

Are Ammonia Sensors Ready for Outdoor Use?

Pablo Espina-Martin,* Sarah R. Leeson, Robert Nicoll, Clare Pearson, Cristina Martin Hernandez, Nathalie Redon, Neil J. Mullinger, Karen Yeung, Marsailidh M. Twigg, Ajinkya G. Deshpande, Matthew R. Jones, Hilary Costello, Graham Spelman, and Christine F. Braban

Cite This: *ACS Omega* 2026, 11, 917–929

Read Online

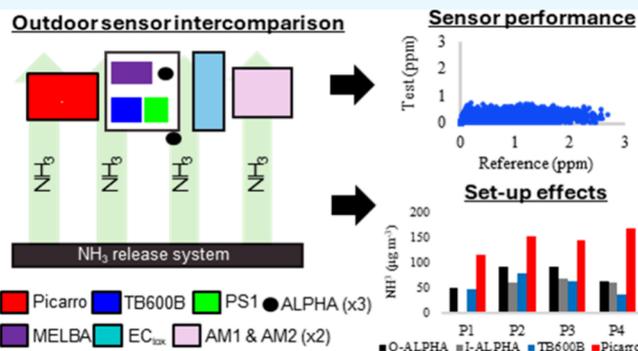
ACCESS |

Metrics & More

Article Recommendations

Supporting Information

ABSTRACT: Ammonia (NH₃) gas is primarily an agriculture atmospheric pollutant, and measuring near-emission sources is essential for understanding NH₃ emission plumes. Sensors in theory are attractive alternative monitoring methods due to their high-time data resolution, size, and lower costs; however, there are metrological and technical challenges. NH₃ sensors operating in the subppm range (typical of near-emission source concentrations) are relatively new to the market, and while promising, there are metrological and technical challenges, especially in outdoor environments. Six NH₃ sensors were evaluated under field conditions at a poultry house emission simulation site, Whim Bog, Scotland (3.4 g of NH₃ min⁻¹). Five electrochemical (TB600B, PS1, EC_{tox}, duplicated AM1 low concentration (LC), and AM2 high concentration (HC)) and one chemiresistive-polymer (MELBA) sensors were tested and compared to a cavity ring-down instrument (Picarro G2103 NH₃ analyzer) as a reference method. Only the TB600B ($R^2 = 0.59–0.84$), AM1 LC ($R^2 = 0.7–0.9$), and AM2 HC ($R^2 = 0.71–0.9$) demonstrated a positive correlation to the reference analyzer, being potentially capable of delivering indicative NH₃ concentrations, with the caveat that the AM sensors had very low data capture and their performance may improve once the sensors operate for longer. All sensors tested have major technical challenges including accuracy, precision, response time, manufacturer deployment guidelines, sensor lifecycle metrics, software engineering, and data traceability. This study highlights the need for improvement in the NH₃ sensor industry and among suppliers, and concludes that outdoor ammonia sensor measurements are not yet ready for routine use.



1. INTRODUCTION

Ammonia (NH₃) is the major alkaline gas in the atmosphere.¹ Although there are natural emissions, agriculture and particularly animal husbandry and fertilizer management emissions account for ~90% of the total global emissions.^{2,3} Other emissions include traffic, refrigerants, and industry.^{4–6} Ammonia has also increasingly been used as an energy carrier and shipping fuel; therefore, new emission sources are likely to gain importance in the future.^{7,8} Policy makers have identified NH₃ as a priority pollutant to mitigate⁹ due to the impacts to human health as one of the main drivers for PM_{2.5} formation,^{10,11} associated with several adverse health conditions.^{12,13}

Accurate and precise measurements of NH₃ are essential for both low-concentration environments^{14,15} (e.g., ecosystem protection; critical levels over sensitive ecosystems are set to 1–3 μg m⁻³) and near-source high-concentration environments^{16,17} (e.g., quantification of emission sources), as NH₃ excessive deposition provokes acidification and eutrophication, leading to biodiversity losses.^{14,18} Measuring NH₃ is challenging due to its physicochemical properties: semivolatile, highly reactive, and hydrophilic. Surface ambient atmospheric

concentrations have high spatial and temporal variability as NH₃ deposits readily to the surface, interacts with gasses to be taken up onto aerosol and water droplets,^{19,20} and has the potential to be re-emitted²¹ through volatilization processes.

Ammonia measurements are mostly done using diffusive sampling methods with offline chemical analysis.^{20,22,23} These methods have available published standards for diffusive sampling of ammonia in ambient air. Diffusive samplers are low-cost and typically used to provide exposure data ranging from one week or less to a full month²⁴, reporting average concentrations over the integrated exposure period.^{22,25} There are a substantial number of automatic analyzers on the market, which generally require significant investment and expert users

Received: August 6, 2025
Revised: December 14, 2025
Accepted: December 18, 2025
Published: December 29, 2025



to ensure quantitative accurate measurements.^{19,26–28} There is no reference method for the automatic NH₃ measurement.²⁶

Theoretically, sensors combine the affordability and spatial flexibility of passive samplers with the high temporal resolution of automatic analyzers. Most NH₃ sensors on the market are electrochemical (EC), where an electrolyte within the sensor reacts with the target gas producing an electrical signal proportional to the target gas concentration.^{28,29} Technical specifications of these sensors indicate that they are able to have good performance below 1 ppm of NH₃; however, there is extremely limited evidence of the performance of these sensors in outdoor environmental conditions. EC sensor performance can be highly variable, with known challenges regarding accuracy and interferences from temperature and relative humidity (RH).^{30–34} These sensitivities make it challenging to monitor NH₃ concentrations using EC sensors, both indoors and outdoors. Particularly critical are the potential cross-interferences of water molecules when quantifying NH₃, as H₂O molecules interact with the sensing surface.³⁵

This paper represents, to the best of the author's knowledge, the first outdoor ambient NH₃ sensor intercomparison at a controlled NH₃ release facility. We evaluated the performance of five commercially available NH₃ sensors and an experimental chemiresistive sensor compared to an established high-time resolution NH₃ analyzer under ambient conditions and both ambient level and high-concentration levels that are commonly observed near point sources. In addition to the analytical assessment challenges, the NH₃ sensor market is difficult to navigate for nontechnical users and this study reports routes to manage these challenges associated with NH₃ sensor calibration, setup, and deployment, reporting outcomes and recommendations for both sensor manufacturers and sensor users.

2. MATERIALS AND METHODS

2.1. Sensor Selection. This study undertook market research on the commercially available NH₃ sensors in the autumn of 2023 to select the most suitable options for outdoor monitoring. Based on technical and operational criteria (Table 1), five out of 15 (Table S1) commercially available EC NH₃ sensors were selected: TB600B-NH₃-10 (ECsense, Germany), EC_{tox}-50-NH₃ (ECsense, Germany), PS1-10-NH₃ (SGX Sensortech, Switzerland), and the AM1 low-concentration

Table 1. Market Research Criteria Used to Select the NH₃ Sensor Participating in the Whim Bog Campaign

criteria type	description of the specifications desired for the NH ₃ sensor
operational	the sensor needs to be <2 kg
	the sensor is installed in a device or control board that eases the user experience
	the sensor output is a digital signal
	the sensor needs to work under UK normal weather conditions (−10 to 30° and 50–100% RH)
technical	the sensor needs to have specificity toward NH ₃ in the range 0–20 ppm
	the LOD must be ≤1 ppm of NH ₃
	the resolution of the sensor must be ≤0.1 ppm
	the accuracy must be ≥5%
	the sensors lifetime is at least 12 months
	information present on cross-interferences occurring with other gaseous species
	the sensor adds other useful measurements such as T, RH, or other gaseous species

(LC) and AM2 high-concentration (HC) sensors (Scentroid, Canada), designed to measure low and high NH₃ concentration ranges, respectively. The MELBA sensor (IMT Nord Europe, France), based on chemiresistive detection,³⁶ was added to the tested sensors as it complied with most of Table 1 requirements.

2.2. Field Site Description. Whim Bog is an ombrotrophic blanket bog located 11 km south of Edinburgh (NT 204532) 3°16' W and 55° 46' N. Whim Bog has been operated as an experimental nitrogen enhancement site since 2002, where ecosystem and species responses to N pollution (wet and dry deposited) are investigated. The site includes a dry NH₃ gas enhancement transect^{37–40} with an ammonia plume dispersing over a distance of ~100 m.

The NH₃ enhancement field release system has previously been described.^{37,38} Ammonia is released when the wind blows at >2.5 m s^{−1} from the sector 180–215° for more than one minute. The release rate is set at 3.4 g NH₃ min^{−1} from a 29 kg anhydrous NH₃ cylinder with the flow rate fixed at 4.6 L min^{−1} determined by an Aera -FC7710C flow controller (maximum flow 10 L min^{−1} at STP). The gaseous NH₃ passes along a 6 mm stainless steel tube before being injected into the airflow generated from a Wolter GMBH EK31 fan delivering ~10 m³ min^{−1}. The diluted NH₃ concentration is distributed from a 10 m line source (254 mm diameter pipe, with 4 mm holes perforated around and along the length of the pipe at 25 cm intervals), mounted 0.5 m above the vegetation. Annual average ammonia concentrations range from ~70–100 μg m^{−3} (< 12 m) to ~1–3 μg m^{−3} (ambient concentrations) (80–100 m) (Figure S1), with short-term peaks reaching very high concentrations up to >1000 μg m^{−3}.

2.3. Reference Analyzer and Sensor Setup. The Picarro G2013 NH₃ analyzer and sensors were installed 8 m away from the NH₃ release system at Whim Bog (Figure 1a,b), in close

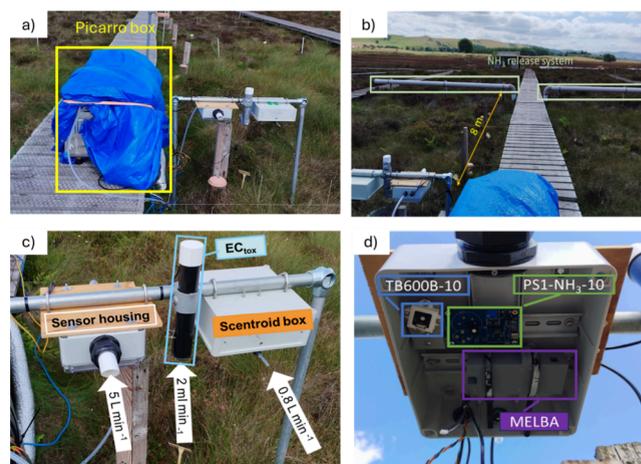


Figure 1. (a) Picarro box (left) and tested sensors (right). (b) Position of the NH₃ release system from the sensor ensemble. (c) Disposition of the sensors in the sensor rack. (d) Sensors inside the sensor housing.

proximity to the release point to ensure high concentrations (Figure S1). The experiment was carried out from 24/07/2024 to 28/08/2024. Both the Picarro analyzer and the sensors were placed 0.5 m above the boardwalk.

The Picarro analyzer was placed inside a weatherproof air-conditioned box with temperature control. The sensor housing (SH) was installed next to the Picarro box (Figure 1c). The

Table 2. NH₃ Sensor Details (Based on the Manufacturers' Technical Datasheets)^a

sensor	detection	range (ppm)	LOD (ppm)	sensitivity (ppm)	time resolution (s)	response time (s)	airflow (l min ⁻¹)	other variables measured	price range (€)
TB600B-NH ₃ -10	EC	0–10	0.01	0.01	60	3	n.a	T, RH	<150
PS1–10-NH ₃	EC	0–10	1	0.01	60	n.p	n.a	T, RH	<150
EC _{tox} -50	EC	0–50	0.1	0.01	120 ¹	60–600 ¹	0.0002	T, RH,	650
AM1 LC	EC	0–10	0.03	0.001	60	40	0.8	T, RH, pressure, CO ₂ ;	20,000 ²
AM2 HC	EC	0–100	3	1	60	50	0.2	PM _x	
MELBA	chemiresistive	0–1	0.01	0.01	60	n.a	0.2	T, RH, fan speed	n.a.

^an.a: not applicable; n.p: not present; 1: depends on concentration; and 2: price refers to the DR2000R unit.

SH was built for this experiment and consisted of a polycarbonate weatherproof box (24.5 cm × 20.5 cm × 9.5 cm) coated with PTFE to minimize surface absorption of water and NH₃. The SH contained the PS1, TB600B, and MELBA sensors (Figure 1d). An external pump drew air at 5.5 L min⁻¹ through a 30 cm PVC inlet allowing for the collocation of air sampling (residence time ~ 52 s). From 19/8/24, 10 L min⁻¹ flow was used to assess the influence of higher airflow (residence time ~ 29 s). The EC_{tox} and Scentroid DR2000 units were placed next to the SH, sampling ambient air directly. The EC_{tox} was installed so its inlet probe initially oriented parallel to the ground; however, on 19/08/2024, it was rotated 45° toward the release system to enhance the exposure to the air stream released from the high NH₃ emission system. The DR2000 unit was placed under a weatherproof box with a PFA inlet <10 cm and a 0.8 L min⁻¹ flow (residence time ~ 0.2 s).

2.4. Instrumentation. **2.4.1. NH₃ Sensors.** The technical specifications of the TB600B-NH₃-10, EC_{tox}-50-NH₃, PS1–10-NH₃, the AM1 LC and AM2 HC sensors, and the MELBA are summarized in Table 2. The AM1 LC and AM2 HC sensors were installed in duplicate in the Scentroid air quality monitoring product (DR2000). This unit also included particulate matter (PM) and carbon dioxide (CO₂) sensors. All of the sensors have NH₃ concentration ranges targeting between 0 and 10 ppm, with LODs between 0.01 and 3 ppm, and are designed to operate under “ambient conditions”, with most of them having optimal operational conditions of 20 °C and 50% RH.

The PS1 and TB600B are 3-way electrode EC sensors attached to electronic boards that enable USB connectivity with a laptop running the supplier software for data recording and extraction (Figure S2). An external pump is required to pass air over the sensitive surface. The TB600B is a “ready to be used as soon as it is connected” sensor. The PS1 is sold as such, but it requires a two-point calibration before use (zero and span) to be carried out by the user. This was done in a laboratory chamber (0.28 l, polycarbonate) with N₂ (99.998% purity, BOC) for the zero calibration and 100 ppm of NH₃ (N₂ 99.99%, NH₃ 0.01%; BOC) diluted with N₂ for span calibration to achieve 1 ppm NH₃ (Figures S2 and S3). The supplier does calibrate the sensor in humid conditions; however, this was not possible to achieve due to laboratory setup limitations. The PS1 and TB600B sensors have an adjustable reporting time from one s up to one minute. The sampling period for the campaign was set to 1 min.

The EC_{tox} sensor consists of a 16 cm stainless steel probe with one end covered by a PTFE membrane that protects the sensing chamber. It samples air at 2 mL min⁻¹ and analyzes for one minute. The EC_{tox} sensor used the calibration version of TB600B software to adjust the sampling time and record data.

The AM1 and AM2 sensors come as a part of the Scentroid DR2000R air lab product, a “black box” device equipped with T, RH, and seven atmospheric pollutant sensors designed to be installed into unmanned aerial vehicles for urban air quality surveys. It samples air at 0.8 L min⁻¹ from the inlet located in front of the unit. Data collected by the DR2000R box are transmitted to a tablet-based ground station through wireless connection using a long-range protocol in real-time. The ground station is equipped with visualization and processing software to visualize and export the data; however, if the DR2000R connection is lost, data recording stops and needs to be restarted manually. The system battery and the ground station have a 2-h battery life, requiring a continuous power supply to enable extended monitoring.

2.4.2. Picarro G2013 Analyzer. The Picarro G2013 NH₃ Cavity ring-down spectroscopy (CRDS) analyzer uses infrared absorption.¹⁹ A 20 cm PFA inlet with a PTFE guard filter (0.001 μm porosity) sampled air at 1.5 L min⁻¹ (residence time ~ 0.22 s). The instrument's NH₃ response (linearity and intercept) was checked in the laboratory before and after deployment (Table S2). A 100 ppm of the NH₃ cylinder (N₂ 99.99%, NH₃ 0.01%; BOC) was diluted with N₂ (99.998% purity, BOC) through mass flow controllers (MFCs) (Bronkhorst Ltd., Netherlands) (Figure S3). The Picarro prior to and after deployment demonstrated excellent linearity (R² = 0.999) across the whole concentration range (Figure S4). The slopes of the theoretical to measured concentrations were 0.90 (pre deployment) and 0.87 (post deployment). Prior to the deployment on Whim Bog, new guard PTFE filters (0.015 μm pore size, Entegris) were placed to protect the Picarro's analytical cavity. They were kept through the precampaign (no use) to the postcampaign (three months of use) linear check to assess if the exposure to high concentrations of NH₃ during the intercomparison impacted the Picarro's response. Picarro NH₃ concentrations were not corrected to theoretical values due to potential losses of NH₃ within the setup used to check the linearity of the instrument. For the purposes of testing the sensors, the Picarro was used as the “reference” with the assumption of a minimum of ± 15% uncertainty; however, previous tests¹⁹ show that the uncertainty lies within 5–7%. More information can be found in S4. The Picarro data's QA/QC involved checking the daily data streams and removing any data that would be out of the normal operational ranges of the temperature and pressure within the internal cavity.

2.4.3. ALPHA Samplers. Adapted Low-cost Passive High Absorption diffusive samplers (UKCEH ALPHA)^{22,23} were deployed in triplicates on a weekly basis from 29/07/2024 until 28/08/2024 outside and inside the SH to estimate the average NH₃ concentrations at each compartment and assess the potential gradient of NH₃ concentrations. Table 3 shows

the exposure periods and the amount of NH_3 released at each one.

Table 3. Exposure Periods for the ALPHA Samplers during the Whim Bog Campaign^a

period	ALPHA exposed	ALPHA removed	NH_3 released (kg)
period 1	29/07/2024 16:27	05/08/2024 12:21	6.20
period 2	05/08/2024 12:35	12/08/2024 13:45	6.63
period 3	12/08/2024 13:45	19/08/2024 12:18	6.71
period 4	19/08/2024 12:32	24/08/2024 13:26	5.34

^aTime is expressed as a local time.

2.4.4. Data Analysis of Sensor Data against the Reference Instrument. The performance of the sensors during the campaign was assessed by checking the linear regression statistics of the 1, 15, and 60 min averaged data sets against the Picarro. As an additional evaluation, a set of statistical metrics⁴¹ were used to evaluate how well the sensors aligned with the reference. This approach is widely used to assess the performance and accuracy of dispersion pollutant models against real observations.^{42,43} This study used this methodology to evaluate the Whim Bog sensors (considered the tested models) against the Picarro analyzer (used as the reference) and assess their performance in both ambient and high concentration environments. The metrics used are fractional bias (FB), geometric mean bias (MG), normalized mean square error (NMSE), geometric variance (VG), correlation coefficient (R), and fraction of predictions within a factor of 2 of observations (FAC2). Details on the equations can be found in the study by Chang and Hanna.⁴⁴ For a perfect agreement between the test and reference data sets, the ideal values are 1.0 for FAC2, MG, and VG and 0.0 for NMSE and FB. FB and MG measure mean relative bias, capturing only systematic errors, whereas NMSE and VG assess mean relative scatter, reflecting both systematic and random errors.

3. RESULTS

3.1. Overview of the Campaign. Figure 2 presents the meteorological conditions during the campaign. The temperatures ranged from 13.6 ± 3 °C and humidity ranged from $81.2 \pm 12.8\%$. While these conditions are within the typical range for Scotland, they are significantly different from the test conditions reported by the manufacturers (≈ 20 °C, 50% RH). The mean wind speed was 4.3 ± 2.2 m s⁻¹, with wind direction predominantly from the SW–SE, with occasional N–NE. The NH_3 release system was on $\sim 18\%$ of the time during the campaign. This resulted in both high and low NH_3 concentrations. Sporadic rainfall events occurred throughout the campaign, particularly during the periods 4–10th August and 12–7th August.

Figure 3 shows the reported NH_3 concentration time series alongside the release system activation. Data capture (DC) was variable, with the Picarro analyzer (99.7%), PS1 (88.2%), TB600B and EC_{tox} (68.4%), and AM1 LC and AM2 HC sensors (5.6% each). Two periods of system downtime (first period: 02/08/2024 05:13–02/08/2024 15:44; second period: 11/08/2024 23:08–12/08/2024 00:07) were excluded from the statistical analysis. The data losses from the TB600B and EC_{tox} were caused by software crashes and malfunctions. The low DC from the AM sensors was due to the DR2000R unit software shutting down the data recording after 6 h of operation, requiring a manual restart after the shutdown of both the data recording software and the DR2000R unit; this prevented using an automatic restart system, leading to unavoidable data losses. The MELBA sensor worked only for a couple of hours of exposure and then saturated after 12 h of exposure. The MELBA was therefore excluded from further inclusion in the study. The data obtained is shown in S4 of the Supporting Materials.

The reported NH_3 concentrations by the Picarro ranged between 0.001 and 3.5 ppm of NH_3 , covering ambient background through to near-source concentrations. The Picarro responded rapidly (<1 min) to concentration changes between the release and nonrelease periods (Figure 3). The

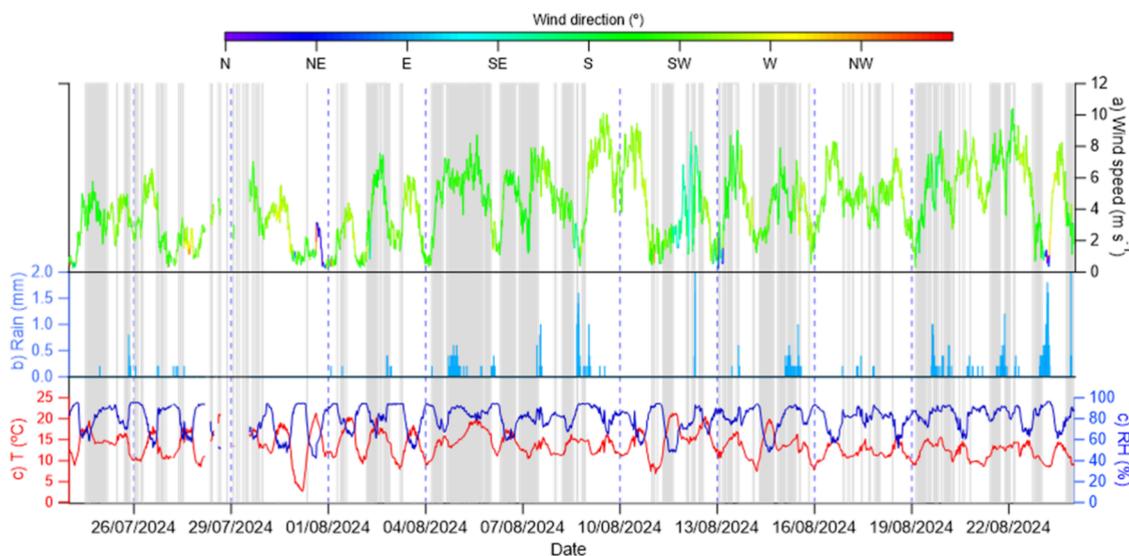


Figure 2. Time series of meteorological conditions during the campaign (top) including (a) wind speed and direction, (b) precipitation, and (c) air temperature and RH at the field Whim Bog for the period 24/07/2024 to 28/08/2024. Gray bars in the top panel are when the NH_3 release system was activated, releasing NH_3 at a rate of 3.4 g NH_3 min⁻¹.

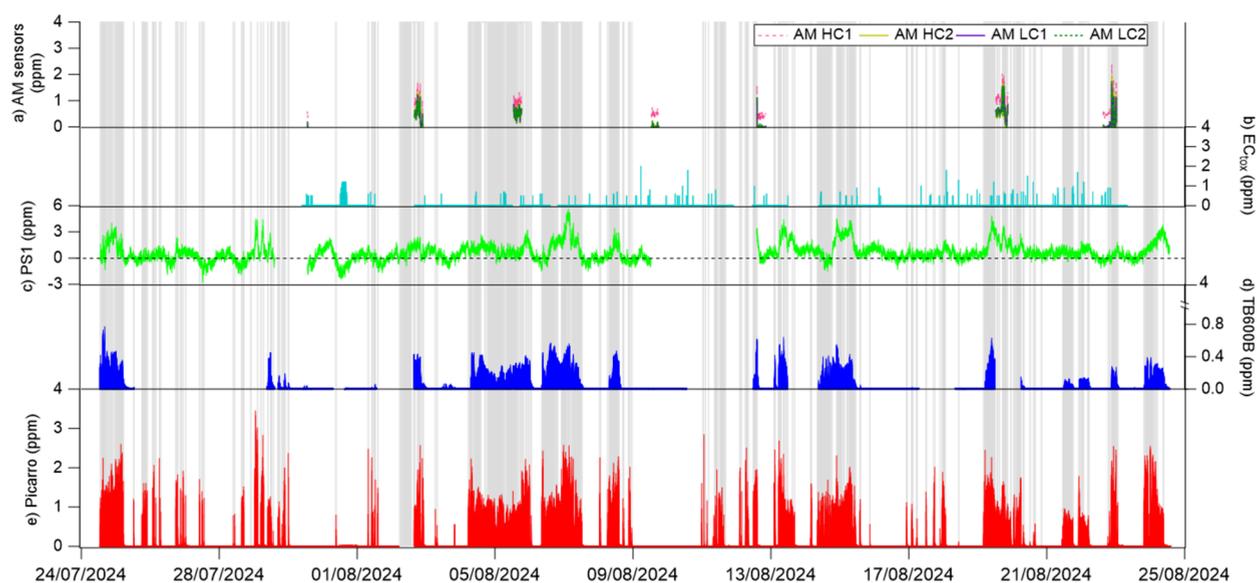


Figure 3. Time series of NH_3 concentrations reported by the CRD and sensors during the Whim Bog campaign for the period from 24/07/2024 to 28/08/2024. From top to bottom: (a) AM sensors, (b) EC_{tox} , (c) PS1, (d) TB600B, and (e) Picarro analyzer. The dashed line in the PS1 sensor corresponds to the 0-ppm value. Gray bars indicate the NH_3 release system being on.

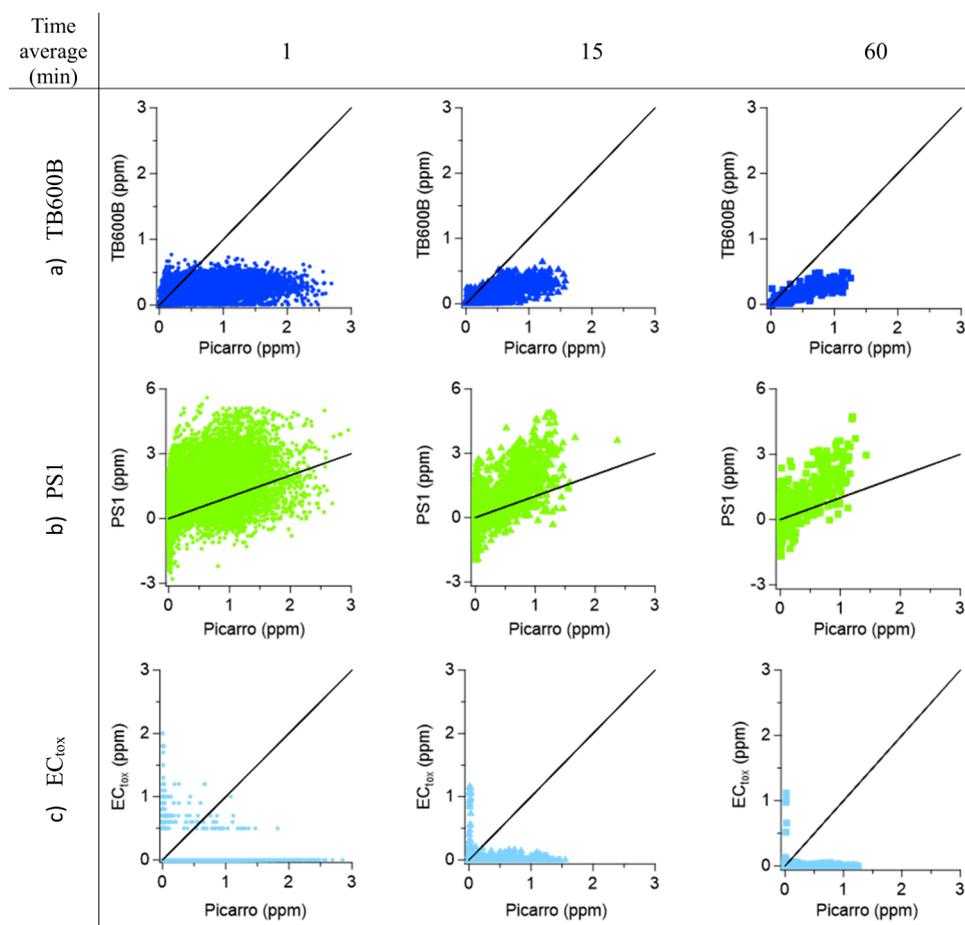


Figure 4. Linear regression plots between the Picarro analyzer's (x axis) and sensors' (y axis) NH_3 concentrations (expressed in ppm) during the Whim Bog campaign at 1-, 15-, and 60 min time resolution for the TB600B (a), PS1 (b), and EC_{tox} (c). The black lines on the graphs represent the 1:1 line.

sensor responses when the release system started were highly variable: The TB600B reported higher NH_3 concentrations when the release system was active, although the absolute

concentration remained below 1 ppm and did not always follow the same temporal patterns as the Picarro. The PS1 output was highly variable with readings between -3 and 6.5

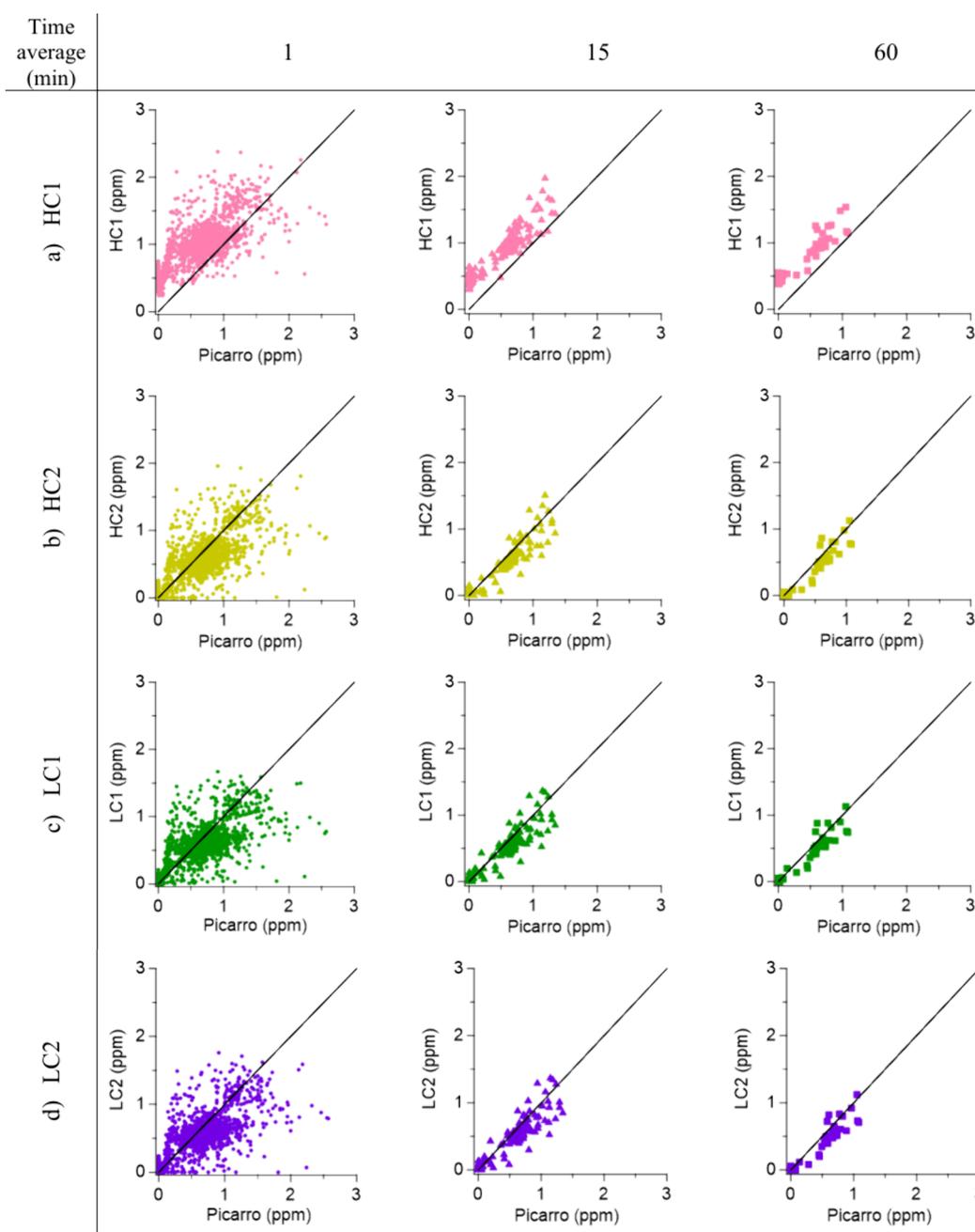


Figure 5. Linear regression plots between the Picarro analyzer's (x axis) and sensors' (y axis) NH_3 concentrations (expressed in ppm) during the Whim Bog campaign at 1-, 15-, and 60 min time resolution for the AM1 HC1 (a), AM1 HC2 (b), AM2 LC1 (c), and AM2 LC2 (d). The black lines on the graphs represent the 1:1 line.

ppm of NH_3 . The higher concentrations recorded corresponded to the NH_3 release (e.g., during the evening of 06/08/2024, when >4 ppm of NH_3 was observed), but the signal became unstable and noisy as NH_3 concentration returned to ambient values. The EC_{tox} reported 0 ppm for most of the campaign and was unresponsive to high concentrations during release periods; instead the sensor reported high concentrations randomly in the output, such as those observed on 09/08/2024. The low DC of the AM sensors made it difficult to assess their performance; however, it is noted that the data from those operational periods showed a fast response to increases in NH_3 .

3.2. Statistical Analysis between Sensors and the Reference. 3.2.1. Linear Regressions between Picarro and

Test Sensors. The performance of the sensors against the reference was assessed by plotting the data sets at 1-, 15-, and 60 min averages. The linear regression fit and correlation statistics calculated are shown in Figures 4, 5, and Table 4. The EC_{tox} did not demonstrate a relationship with the reported concentrations from the Picarro for all signal averages periods; therefore, no statistics are shown. The AM1 LC and AM2 HC sensors had the best correlation statistics with good slopes (AM1 LC1: 0.68, 0.83, 0.85; AM1 LC2: 0.68, 0.82, 0.83; AM2 HC1: 0.7, 0.84, 0.84; AM2 HC2: 0.72, 0.87, 0.87) and the best R^2 out of all sensors (AM1 LC1: 0.7, 0.89, 0.9; AM1 LC2: 0.7, 0.88, 0.9; AM2 HC1: 0.71, 0.88, 0.88; AM2 HC2: 0.72, 0.9, 0.9); however, their very low DC (5.6%) is too low for meaningful statistical validation or as a representation of the

Table 4. Correlation Parameters for the Linear Regressions between the Picarro and Tested Sensors^a

sensor	parameter	time average (min)		
		1	15	60
TB600B	slope	0.23	0.3	0.32
	offset	0.03	0.02	0.01
	R ²	0.59	0.77	0.84
	N data	30,349	2034	515
PS1	slope	1.41	1.78	1.99
	offset	0.32	0.23	0.19
	R ²	0.33	0.44	0.5
	N data	38,243	2551	641
AM1 LC1	slope	0.68	0.83	0.85
	offset	0.06	0.01	0
	R ²	0.7	0.89	0.9
	N data	2449	170	47
AM1 LC2	slope	0.68	0.82	0.83
	offset	0.06	0	0
	R ²	0.7	0.88	0.9
	N data	2449	170	47
AM2 HC1	slope	0.7	0.84	0.84
	offset	0.5	0.45	0.44
	R ²	0.71	0.88	0.88
	N data	2449	170	47
AM2 HC2	slope	0.72	0.87	0.87
	offset	0.05	−0.01	−0.01
	R ²	0.72	0.9	0.9
	N data	2449	170	47

^aSlopes between 0.8 and 1.2 and R² values above 0.8 are highlighted in bold.

sensor's capabilities. The slopes of the TB600B (0.23, 0.3, 0.32) and PS1 (1.41, 1.87, 1.99) show an underestimation and overestimation of NH₃ concentrations, respectively, although the R² coefficients are quite satisfactory for the TB600B (0.59, 0.77, 0.84).

The sensors inside the SH show distinctive behaviors. The TB600B 1 min time resolution data set has a low slope (0.23) but a moderate R² (0.59). The 1-h data set improves the regression parameters (slope = 0.32; R² = 0.84); however, the sensor consistently underestimates NH₃ concentrations by a factor of 4–5 times. The PS1 sensor exhibits high variability in its concentration range, from −3 to 2 ppm of NH₃ in ambient air up to 6.5 ppm of NH₃ when the release system was on. The EC_{tox} showed no correlation with the reference, as the higher concentration peaks occurred during periods when no NH₃ was being released (Figure 4). The AM1 LC and AM2 HC sensors were present as duplicates in the DR2000. Figure S6

shows that the correlation plots between the AM2 HC sensors are similar; however, HC1 had an offset of 0.45 ppm of NH₃ (Table S3). The AM LC sensors behave similarly both among themselves (slope = 0.99, R² = 0.97) and against the Picarro analyzer.

From this study, only the TB600B would be considered potentially suitable for ambient outdoor monitoring purposes in the “out of the box” application; however, further testing would be required to understand the baseline and range of the sensor. The AM1 LC and AM2 HC showed promising results, but more data is required to understand the true capabilities of the AM sensors.

3.2.2. Evaluation of the Sensors against the Reference.

The results of the performance evaluation of the tested sensors against Picarro are shown in Table 5. The 15 min data set was used for this comparison as a compromise between the smoothing of the sensors' data and the available number of data points used for the comparison.

All measurements are subject to uncertainties, and the performance metrics selected are inherently nonexhaustive. Hanna and Chang⁴⁵ proposed that even an acceptable model may not meet all acceptability criteria for all experiments and thus set that at least half of the performance tests should be successfully passed in order to consider a test sample comparable to the reference.

All sensors had at least two of the six metrics within the acceptable range. The lowest performing sensors were EC_{tox} and the PS1. The EC_{tox} passed the FB (−0.05) and NMSE (−25.1) metrics accounting for systematic bias and random scatter; however the EC_{tox} recorded zero concentrations for most of the campaign; when responded, it appeared to be independent of the NH₃ release system, which explains its poor statistical performance overall. The other sensor with deficient performance was the PS1, only passing the NMSE (−1.42) and R (0.66) metrics; the latter was the lowest value among all accepted sensors. The PS1 sensor had issues stabilizing at ambient concentration levels, fluctuating between −2.5 and 3 ppm of NH₃. This indicates that the sensor performance is affected by outdoor environmental conditions and probably noise is dominating the signal.

The TB600B passed the NMSE (0.61), VG (3.16), R (0.86), and FAC2 (0.53) metrics, failing the FB and MG, which mainly account for systematic bias. This is not surprising, as the FB is influenced by high outliers and the MG by near-zero concentration values. The TB600B consistently reacted to the high NH₃ emission periods, yet consistently underestimated the reference NH₃ concentrations by ~75% and was below the sensor detection limit periods when the NH₃ was not being released (from manufacturer specifications). Although the

Table 5. Performance Metrics for the 15 min Resolution Dataset between the Test Sensors and the Picarro Analyzer^a

sensor	FB (−0.3 < FB < 0.3)	MG (0.7 < MG < 1.3)	NMSE (<1.5)	VG (VG < 4)	R (%) (>0.5)	FAC2 (%) (>0.5)	# data	DC (%)
TB600B	0.95	1.81	0.61	3.16	0.86	0.53	1512	68.87
PS1	−0.99	0.14	−1.42	687.51	0.66	0.22	1517	88.18
EC _{tox}	−0.05	0.42	−25.10	428.21	−0.29	0.11	112	68.41
HC1	−0.53	0.27	−0.41	31.98	0.93	0.62	132	5.6
HC2	0.17	1.35	0.31	1.42	0.88	0.89	97	5.6
LC1	0.15	1.13	0.38	1.24	0.89	0.89	112	5.6
LC2	0.20	1.29	0.34	1.55	0.88	0.82	107	5.6

^aBelow the header of each metric is shown the acceptance range. Sensors within the acceptance threshold are highlighted in bold. A perfect model would have MG, VG, R, and FAC2 = 1.0 and FB and NMSE = 0.0.

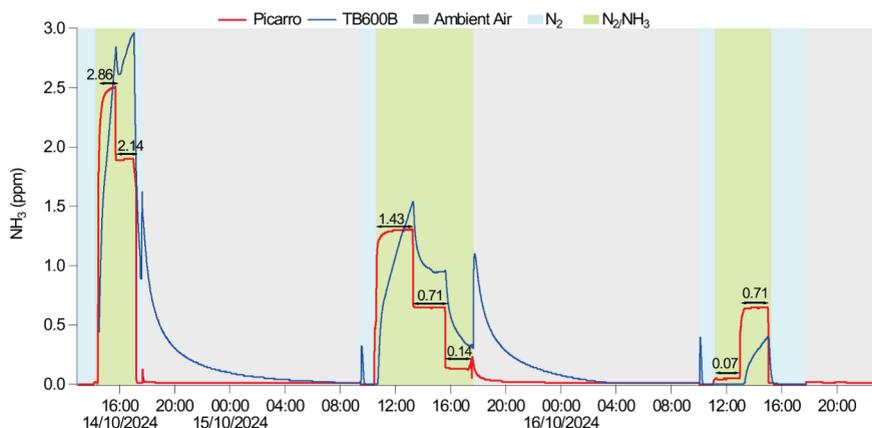


Figure 6. Time series of NH_3 concentration recorded by the Picarro and TB600B instrument during the test chamber experiment. The colored backgrounds indicate whether the sensors were exposed to ambient air (gray), pure N_2 (blue), or NH_3/N_2 mixtures (green). The arrows and concentrations above the Picarro plateau stages correspond to the theoretical NH_3 concentration values in ppm.

Picarro and TB600B have a degree of agreement, these metrics fail and are thought to be from analytical capabilities of each technique and a calibration/scaling issue with the TB600B.

The AM1 LC and AM2 HC sensors had variable performance. The LC series performed better than the HC ones, as the HC1 sensor only passed NMSE (-0.41), R (0.93), and FAC2 (0.62), while the HC2 sensor passed all metrics except MG (1.35). Even though both sensors fail the MG metric, they do fall on the opposite sides of the accepted value range; the HC1 sensor has a systematic offset of 0.44 ppm, likely causing the disagreement between the Picarro and AM sensor for FB, MG and VG, while the HC2 scores were almost within the accepted range for MG, indicating an overall better performance of the system when the offset is not present. The LC series achieved all metrics within the acceptable range, indicating the overall best performance for the available data. Although the AM LC sensors demonstrated the best performance among all of the sensors, the low DC limits the applicability of the Chang and Hanna tests.

3.2.3. Response Time Tests. NH_3 concentrations have high temporal variability in outdoor environments, making response time one of the most critical parameters to consider when selecting a sensor. Following the field intercomparison, a short laboratory test of the response of the TB600B was carried out in a test chamber previously used to calibrate the PS1 (Figure S2) to assess its performance while conducting the postcampaign linear check of the Picarro (Figure S4). The TB600B was placed <5 cm from the inlet tube with the sensitive element oriented perpendicularly to the inlet. Figure 6 shows the time series for the reported NH_3 concentrations for Picarro and TB600B.

The Picarro quickly responded to concentration changes between N_2 , the N_2/NH_3 mixture, and ambient air. This was particularly evident during the ascent periods when it plateaued after ~ 30 min. The TB600B consistently showed slower responses and did not stabilize at any concentration level. This responsiveness lag was most pronounced after NH_3 exposure, where the TB600B took ~ 11 h to decrease from the maximum concentration level to ambient air concentrations. Similar patterns were observed when testing the TB600B between 1 and 2 ppm of NH_3 ; however, it was impractical to assess whether extended sampling times would have resulted in achieving a concentration plateau. Notably, the Picarro followed stepwise decreases from theoretical 2.87 ppm of

NH_3 down to 2.14 ppm of NH_3 , whereas during this phase, the TB600B increased its concentration reading to 2.97 ppm of NH_3 . It is unclear whether this was caused by the slow response time of the sensor reacting to the previous concentration level or due to a small pressure change caused by the changes in N_2/NH_3 mixtures from the MFCs. Small concentration spikes were observed by the TB600B as the flow settings were changed, which may indicate that the sensor electronics are susceptible to sudden pressure and RH changes; however, these were not captured by the Picarro. The TB600 suppliers do not recommend using the sensor below 40% RH; therefore, these results may not be representative of normal performance. This restriction raises challenges in performance testing with traceable $\text{NH}_3/\text{H}_2\text{O}/\text{N}_2$ mixtures and further reinforces the necessity for suppliers and the metrological community to develop methodologies that allow testing these types of sensors without compromising their effective life use.

3.2.4. Sensor Housing Effects over Sensor Measurements.

To assess if NH_3 concentrations inside the SH were different from those outside the SH, ALPHA samplers were deployed both outside (O-ALPHA) and inside (I-ALPHA) during the four periods. Figure 7 shows the average ALPHA NH_3 measurements compared to the averaged Picarro and TB600B- NH_3 concentrations during the ALPHA exposure periods (Table 3).

The Picarro recorded the highest NH_3 , as it captured NH_3 spikes unresolved by ALPHA and TB600B (Table S5). The O-ALPHA measured concentrations $\approx 60\%$ lower than the

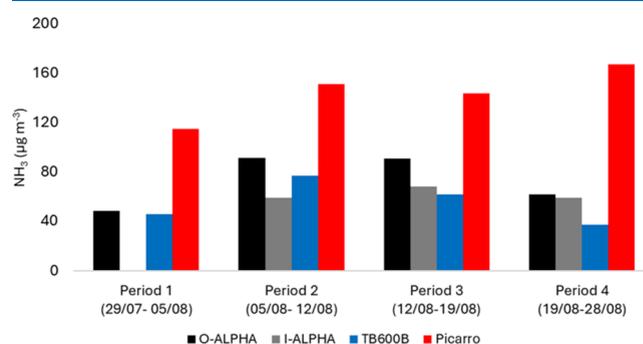


Figure 7. Average NH_3 concentrations for O-ALPHA, I-ALPHA, TB600B, and Picarro for the ALPHA exposure periods.

Picarro, except for Period 1 (40%; Table S6), likely because O-ALPHA was particularly wet during Period 1; excessive moisture in an ALPHA sampler can lead to reactive coating loss. Period 1 I-ALPHA samples were discarded as they were soaked upon retrieval.

On average, O-ALPHA measured 21% higher NH₃ concentrations than I-ALPHA except during Period 4, where differences narrowed to 4%. This change may be attributed to the increased airflow (5.5–10 L min⁻¹), enhancing diffusion within the SH and reducing the internal concentration gradient. However, this contrasts with the TB600B-Picarro comparison: during Period 4, the TB600B underestimated NH₃ concentrations by a factor of 4.45, compared to a factor of 2.3 observed during Periods 1–3. These inconsistencies are likely caused by the sampling setup and analytical differences, limiting the conclusions on the relationships between the sampling rate, NH₃ concentrations measured, and sensor sensitivity.

Overall, the results indicate that the SH impacted measured NH₃ concentrations, highlighting the need for optimized sensor setups. Further research is required to properly characterize SH effects for effective sensor deployment strategies for outdoor monitoring purposes.

4. DISCUSSION

4.1. Sensor Performance. This study has tested the performance of commercially available NH₃ sensors under outdoor conditions at concentrations near NH₃ emission sources. None of the sensors had quantitative ($\pm 15\%$) or even qualitative performance ($\pm 30\%$) compared to the reference. Sensor response times for both concentration increases and decreases were highly variable and in general significantly slower than NH₃ concentration fluctuations (Figure 6). The EC_{tox} worked for more than half of the campaign, but its response did not correlate with the NH₃ emission source. The PS1 operated continuously throughout the intercomparison, yet it did not correlate with the Picarro's NH₃ concentration. The AM1 LC and AM2 HC sensors had the best linear regressions and statistical performance metrics for the short periods they were operational, but they cannot be taken as representative of their performance due to the very low DC (5.6%).

The TB600 passed 4 out of 6 performance metrics and worked for more than half of the intercomparison, indicating a good degree of agreement with the Picarro and providing a representative assessment of its capabilities. The TB600 signal responds in proportion to the NH₃ release; however it does not measure the expected/theoretical concentrations. Field concentrations were underestimated consistently, while the laboratory testing overestimated them, hence the TB600 did not reach the qualitative or quantitative standard. The sensor has a fast and a slow response component: with a rapid response to changing NH₃ concentration but a slow response component to get a stable reading. This indicates that accurate concentration measurements with the TB600 in a fluctuating NH₃ concentration field are not possible; however, indicative relative changes of NH₃ concentrations are recorded. In theory, as long as the peak concentration is proportional to the accurate concentration and this does not change as a function of time when the sensor is operating, this characteristic could serve as a useful response function, with regular calibration. However, the TB600B outdoor applications are very limited by the systematic underestimation of near-source NH₃ concen-

trations by a factor of two to four, and improvements on the sensor technology and SH are needed in future developments to decrease this bias.

One concern when placing the sensors inside the SH is the NH₃ concentration gradient between outdoors and indoors (Section 3.2.4). The SH is necessary for outdoor operation, protecting sensors from hazards such as rain, dust, or insects. However, NH₃ adsorption onto internal SH surfaces likely reduces internal concentrations compared with outdoor levels, but this should be systematic over time. Sensor developers must take into consideration this gradient when designing the SH for the next generation of sensors. Laboratory tests⁴⁶ showed that better performing sensors feature large effective surface areas, high airflow, and a perpendicular (90°) orientation to the analyte stream. To prevent potential outdoor hazards, sensors in this study were mounted facing downward (180°) in parallel to the airstream.

Although T and RH may influence sensor performance and should be isolated in the laboratory from other variables present in outdoor environments, their influence was estimated via linear regression against the measured NH₃ concentrations when the release system was on, as ambient NH₃ levels were below the sensor's LODs. Table 6 and Table 7 show the linear regression statistics for T and RH, respectively.

Table 6. Linear Regression Parameters of T against NH₃ Concentrations (1 min) for the Different Sensors while the NH₃ Release System Was On

sensor	slope \pm error	offset \pm error	N data	R ²
Picarro	1.28 \pm 0.03	-0.03 \pm 0.001	7689	0.04
TB600B	0.14 \pm 0.01	0.01 \pm 0.001	6416	0.03
PS1	3.05 \pm 0.07	-0.1 \pm 0.01	7836	0.05
EC _{tox}	0.003 \pm 0.01	0.0002 \pm 0.0004	5709	2.99 $\times 10^{-5}$
AM HC1	1.94 \pm 0.04	-0.05 \pm 0.003	1019	0.26
AM HC2	1.28 \pm 0.05	-0.04 \pm 0.003	1019	0.14
AM LC1	1.21 \pm 0.04	-0.03 \pm 0.003	1017	0.14
AM LC2	1.25 \pm 0.04	-0.04 \pm 0.003	1017	0.15

Table 7. Linear Regression Parameters of RH against NH₃ Concentrations (1 min) for the Different Sensors while the NH₃ Release System Was On

sensor	slope \pm error	offset \pm error	N data	R ²
Picarro	0.16 \pm 0.04	0.01 \pm 0.001	8072	0.03
TB600B	0.63 \pm 0.01	-0.004 \pm 0.0002	6416	0.11
PS1	0.81 \pm 0.11	0.0001 \pm 0.0001	7836	0.01
EC _{tox}	-0.05 \pm 0.01	0.0001 \pm 0.001	5709	0.0001
AM HC1	-0.5 \pm 0.13	0.02 \pm 0.002	1019	0.13
AM HC2	-0.81 \pm 0.14	0.02 \pm 0.002	1019	0.10
AM LC1	-0.69 \pm 0.12	0.02 \pm 0.001	1017	0.11
AM LC2	-0.75 \pm 0.13	0.02 \pm 0.002	1017	0.10

Very weak correlations ($R^2 < 0.3$) were observed between sensors, RH, and T. Positive trends were observed for TB600B with T (Figure S7b), RH, and AM sensors (Figure S10), while negative trends were observed for Picarro, PS1, and AM sensors with T (Figures S7a and S8). Table S4 shows that sensors were used out of the suppliers' expected ranges of RH (mostly due to rain events, Figure 2), and in the case of the MELBA, the NH₃ range (Figure S5); however, future improvements need to address their performance under harsh outdoor conditions.

According to suppliers, most sensors correct the raw signal with T and RH through proprietary algorithms. Assessing T and RH biases in outdoor conditions is challenging due to the high variability of NH₃ concentrations, influenced by the release system, the atmospheric dispersion, and deposition and remission processes. Further laboratory testing and greater transparency from suppliers would help optimize sensor selection for specific applications.

It is beyond the scope of this study to establish clear relationships between the sampling rate, NH₃ concentrations measured, and changes in sensitivity of the sensor as this intercomparison aim was to test basic NH₃ sensor performance in outdoor conditions. The airflow change from 5.5 to 10 L min⁻¹ in the SH did not change the TB600B performance compared to the Picaro (Figure S11), likely due to the uneven amount of data across periods; therefore, definitive conclusions cannot be extracted. NH₃ sensor manufacturers and distributors should provide more detailed information regarding the sampling method and airflow. The physical setup is as important as sensor capability for outdoor measurements of NH₃, as previously noted for the automatic NH₃ analyzers.¹⁹

4.2. Available Information for the End User. One of the main challenges when starting to use NH₃ sensors, despite the variety on the market, is the lack of information provided by sellers. Topics such as detailed information on the sensor working principle, data collection, and how to install and operate them to obtain meaningful measurements are not covered. In the market research the authors undertook in planning the intercomparison, the technical terminology was not consistent across manufacturer/seller technical sheets. Operational time resolution, limits of detection, response time, and cross interference lists were missing for some sensors.

Calibration certificates were provided for the TB600B and AM sensors by the manufacturers. The TB600B had a manufacturer 2-point calibration (0 and 8 ppm of NH₃), while the AM sensors had a 3-point calibration: the HC sensors were documented as tested for 24, 10, and 5 ppm of NH₃, while the LC sensors were tested for 10, 5, and 1 ppm of NH₃. These concentration levels are within the expected range for indoor agricultural and industrial uses; however, they are far from the theoretical LOD reported in the datasheets (Table 2). Furthermore, the TB600B, AM1 LC, and AM2 HC sensors were tested under similar environmental conditions (22.5–23 °C and 45–50% RH), which are applicable to indoor environments. However, the AM sensors are part of an outdoor air quality monitoring product, which should be designed for ambient RH values (typically 60–99%) and ambient temperatures (e.g., in Scotland –10 to 30 °C). The technical sheets record the change of sensitivity in nA per ppm of NH₃ at a specific temperature. The issue of RH affecting response is also an issue for nonwet chemistry based NH₃ analyzers⁴⁷ and should be reported in the technical specifications.

The TB600B and Scentroid AM1 and AM2 systems were ready to be used as they arrived from the supplier, albeit with limited information on how to setup and run, and only the Scentroid DR came with a user guide to start the measurements. The EC_{tox} and PS1 sensors required some degree of laboratory preparation that was not specified in the technical sheet. This was a particular issue for the PS1, as it requires calibration by the user prior to deployment, either by using a gas hood purchased separately from the manufacturer or directly exposing the sensor to controlled concentrations of

NH₃. The EC_{tox} sensor has an integral pump and a sensing chamber inside its housing; however, as no information on the working principle was available, supplier support was needed to get the sensor working and, later in the campaign, to change the sampling time to be comparable to other sensors.

Understanding cross-interferences from other gaseous species is important for using EC sensors; however, even though all of the sensors are EC-based, different cross-interferences were recorded in their technical sheets. SO₂ and CO are listed as cross-interferences for the PS1 and EC_{tox}; however, the direction and magnitude of the interference varied between sensors. This could be understandable if the 3-way electrode sensors were different; however, conversations with some of the suppliers revealed that all of the 3-way electrode sensors came from the same manufacturer, with sensor suppliers implementing different signal processing, physical protocols, software visualization, or integration. Some of these cross-interferences could be attenuated by establishing regular comparisons between standardized analyzers and sensors, a common practice when using low-cost sensors as their data sets can be checked and correction factors could be applied if the comparison highlights potential cross-interferences and sensor drift.⁴⁸ Regulated pollutants such as PM_x and NO_x have standardized high-temporal-resolution methods for their measurement^{9,49,50} or even standardized performance evaluation methods for portable sensors.⁵¹ In contrast, passive diffusive samplers remain the only standardized method for NH₃,⁵² limiting the high-time-resolution capabilities of NH₃ sensors. Future improvements in high-time-resolution NH₃ methods will allow for the correction and calibration of these sensors.

5. CONCLUSIONS

This study compared the performance of six sensors, TB600B, PS1, AM series, MELBA, and EC_{tox} against a high-time-resolution Picarro NH₃ analyzer under outdoor conditions at an experimental NH₃ enhancement field site. Results demonstrated that NH₃ sensors are not ready to be used without expert assessment and even then do not provide more than indicative NH₃ concentrations.

The TB600B and AM sensors show promise for near-source outdoor NH₃ monitoring, with the caveats that the TB600B notably underestimated concentrations due to technical constraints and housing effects, while AM sensors displayed the best agreement with the reference analyzer, but suffered from a low DC. No significant T or RH effects were observed except for the MELBA sensor, which saturated at RH > 90% and NH₃ > 1 ppm; caution is required not to over interpret these results, as the opacity of the sensors' data processing makes it challenging to assess the influence of environmental parameters in the field. Further laboratory characterization is needed to correct these biases and optimize sensor performance.

This study highlighted the need for the NH₃ sensor industry suppliers to improve harmonization and for NH₃ sensor users to be rigorous around using standardized testing protocols for calibrating, maintaining, and performing QA/QC on the sensor data sets. Future improvements of NH₃ sensors should improve the sensitivity and response time to meet the need for monitoring NH₃ high temporal variability.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsomega.5c07873>.

Sensor selection process, the setup on Whim Bog, the linear checks carried for both the reference analyzer and NH₃ sensors, the performance of the MELBA sensor, the intrasensor variability between AM sensors, the potential interferences of T and RH over sensor's NH₃ measurements, and the potential influence of changes in the setup over sensor's NH₃ measurements (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Pablo Espina-Martin – UK Centre for Ecology and Hydrology, Penicuik EH26 0QB, U.K.; orcid.org/0000-0001-7995-1033; Email: pabesp@ceh.ac.uk

Authors

Sarah R. Leeson – UK Centre for Ecology and Hydrology, Penicuik EH26 0QB, U.K.
Robert Nicoll – UK Centre for Ecology and Hydrology, Penicuik EH26 0QB, U.K.
Clare Pearson – UK Centre for Ecology and Hydrology, Penicuik EH26 0QB, U.K.
Cristina Martin Hernandez – UK Centre for Ecology and Hydrology, Penicuik EH26 0QB, U.K.
Nathalie Redon – Centre for Energy and Environment, IMT Nord Europe, Institut Mines-Télécom, Univ. Lille, F-59000 Lille, France
Neil J. Mullinger – UK Centre for Ecology and Hydrology, Penicuik EH26 0QB, U.K.; orcid.org/0000-0002-3148-6950
Karen Yeung – UK Centre for Ecology and Hydrology, Penicuik EH26 0QB, U.K.
Marsailidh M. Twigg – UK Centre for Ecology and Hydrology, Penicuik EH26 0QB, U.K.
Ajinkya G. Deshpande – UK Centre for Ecology and Hydrology, Penicuik EH26 0QB, U.K.
Matthew R. Jones – UK Centre for Ecology and Hydrology, Penicuik EH26 0QB, U.K.
Hilary Costello – Limosaero Limited, King's Lynn PE31 7NY, England
Graham Spelman – Limosaero Limited, King's Lynn PE31 7NY, England
Christine F. Braban – UK Centre for Ecology and Hydrology, Penicuik EH26 0QB, U.K.

Complete contact information is available at:

<https://pubs.acs.org/doi/10.1021/acsomega.5c07873>

Author Contributions

Conceptualization: P.E.M., C.F.B., S.R.L., H.C., and G.S.; methodology: P.E.M., C.F.B., S.R.L., K.Y., N.M., R.N., N.R., and C.M.H.; software: R.N., C.P., H.C., and G.S.; data acquisition: P.E.M., S.R.L., K.Y., N.M., and R.N.; data curation: P.E.M., S.R.L., and R.N.; formal analysis: P.E.M., C.F.B., N.R., and C.M.H.; visualization: P.E.M. and C.P.; funding acquisition: C.F.B., H.C., and G.S.; investigation: P.E.M., S.R.L., C.F.B., R.N., N.R., and M.T.; project administration: P.E.M., C.F.B., H.C., and G.S.; resources: P.E.M. and C.F.B.; software: S.R.L., R.N., C.P., H.C., and G.S.; supervision: P.E.M., C.F.B., S.R.L., M.T., H.C., and G.S.;

validation: P.E.M., S.R.L., C.F.B., A.D., and M.J.; writing—original draft: P.E.M., C.F.B., and C.M.H.; and writing—review and editing: P.E.M., S.R.L., C.F.B., C.M.H., K.Y., N.M., N.R., M.T., A.D., and M.T.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors would like to thank Defra for funding this work through the SBRI call, project reference number 10109717. The authors would like to thank Peter Koller, Lukas Schwartz, and Killian Altan from ECSense for their support and guidance on setting up and recording the data from the TB600B and EC_{tox} during the sensor intercomparison and follow up conversations regarding data interpretation. Thanks to Loïc Marlot from IMT Nord Europe for his additional support with the questions related to the MELBA sensor during the review of this manuscript. Whim Bog facility is supported by NERC, through the UKCEH National Capability for UK Challenges Programme NE/Y006208/1.

■ REFERENCES

- (1) Sutton, M. A.; van Dijk, N.; Levy, P. E.; Jones, M. R.; Leith, I. D.; Sheppard, L. J.; Leeson, S.; Sim Tang, Y.; Stephens, A.; Braban, C. F.; Dragosits, U.; Howard, C. M.; Viena, M.; Fowler, D.; Corbett, P.; Naikoo, M. I.; Munzi, S.; Ellis, C. J.; Chatterjee, S.; Steadman, C. E.; Möring, A.; Wolseley, P. A. Alkaline Air: Changing Perspectives on Nitrogen and Air Pollution in an Ammonia-Rich World. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **2020**, *378* (2183), 20190315.
- (2) Bouwman, A. F.; Lee, D. S.; Asman, W. a. H.; Dentener, F. J.; Van Der Hoek, K. W.; Olivier, J. G. J. A global high-resolution emission inventory for ammonia. *Global Biogeochem. Cycles* **1997**, *11*, 561–587.
- (3) Backes, A.; Aulinger, A.; Bieser, J.; Matthias, V.; Quante, M. Ammonia emissions in Europe, part I: Development of a dynamical ammonia emission inventory. *Atmos. Environ.* **2016**, *131*, 55–66.
- (4) Behera, S. N.; Sharma, M.; Aneja, V. P.; Balasubramanian, R. Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. *Environ. Sci. Pollut. Res.* **2013**, *20*, 8092–8131.
- (5) Reche, C.; Viana, M.; Karanasiou, A.; Cusack, M.; Alastuey, A.; Artiñano, B.; Revuelta, M. A.; López-Mahía, P.; Blanco-Heras, G.; Rodríguez, S.; Sánchez de la Campa, A. M.; Fernández-Camacho, R.; González-Castanedo, Y.; Mantilla, E.; Tang, Y. S.; Querol, X. Urban NH₃ levels and sources in six major Spanish cities. *Chemosphere* **2015**, *119*, 769–777.
- (6) Sun, K.; Tao, L.; Miller, D. J.; Pan, D.; Golston, L. M.; Zondlo, M. A.; Griffin, R. J.; Wallace, H. W.; Leong, Y. J.; Yang, M. M.; Zhang, Y.; Mauzerall, D. L.; Zhu, T. Vehicle Emissions as an Important Urban Ammonia Source in the United States and China. *Environ. Sci. Technol.* **2017**, *51*, 2472–2481.
- (7) Laursen, R.; Barcarolo, D.; Patel, H.; Dowling, M.; Pendfold, M.; Faber, J.; Kiraly, J.; van der Veen, R.; Pang, E.; van Grinsven, A. *Potential of Ammonia as Fuel in Shipping* (No. 4837444); European Maritime Safety Agency, 2023.
- (8) Zhou, X.; Li, T.; Chen, R.; Wei, Y.; Wang, X.; Wang, N.; Li, S.; Kuang, M.; Yang, W. Ammonia marine engine design for enhanced efficiency and reduced greenhouse gas emissions. *Nat. Commun.* **2024**, *15*, 2110.
- (9) EC. *Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on Ambient Air Quality and Cleaner Air for Europe (Recast)*; 2024. <http://data.europa.eu/eli/dir/2024/2881/oj/eng> (accessed 2025-04-08).
- (10) Gu, B.; Zhang, L.; Van Dingenen, R.; Viena, M.; Van Grinsven, H. J.; Zhang, X.; Zhang, S.; Chen, Y.; Wang, S.; Ren, C.; Rao, S.;

- Holland, M.; Winiwarter, W.; Chen, D.; Xu, J.; Sutton, M. A. Abating ammonia is more cost-effective than nitrogen oxides for mitigating PM_{2.5} air pollution. *Science* **2021**, *374*, 758–762.
- (11) Espina-Martin, P.; Perdrix, E.; Alleman, L. Y.; Coddeville, P. Origins of the seasonal variability of PM_{2.5} sources in a rural site in Northern France. *Atmos. Environ.* **2024**, *333*, No. 120660.
- (12) Barrett, K.; de Leeuw, F.; Fiala, J.; Larssen, S.; Sundvor, I.; Fjellsbø, L.; Dusinska, M.; Ostatnická, J.; Horálek, J.; Černíkovský, L. *Health impacts and air pollution—an exploration of factors influencing estimates of air pollution impact upon the health of European citizens*; European Topic Centre on Air and Climate Change: Bilthoven, 2008; (ETC/ACC Technical Paper 2008/13).
- (13) Apte, J. S.; Brauer, M.; Cohen, A. J.; Ezzati, M.; Pope, C. A. Ambient PM_{2.5} Reduces Global and Regional Life Expectancy. *Environ. Sci. Technol. Lett.* **2018**, *5*, 546–551.
- (14) Cape, J. N.; van der Eerden, L. J.; Sheppard, L. J.; Leith, I. D.; Sutton, M. A. Evidence for changing the critical level for ammonia. *Environ. Pollut.* **2009**, *157*, 1033–1037.
- (15) Franzaring, J.; Kössler, J. *Review of internationally proposed critical levels for ammonia*; University of Hohenheim: Stuttgart, 2022.
- (16) Pinder, R. W.; Adams, P. J.; Pandis, S. N.; Gilliland, A. B. Temporally resolved ammonia emission inventories: Current estimates, evaluation tools, and measurement needs. *J. Geophys. Res.: Atmos.* **2006**, *111*.
- (17) Reis, S.; Pinder, R. W.; Zhang, M.; Lijie, G.; Sutton, M. A. Reactive nitrogen in atmospheric emission inventories. *Atmospheric Chemistry and Physics* **2009**, *9*, 7657–7677.
- (18) Manninen, S.; Jääskeläinen, K.; Stephens, A.; Iwanicka, A.; Tang, S.; van Dijk, N. NH₃ concentrations below the current critical level affect the epiphytic macrolichen communities – Evidence from a Northern European City. *Sci. Total Environ.* **2023**, *877*, No. 162877.
- (19) Twigg, M. M.; Berkhout, A. J. C.; Cowan, N.; Crunaire, S.; Dammers, E.; Ebert, V.; Gaudion, V.; Haaïma, M.; Häni, C.; John, L.; Jones, M. R.; Kamps, B.; Kentisbeer, J.; Kupper, T.; Leeson, S. R.; Leuenberger, D.; Lüttschwager, N. O. B.; Makkonen, U.; Martin, N. A.; Missler, D.; Mounsor, D.; Neftel, A.; Nelson, C.; Nemitz, E.; Oudwater, R.; Pascale, C.; Petit, J.-E.; Pogany, A.; Redon, N.; Sintermann, J.; Stephens, A.; Sutton, M. A.; Tang, Y. S.; Zijlman, R.; Braban, C. F.; Niederhauser, B. Intercomparison of in situ measurements of ambient NH₃: instrument performance and application under field conditions. *Atmospheric Measurement Techniques* **2022**, *15*, 6755–6787.
- (20) Nair, A. A.; Yu, F. Quantification of Atmospheric Ammonia Concentrations: A Review of Its Measurement and Modeling. *Atmosphere* **2020**, *11*, 1092.
- (21) Jones, M. R.; Leith, I. D.; Raven, J. A.; Fowler, D.; Sutton, M. A.; Nemitz, E.; Cape, J. N.; Sheppard, L. J.; Smith, R. I. Concentration-Dependent NH₃ Deposition Processes for Moorland Plant Species with and without Stomata. *Atmos. Environ.* **2007**, *41* (39), 8980–8994.
- (22) Tang, Y. S.; Cape, J. N.; Sutton, M. A. Development and types of passive samplers for monitoring atmospheric NO₂ and NH₃ concentrations. *ScientificWorldJournal* **2001**, *1*, 513–529.
- (23) Tang, Y. S.; Braban, C. F.; Dragosits, U.; Dore, A. J.; Simmons, I.; van Dijk, N.; Poskitt, J.; Dos Santos Pereira, G.; Keenan, P. O.; Conolly, C.; Vincent, K.; Smith, R. I.; Heal, M. R.; Sutton, M. A. Drivers for Spatial, Temporal and Long-Term Trends in Atmospheric Ammonia and Ammonium in the UK. *Atmos. Chem. Phys.* **2018**, *18* (2), 705–733.
- (24) Loubet, B.; Carozzi, M.; Voylokov, P.; Cohan, J.-P.; Trochard, R.; Génermont, S. Evaluation of a New Inference Method for Estimating Ammonia Volatilisation from Multiple Agronomic Plots. *Biogeosciences* **2018**, *15* (11), 3439–3460.
- (25) Woutersen, A.; de Ruiter, H.; Wesseling, J.; Hendrix, W.; Blokhuis, C.; van Ratingen, S.; Vegt, K.; Voogt, M. Farmers and Local Residents Collaborate: Application of a Participatory Citizen Science Approach to Characterising Air Quality in a Rural Area in The Netherlands. *Sensors (Basel)* **2022**, *22* (20), 8053.
- (26) Bobrutski, K. von; Braban, C. F.; Famulari, D.; Jones, S. K.; Blackall, T.; Smith, T. E. L.; Blom, C.; Coe, H.; Gallagher, M.; Ghalaïeny, M.; McGillen, M. R.; Percival, C. J.; Whitehead, J. D.; Ellis, R.; Murphy, J.; Mohacsi, A.; Pogany, A.; Junninen, H.; Rantanen, S.; Sutton, M. A.; Nemitz, E. Field inter-comparison of eleven atmospheric ammonia measurement techniques. *Atmos. Meas. Techniq.* **2010**, *3*, 91–112.
- (27) Martin, N. A.; Ferracci, V.; Cassidy, N.; Hook, J.; Battersby, R. M.; di Meane, E. A.; Tang, Y. S.; Stephens, A. C. M.; Leeson, S. R.; Jones, M. R.; Braban, C. F.; Gates, L.; Hangartner, M.; Stoll, J.-M.; Sacco, P.; Pagani, D.; Hoffnagle, J. A.; Seidler, E. Validation of Ammonia Diffusive and Pumped Samplers in a Controlled Atmosphere Test Facility Using Traceable Primary Standard Gas Mixtures. *Atmos. Environ.* **2019**, *199*, 453–462.
- (28) Khan, M. A.; Qazi, F.; Hussain, Z.; Idrees, M. U.; Soomro, S.; Soomro, S. Recent Trends in Electrochemical Detection of NH₃, H₂S and NO_x Gases. *Int. J. Electrochem. Sci.* **2017**, *12*, 1711–1733.
- (29) Insausti, M.; Timmis, R.; Kinnersley, R.; Rufino, M. C. Advances in sensing ammonia from agricultural sources. *Science of The Total Environment* **2020**, *706*, No. 135124.
- (30) Castell, N.; Dauge, F. R.; Schneider, P.; Vogt, M.; Lerner, U.; Fishbain, B.; et al. Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? *Environ. Int.* **2017**, *99*, 293–302.
- (31) Cross, E. S.; Williams, L. R.; Lewis, D. K.; Magoon, G. R.; Onasch, T. B.; Kaminsky, M. L.; Worsnop, D. R.; Jayne, J. T. Use of Electrochemical Sensors for Measurement of Air Pollution: Correcting Interference Response and Validating Measurements. *Atmospheric Measurement Techniques* **2017**, *10* (9), 3575–3588.
- (32) Peltier, R. E. *An Update on Low-cost Sensors for the Measurement of Atmospheric Composition*; World Meteorological Organization: Geneva, 2020.
- (33) BSI. *Selection, Deployment and Quality Control of Low-Cost Air Quality Sensor Systems in Outdoor Ambient Air – Code of Practice*; PAS 4023:2023; British Standards Institution, 2023. <https://knowledge.bsigroup.com/products/selection-deployment-and-quality-control-of-low-cost-air-quality-sensor-systems-in-outdoor-ambient-air-code-of-practice> (accessed 2025–06–02).
- (34) WMO. *Integrating Low-Cost Sensor Systems and Networks to Enhance Air Quality Applications*; GAW Report; 293; 2024; p 80. <https://library.wmo.int/idurl/4/68924> (accessed 2025–06–02).
- (35) Ng, R. B. F.; Wang, J.; Luo, Y.; Chen, X. Humidity Tolerant Sub-PPM Ammonia Gas Sensors. *IEEE Nanotechnology Magazine* **2024**, *18* (1), 13–22.
- (36) da Silva, E. A.; Samuel, C.; Furini, L. N.; Constantino, C. J. L.; Redon, N.; Duc, C. Poly(aniline)-based ammonia sensors: Understanding the role of polyurethane on structural/morphological properties and sensing performances. *Sens. Actuators, B* **2023**, *397*, No. 134664.
- (37) Leith, I.; Sheppard, L.; Fowler, D.; Cape, J.; Jones, M.; Crossley, A.; Hargreaves, K.; Tang, S.; Theobald, M.; Sutton, M. Quantifying Dry NH₃ Deposition to an Ombrotrophic Bog from an Automated NH₃ Field Release System. *Water, Air, & Soil Pollution: Focus* **2004**, *4*, 207–218.
- (38) Sheppard, L. J.; Crossley, A.; Leith, I. D.; Hargreaves, K. J.; Carfrae, J. A.; van Dijk, N.; Cape, J. N.; Sleep, D.; Fowler, D.; Raven, J. A. An Automated Wet Deposition System to Compare the Effects of Reduced and Oxidised N on Ombrotrophic Bog Species: Practical Considerations. *Water Air Soil Pollut: Focus* **2004**, *4*, 197–205.
- (39) Sheppard, L. J.; Leith, I. D.; Mizunuma, T.; Neil Cape, J.; Crossley, A.; Leeson, S.; Sutton, M. A.; van Dijk, N.; Fowler, D. Dry deposition of ammonia gas drives species change faster than wet deposition of ammonium ions: evidence from a long-term field manipulation. *Global Change Biol.* **2011**, *17*, 3589–3607.
- (40) Levy, P.; van Dijk, N.; Gray, A.; Sutton, M.; Jones, M.; Leeson, S.; Dise, N.; Leith, I.; Sheppard, L. Response of a peat bog vegetation community to long-term experimental addition of nitrogen. *J. Ecol.* **2019**, *107*, 1167–1186.

(41) Hanna, S. R.; Strimaitis, D. G.; Chang, J. C. *Hazard Response Modeling Uncertainty (A Quantitative Method). Volume 1. User's Guide for Software for Evaluating Hazardous Gas Dispersion Models*; SIGMA Research Corp Westford MA, 1991; p 83. <https://apps.dtic.mil/sti/citations/ADA270094> (accessed 2025-07-01).

(42) Hasenfratz, D.; Saukh, O.; Walser, C.; Hueglin, C.; Fierz, M.; Arn, T.; Beutel, J.; Thiele, L. Deriving high-resolution urban air pollution maps using mobile sensor nodes. *Pervasive and Mobile Computing. Selected Papers from the Twelfth Annual IEEE International Conference on Pervasive Computing and Communications (PerCom 2014)* **2015**, *16*, 268–285.

(43) Bisignano, A.; Carotenuto, F.; Zaldei, A.; Giovannini, L. Field calibration of a low-cost sensors network to assess traffic-related air pollution along the Brenner highway. *Atmos. Environ.* **2022**, *275*, No. 119008.

(44) Chang, J. C.; Hanna, S. R. Air quality model performance evaluation. *Meteorol Atmos Phys.* **2004**, *87*, 167–196.

(45) Hanna, S.; Joseph, C. Setting Acceptance Criteria for Air Quality Models. In *Air Pollution Modeling and its Application XXI*; Springer, 2011; pp 479–484.

(46) Sedlák, P.; Kuberský, P. The Effect of the Orientation Towards Analyte Flow on Electrochemical Sensor Performance and Current Fluctuations. *Sensors* **2020**, *20*, 1038.

(47) Martin, N. A.; Ferracci, V.; Cassidy, N.; Hoffnagle, J. A. The Application of a Cavity Ring-down Spectrometer to Measurements of Ambient Ammonia Using Traceable Primary Standard Gas Mixtures. *Appl. Phys. B: Laser Opt.* **2016**, *122* (8), 219.

(48) US EPA. *How to Use Air Sensors: The Enhanced Air Sensor Guidebook*; US EPA, **2022**.

(49) CEN/TC. EN 16450:2017 - Ambient air - Automated measuring systems for the measurement of the concentration of particulate matter (PM10; PM2,5), **2017**.

(50) CEN/TC. EN 14211:2024 - Ambient air - Standard method for the measurement of the concentration of nitrogen dioxide and nitrogen monoxide by chemiluminescence, **2024**.

(51) CEN/TS. CEN/TS 17660-2:2024 - Air quality - Performance evaluation of air quality sensor systems - Part 2: Particulate matter in ambient air, **2024**.

(52) CEN/TC. EN 17346:2020 - Ambient air - Standard method for the determination of the concentration of ammonia using diffusive samplers, **2020**.



CAS BIOFINDER DISCOVERY PLATFORM™

CAS BIOFINDER HELPS YOU FIND YOUR NEXT BREAKTHROUGH FASTER

Navigate pathways, targets, and
diseases with precision

Explore CAS BioFinder

