described as follows.

- **Sensor:** The E-nose can be equipped with multiple sensors, allowing for the simultaneous detection of multiple VOCs, including ammonia, providing a more comprehensive analysis of the air quality [93]. Some of the most commonly used sensor types for this purpose are listed below:
  - **Metal-oxide Semiconductor (MOS) Gas Sensor:** MOS sensors operate by measuring the change in electrical resistance when exposed to gases such as ammonia. They are cost-effective and can be used for continuous monitoring of ammonia levels in farmland. Some commonly known models of these sensor types include the Figaro TGS2600, SPEC Sensors MQ-137, and Winsen MQ135 [94].
  - **Electrochemical Gas Sensor:** Electrochemical sensors are commonly used for gas detection, including ammonia gas. They operate by measuring the electrical current produced when ammonia gas reacts with an electrode, providing real-time data on ammonia concentration in the surrounding air. The most commonly used models for these sensors include the Alphasense NH_3-B1, City Technology 4NH_3-100 C, and Membrapor EC_4-NH_3 [95].
  - **Photoionization Detector (PID):** PID sensors use ultraviolet light to ionize gas molecules, including ammonia, and measure the resulting electrical current. They are highly sensitive and can provide instant readings of ammonia concentration in the air, making them suitable for farmland applications. The following models,

such as the Honeywell MiniRAE 3000, Ion Science TigerLT, and RKI Instruments Eagle 2 PID, are widely recognized and commonly used for this sensor group [96].

– **Non-Dispersive Infrared (NDIR) Sensors:** Infrared sensors work by measuring the absorption of infrared light by gases, including ammonia. They are highly selective and can provide accurate readings of ammonia concentration in the air, making them ideal for farmland applications. Some notable models for this sensor type include the SGX Sensortech AMMONIA-1C-N, and Winsen ME2-NH_3. These models have gained significant recognition in the industry [42].
– **Wireless Sensor Networks (WSN):** WSNs consist of multiple sensor nodes deployed in a farmland area, interconnected wirelessly to collect and transmit data, including ammonia gas concentrations, in real-time. They can provide comprehensive coverage of farmland areas and enable remote monitoring of ammonia levels. The gas sensing boards commonly employed for these types of applications include the Libelium Waspmote Gas Sensor Board, which integrates a range of sensors capable of detecting gases such as ammonia [97].

Table 2, offers a comprehensive overview of different ammonia detection sensors, encompassing their detection principles, advantages, and disadvantages.

Table 2. E-nose Sensor type used in ammonia comparison, Metal-oxide Semiconductor (MOS), Photoionization Detector (PID), Non-Dispersive Infrared (NDIR), Wireless Sensor Networks (WSN).

Sensor Type	Principle	Advantages	Disadvantages
MOS	Change in electrical resistance when exposed to gases absorption of infrared light by gases, including ammonia	Cost-effective; Compact size; Relatively fast response time; Suitable for continuous monitoring of ammonia levels in farmland	Limited sensitivity; susceptible to environmental factors and interfering gases; requires periodic recalibration
Electrochemical	Electrochemical reaction of ammonia gas with an electrode	High sensitivity; Good selectivity; Wide measurement range; Relatively low power consumption; Real-time data on ammonia concentration in the surrounding air; commonly used for gas detection	Limited lifespan; sensitivity to temperature and humidity variations; Requires periodic calibration and maintenance
PID	Ionization of gas molecules by ultraviolet light	High sensitivity; fast response time; capable of detecting low concentrations; can detect a wide range of volatile organic compounds (VOCs)	Higher cost compared to other sensors; potential interference from other gases; requires periodic calibration.
NDIR	Absorption of infrared light by gases, including ammonia	High accuracy; Good selectivity; Long lifespan; Stable and reliable performance	Higher cost compared to some other sensors; Slower response time; Larger physical size
WSN	Multiple sensor nodes interconnected wirelessly	Remote monitoring capability; Real-time data collection; scalability; Flexibility in sensor placement; Potential for comprehensive coverage	Costly infrastructure setup; potential for signal interference; complex data management and analysis; requires power and communication resources.

The Table 2 illustrates that all sensor types, including MOS, electrochemical, PID, NDIR, as well as WSN, offer viable options for ammonia gas detection. These technologies hold the potential to revolutionize agricultural practices and environmental monitoring by delivering precise and real-time measurements of ammonia gas concentration. Their collective capabilities facilitate comprehensive monitoring and data collection, enabling informed decision-making for enhanced efficiency and sustainability.

2.2.3. E-Nose Signal Processing Method

Various methods are employed in E-nose systems to analyze sensor data, including Principal Component Analysis (PCA), Artificial Neural Networks (ANN), Support Vector Machines (SVM), Artificial Olfactory System (AOS), and Fuzzy Logic. These methods enable the effective processing and interpretation of sensor data, facilitating accurate and reliable analysis in E-nose applications. It should mentioned that the choice of method depends on factors such as the characteristics of the data, complexity of the detection task, and available computational resources. Often, a combination of these methods or hybrid approaches are utilized to leverage their individual strengths and mitigate their limitations.

- **Principal Component Analysis (PCA):** PCA is a widely used technique for feature extraction and dimensionality reduction. It analyzes the correlation between sensor responses and identifies the principal components that capture the most significant variations in the data. By applying PCA to the sensor data, the E-nose system can reduce the dimensionality of the input and improve classification accuracy. This method offers several advantages, including the reduction of data dimensional, capturing significant variations, facilitating data visualization, and enabling feature extraction. However, it is important to note that this method assumes linearity in the data and may not effectively handle nonlinear relationships [98].
- **Artificial Neural Networks (ANN):** ANN algorithms are frequently employed in E-nose systems for pattern recognition and classification. These algorithms consist of interconnected nodes or "neurons" that learn from the sensor data and make predictions based on the acquired knowledge. ANN can be trained to recognize specific patterns associated with ammonia gas, enabling accurate detection and classification. When considering the advantages of this method, it is reported that it excels in handling complex and nonlinear relationships, demonstrating robustness in pattern recognition and classification tasks. Additionally, it possesses the ability to learn from data and generalize its findings. However, it should be noted that this method does have certain disadvantages, including the requirement for substantial computational resources and training time. Furthermore, it is sensitive to factors such as network architecture and hyperparameters, which need to be carefully considered during implementation [99].
- **Support Vector Machines (SVM):** SVM is a supervised machine learning algorithm used for classification tasks. It separates data into different classes by creating an optimal hyperplane in a high-dimensional feature space. SVM can be trained on labeled sensor data to distinguish between ammonia and non-ammonia samples, making it suitable for ammonia gas detection in E-nose systems. The Support Vector Machines (SVM) offers several advantages in data analysis and classification, including effectiveness for binary classification tasks, good performance in high dimensional feature spaces, robustness against over fitting, and capability of handling nonlinear relationships through kernel functions. However, it is important to consider the following disadvantages when using SVM: it is computationally intensive, especially for large datasets, may not scale well with extensive amounts of data, and requires careful selection of the appropriate kernel and tuning of hyper parameters. Despite these challenges, SVM remains a powerful tool in machine learning and data analysis, particularly for binary classification problems in high-dimensional spaces [100].
- **Artificial Olfactory System (AOS):** AOS is an approach inspired by the olfactory system of living organisms. It involves modeling the sensor responses based on biological principles and implementing algorithms that mimic the odor perception and recognition process. AOS methods can be applied to E-nose systems for ammonia detection, enabling more accurate and reliable results. Advantages of an Artificial Olfactory System (AOS) include its inspiration from biological olfactory systems, enabling the capture of complex odor perception and recognition, thereby potentially enhancing accuracy in odor analysis. However, AOS implementation and modeling can be com-

plex, requiring extensive training and optimization. Additionally, the availability of standardized AOS methods is limited [97].

- **Fuzzy Logic (FL):** Fuzzy logic is a mathematical framework that deals with uncertainty and imprecision. It is often utilized in E-nose systems to handle the inherently fuzzy nature of sensor data and decision-making processes. By incorporating fuzzy logic techniques, the E-nose can effectively handle variations in sensor responses and provide more robust ammonia detection results. The advantages of fuzzy logic can be summarized as follows: it effectively deals with uncertainty and imprecision in data, provides a suitable framework for handling fuzzy relationships, and allows for the incorporation of expert knowledge into the system. However, it is important to note that fuzzy logic also has its limitations, such as the subjective design of fuzzy rule sets and the need for tuning membership functions and fuzzy operators to achieve optimal performance [93].

2.2.4. Pattern Recognition (PR)

Pattern recognition in E-nose refers to the process of analyzing sensor data to identify and classify specific patterns associated with the presence of gases or odors. It plays a vital role in the accurate detection and recognition of target substances. Pattern recognition plays a crucial role in E-nose systems by facilitating accurate and reliable detection, classification, and interpretation of sensor data. It enhances the system's ability to monitor gases and odors, enabling various applications such as environmental monitoring, quality control, and safety assurance. Advantages of pattern recognition in E-nose systems include its ability to analyze patterns in sensor data, enabling the classification and identification of target substances. It also plays a crucial role in facilitating real-time monitoring and decision-making processes. However, it is important to note that the performance of pattern recognition is dependent on the quality of the extracted features and the chosen classification algorithm.

The prevailing pattern recognition methodologies employed in E-nose systems encompass Long Short-Term Memory (LSTM), Partial Least Squares (PLS), and Linear Discriminant Analysis (LDA) [101,102]. The mentioned methods are described as follows.

- **Long Short-Term Memory (LSTM):** LSTM is a recurrent neural network (RNN) architecture that has been successfully applied in various fields, including ammonia detection in E-nose systems. LSTM networks are designed to capture long-term dependencies and temporal patterns in sequential data, making them well-suited for time-series analysis. The method offers several advantages, including its ability to capture temporal dependencies in sequential data, effectiveness in time-series analysis, and the capability to learn long-term dependencies. However, it is worth noting that this method has a few disadvantages, such as the requirement of a large amount of training data, the complexity of its architecture, and its computational intensity [103].
- **Partial Least Squares (PLS):** PLS is a statistical method commonly used in E-nose systems for data analysis and modeling. PLS is a valuable tool in E-nose detection, allowing for effective modeling of sensor data, feature selection, and prediction of target substance concentrations. It helps to overcome multicollinearity and provides insights into the underlying relationships between sensor responses and the target substance, contributing to accurate and reliable detection in E-nose systems. PLS offers several advantages in E-nose detection. It excels in handling multicollinearity in data, making it suitable for modeling complex relationships. It can also enable feature selection and analysis of variable importance, allowing for a more focused and efficient analysis of the sensor data. However, it is important to consider the limitations of PLS. One drawback is its sensitivity to outliers in the data, which can impact the accuracy of the model. Additionally, when dealing with small datasets, PLS has the potential to overfit the model, resulting in overly complex and less generalizable predictions. In whole, PLS provides valuable benefits in E-nose detection, including its ability to handle multicollinearity, model complex relationships, and conduct feature selection.

Nonetheless, its sensitivity to outliers and the risk of overfitting with small datasets should be taken into account during its implementation and interpretation [104].

- **Linear Discriminant Analysis (LDA):** LDA is a commonly used method in E-nose systems for ammonia gas detection and konwn as a supervised classification algorithm that aims to find a linear combination of features that maximizes the separation between different classes of data. The combination of E-nose and LDA can provide accurate and reliable detection of ammonia gas, contributing to applications in environmental monitoring, industrial safety, and agriculture. The LDA offers benefits such as dimensionality reduction, multiclass classification capability, and statistical inference. Its assumptions of linearity and limited ability to model nonlinear decision boundaries should be considered when applying it in the context of ammonia gas detection using E-nose systems [105].

The review of the research paper focused on the application of Electronic noses (E-nose) and the methods used in farm land and food quality, revealing several key findings. To provide secure and effective storage for food, ref. [98] proposed an E-nose system combined with an embedded system. The system was designed to prevent the spoilage of food under different circumstances and conditions. The authors used the α-Fox 2000 E-nose system to collect data on rice, millet, and wheat under varying conditions, such as cold temperature, room temperature, pest infestation, and high humidity levels. Through principal component analysis (PCA) and discriminant function analysis (DFA), the authors observed that different conditions of grains occurred in different areas, indicating that E-nose systems can differentiate between them. This study demonstrates the potential of E-nose technology for effectively monitoring and preventing food spoilage in various conditions.

The authors of [29] conducted a study on E-nose systems that operate on embedded systems. They presented a portable and cost-effective E-nose system that can analyse odor signals from various sources such as onions, tomatoes, garlic, and oranges. The authors observed that the E-nose system exhibited different responses for each sample, and the results were found to be highly accurate and successful. Similarly, ref. [99] used an Electronic nose for the detection of early blight disease in tomatoes. In another study, ref. [102] presented the development of E-nose in agriculture to ensure better food quality. The authors described the use of Artificial Neural Networks (ANNs), Principal Component Analysis (PCA), and Linear Discriminant Analysis (LDA) methods to achieve this goal. The authors discussed different experiments conducted for various agricultural products, with results showing good accuracy and recognition skills of the E-nose systems. While the field of E-nose in agriculture has shown promising results, advancements are still necessary, such as improved detection accuracy, better recognition of judgments and identification, and enhanced decision-making processes. The paper by [106] provides a comprehensive review of the development of an E-nose system for analyzing food quality and safety, highlighting its non-invasive nature, speedy analysis, and ease of use. This makes it a superior online monitoring tool for ensuring food safety and quality. The authors of [100] examined the application of E-nose and e-tongue technologies in recognizing food quality, using various pattern recognition algorithms including ANN, CNN, PCA, PLS, and SVM.

This advanced technology yields a powerful systematic tool for food quality control, offering the benefits of low cost, fast analysis speed, and high accuracy (between 70% and 95% in different study). With control over the preparation of samples, sampling process, and data processing, E-nose and e-tongue technologies, when combined with these pattern recognition algorithms, provide a comprehensive solution for food quality analysis.

The E-nose technology has played a critical role in detecting ammonia emissions in agriculture and has helped to improve environmental control, animal health, and productivity in various livestock settings [101]. The study evaluates the effectiveness of E-nose technology in detecting and measuring ammonia levels in a specific context. The study [107] detected ammonia in poultry farming using an E-nose. The author Supchocksoonthornoo [105] reviewed carbon dots in an optical E-nose that could sense ammonia vapors and some VOCs (Volatile Organic Compounds). One of the best advantages of the method is that it could identify the concentration of ammonia and differentiate the ammonia in different mixtures that contain methanol and water and from ethylenediamine and triethylamine. For the detection of NH_3 gas in 100 ppb, the gas-sensing properties of halogenated chloroaluminum phthalocyanine (ClAlP) narrow features with a rotating layer were taken into consideration by author [108].

After conducting some experiments, the authors noticed that the CIAIPc sensor was attracted more towards NH_3 (ammonia gas) in comparison to other gases. To recognize the NH_3 (ammonia gas) author [97], presented a Sr-ZnO gas sensor which helps self-protection action against hazardous gases like NH_3. The artificial olfactory presented in the paper provides a promising strategy for future bio-inspired electronics research, especially in the field of mimicking biological sensory systems. The automatic detection of harmful gases by using the technology of E-nose was studied by [109]. The detection of these gases can be helpful in industrial areas because such harmful gases as ammonia can be very dangerous to human health. The main advantage of the study is to detect gases within the environment and inform the user about the gas name and the amount of gas level in that particular environment. The precise estimation of gas levels to increase the sorting and reversion success of concentration values for four dissimilar gases detected by four different metal oxide gas sensors was presented by [103]. The SVM (Support Vector Machine) was used to carry out the classification. After classifying with SVM the classification accuracy was raised to 90.8%. For the regression success feature extraction was applied. Four sensors were used, among which TGS2602 was able to detect the concentration of ammonia. Another study about the NH_3 sensor which was based on ZnO nanostructures combined with graphene quantum dots (GQDs) to select the ammonia effectively was presented by [104]. The ammonia-sensing output shows that ZnO: GQDs sensors with a volume of 15 μL have ideal sensor feedback at a level of 1000 ppm and value of 6047. This study identified volatile compounds from green tea leaves using an E-nose [110].

In a study by [111], the E-nose was used to detect ammonia in the air of a pigpen and was found to provide reliable results in real-time, with a high degree of accuracy and sensitivity.

$$S = \frac{R_f - R_s}{R_s} \times 100 \quad (2)$$

The similarity between the gas detector and sensor was compared with the formula shown in Equation (2). Here S represents similarity, R_f is the gas detector and R_s is the sensor used. The gas detector and sensor were compared, and the similarity between them was very high.

2.2.5. E-Nose Sensor Type vs. Signal Processing Method

To gain a comprehensive understanding of E-nose systems, Table 3 presents a detailed comparison of sensor types and signal processing methods. This table emphasizes the significance of these components as the core elements of the E-nose system. The comparison primarily focuses on crucial factors such as cost, speed, and accuracy, providing a valuable overview of their relative strengths and weaknesses [112].

Table 3 shows the comparison is focused on cost, speed, and accuracy aspects of different sensor types and WSN implementation along with signal processing and analysis methods used in E-nose systems. The cost comparison provides insights into the relative affordability of MOS, electrochemical, PID, and NDIR sensors. Considering the Speed comparison highlights the response times of MOS, electrochemical, PID, and NDIR sensors, as well as the real-time capabilities of WSNs. And with respect to the Accuracy assessment considers the sensitivity, selectivity, and overall accuracy of electrochemical, MOS, PID, NDIR sensors, and WSNs. On the other hand, MOS sensors are generally low-cost, while electrochemical sensors' cost varies depending on the model and brand. PID sensors are generally more expensive, and NDIR sensors are generally more expensive compared to some other sensor types. WSN implementation involves higher upfront costs due to infrastructure setup and sensor deployment. MOS, electrochemical, and PID sensors offer fast response times, while NDIR sensors typically have a slower response time compared to other sensor types. WSNs provide real-time data collection and monitoring capabilities, but the comparison does not mention the speed of WSNs explicitly and electrochemical sensors provide high sensitivity and good selectivity, resulting in accurate measurements.

Table 3. Metal Oxide Semiconductor (MOS), Electrochemical Sensors (ES), Photoionization Detectors (PID), Non-Dispersive Infrared (NDIR), Wireless Sensor Networks (WSN), Principal Component Analysis (PCA), Artificial Neural Networks (ANN), Support Vector Machines (SVM), Artificial Olfactory System (AOS), Fuzzy Logic (FL), Pattern Recognition (PR), Long Short-Term Memory (LSTM), Partial Least Squares (PLS), and Linear Discriminant Analysis (LDA).

A: Sensor:				
	Cost	**Speed**	**Accuracy**	**Reference**
MOS	Low-cost	Fast	Depend	[109]
ES	Vary in cost	Fast	Accurate	[108]
PID	More expensive	Fast	Accurate	[96]
NDIR	More expensive	Slow	High Accuracy	[42]
WSN	Higher upfront costs	Fast	High accuracy	[97]
B: Method:				
	Cost	**Speed**	**Accuracy**	**Reference**
PCA	NO additional costs	Fast	Accurate	[98]
ANN	Vary in cost	Depend	High Accuracy	[99]
SVM	Cost-effective	Fast	High Accuracy	[100]
AOS	Vary in cost	Depend	High Accuracy	[97]
FL	NO additional costs	Fast	Accurate	[93]
PR	NO specific costs	Fast	Depend	[101,102]
LSTM	Vary in cost	Slower	Depend	[103]
PLS	NO additional costs	Fast	Accurate	[104]
LDA	NO additional costs	Fast	Accurate	[105]

MOS sensors may have limited sensitivity and can be influenced by environmental factors and interfering gases, affecting their accuracy. PID sensors provide high sensitivity and accurate detection of low gas concentrations. NDIR sensors offer high accuracy and good selectivity for gas detection. WSNs can achieve high accuracy depending on the quality and calibration of the deployed sensors, but the specific metrics or comparisons are not mentioned. Evaluating the signal processing and analysis methods used in E-nose systems like PCA, ANN, SVM, AOS, Fuzzy Logic, Pattern Recognition, LSTM, LDA, and PLS shows that these methods aim to extract meaningful information from sensor data and improve the detection and classification of ammonia gas. They contribute to enhancing accuracy and understanding patterns in sensor data. All methods can be applied in E-nose systems to improve ammonia gas detection and monitoring. Their effectiveness depends on appropriate training, calibration, and optimization. Each method operates based on different underlying principles and algorithms. The implementation costs can vary for different methods. PCA and some other methods do not incur significant additional costs, while ANN and AOS implementations can be more costly. Speed of processing differs across methods. Some methods, like PCA and pattern recognition, offer faster computation, while others like LSTM may be slower due to sequential processing. Accuracy levels vary among the methods. SVM, ANN, AOS, and PLS have the potential for high accuracy, while others like PCA and LDA may have limitations due to assumptions or reduced dimensionality. Some methods, like ANN and LSTM, can capture temporal dependencies, while others focus more on data patterns or statistical inference.

As the reviewed papers have shown, the E-nose varies in terms of sensor array size, detection limits, and specific applications, but all show promise for real-time, non-invasive ammonia detection. The E-nose is capable of detecting ammonia in real time and can provide rapid results, reducing the time required for analysis compared to traditional methods such as gas chromatography and spectrophotometry [26].

3. Performance Evaluation of Traditional Methods vs. E-Nose

The traditional methods have been used in agriculture for many years and are still widely used due to their simplicity, affordability, and ease of use. However, they also have limitations, such as the need for manual sampling, the potential for measurement errors, and time-consuming laboratory analysis. These methods can provide accurate and reliable results for ammonia detection, but their performance may vary depending on factors such as sensitivity, specificity, real-time monitoring capability, ease of use, and maintenance requirements. This has led to the emergence of alternative methods, such as E-nose, which offer potential advantages in terms of real-time, non-invasive, and automated ammonia detection in agricultural settings. When selecting a method for ammonia detection, it is crucial to consider both the specific application and the desired level of accuracy. The cost, speed, and accuracy of ammonia detection methods in agriculture can vary greatly depending on the method used and should be taken into account.

According to [113], the most used methods in agriculture, one of the most commonly used methods for ammonia detection is the use of Electrochemical sensors. Electrochemical sensors are widely employed for their high sensitivity, good selectivity, and relatively fast response time. These sensors are capable of accurately measuring ammonia gas concentrations in the agricultural environment, making them suitable for applications such as monitoring livestock facilities, assessing fertilizer efficiency, and managing air quality in crop production. Electrochemical sensors offer several advantages for ammonia detection in agriculture. They are cost-effective, easy to use, and provide real-time measurements.

Additionally, they can detect low concentrations of ammonia gas accurately, enabling farmers to monitor and adjust ammonia levels to optimize crop growth and minimize environmental impact . It is important to note that, while electrochemical sensors are commonly used, the choice of ammonia detection method can vary depending on specific agricultural practices, regulatory requirements, and the desired level of accuracy and monitoring capabilities. A deeper comparison shows that the cost of these methods can vary, with Calorimetric Methods and Spectroscopic Methods generally being more expensive, while Electrochemical and Gas Sensitive Tube methods tend to be more affordable. In terms of speed, Electrochemical sensors and Gas Sensitive Tubes offer fast response times, while Sampling and Laboratory Analysis and Spectroscopic Methods can be slower due to the need for sample collection and analysis. Regarding accuracy, Calorimetric Methods [28], Electrochemical sensors [33], Ion Selective Electrode (ISE) [38], and Spectroscopic Methods [49] are known for providing high accuracy in ammonia detection. The measurement range can vary depending on the specific method and equipment used. Generally, Electrochemical sensors have a moderate to wide measurement range, while Calorimetric Methods and Ion Selective Electrode (ISE) have a narrower to moderate range.

E-nose can also be used for spatial mapping of ammonia levels across large areas, providing valuable information for site-specific management strategies. Additionally, E-nose has the potential to detect other odor compounds or gases that may be indicative of specific agricultural practices or environmental conditions [23]. However, E-nose also has limitations. It may require calibration and validation against reference methods to ensure accuracy and reliability. The cost of initial investment and maintenance may be higher compared to some traditional methods. The complexity of data analysis and interpretation may also pose challenges, as E-nose generates large amounts of data that require advanced analytical techniques [26]. The comparative analysis of advantages and disadvantages pertaining to diverse domains concerning Electronic nose (E-nose) and conventional methodologies are elucidated in Table 4 presented hereunder.

Table 4. Advantages of E-nose and Traditional Methods.

Advantages	**E-Nose**	**Traditional Methods**
Sensitivity	High detection limits in the low ppm or even ppb range	Highly selective for ammonia
Precision and Accuracy	Precise and accurate measurements	Familiarity and wide adoption
Real-time Monitoring and Rapid Results	Provides real time monitoring and quick results	Easier to implement and validate
Portability and Ease of Use	Very portable and easy to use	High accuracy and precision in ammonia measurement
Potential Selectivity towards Specific Analytes	Including ammonia	Potentially reducing interference from other compounds in the sample
Disadvantages	**E-Nose**	**Traditional Methods**
Sensor Limitations	It has sensor limitations	Require complex sample preparation steps
Cost	E-nose devices can have varying costs depending on the complexity of the sensor array	Longer analysis times compared to E-nose
Standardization	Lack standardized methods or regulatory guidelines for ammonia measurement	Require specialized equipment, reagents, and skilled personnel for operation and maintenance
Application Range	Limited	Less portable compared to E-nose devices

According to the findings presented in Table 4, it can be deduced that E-nose devices present a plethora of advantages in the realm of ammonia detection. These advantages encompass heightened sensitivity, instantaneous tracking capabilities, convenient portability, swift response times, and the ability to discern specific analytes. Consequently, E-nose devices have found widespread utility across diverse industries and sectors. Conversely, traditional methods possess well-established methodologies, exhibit selectivity towards ammonia, boast familiarity among operators, and have demonstrated commendable precision and accuracy. Nevertheless, E-nose devices do have certain limitations, such as limited sensing strength, susceptibility to cross-sensitivity, calibration prerequisites, and a lack of standardized procedures. Moreover, they necessitate significant upfront investment and ongoing maintenance. A comprehensive comparison was conducted between traditional methods such as calorimetric methods, electrochemical sensors, titration methods, ion selective electrodes (ISE), gas-sensitive tubes, spectroscopic methods, sampling with laboratory analysis, and the emerging technology of E-nose.

In this comparative analysis, a comprehensive analysis was conducted utilizing a radar graph framework, drawing upon meticulously documented data. In the analysis the sensitivity, accuracy, analysis time, real-time monitoring, portability, versatility, and cost were as the main parameters. To facilitate a systematic evaluation, each of these critical parameters assigned a numerical rating, adhering to a refined metric scale ranging from 0 to 5. In this scale, the quantitative correspondences are assigned as follows: low corresponds to 0, moderate corresponds to 2.5, high corresponds to 5, limited corresponds to 1.5, and affirmatives like “yes” and “no” are respectively associated with the numerical values of 5 and 0. The findings of this analysis are presented in Figure 7 as a radar chart.

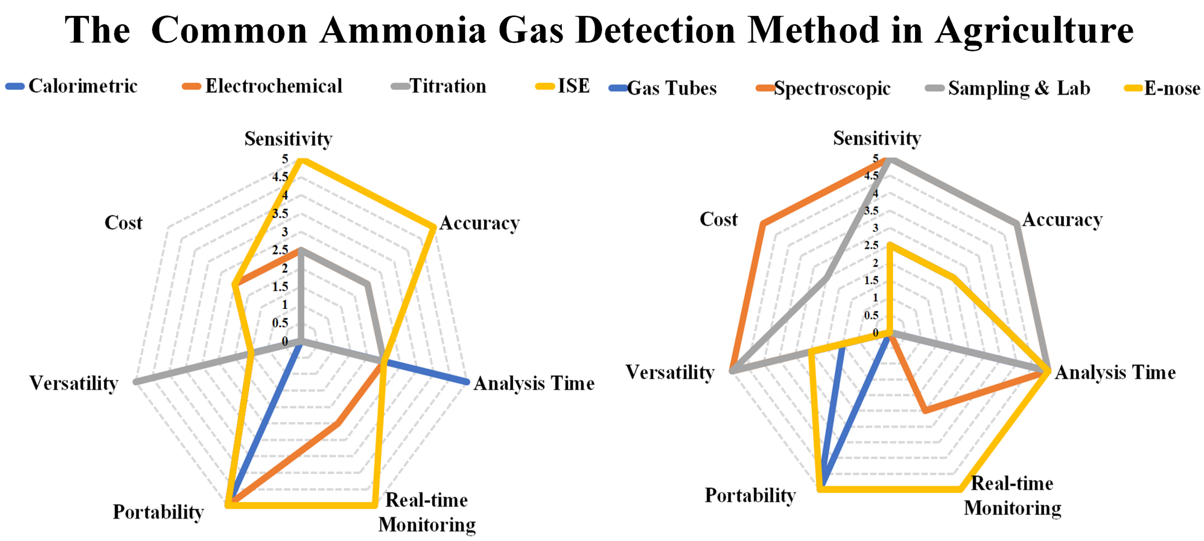

Figure 7. The trend of E-nose VS ammonia detection.

Figure 7 shows, the sensitivity of various analytical methods plays a crucial role in determining their effectiveness in detecting and measuring substances of interest. Calorimetric methods exhibit a moderate to high sensitivity, which depends on the specific method and equipment employed. The gas-sensitive tubes method displays moderate sensitivity, subject to variation based on the type of tube and gas being detected. The Ion Selective Electrodes (ISE) method shows high sensitivity for specific ions, although this can vary depending on the electrode and analyte involved. Electrochemical methods offer a sensitivity ranging from moderate to high, depending on the electrode and technique utilized. Titration methods generally possess moderate sensitivity, with variations based on the specific method and indicator employed. Spectroscopic methods, particularly UV-Vis, fluorescence, or atomic absorption spectroscopy, exhibit high sensitivity. Sensitivity in sampling and laboratory analysis relies on the specific analytical methods utilized. E-nose demonstrates moderate to high sensitivity, contingent upon the sensors and algorithms employed.

The accuracy of different methods used in scientific measurements varies depending on specific factors and conditions. Calorimetric methods generally exhibit a high level of accuracy, although this accuracy can fluctuate depending on the chosen method and experimental conditions. Electrochemical methods are generally accurate, but their precision relies heavily on proper calibration and the specific experimental conditions in place. Titration methods can achieve accurate results when executed and calibrated correctly. The Ion Selective Electrodes (ISE) method provides accurate measurements for targeted ions, provided proper calibration is carried out. The gas-sensitive tubes method accuracy is influenced by environmental factors and limited to specific ranges and conditions. Spectroscopic methods yield accurate results when appropriately calibrated and operated. The accuracy of sampling and laboratory analysis techniques varies depending on the utilized equipment and techniques. Lastly, the accuracy of the E-nose technique is subject to variation and can be affected by environmental factors and the limitations of the sensors employed.

The analysis time varies across different methods used in scientific research and analysis. Electronic noses (E-nose) and Ion Selective Electrodes (ISE) exhibit relatively fast analysis times, typically within minutes. The gas-sensitive tubes method also provides generally quick analysis times, often within minutes. However, in Spectroscopic Methods, the analysis times can vary greatly, ranging from seconds to minutes, depending on the complexity and technique employed. Sampling and laboratory analysis involves analysis times that can span from minutes to hours, depending on the intricacy of the sample and the required analyses. For Calorimetric Methods, particularly simple tests, the analysis time is relatively fast. On the other hand, analysis times for Titration Methods can vary from a few minutes to several hours, depending on the specific method employed. Understanding the analysis times associated with these different methods is crucial for researchers and scientists to plan their experiments and allocate resources accordingly.

Real-time monitoring techniques vary in their applicability across different analytical methods. Titration methods typically do not employ real-time monitoring, while Ion Selective Electrodes (ISE) method often utilizes it to monitor specific ion concentrations. Gas-sensitive tubes method commonly employs real-time monitoring to track gas concentrations. Spectroscopic methods can be used for real-time or near real-time monitoring, depending on the equipment and method employed. Real-time monitoring is not typically used in Calorimetric Methods [28]. Electrochemical methods, however, generally offer quick results, especially when well-optimized, making real-time monitoring a common practice due to their fast response times. In the context of sampling and laboratory analysis [69], real-time monitoring is not commonly employed as it typically involves sample collection and subsequent analysis. Finally, real-time monitoring finds extensive usage in E-nose for the real-time assessment of odor or volatile compound profiles. The choice of employing real-time monitoring depends on the specific method and the desired monitoring objectives.

The portability of various analytical methods depends on the specific techniques and equipment employed. Calorimetric methods may offer portability, contingent upon the equipment utilized. Electrochemical methods, especially those utilizing handheld devices, exhibit potential for portability. Conversely, titration methods are generally not portable due to the requirement of a controlled laboratory environment. Ion selective electrodes (ISE) methods [42] can be made portable, particularly with handheld ISE devices. The gas-sensitive tubes method can also be conveniently portable, especially with the use of handheld devices. The portability of spectroscopic methods varies depending on the technique and equipment utilized. Sampling and laboratory analysis are not portable as they require specialized equipment and controlled laboratory conditions. On the other hand, in the realm of E-nose, portability can be achieved, particularly with handheld E-nose devices.

The parameter of versatility serves as a critical factor in evaluating the effectiveness of different methods in various scientific analyses. Calorimetric methods, while valuable in specific types of reactions, exhibit limited versatility. On the other hand, electrochemical methods offer a high degree of versatility, accommodating a wide range of analytes and applications. Titration methods also display significant versatility, making them suitable for diverse applications and a broad spectrum of analytes. However, the ion-selective electrodes (ISE) method falls short in terms of versatility, as it is restricted to specific ions and applications compared to other methods. Similarly, the gas-sensitive tubes method is limited to particular gases and applications. Spectroscopic methods, in contrast, provide extensive versatility, allowing for analysis across a wide range of analytes and applications. The field of sampling and laboratory analysis demonstrates remarkable versatility, covering a diverse array of samples and analytes. Lastly, the E-nose technique proves highly versatile in detecting and distinguishing various odors and volatile compounds. Overall, versatility plays a crucial role in determining the suitability and applicability of different methods in scientific analyses. The cost considerations for various analytical methods differ significantly. The Calorimetric Methods are generally considered cost-effective, offering an economical approach. The Electrochemical Methods are particularly cost-effective, especially for basic electrochemical techniques. Titration Methods are relatively cost-effective due to the affordability of equipment and reagents. However, the Ion Selective Electrodes (ISE) method is moderately expensive due to the specialized electrodes and equipment required. The Gas-sensitive tubes method is relatively cost-effective, as gas-sensitive tubes are often affordable. The cost of Spectroscopic Methods varies greatly depending on the specific technique and equipment used, with some advanced instruments being quite expensive. Sampling and laboratory analysis costs can vary based on complexity and the number of required analyses, with specialized tests tending to be more expensive. Lastly, the cost of E-nose devices can be relatively high, depending on complexity and quality. It is important for researchers and analysts to consider the cost implications when choosing the most suitable analytical method for their specific needs.

In contrast, traditional methods tend to be time-consuming, necessitate specialized equipment and personnel, and suffer from limited portability. In scenarios where adherence to regulations or standardized procedures is indispensable, traditional methods may be the preferred choice.

4. Conclusions

Ammonia detection is vital for successful crop cultivation, as it allows growers to predict potential soil fertility problems before planting. Nitrogen-rich ammonia is a key component of plant nutrition, but an excess of it can harm both plants and animals by increasing the level of acidity in the environment. Ammonia can exist in low concentrations that are undetectable to the human nose, but it can also exist in larger concentrations with a noticeable odor. This can result in health problems for humans, including respiratory illness and even death if left unchecked for extended periods. It can also cause a damage to the agriculture sector if not detected in time. In order to detect the ammonia some traditional and E-nose methods are used. Traditional methods and E-nose have their respective strengths and weaknesses for ammonia detection in agriculture. Traditional methods are simple, affordable, and widely used, but may have limitations in terms of manual sampling, measurement errors, and delays in obtaining results. E-nose offers potential advantages in terms of real-time, non-invasive, and automated monitoring, but may require calibration, data analysis, and higher costs. Both traditional methods and E-nose can be valuable tools for ammonia detection in agriculture, and the choice of method may depend on the specific needs, resources, and objectives of the agricultural system under consideration.

Recent studies show that E-nose technology is a promising tool for detecting ammonia in agricultural settings, with the potential for monitoring air quality, reducing harmful emissions, and improving animal health. The Electronic nose is a tool used for odor detection and identification. It functions by measuring an odor's chemical composition using a range of sensors, which can then be compared to known odor patterns to identify it. The E-nose ability to detect ammonia in various conditions is one of its applications, which can be beneficial for analyzing potential health hazards caused by exposure to high levels of this gas or for monitoring air quality in industrial environments where ammonia may be present. In terms of cost, the E-nose ammonia detection method in agriculture can vary greatly depending on the sensor type, system size, and complexity. Generally, more complex systems are more expensive, while simpler systems tend to be less so. For instance, a metal oxide semiconductor (MOS) sensor is usually less expensive than other used sensor. The speed of E-nose ammonia detection methods in agriculture also varies based on the sensor type and sample size, with some methods providing results in as little as 10 s and others taking several minutes. The accuracy of E-nose ammonia detection methods in agriculture can also vary based on the sensor type and sample size, with some sensors being known for their high accuracy while others may not be as precise. Various types of sensors are used in the E-nose system to measure volatile organic compounds (VOCs) related to ammonia presence. The utilization of E-nose technology in ammonia gas detection for agricultural purposes endows it with remarkable value. It serves as an invaluable tool for enhancing monitoring efficiency, facilitating timely interventions, and fostering sustainable farming practices. This is achieved through the incorporation of a versatile Multi-sensor Array, enabling simultaneous and comprehensive gas detection capabilities. The E-nose system further facilitates Real-time Monitoring, enabling farmers to obtain instantaneous and up-to-date information regarding ammonia levels. Moreover, the implementation of Non-destructive Sampling methods eliminates the need for cumbersome and time-consuming physical sample collection, thus streamlining the monitoring process. The inherent rapid response and portability of E-nose technology equip agricultural practitioners with the ability to promptly address fluctuations in ammonia concentrations, irrespective of the farming context. Additionally, E-nose systems harness sophisticated data analysis techniques to extract valuable insights from the acquired sensor data, employing advanced algorithms to detect and identify specific gas signatures accurately. These systems also exhibit commendable capabilities in terms of Remote Monitoring and Connectivity, enabling farmers to remotely access real-time data and receive timely notifications and alerts through interconnected devices. By consistently monitoring and evaluating ammonia levels, E-nose systems play a pivotal role in comprehensively assessing and managing the environmental impact of agricultural activities. They prove instrumental in optimizing fertilization practices, effectively managing livestock waste, and curtailing emissions to minimize detrimental ecological consequences.

To summrize:

- Ammonia detection is crucial for successful crop cultivation to predict soil fertility issues, as excess ammonia harms plants, animals, and the environment due to increased acidity levels.
- Traditional methods for ammonia detection are simple, affordable, but have limitations such as manual sampling, measurement errors, and delays in obtaining results.
- E-nose technologies offer real-time, non-invasive, and automated monitoring advantages, but may require calibration, data analysis, and higher costs.
- E-nose technology shows promise in agriculture for ammonia detection, improving air quality, reducing emissions, and enhancing animal health.
- The cost of E-nose ammonia detection varies based on sensor type and system complexity, with simpler systems being less expensive.
- E-nose ammonia detection methods vary in speed, with some providing results in seconds, while others take minutes.
- Accuracy of E-nose ammonia detection methods varies based on the sensor type, with some sensors known for high accuracy.
- The utilization of E-nose technology in agriculture enhances monitoring efficiency, enables real-time monitoring, and facilitates non-destructive sampling.

The future challenges and prospects are listed as below: Traditional ammonia detection methodologies exhibit promising future prospects, encompassing the refinement of sensing technologies, the advancement of miniaturization techniques, and seamless integration with the Internet of Things (IoT). Concurrently, these prospects are juxtaposed with challenges pertaining to mitigating interference effects, ensuring precise calibration procedures, and safeguarding occupational well-being. In the realm of E-nose technologies, notable strides are anticipated in sensor development, notably with respect to the creation of sophisticated sensor arrays. Further advances are envisaged in machine learning integration, wherein the utilization of sophisticated algorithms for pattern recognition will fortify the analytical capabilities of E-nose systems. Additionally, standardization efforts will enhance the coherence and comparability of results obtained from diverse E-nose devices. However, challenges arise in areas such as optimizing sensor selectivity, bolstering sensor stability, and adapting E-nose technologies to dynamic real-world settings.

As the utilization of deep learning methods for ammonia detection in farmland remains relatively uncommon, this area represents a promising avenue for future research. Incorporating deep learning techniques into the E-nose system can enhance its capabilities in accurately identifying and quantifying ammonia gas concentrations. Deep learning algorithms, such as convolutional neural networks (CNNs) or recurrent neural networks (RNNs), can be trained on large datasets of sensor responses to ammonia and other relevant environmental factors. This approach has the potential to improve the sensitivity, specificity, and overall performance of the E-nose system for ammonia detection. Field validation studies focusing on the application of deep learning models in real-world agricultural settings would be essential to assess their effectiveness and practicality. By conducting field trials and comparing the results with traditional methods, the viability of deep learning-based E-nose systems for ammonia detection can be evaluated, providing valuable insights for their potential integration into agricultural practices.

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