1 **Advances in sensing ammonia from agricultural sources**

2

3 Matías Insausti[a,b*], Roger Timmis[c], Rob Kinnersley[d], Mariana C. Rufino[b]

4

5 [a]INQUISUR (UNS-CONICET), Universidad Nacional del Sur, B8000CPB, Argentina

6 [b]Lancaster Environment Centre, Lancaster University, LA1 4YQ, United Kingdom

7 [c]Environment Agency, Lancaster University, Lancaster, LA1 4YQ, United Kingdom

8 [d]Environment Agency, Evidence Directorate, Deanery Road, Bristol, BS1 5AH, United

9 Kingdom

10

11 *corresponding author, email: matiasi@conicet.gov.ar

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

Abstract

Reducing ammonia emissions is one of the most difficult challenges for environmental regulators around the world. About 90% of ammonia in the atmosphere comes from agricultural sources, so that improving farm practices in order to reduce these emissions is a priority. Airborne ammonia is the key precursor for particulate matter (PM2.5) that impairs human health, and ammonia can contribute to excess nitrogen that causes eutrophication in water and biodiversity loss in plant ecosystems. Reductions in excess nitrogen (N) from ammonia are needed so that farms use N resources more efficiently and avoid unnecessary costs. To support the adoption of ammonia emission mitigation practices, new sensor developments are required to identify sources, individual contributions, to evaluate the effectiveness of controls, to monitor progress towards emission-reduction targets, and to develop incentives for behavioural change. There is specifically a need for sensitive, selective, robust and user-friendly sensors to monitor ammonia from livestock production and fertiliser application. Most currently-available sensors need specialists to set up, calibrate and maintain them, which creates issues with staffing and costs when monitoring large areas or when there is a need for high frequency sampling. This paper reports advances in monitoring airborne ammonia in agricultural areas. Selecting the right method of monitoring for each agricultural activity will provide critical data to identify and implement appropriate ammonia controls. Recent developments in chemo-resistive materials allow electrochemical sensing at room temperature, and new spectroscopic methods are sensitive enough to determine low concentrations in the order of parts per billion. However, these new methods still compromise selectivity and sensitivity due to the presence of ambient dust and other interferences, and are not yet suitable to be applied in agricultural monitoring. This review considers how ammonia measurements are made and applied, including the need for sensors that are suitable for routine monitoring by non-specialists. The review evaluates how monitoring information can be used for policies and regulations to mitigate ammonia emissions. The increasing concerns about ammonia emissions and the particular needs

55 from the agriculture sector are addressed, giving an overview of the state-of-the-art and an

56 outlook on future developments.

57 **Keywords:** Ammonia, Sensors, Nitrogen losses, Livestock production, Fertiliser Application.

58

59 **1. Introduction**

60 In most developed countries, the dominant source of ammonia (NH_3) emissions is the agro-

61 industry . Efforts to mitigate these emissions must therefore focus on improving those

62 agricultural activities that are important contributors - such as livestock feeding and housing,

63 excreta management, and fertilisation practices. To develop better agricultural practices it is

64 critical to know which sources contribute to these emissions, when, and by how much.

65 Ammonia measurements are primarily needed to understand emission rates, the

66 effectiveness of control measures, the impact of atmospheric processes and the outcomes

67 of exposure. Many types of sensors and devices for measuring NH_3 are commercially

68 available, and some promising new developments will be discussed in this paper. However,

69 most of the current devices are relatively specialised, costly or difficult to apply in "real world"

70 farming situations, so they are not readily used for day-to-day monitoring by non-specialist

71 practitioners. Also, there are only a few sensors that have enough sensitivity to measure

72 NH_3 emissions from fertilised soils, such as those using mid-ultraviolet absorption

73 spectroscopy , photoacoustic spectroscopy or the recent artificial nose with fluorescence

74 detection . NH_3 measurements are needed to improve agricultural efficiency, and to

75 contribute to a better quality of life – because excess concentrations of NH_3 lead to adverse

76 impacts on human health and on the health and diversity of ecosystems. Reductions in NH_3

77 emissions would support more efficient food production that uses fewer resources, and so

78 would reduce the environmental impacts of food supply chains. Availability of simple, reliable

79 and low cost measurements and procedures will help developing an improved understanding

80 of NH_3 emissions which is important for:

81   i)   Agricultural producers: reduced NH_3 emission will generate savings in nitrogen

82   fertilisers . More efficient use of crude protein in animal feed reduces N excretion,

3

83   and these emission reductions could attract farm payments if they are linked to

84   environmental improvements.

85   ii) Researchers: to develop new and more suitable technologies to reduce emissions

86   and solve problems for the agroindustry and society.

87   iii) Wider society and the economy: to decrease the combined cost for human health

88   and biodiversity from excess NH_3, which is estimated to be 4-30 euros per kg N

89   pollution in 2011 .

90   iv) Regulators: to target control measures effectively onto culpable sources, and to

91   evaluate source performance and the effectiveness of controls.

92   v) Policymakers and government: monitoring NH_3 emissions is required to meet

93   international emission reduction targets .

2. Ammonia in the environment

95 The distinct smell of ammonia is often noticed in rural parts of developed countries with high-

96 density livestock farming, especially near intensive pig, poultry or cattle facilities or after

97 liquid manure has been spread on the land. NH_3 is a colourless with a very perceptible

98 odour, even at very low concentrations. It is a common gas that is released in the natural

99 environment from decomposing organic material and animal waste. In the agricultural

100 industry, NH_3 can be used as a fertiliser in the pure gas form of anhydrous NH_3, but it is also

101 widely used to make nitrogen-based fertilisers such as urea, urea-ammonium nitrate,

102 ammonium sulfate, ammonium nitrate and diammonium phosphate. NH_3 is also used as a

103 refrigerant, and in the manufacture of plastics, explosives, textiles, pesticides, dyes and

104 other chemicals. Although NH_3 is commonly present in nature and widely used in industry, it

105 is classified as an extremely hazardous substance because it is both caustic and flammable

106 . The United States Environmental Protection Agency has classified NH_3 as a hazardous

107 substance because of its toxicity to humans, and has set a maximum safe level of 25 ppm

108 for long term exposure (8 hours) and of 35 ppm for short term exposure (15 min) . For

109 livestock, exposure to 25 ppm of NH_3 can adversely affect weight gain, feed conversion and

110 mortality rates   . Several institutions regulate exposure and peak instantaneous

111 concentrations, but there are no regulations for NH_3 emission rates. The 'Environmental

112 Permitting Regulations' relate to ammonia emissions , which set a limit for large livestock

113 facilities on the number of animals that can be kept near a sensitive habitat. Critical level of

114 ammonia concentration cannot be exceeded, and these concentrations are calculated based

115 on accepted emission factors for livestock for different production systems. Another relevant

116 piece of legislation is the National Emission Ceilings Directive (NECD), which sets targets for

117 maximum annual emissions from individual European countries . There is also the

118 Gothenburg Protocol of The United Nations Economic Commission for Europe (UNECE)

119 which is an international agreement to abate acidification, eutrophication and ground-level

120 ozone, that aims to reduce emissions of several pollutants including NH_3 .

121

122 Livestock excreta and fertilisers are major sources of ammonia. Large amounts of NH_3 are

123 released from excreta immediately after deposition and during decomposition. Livestock are

124 often fed high-protein feeds containing N to ensure that their nutritional requirements are

125 met, but the N that is not converted to animal protein is excreted in the urine and the faeces.

126 Once the N compounds are in the faeces or urine, enzyme reactions or microbial activity

127 quickly release NH_3 to the atmosphere . This is because the urea produced and excreted by

128 mammals is rapidly converted to NH_3 gas by the urease enzyme. In the case of poultry, it is

129 uric acid that is excreted and mostly converted to urea, and then to NH_3. There are several

130 technologies that can be implemented to reduce NH_3 emissions by reducing the availability

131 of both precursors (urea and the urease enzyme) such as controlling the contents of

132 livestock diets or using urease inhibitors such as is N-(n-Butyl)-thiophosphoric triamide

133 (NBPT) . Another control option is to reduce urea hydrolysis by separating the urea and

134 faeces . Key methods to control ammonia emissions from animal excreta are to keep it as

135 dry as possible (i.e. by using indirect heating or heat exchangers); to keep it covered (e.g.

136 floating covers for slurry stores and lagoons); to acidify it; and to avoid adverse weather

137 conditions such as high temperatures, high humidity and adverse wind direction when

138 manure is injected into the soil. The other large source of NH_3 gas is the application of N

fertilisers, which represents a significant fraction (23%) of NH_3 emissions (Figure 1, data from the UK Code COGAP). All fertilisers containing ammonium (NH_4^+) are subject to volatile losses and the NH_3 emissions is largely controlled by pH . Precision agriculture can help adjusting fertiliser rates to reduce excess N application and hence losses by volatilization or run-off.
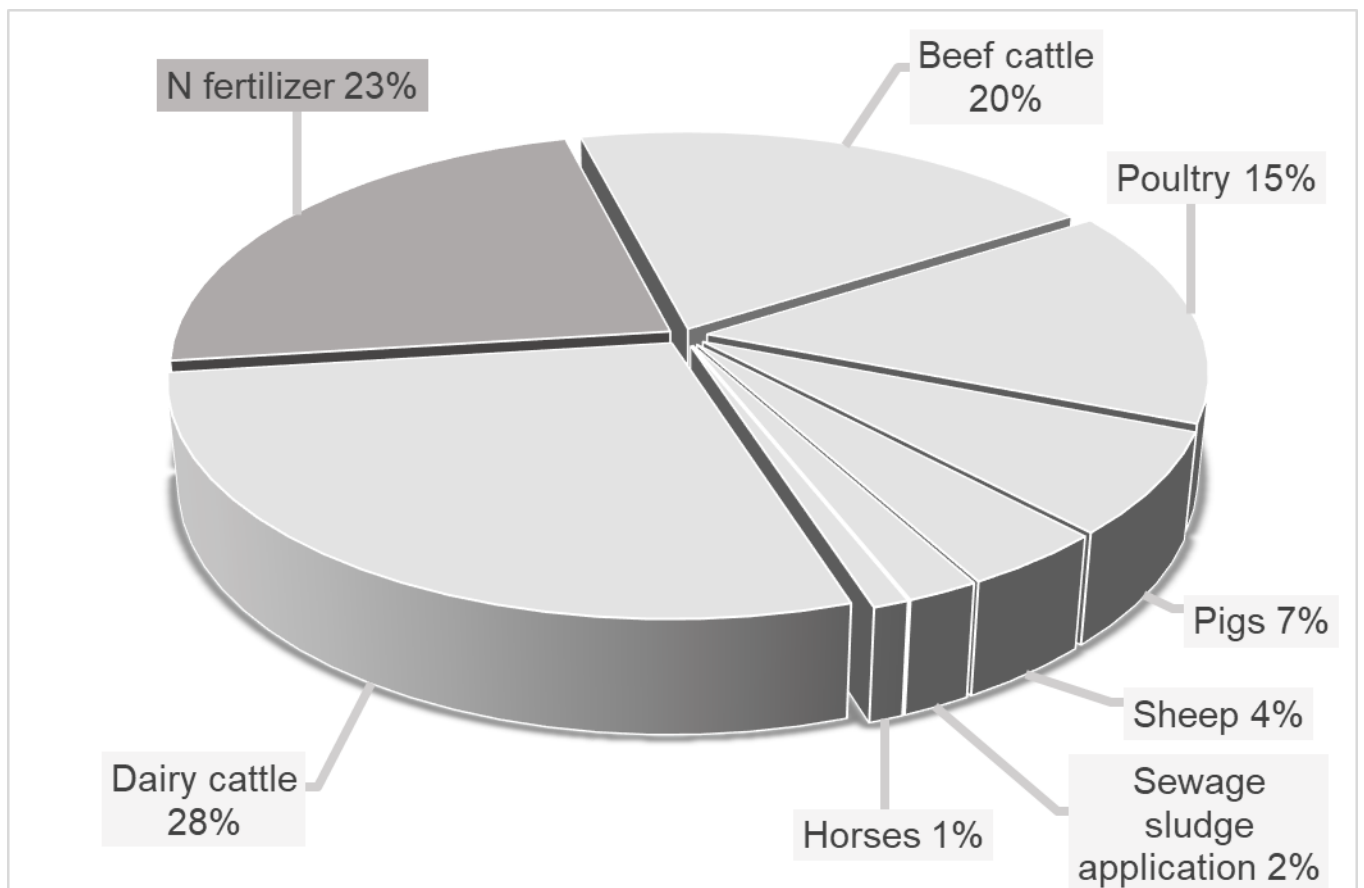
Figure 1: Agricultural NH_3 emissions in the UK by livestock (light grey) and fertiliser category .

Presently, NH_3 stands out as the air pollutant whose ambient concentrations are not decreasing rapidly, and occasionally increase slightly. Similarly, emissions of NH_3 during the last 3 decades have reduced much more slowly than those of other major air pollutants such as NO_x, SO_2 and non-methane volatile organic compounds . A recent study shows that there are numerous NH_3 hotspots and unknown sources unidentified around the world . Areas with high beef cattle density are reported to produce an average of 50 µg N m^{-2} s^{-1} (85 g animal^{-1}

154   day^{-1}) . The Po Valley in northern Italy is considered the region in Europe with the highest

155   intensity of NH_3 emissions, which can reach maximum values close to 250 µg m^{-2} s^{-1} during

156   the season of manure application . After urea application to soils, NH_3 emissions can reach

157   an peak of about 5 µg m^{-2} s^{-1} around midday if there is no rain . In order to address the

158   environmental burden of NH_3 emissions and to design management strategies, it is

159   necessary to distinguish the main sources of agricultural NH_3, because 88-94% of NH_3 in the

160   troposphere comes from farming practices , of which 65-71% is from livestock and 16-23%

161   from fertiliser application. There are several options to mitigate NH_3 emissions and

162   increased efforts are needed to lower concentrations to safer levels. To support the

163   implementation of policies and changes to farming practices are effective, there is a need to

164   monitor emissions and ambient levels of NH_3. For that purpose, a transformative

165   improvement in monitoring technology is required to get real-world data from multiple sites

166   and activities.

167

3. Impacts of ammonia emissions

169   Ammonia in the atmosphere has become a concern for environmental and health agencies

170   for two main reasons: because of excess N deposition and because NH_3 is a precursor of

171   fine particulate matter, both of which can impair human health. NH_3 is an alkaline compound,

172   and when released into the air it is rapidly adsorbed to surfaces and significant deposition

173   (up to 20%) may occur over distances ranging from a few hundreds of meters of the source

174   to hundreds of miles . The remaining atmospheric NH_3 can rapidly react with acid gas

175   compounds (such as SO_2 and NO_x from vehicular and industrial combustion processes) to

176   form very small secondary aerosol particles . This fine particulate matter has an

177   aerodynamic equivalent diameter of <2.5 microns (referred to as PM2.5), having a lifespan

178   of up to 2 weeks and contributing to atmospheric haze and low visibility . NH_3 is transported

179   by wind and deposited not far away from the source where it can promote plant growth in

180   areas where N was previously a limiting factor . An example of this phenomenon is the

181   eutrophication in catchments, including algal blooms that impair water quality and can harm

182 ecosystems and people . Dry N deposition is a continuous process where the gases and

183 aerosols from the atmosphere are transferred to the surface by atmospheric turbulence and

184 diffusion, whereas wet deposition is the intermittent removal of chemical species from the

185 atmosphere by precipitation. Airborne NH_3 concentrations reflect and approach a dynamic

186 equilibrium between deposition and re-emission, an ongoing exchange between the surface

187 and the atmosphere. Changes in plant species composition have been observed in natural

188 ecosystems where high N deposition occurs . There is a loss of biodiversity because N-

189 intolerant plants become depleted and N-tolerant plants become dominant . An example of

190 this effect is the direct damage to sensitive vegetation such as lichens and bryophytes that

191 occur even at very low NH_3 concentrations of around 1 µg NH_3 m^{-3} . Moreover, the

192 deposition of N onto soils with a low buffering capacity can result in soil acidification and

193 consequently basic cation depletion . Harm to human beings is caused by the fine particles

194 that are inhaled deeply into the lungs and impair respiratory function and cardiovascular

195 health . In addition, high concentrations (25 ppm) of atmospheric NH_3, as it is an irritant

196 compound, have a negative effect on animal production in confined buildings and farm

197 workers should avoid prolonged exposure .

198

199 **4. Detection and quantification of ammonia**

200 We review here the methods currently available to measure NH_3 and discuss some of the

201 previous and significant developments in the field. The instant value of NH_3 concentration in

202 the air, a measure that the currently available sensors usually provide, is only useful to meet

203 the requirements of regulations in different activities. For some farming activities, regulators

204 require instantaneous measurements of NH_3 concentrations, but these measurements have

205 to be used in modelling platforms with other data to estimate wider emissions and impacts of

206 airborne ammonia. To be able to manage emissions from agriculture there is a need for

207 sensors to identify and quantify different sources, including point, area and volume sources,

208 and to identify major contributors. Monitoring programmes should provide data on NH_3

209 concentrations across a range of different scales and environments linking sources and

210 receptors. At present a major challenge is to detect the low concentrations occurring in the

211 troposphere (0.3–6 ppb) . Moreover, when the aim is to provide meso-scale and regional

212 patterns, in traditional monitoring schemes, low-frequency (weekly, monthly) sampling is

213 usually selected, which presents the challenge of delivering data over long periods. Most of

214 the available sensors require a qualified operator to set up, calibrate, maintain and de-

215 commission the measurements, which creates issues with staffing and costs when

216 monitoring large areas or when there is a need for high frequency sampling. One of the

217 biggest challenges is to design monitoring that can be used successfully by non-specialists

218 e.g. farmers. A range of monitoring techniques is required that covers different levels of

219 complexity and detail e.g. cheap and easy-to-deploy methods that non-specialists can use

220 for basic reconnaissance and scoping of sources, and more sophisticated methods can be

221 used to identify individual source contributions and performance in complex or specialised

222 studies. Quantifying NH_3 gas emissions needs devices that measure concentrations but also

223 modelling methods to scale concentrations and to calculate emission rates . Also, important

224 critical information is needed to achieve accurate estimations of emission rates, like

225 information on livestock housing facilities, feeds, temperature, wind speed, ventilation rates,

226 among others. Several modelling approaches have been used to estimate NH_3 emission

227 rates, and in order to obtain robust estimates they must take account of variables like wind

228 speed, humidity and air temperature at different heights – which may be measured or

229 derived from numerical weather prediction models. There are particular challenges when

230 measuring NH_3 at low concentrations, because the polarity and geometry of the molecule

231 make it highly soluble in water so it tends to adsorb onto surfaces such as air sampling

232 tubes, which can result in significant errors when concentrations are low .

233

234 For review purposes, the range of sensors available can be classified by different aspects,

235 such as cost, temporal resolution, and level of automation. In this review, sensors were

236 classified by the analytical technique used to detect NH_3 molecules. The sensors covered

237 are only those considered suitable for agricultural applications. These sensors need to be

9

238   portable, and be selective for NH_3 so that measurements are not compromised by

239   interference from other ambient chemicals. They also need to   have a wide range of

240   operation to measure concentrations found in farming and sensitive ecosystem situations,

241   including the low concentrations that occur in some environments. Some sensors are

242   suitable for measurements in livestock housing and manure storage situations, whereas

243   others are suitable for measuring lower concentrations of NH_3 from fields (Figure 2 and

244   Table 1). As shown in Table 2, only high-cost equipment (e.g. chemiluminescent or

245   photoacoustic, cost >$25.000) is suitable for directly measuring low concentrationsof NH_3

246   (<0.1ppm). Lower-cost sensors (electrochemical types, cost $500-$2000) are generally

247   designed for higher-concentration situations e.g. for NH_3 leak detection (>1 ppm) . An

248   alternative to high-cost sensors is the use of passive and active samplers that can

249   accumulate NH_3 over long periods (usually between 1 week and 1 month), which enables

250   them to detect low time-averaged concentrations . Moreover, an interesting new device can

251   provide information about the location of a source without needing a power supply. This is a

252   directional passive air sampler which resolves concentrations into 12 x 30° sectors, and

253   combines a static carousel containing passive samplers with a rotatable inlet that aligns with

254   the wind . Passive samplers tend to be cheaper and easier to deploy than active (powered)

255   samplers, but they provide lower temporal resolution and still need laboratory analysis to

256   obtain an average value of NH_3 concentration.

257

258
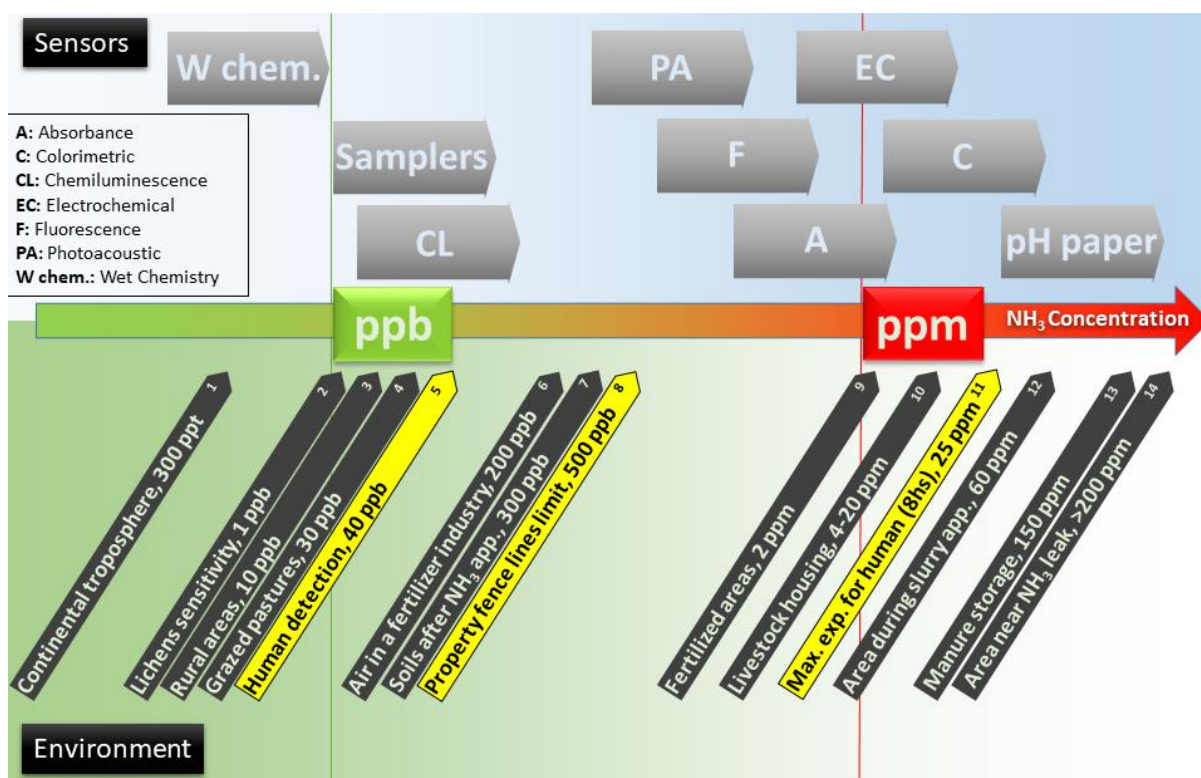
Figure 2. Reported NH$_3$ concentrations in different environments and sensor techniques for different concentration; see Table 1 for details. The yellow arrows indicate established limits for NH$_3$ in air. 1) , 2) , 3), 4) , 5) , 6) , 7) , 8) , 9) , 10) , 11) , 12) , 13) , 14) .

262 **Table 1. Concentrations and limits for airborne ammonia**

263 Typical concentrations are shown for different source and receptor situations, ranging from remote background locations to near-source

264 storage and leakage situations

Source/Environment	Reported concentrations[*]				Reference
Continental Troposphere	0.1-1.5	ppb	0.13-1.9	µg NH$_3$ m^{-3}	
Lichens sensitivity	1	ppb	1.3	µg NH$_3$ m^{-3}	
Rural areas	10	ppb	13	µg NH$_3$ m^{-3}	
Urban areas	10.9-15.3	ppb	1.4-2.0x10^1	µg NH$_3$ m^{-3}	
Industrial areas	20	ppb	2.6x10^1	µg NH$_3$ m^{-3}	
Grazed pastures	40	ppb	5.2x10^1	µg NH$_3$ m^{-3}	
Odour threshold for human detection	40	ppb	5.2x10^1	µg NH$_3$ m^{-3}	
Near-road	41.3	ppb	5.4x10^1	µg NH$_3$ m^{-3}	
Air in fertiliser industry	30-380	ppb	0.39-4.9x10^2	µg NH$_3$ m^{-3}	
Soils after anhydrous ammonia applied	400	ppb	5.2x10^2	µg NH$_3$ m^{-3}	
Property fence lines limit	500	ppb	6.5x10^2	µg NH$_3$ m^{-3}	
Dairy wastewater lagoons	0.4-1.6	ppm	0.52-2.1x10^3	µg NH$_3$ m^{-3}	

Areas after manure or synthetic fertilise application	0.01-5	ppm	$0.01\text{-}6.5\text{x}10^3$	µg NH_3 m^{-3}
Beef cattle housing	4	ppm	$5.2\text{x}10^3$	µg NH_3 m^{-3}
Dairy Housing	0.8-10	ppm	$0.1\text{-}1.3\text{x}10^4$	µg NH_3 m^{-3}
Hog housing	5-28	ppm	$0.7\text{-}3.6\text{x}10^4$	µg NH_3 m^{-3}
Poultry houses	20	ppm	$2.6\text{x}10^4$	µg NH_3 m^{-3}
Maximum exposure for humans (8hs)	25	ppm	$3.3\text{x}10^4$	µg NH_3 m^{-3}
Area during slurry application	60	ppm	$7.8\text{x}10^4$	µg NH_3 m^{-3}
Manure storage	150	ppm	$2.0\text{x}10^5$	µg NH_3 m^{-3}
Area near an ammonia leak	100-600	ppm	$1.3\text{-}7.8\text{x}10^5$	µg NH_3 m^{-3}

265 *Transformation rate of NH_3 concentrations: 1 µg $m^{-3} \cong 0.774$ ppb.

266 **Table 2.** Reported ammonia sensors and their measured concentrations. The table is separated in commonly reported concentration for each

267 class and outstanding sensors.

Technique or method based	Usual concentration		Sample rate	Concentration of selected sensors		Sample rate	Use	Reference
	LOD	Range		LOD	Range			
Wet chemistry	0.1 ppb	0.1 ppb – 1000 ppm	> min.	0.58 ppt	5.5-30 ppt	-	NH$_3$ concentrations below ppb levels and reference methods.	
Chemiluminescence	0.21 ppm	0.25-100 ppm	> min.	60 ppb	0.31-59.6 ppm	-	Field instrumentation for low ppb NH$_3$ concentrations	
Passive Collectors	0.2 ppb	0.2 -100 ppb	> hours – months.	-	>0.2 ppb	-	NH$_3$ diffusion tubes are useful for providing long-term estimates.	
Photoacoustic	0.3 ppm	0.3-10 ppm	> sec.	0.1 ppb	0.1 ppb - 3 ppm	5 L/min	Laboratory instrumentation for NH$_3$ concentrations below ppm levels	
Fluorescence	0.5	0.5-50	> min.	30	30-380	15	Laboratory instrumentation for NH$_3$	

14

	ppm	ppm		ppb	ppb	L/min	concentrations of low ppm levels	
Absorbance	0.5 ppm	0.1-10 ppm	> sec.	3 ppb	3 ppb-10 ppm	~6 /min	Field sensors for NH_3 concentrations of low ppm levels	
Electrochemical	1 ppm	1-50 ppm	> min.	0.5 ppm	0.5-5 ppm	6 /min	Field sensors for NH_3 concentrations of low ppm levels	
Colorimetric	10 ppm	10-300 ppm	> min.	10 ppm	10-200 ppm	4 /min	Field sensors for NH_3 concentrations of low ppm levels	
pH papers	50 ppm	50 - 1000 ppm	> min.	50 ppm	50-300 ppm	30 /min	Field sensors for NH_3 concentrations above 50 ppm levels	

268 - LOD: Limit of detection.

4.1. **Types of Sensors**

Based on the main system used to detect ammonia, there are two broad types of sensors: electrochemical and spectrometric. There are also two main strategies for obtaining an analytical signal from the NH_3 molecule: direct measurement of NH_3 itself, or indirect measurement of a compound that derives from a reaction with NH_3. Most methods described here rely on collecting gaseous NH_3 in an acidic medium and then measuring the concentration. There is a need to distinguish between gaseous and particulate ammonia. The volume of air passed through a sampler is recorded and the NH_3 concentration in the air is calculated.

4.1.1. **Electrochemical sensors**

The principle of electrochemical sensors involves detecting the change in an electrical signal (resistance, potential, current) caused by adsorption of NH_3 into different materials. Voltametric or potentiometric determinations were developed typically to measure NH_3 in aqueous samples, for which the detection limits (~1-100 ppm) are much higher than for air samples . Although amperometric NH_3 sensors offer high sensitivity, they are characterised by low selectivity because the NH_3 signal cannot be readily distinguished from interfering signals due to other compounds that are present . Because of this interference, these types of sensors are not suitable for agricultural applications and so are not discussed further. Generally, those studies that present new developments in electrochemical sensing are conducted by material scientists, which could explain why their application in agriculture is rarely discussed. In addition, the concentrations investigated in these studies (1-10,000 ppm) tend to be higher than the concentrations applicable to agricultural NH_3 situations (0.01-100 ppm). Nevertheless, the chemical alarm systems used to signal potentially unsafe levels of NH_3 in housing facilities do not require very sensitive sensors, so that small and low-power electronic devices are feasible in these situations. Overall, semiconductor and metal-oxide gas sensors seem best-suited for these chemical alarm applications .

297   Several new materials have been developed which can change their electrical conductivity

298   as a function of the NH_3 concentration in air. Chemi-resistive materials have been used to

299   detect a number of oxidizing or reducing gases such as NH_3, based on the charge transfer

300   that can occur between the sensing element and the redox gas . Typically these detectors

301   incorporate semiconductors that can be categorized as metal oxide, conductive polymers, or

302   combinations of metal nanoparticles and conductive polymers that result in promising

303   composite materials . Metal oxides-based NH_3 sensors have shown good performance

304   compared to carbon materials, and are competitive in analytical performance in relation to

305   conductive polymers . The main disadvantage of metal-oxide-based technologies is the

306   requirement for activation energy to convert the low conductivity of the materials into

307   semiconductors . In metal-oxide-based sensors, the activation energy is usually supplied by

308   using temperatures above 200°C, while conductive polymers are activated through a

309   "doping" synthesis that generates delocalized charges in the sensing element .

310

311   In recent decades, polyaniline-based materials have emerged as the preferred choice

312   among polymer-based sensor materials, because of their cost-effectiveness, ease-of-

313   preparation, and superior sensing performance . Most up-to-date developments have

314   improved stability and repeatability by combining polyaniline with other NH_3-sensing

315   materials, including combinations of polyaniline nanocomposites with metal oxides,

316   graphene, carbon nanotubes, and other carbon nanomaterials . These developments allow

317   polymer-based sensing materials to readily transduce the sorption of NH_3 into an electrical

318   signal at room temperature . Nevertheless, the mechanistic understanding of the mix of this

319   polymer with carbon nanomaterials or metal oxides remains elusive, representing a

320   challenge for the next generation of these sensors. The disadvantages of the conductive

321   material-based sensors are that they require regular maintenance and lack sensitivity and

322   selectivity. For example, conducting polymers need regular regeneration to prevent loss of

323   sensitivity . Most of these developments are not suitable for the agricultural environment

324   where other redox gases are present (N_2O, NO_2, H_2S and CH_4) . Moreover, most of these

325 sensors provide only first order data, reading only one signal value per sample, so no

326 multivariate calibration could be applied to resolve interferences . In addition, there is a need

327 to use non-linear regression models, which adds an extra layer of complexity to these

328 electrochemical determinations. A few minutes per sample is needed to achieve

329 measurements in the order of several ppm which is a high concentration for most

330 agricultural purposes, except for alarm systems in livestock housing facilities . More complex

331 methodologies could be used to address the problem of sensitivity. For example, Timmer et

332 al. (2004) used miniaturization and pre-concentration by membranes and an acid trap to

333 reach the required concentration levels (ppb). Another approach that addresses selectivity is

334 the use of indirect measurements of electrolyte conductivity detection . However, these

335 methods seem to be unsuitable for long term sensing in dusty environments such as

336 agricultural facilities, because their membranes and filters get clogged easily.

337

338 4.1.2. **Spectrometry based-sensors**

339 Optical devices based on spectrometry can meet stringent requirements for sensing, such as

340 strong resistance to electromagnetic noise, high stability, low power consumption, and

341 compatibility with explosive environments.

342

343 **4.1.2.1.   Absorbance-based and colorimetric sensors**

344 The most common absorbance-based and colorimetric sensors involve direct measurements

345 using long-path instruments and NH_3-derived compounds, and indirect measurements of

346 changes in pH. The methods have a broad range of applications, and sensor selection

347 depends mainly on the NH_3 concentrations to be measured. The various methods cover a

348 calibration range between 1 and 18,000 ppm of NH_3, and one study reports a limit of

349 detection of 1 ppb_v NH_3 . Continuous monitoring over large areas or long paths can require

350 low detection limits, and absorbance-based sensors seem to be the best option for these

351 situations (See Table 2). Direct measurements can be done with open-path sensors at

352 infrared (IR) or ultra-violet (UV) wavelengths. The methods can be used to integrate NH_3

18

353 concentrations over several metres of air path up to 120 meters . Another method involving a

354 long optical path is cavity-ringdown spectroscopy which has been used successfully to

355 identify NH_3 emission sources, and when used with real-time data it can explain the

356 correlation between concentrations of NH_3 and other precursor gases for $PM_{2.5}$ in urban air .

357 The main disadvantages of the methods are that the initial costs for equipment and set up

358 are high, that qualified personnel are needed to deploy and maintain the sensors, and that

359 interferences from dust, water vapour and other gases (e.g. NO_x, CO_2, O_2, etc.) commonly

360 occur in agricultural environments . Invalid data from long-path instruments due to dust or

361 laser reflector alignment issues could be avoided using the latest chemometrics approaches

362 that can predict values with uncalibrated interferences . Moreover, miniaturized systems

363 could solve the problem of needing large sample volumes for absorption spectroscopy, or

364 they could enhance the absorption signal by using specific and very sensitive colour

365 reactions that are already available .

366

367 Chemicals for deriving NH_3 concentrations can be held on a variety of surfaces. The most

368 commonly used methods for deriving NH_3 are the Berthelot, Nessler and pyridine-pyrazole

369 reactions, or their modifications . There are two commonly used arrangements that use

370 colour changes to infer a sample gas concentration. One arrangement uses gas tube

371 samplers that are coated inside with colour-change reagent, and are attached to a hand

372 pump that sucks a pre-defined volume of air per stroke . Tubes are available with different

373 measurement ranges e.g. a range of 0.25-30 ppm is suitable for NH_3 in livestock buildings .

374 However, the sensitivity of the tubes is generally too low (>2 ppm) for measuring outdoor

375 NH_3 concentrations. The second arrangement uses a chemcassette system where a coil of

376 paper embedded with chemicals is coupled to a measuring device . The paper acts as both

377 a sampling medium, and as an analysis facility for detecting and measuring nanogram

378 amounts of the target gas. These devices use a small length of paper tape per sample,

379 allowing scheduled automatic measurements. On exposure to the target gas, the tape

380 changes colour in direct proportion to the sample gas concentration, and a photo-optical

381   system measures the colour intensity change from which the sampled gas concentration is

382   determined .

383

384   Other thin-films samplers are reported in the literature but they are still not widely used. An

385   example is the change in optical absorption of a thin dye-doped nanostructure polypyrrole

386   film . Another sensor uses polyaniline deposited on the surface of a polyethylene tube . Also,

387   there are non-specific sensors available like pH papers that measure indirectly the presence

388   of NH_3 in air . This method provides inexpensive *in situ* records for estimating NH_3

389   concentrations by matching the colour change against a calibrated chart. Other sensors use

390   patterns of different dyes to obtain values of NH_3 and to discriminate different interferences

391   like SO_2, Cl_2, CO_2 or volatile amines . Chemometrics analysis is used for multivariate

392   calibration when several dyes are used at the same time . Because these indirect methods

393   have low sensitivity and precision, they could be suitable for preliminary and rapid analysis in

394   high concentration environments like slurry lagoons and housing facilities.

395

396   **4.1.2.2.   Fluorescence-based sensors**

397   Fluorescence is not frequently used to measure air quality in agricultural situations because

398   few relevant compounds fluoresce, compared to those that absorb radiation . However, there

399   is a growing interest in replacing conventional organic dyes with stable semiconductor or

400   carbon-based photo-luminescent nanomaterials for fluorescence-based sensing.

401   Fluorescence sensors offer relatively high sensitivity (~50 ppb), easier design strategies,

402   lower cost, and higher portability. Photo-luminescent carbon dots (CDs) are better than

403   semiconductor nanomaterials in terms of their high biocompatibility, low toxicity and lower

404   cost . To date, fluorescent CDs have been successfully exploited in a wide range of

405   applications and a recent study uses fluorescent determination in solid and liquid samples

406   from agriculture, based on simultaneous extraction and fluorimetric labelling of NH_3, followed

407   by fluorescence measurement. The fluorimetric labelling reagent is the o-phthalaldehyde

408   (OPA), and the reaction is based on the deprotonation of a pH indicator .

409

410 As the NH$_3$ molecule is not fluorescent by itself, quantifications are done using derivatization

411 reactions like that used for the sensor in section 4.1.2.1. The signal recorded is the emission

412 of photons after irradiation of the derivatization reagent. A trapping solution or new porous

413 matrices like sol-gel or latexes have been developed to obtain a fluorescent signal from the

414 non-fluorescent NH$_3$ molecule . Thin films involve the reversible absorption and desorption of

415 NH$_3$ over periods of about one minute, that change the fluorescent signal of the polymer .

416 Future developments could use such fluorescence sensitivity to measure NH$_3$, and current

417 applications of fluorescence-based sensors often measure NH$_3$ concentrations down to

418 about 5-50 ppm.

419

420 Another fluorescent sensor uses an array of seven chemical materials with fluorescent

421 properties as the sensing elements . These kinds of materials can identify interactions

422 between molecules such as p-p molecular complex action, bond formation, acid-base

423 interactions, physical adsorption, and Van der Waal forces. The sensor elements interact

424 with specific gases that can change their fluorescent and photochemical properties, so that

425 the change in their fluorescence can be detected. This approach has been successfully used

426 in detecting NH$_3$ once is dissolved in water, but could also be a good starting point to obtain

427 rapid and inexpensive sensors for NH$_3$ in air. Also, chemometrics could be used to calibrate

428 or to discriminate contributions from other gases present in media, as it has been done with

429 colour dye arrays .

430

431 **4.1.2.3.   Photoacoustic based-sensors**

432 This optical technique involves the absorption of modulated laser radiation with a specific

433 wavelength of ~1530 nm for the NH$_3$ molecule. The deactivation of the excited molecule via

434 collisions is converted into a modulation frequency that induces acoustic waves that can be

435 monitored with a low-noise microphone. The instrument layout consists of a laser source, a

436 resonant photoacoustic (PA) cell, a microphone to monitor the sound waves and an

437 electronic control module for laser modulation and signal processing . The PA spectroscopic

438 gas detection technique has numerous advantages, making it a very promising candidate for

439 NH$_3$ detection in agriculture . PA provides continuous, selective and automatic

440 measurements with outstanding long-term stability . Carbon dioxide (CO$_2$) and water vapour

441 are the major potential interferences, but these can be addressed by using an isotopic ^{13}CO$_2$

442 laser with a different wavelength to suppress the signals . Although PA is a very sensitive

443 technique, it still lacks the robustness needed for use in agricultural environments because

444 the sensors have a significant cross-sensitivity to nitrous oxide (N$_2$O) and methane (CH$_4$) .

445 Moreover, electronic developments are needed to reduce the cost of the equipment (>

446 $10,000) in order to allow large-scale use of PA cells in commercial sensors. Most

447 developments using this technique measure in the range of 0.1 ppm to 100 ppm , so it could

448 be used for monitoring NH$_3$ in poultry houses, dairy wastewater lagoons and at property

449 fence lines where the regulations mandate a maximum concentration of 0.5 ppm .

450

451 4.2. **Use of monitoring to support emission estimates**

452 **4.2.1. Emission factors**

453 Several approaches have been developed with different complexity levels to estimate NH$_3$

454 emissions over large areas. The simplest method is collecting field data through surveys and

455 multiplying each identified source by an emission factor (EF) . For example, official estimates

456 in several countries have been done using livestock numbers and amount of N fertilisers

457 sold per year, multiplying these values by an average EF for each type of livestock and

458 fertiliser . To achieve more accurate results, further developments added more variables to

459 the models because the NH$_3$ emission rate is affected by temperature, wind speed, air

460 humidity, soil type, slurry pH, among others . Specific EF have been developed for each

461 individual emission source with information such as manure management system, housing

462 facilities and season . The official NH$_3$ emission estimates in China include sources like

463 livestock excreta, fertiliser application, type of agricultural soil, nitrogen-fixing plants, crop

464 residue compost, biomass burning, urine from rural populations, chemical industry, waste

465 disposal and traffic . The EFs are disaggregated both spatially and temporally according to
466 the climatic conditions and local practices across the country. The next step increasing
467 complexity and accuracy is inferring NH$_3$ emissions combining survey data with atmospheric
468 dispersion models. This type of approach has demonstrated that is possible to estimate, with
469 reasonable low bias, NH$_3$ emissions from different sources across large areas with high
470 resolution .

471

472 **4.2.2. Emission inventories**

473 Collecting data through farm surveys make the information independent from (subjective)
474 expert judgment. The use of farm surveys to collect field data is an affordable method to
475 populate NH$_3$ inventories that are critical to evaluate policy changes in the agricultural sector
476 and to verify compliance to international agreements . However, these inventories suffer
477 from a number of inadequacies: i) poor spatial resolution, few measurements for large areas,
478 leading generally to overestimations for non-agricultural zones and underestimations for
479 emissions from farms; ii) poor temporal resolution, long term values underestimating the
480 fertiliser application season; and iii) EFs are not specific for each source, average default
481 values are used and several factors are left out of calculations .

482

483 **4.2.3. Monitoring networks and alternative approaches**

484 Higher spatial and temporal resolution and more reliable data are obtained adding
485 measurements collected by sensors that are used to feed dispersion models. Large-area
486 measurements are performed with commercial passive samplers , calibrated monthly
487 against NH$_3$ active sampling devices . An example using a combination of the dispersion
488 model Fine Resolution NH$_3$ Exchange (FRAME) and a network of passive diffusion samplers
489 is the NH$_3$ emission monitoring in the UK . FRAME describes the main atmospheric
490 processes (emission, diffusion, chemistry and deposition) taking place in a column of air
491 moving along straight-line trajectories following specified wind directions, taking into account
492 also the transboundary chemical composition imported from other areas of Europe . Adding

23

493 more variables to the calculations like the size and shape of the source, the locations of
494 targets, the dynamics and magnitude of each source, the meteorological conditions, the
495 background concentration and a set of passive diffusion sensors which integrate over a few
496 hours to weekly periods helped improving the accuracy of the estimates of NH_3 emissions
497 from multiple small fields located near each other . Several passive and active samplers
498 have been placed across countries to establish NH_3 monitoring networks including: the UK
499 (NAMN, National Ammonia Monitoring Network) , the Netherlands (MAN, Measuring
500 Ammonia in Nature) , Switzerland , the United States (AMoN, Ammonia Monitoring Network)
501 and Ireland . The main aim of the networks is to monitor national trends, to assess regional
502 variability and to validate model calculations.

503 Traditional monitoring networks can be expensive, thus, a solution to poor temporal and
504 spatial resolution can be crowdsourced information involving citizens in monitoring . Citizen
505 science projects have become important data sources to scientists, and an attempt to
506 estimate NH_3 concentration from butterflies abundance has been published in a recent study
507 . Others biomonitors can be used to provide valuable spatial information, like biodiversity
508 measures such as lichen surveys .

509

510 **4.2.4. Communication technologies and monitoring**

511 The national inventories of NH_3 emissions can be improved with further developments in
512 low-cost portable devices based on the techniques mentioned in the previous Section 4.1.
513 Nowadays, there is a class of wireless network technologies that enable low power
514 consumption and wide area coverage (LPWANs - Low Power Wide Area Networks) such as
515 Sigfox or LoRa technologies that fit the need of large-area deployments of NH_3 sensors.
516 Usually, these technologies have low-rate sporadic communications under unlicensed
517 frequency bands, obtaining long distance links, normally 5 km in urban or over 25 km in rural
518 or suburban areas . The use of these communication technologies together with sensitive
519 sensors could be next upgrade to national inventories and NH_3 monitoring giving a better
520 temporal resolution.

5. Future NH$_3$ sensing requirements

There is great potential for NH$_3$ sensing technology to contribute to both improving inventories and to the design of emission mitigation strategies. The next generation of sensors has to specifically monitor sources to avoid the harmful effects of NH$_3$ and to help improve the efficiency in N use in the agroindustry. The deployment of appropriate sensors can support data collection to be used for:

i)   Improving the formulation of livestock diets. Urea excretion and subsequent NH$_3$ emissions increase with increased dietary crude protein concentration.

ii)   Developing urea hydrolysis inhibitors, and investigating the effects of other mitigation strategies for NH$_3$ emissions like soil pH control or irrigation after fertilising.

iii) Improving fertilising practices to maximize the N fertiliser value and improving manure management. The magnitude of NH$_3$ losses depends on both weather and management practices so, improving the knowledge of the factors affecting NH$_3$ emissions will help to develop better practices.

iv)   Prompt decision making using real-time data, which is important for corrective actions such as switching on automatic water sprays or ventilation fans when a maximum threshold is reached in livestock housing.

v)   Monitoring and detecting emission sources. NH$_3$ emitted could impair soil, air and water quality by contributing to over-fertilisation, acidity and formation of particulate matter (PM). Monitoring networks can generate long-term emission trends, which are critical for environmental policies . Regulations could be designed for minimum distances between precursor sources. Data from NH$_3$ monitoring networks are transforming the way that we understand and model the natural environment.

Ammonia emissions are indeed an important problem for society, where the dominant source is agriculture, creating not only an environmental problem but also nutrient losses

549 that affect the efficiency of the agroindustry. Developments in NH_3 monitoring can contribute

550 in several ways to mitigate these emissions by improving inventories to set international

551 targets and by forecasting future trajectories of the contribution from the agroindustry to

552 improve farm efficiency. Future monitoring systems built by simple and easy-to-deploy

553 sensors that sample and accumulate ammonia signals over representative periods (e.g. 1-4

554 weeks) can be used to scope farm ammonia performance in sensitive environments. These

555 systems do not need to be highly accurate but they do need to resolve individual farms or

556 significant sources e.g. passive directional samplers located up- and down- wind of intensive

557 livestock buildings. These systems should be deployable by non-specialists, who can send

558 samples to central laboratories for analysis and interpretation.

559

560 The current recommendations in the livestock industry are to avoid alkaline environments for

561 ammonium (pH >9.25), maintaining low temperature and avoiding air exchange in the

562 superficial layer of manure (NH_3 vapour equilibrium). Nevertheless, every farm has its own

563 characteristics in terms of climate, soil condition, type of manure, fertiliser applied, farm

564 facilities and equipment, etc. So, weather data acquisition is essential for interpreting air-

565 quality data, and can be either measured or extracted from numerical weather prediction

566 models. Tailored advice on manure and fertiliser management, and on livestock diets will

567 have an important impact on nutrient balances in order to avoid unnecessary costs. There is

568 also a need for activity data to be collected and reported alongside air quality data, so the

569 data can be interpreted and attributed to specific activities.

570

571 Currently and despite advances in monitoring devices, direct measurements at each

572 farmyard and plot are impractical due to the cost and labour involved. Additional research is

573 needed to extend cost-effective monitoring to large areas. An important contribution could be

574 the use of wireless technology to connect sensors to make large deployments without

575 human intervention during long periods of time. In addition, the air produced in agriculture

576 environments is a mixture of a large number of gases plus relatively high moisture content.

577   Some of the currently available sensors are prone to have severe interferences since they

578   are sensitive to water vapour and other gases than NH_3. Therefore there is a need for new

579   measurement methods customized for agriculture environments, where interferences are

580   correctly calibrated. Future sensors should provide multivariate signals about the target

581   compounds and interferences, for the application of statistical modelling.

582

583   **6. Conclusions**

584   Agricultural emissions of NH_3 are primarily associated with livestock production where the

585   losses are notably high and there is a pressing need for new developments so that farmers

586   monitor and control NH_3 emissions from fertiliser use. New user-friendly sensors are needed

587   with enough sensitivity for monitoring low concentration (ppb). For this purpose,

588   spectroscopic sensors can provide appropriately selective and sensitive measurements

589   because the spectra from these sensors usually include information that allows interferences

590   to be removed or reduced. Also, spectroscopic sensors can be automated and miniaturized

591   to create low-cost sensors that offer real-time data for day-to-day decisions on ammonia

592   control. The key improvements required in electrochemical sensors are better sensitivity and

593   the development of sensing materials that work at room temperature. Photoacoustic sensors

594   require new advances in electronics to lower their cost. It can be concluded that there is an

595   immediate need of sensors that are more sensitive, selective, low-cost and user-friendly.

596   Sensors must be capable of dealing with the high interferences arising in agricultural

597   environments. Above all, there is an urgent need for new sensors to support the optimal use

598   of N in agriculture so that nutrient pollution in the troposphere is minimised.

599

27

603 the financial contribution of the Argentinean National Research Council (CONICET),

604 Universidad Nacional del Sur, Lancaster University and UK Environmental Agency.

605

606 **Conflict of interest**

607 None.

608

609 **Disclaimer**

610 The views expressed are those of the authors and not necessarily those of the UK

611 Environment Agency.

612

613 **References**

614

615 Ates, M., 2013. A review study of (bio) sensor systems based on conducting polymers. J

616 Materials Science and Engineering 33(4): 1853-1859.

617 ATSDS, 2004. Agency for Toxic Substances and Disease Registry . Public health statement

618 - Ammonia CAS 7664-41-7**:** 1-7.

619 Ayres, J., 2009. Long-term exposure to air pollution: effect on mortality. Didcot: Committee

620 on the Medical Effects of Air Pollutants: 1-187.

621 Azcarate, S., A. de Araújo Gomes, A. M. de la Peña and H. C. Goicoechea, 2018. Modeling

622 second-order data for classification issues: Data characteristics, algorithms, processing

623 procedures and applications. TrAC Trends in Analytical Chemistry(107): 151-168.

624 Bai, H. and G. Shi, 2007. Gas sensors based on conducting polymers. Sensors 7(3): 267-

625 307.

626   Baskar, C., N. Nesakumar, J. B. B. Rayappan and M. Doraipandian, 2017. A low power
627   ammonia sensor node embedded with a light weight non-linear analytics. Sensors Actuators
628   A: Physical 263: 357-362.

629   Battye, R., W. Battye, C. Overcash and S. Fudge, 1994. Development and selection of
630   ammonia emission factors. EPA, US. U. EPA. US, Atmospheric Research and Exposure
631   Assessments Laboratory.

632   Behera, S. N. and M. Sharma, 2010. Investigating the potential role of ammonia in ion
633   chemistry of fine particulate matter formation for an urban environment. Science of the Total
634   Environment 408(17): 3569-3575.

635   Bell, M., C. Flechard, Y. Fauvel, C. Häni, J. Sintermann, M. Jocher, H. Menzi, A. Hensen
636   and A. Neftel, 2017. Ammonia emissions from a grazed field estimated by miniDOAS
637   measurements and inverse dispersion modelling. Atmospheric Measurement Techniques
638   10(5): 1875-1892.

639   Bhopate, D., K. Kim, P. Mahajan, A. Gore, S. Patil and S. Majhi, 2017. Fluorescent
640   chemosensor for quantitation of multiple atmospheric gases. Journal of Nanomed
641   Nanotechnology 8(2): 1-9.

642   Bicudo, J. R., C. L. Tengman, L. D. Jacobson and J. E. Sullivan, 2000. Odor, hydrogen
643   sulfide and ammonia emissions from swine farms in Minnesota. Proceedings of the Water
644   Environment Federation 2000(3): 589-608.

645   Bittman, S., M. Dedina, C. Howard, O. Oenema and M. Sutton, 2014. Options for ammonia
646   mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen, NERC/Centre for
647   Ecology & Hydrology.

648   Bittman, S. and R. Mikkelsen, 2009. Ammonia emissions from agricultural operations:
649   livestock. Better Crops 93(1): 28-31.

Bor, M., J. E. Vidler and U. Roedig, 2016. LoRa for the Internet of Things. Proceedings of the 2016 International Conference on Embedded Wireless Systems and Networks (EWSN '16), TU Graz, Austria.

Bor, M. C., U. Roedig, T. Voigt and J. M. Alonso, 2016. Do LoRa low-power wide-area networks scale? Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, ACM.

Bouwman, A., D. Lee, W. Asman, F. Dentener, K. Van Der Hoek and J. Olivier, 1997. A global high-resolution emission inventory for ammonia. Global Biogeochemical Cycles 11(4): 561-587.

Brigden, K. and R. Stringer, 2000. Ammonia and urea production: Incidents of ammonia release from the Profertil urea and ammonia facility, Bahia Blanca, Argentina 2000. Greenpeace reports. S. p. A. Tour. Exeter UK, Greenpeace Research Laboratories, Department of Biological Sciences, University of Exeter, Exeter, UK**: 1-13.

Brink, C. and H. Van Grinsven, 2011. Costs and benefits of nitrogen in the environment. The European Nitrogen Assessment: Sources, Effects and Policy Perspectives. M. Sutton, C. M. Howard, J. W. Erisman et al.**: 513-540.

Cape, J., L. Van der Eerden, L. Sheppard, I. Leith and M. Sutton, 2009. Evidence for changing the critical level for ammonia. Environmental Pollution 157(3): 1033-1037.

Carozzi, M., R. M. Ferrara, M. Acutis and R. G., 2012. Dynamic of ammonia emission from urea spreading in Po Valley (Italy): relationship with nitrogen compounds in the soil. Proceeding of 17th International Nitrogen Workshop. Wexford, 26-29 June 2012.

Changwen, D., W. Jiao, Z. Zijun, S. Yazhen and Z. Jianmin, 2015. In situ measurement of ammonia concentration in soil headspace using Fourier transform mid-infrared photoacoustic spectroscopy. Journal of Pedosphere 25(4): 605-612.

Chen, X., L. Lin, P. Li, Y. Dai and X. Wang, 2004. Fluorescent response of sol–gel derived ormosils for optical ammonia sensing film. Analytica Chimica Acta 506(1): 9-15.

676   Chen, Y., Q. Zhang and D. Petkau, 2001. Evaluation of different techniques for liquid
677   manure application on grassland. Applied Engineering in Agriculture 17(4): 489.

678   Cho, Y. B., S. H. Jeong, H. Chun and Y. S. Kim, 2018. Selective colorimetric detection of
679   dissolved ammonia in water via modified Berthelot's reaction on porous paper. Sensors
680   Actuators B: Chemical 256: 167-175.

681   Darwish, A. M., S. Wilson, A. Balckwell, K. Taylor, S. S. Sarkisov, D. N. Patel and B. Koplitz,
682   2015. Ammonia sensor based on polymer-inorganic nano-composite thin film upconversion
683   light emitter prepared by double-beam pulsed laser deposition. American Journal of
684   Materials Science 5(3A): 8-15.

685   Das, P., J.-H. Sa, K.-H. Kim and E.-C. Jeon, 2009. Effect of fertilizer application on ammonia
686   emission and concentration levels of ammonium, nitrate, and nitrite ions in a rice field.
687   Environmental monitoring and assessment 154(1-4): 275-282.

688   Dasari, B., W. Taube, P. Agarwal, M. Rajput, A. Kumar and J. Akhtar, 2015. Room
689   Temperature Single Walled Carbon Nanotubes (SWCNT) Chemiresistive Ammonia Gas
690   Sensor Sensors and Transducers 190(7): 24-30.

691   Daughton, C., J. Cantor, M. Jones and R. Sakaji, 1982. Chapter III - Ammonia determination

692   Quantitation of oil shale wastewater quality. A manual of analytical methods. C. Daughton.
693   Berkeley, USA, University of California.

694   DEFRA, 2018. Code of Good Agricultural Practice (COGAP) for Reducing Ammonia
695   Emissions. London TW9 4DU, Department for Environment Food & Rural Affairs, UK
696   Government.

697   Denmead, O., J. Freney and J. Simpson, 1983. Dynamics of ammonia volatilization during
698   furrow irrigation of maize. Soil Science Society of America Journal 47(3)

699   Denmead, O., J. Simpson and J. Freney, 1974. Ammonia flux into the atmosphere from a
700   grazed pasture. Science 185(4151): 609-610.

701   Dewey, C. E., B. Cox and J. Leyenaar, 2000. Measuring ammonia concentrations in the barn
702   using the Draeger (TM) and pHydrion (TM) tests. Journal of Swine Health and Production
703   8(3): 127-131.

704   Djambazov, G. and K. Pericleous, 2015. Modelled atmospheric contribution to nitrogen
705   eutrophication in the English Channel and the southern North Sea. Atmospheric
706   Environment 102: 191-199.

707   Dore, A., D. Carslaw, C. Braban, M. Cain, C. Chemel, C. Conolly, R. Derwent, S. Griffiths, J.
708   Hall and G. Hayman, 2015. Evaluation of the performance of different atmospheric chemical
709   transport models and inter-comparison of nitrogen and sulphur deposition estimates for the
710   UK. Atmospheric Environment 119: 131-143.

711   Doyle, B., T. Cummins, C. Augustenborg and J. Aherne, 2014. Ambient Atmospheric
712   Ammonia in Ireland, 2013-2014. Environmental Protection Agency of Ireland, report(193).

713   Dumitras, D., D. Dutu, C. Matei, A. Magureanu, M. Petrus and C. Popa, 2007. Laser
714   photoacoustic spectroscopy: principles, instrumentation, and characterization. Journal of
715   Optoelectronics Advanced Materials 9(12): 3655.

716   EAA, 2014. European Environment Agency. Ammonia (NH3) emissions. European
717   Environment Agency Retrieved 02/01/2019, 2019, from http://www.eea.europa.eu/data-and-
718   maps/indicators/eea-32-ammonia-nh3-emissions-1/assessment-4.

719   EAA, 2016. National Emission Ceilings Directive. European Environment Agency. Denmark,
720   European Environment Agency.

721   EPA, 2016. U.S. Environmental Protection Agency. Toxicological Review of Ammonia
722   (EPA/635/R-16/163Fa). Integrated Risk Information System. Washington, DC.

723   EUROSTAT, 2016. Agriculture, forestry and fishery statistics. Belgium, European Union,
724   2016.

725 Fan, H., Z. Peng, H. Yang and K. Zhou, 2016. A new cataluminescence-based gas sensor
726 for simultaneously discriminating benzene and ammonia. Analytical Methods 8(6): 1257-
727 1264.

728 Feng, L., C. J. Musto, J. W. Kemling, S. H. Lim, W. Zhong and K. S. Suslick, 2010.
729 Colorimetric sensor array for determination and identification of toxic industrial chemicals.
730 Analytical Chemistry 82(22): 9433-9440.

731 Fenn, L. and L. Hossner, 1985. Ammonia volatilization from ammonium or ammonium-
732 forming nitrogen fertilizers. Advances in Soil Science **:** 123-169.

733 Ferrara, R. M., M. Carozzi, P. Di Tommasi, D. D. Nelson, G. Fratini, T. Bertolini, V. Magliulo,
734 M. Acutis and G. Rana, 2016. Dynamics of ammonia volatilisation measured by eddy
735 covariance during slurry spreading in north Italy. Agriculture, Ecosystems Environment 219:
736 1-13.

737 Fitzpatrick, R. B., 2004. Haz-Map: information on hazardous chemicals and occupational
738 diseases. Medical Reference Services Quarterly 23(2): 49-56.

739 Fournier, N., V. A. Pais, M. A. Sutton, K. J. Weston, U. Dragosits, S. Y. Tang and J. Aherne,
740 2002. Parallelisation and application of a multi-layer atmospheric transport model to quantify
741 dispersion and deposition of ammonia over the British Isles. Environmental Pollution 116(1):
742 95-107.

743 Ganiga, M. and J. Cyriac, 2016. FRET based ammonia sensor using carbon dots. Sensors
744 and Actuators B: Chemical 225: 522-528.

745 García, M. S., R. Timmis, N. Van Dijk, J. Whyatt, I. Leith, S. Leeson, C. Braban, L.
746 Sheppard, M. Sutton and Y. Tang, 2017. Directional passive ambient air monitoring of
747 ammonia for fugitive source attribution; a field trial with wind tunnel characteristics.
748 Atmospheric Environment 167: 576-585.

749 Goebes, M. D., R. Strader and C. Davidson, 2003. An ammonia emission inventory for
750 fertilizer application in the United States. Atmospheric Environment 37(18): 2539-2550.

751 Guimard, N. K., N. Gomez and C. E. Schmidt, 2007. Conducting polymers in biomedical

752 engineering. Progress in Polymer Science 32(8-9): 876-921.

753 Guthrie, S., S. Giles, F. Dunkerley, H. Tabaqchali, A. Harshfield, B. Ioppolo and C. Manville,

754 2018. The impact of ammonia emissions from agriculture on biodiversity. JOURNAL?

755 Harper, L., V. Catchpoole, R. Davis and K. Weir, 1983. Ammonia Volatilization: Soil, Plant,

756 and Microclimate Effects on Diurnal and Seasonal Fluctuations 1. Agronomy Journal 75(2):

757 212-218.

758 Harper, L. A., R. R. Sharpe and T. B. Parkin, 2000. Gaseous nitrogen emissions from

759 anaerobic swine lagoons: Ammonia, nitrous oxide, and dinitrogen gas. Journal of

760 Environmental Quality 29(4): 1356-1365.

761 Horswill, P., O. O'Sullivan, G. K. Phoenix, J. A. Lee and J. R. Leake, 2008. Base cation

762 depletion, eutrophication and acidification of species-rich grasslands in response to long-

763 term simulated nitrogen deposition. Environmental Pollution 155(2): 336-349.

764 Hu, J., L. Zhang and Y. Lv, 2018. Recent advances in cataluminescence gas sensor:

765 Materials and methodologies. Applied Spectroscopy Reviews (VOL?): 1-19.

766 Huang, X., Y. Song, M. Li, J. Li, Q. Huo, X. Cai, T. Zhu, M. Hu and H. Zhang, 2012. A

767 high-resolution ammonia emission inventory in China. Global Biogeochemical Cycles 26(1).

768 Huszár, H., A. Pogány, Z. Bozóki, Á. Mohácsi, L. Horváth and G. Szabó, 2008. Ammonia

769 monitoring at ppb level using photoacoustic spectroscopy for environmental application.

770 Sensors Actuators B: Chemical 134(2): 1027-1033.

771 Ibanez, J. G., M. E. Rincón, S. Gutierrez-Granados, M. h. Chahma, O. A. Jaramillo-Quintero

772 and B. A. Frontana-Uribe, 2018. Conducting polymers in the fields of energy, environmental

773 remediation, and chemical–chiral sensors. Chemical reviews 118(9): 4731-4816.

774 Jalalvand, A. R., M. Roushani, H. C. Goicoechea, D. N. Rutledge and H.-W. Gu, 2018.

775 MATLAB in electrochemistry: A review. Talanta. INCOMPLETE

34

776 Jin, Z., Y. Su and Y. Duan, 2001. Development of a polyaniline-based optical ammonia
777 sensor. Sensors and Actuators B: Chemical 72(1): 75-79.

778 Kelleghan, D. B., E. T. Hayes, M. Everard and T. P. Curran, 2019. Mapping ammonia risk on
779 sensitive habitats in Ireland. Science of the Total Environment 649: 1580-1589.

780 Khan, E. A., 2016. Dap-1 ammonia tank explosion: safety and security concerns in chemical
781 process plant in Bangladesh. International Journal of Petrochemical Science & Engineering
782 1(1): 10-11.

783 Khan, M. A., F. Qazi, Z. Hussain, M. U. Idrees, S. Soomro and S. Soomro, 2017. Recent
784 Trends in Electrochemical Detection of NH3, H2S and NOx Gases. International Journal of
785 Electrochemical Science 12(3): 1711-1733.

786 Koerkamp, P. G., J. Metz, G. Uenk, V. Phillips, M. Holden, R. Sneath, J. Short, R. White, J.
787 Hartung and J. Seedorf, 1998. Concentrations and emissions of ammonia in livestock
788 buildings in Northern Europe. Journal of Agricultural Engineering Research 70(1): 79-95.

789 Lakowicz, J. R., 1999. Instrumentation for fluorescence spectroscopy. Principles of
790 fluorescence spectroscopy, Springer**:** 25-61.

791 Lau, K. T., S. Edwards and D. Diamond, 2004. Solid-state ammonia sensor based on
792 Berthelot's reaction. Sensors and Actuators B: Chemical 98(1): 12-17.

793 Lavrsen Kure, J., J. Krabben, S. Vilms Pedersen, M. Carozzi and S. Sommer, 2018. An
794 Assessment of Low-Cost Techniques to Measure Ammonia Emission from Multi-Plots: A
795 Case Study with Urea Fertilization. Agronomy Journal 8(11): 245.

796 Le Maout, P., J.-L. Wojkiewicz, N. Redon, C. Lahuec, F. Seguin, L. Dupont, S. Mikhaylov, Y.
797 Noskov, N. Ogurtsov and A. Pud, 2018. Polyaniline nanocomposites based sensor array for
798 breath ammonia analysis. Portable e-nose approach to non-invasive diagnosis of chronic
799 kidney disease. Sensors and Actuators B: Chemical 274: 616-626.

800 Lei, J., C. Hou, D. Huo, Y. Li, X. Luo, M. Yang, H. Fa, M. Bao, J. Li and B. Deng, 2016.

801 Detection of ammonia based on a novel fluorescent artificial nose and pattern recognition.

802 Atmospheric Pollution Research 7(3): 431-437.

803 Li, H., C. Zhang and H. Xin, 2015. Performance of an infrared Photoacoustic single gas

804 analyzer in measuring ammonia from poultry houses. Applied Engineering in Agriculture

805 31(3): 471-477.

806 Li, X., X. Li, Z. Li, J. Wang and J. Zhang, 2017. WS2 nanoflakes based selective ammonia

807 sensors at room temperature. Sensors Actuators B: Chemical 240: 273-277.

808 Lolkema, D., H. Noordijk, A. Stolk, R. Hoogerbrugge, M. van Zanten and W. van Pul, 2015.

809 The measuring ammonia in nature (MAN) network in the Netherlands. Biogeosciences

810 12(16): 5133-5142.

811 Loubet, B., M. Carozzi, P. Voylokov, J.-P. Cohan, R. Trochard and S. Génermont, 2018.

812 Evaluation of a new inference method for estimating ammonia volatilisation from multiple

813 agronomic plots. Biogeosciences 15(11): 3439.

814 Maciak, E. and T. Pustelny, 2013. An optical ammonia (NH3) gas sensing by means of

815 Pd/CuPc interferometric nanostructures based on white light interferometry. Sensors

816 Actuators B: Chemical 189: 230-239.

817 Manap, H., G. Dooly, S. O'Keeffe and E. Lewis, 2011. Cross-sensitivity evaluation for

818 ammonia sensing using absorption spectroscopy in the UV region. Sensors Actuators B:

819 Chemical 154(2): 226-231.

820 McGinn, S., H. Janzen, T. Coates, K. Beauchemin and T. Flesch, 2016. Ammonia emission

821 from a beef cattle feedlot and its local dry deposition and re-emission. Journal of

822 Environmental Quality 45(4): 1178-1185.

823 Meng, Z.-Y., X.-B. Xu, T. Wang, X.-Y. Zhang, X.-L. Yu, S.-F. Wang, W.-L. Lin, Y.-Z. Chen,

824 Y.-A. Jiang and X.-Q. An, 2010. Ambient sulfur dioxide, nitrogen dioxide, and ammonia at

ten background and rural sites in China during 2007–2008. Atmospheric Environment 44(21-22): 2625-2631.

Mikkelsen, R., 2009. Ammonia emissions from agricultural operations: fertilizer. Better Crops 93(4): 9-11.

Miles, D., 2008. Vertical stratification of ammonia in a broiler house. Journal of Applied Poultry Research 17(3): 348-353.

Mills, A., L. Wild and Q. Chang, 1995. Plastic colorimetric film sensors for gaseous ammonia. Microchimica Acta 121(1-4): 225-236.

Misselbrook, T., S. Gilhespy, L. Cardenas, J. Willimas and U. Dragosits, 2015. Inventory of Ammonia Emissions from UK, Agriculture. 2014. UK., DEFRA. Department for Environment, Food and Rural Affairs.

Moum, S. G., W. Seltzer and T. M. Goldhaft, 1969. A simple method of determining concentrations of ammonia in animal quarters. Poultry Science 48(1): 347-348.

Mount, G. H., B. Rumburg, J. Havig, B. Lamb, H. Westberg, D. Yonge, K. Johnson and R. Kincaid, 2002. Measurement of atmospheric ammonia at a dairy using differential optical absorption spectroscopy in the mid-ultraviolet. Atmospheric Environment 36(11): 1799-1810.

Mukhtar, S., A. Rose, S. Capareda, C. Boriack, R. Lacey, B. Shaw and C. Parnell, 2003. Assessment of ammonia adsorption onto Teflon and LDPE tubing used in pollutant stream conveyance.

Naseem, S. and A. J. King, 2018. Ammonia production in poultry houses can affect health of humans, birds, and the environment—techniques for its reduction during poultry production. Environmental Science Pollution Research: 1-25.

Ni, J.-Q. and A. J. Heber, 1998. Sampling and measurement of ammonia concentration at animal facilities–A review. 2001 ASAE Annual Meeting, American Society of Agricultural and Biological Engineers.

850 Ni, J.-Q. and A. J. Heber, 2008. Sampling and measurement of ammonia at animal facilities.

851 Advances in Agronomy 98: 201-269.

852 NRC, 2003. National Research Council. Air emissions from animal feeding operations:

853 Current knowledge, future needs. National Academies Press.

854 Oenema, O., H. Witzke, Z. Klimont, J. Lesschen and G. Velthof, 2009. Integrated

855 assessment of promising measures to decrease nitrogen losses from agriculture in EU-27.

856 Agriculture, Ecosystems Environment 133(3-4): 280-288.

857 Pan, B., S. K. Lam, A. Mosier, Y. Luo and D. Chen, 2016. Ammonia volatilization from

858 synthetic fertilizers and its mitigation strategies: a global synthesis. Agriculture, Ecosystems

859 Environment 232: 283-289.

860 Pavlovic, R. T., U. Nopmongcol, Y. Kimura and D. T. Allen, 2006. Ammonia emissions,

861 concentrations and implications for particulate matter formation in Houston, TX. Atmospheric

862 Environment 40: 538-551.

863 Phan, N.-T., K.-H. Kim, Z.-H. Shon, E.-C. Jeon, K. Jung and N.-J. Kim, 2013. Analysis of

864 ammonia variation in the urban atmosphere. Atmospheric Environment 65: 177-185.

865 Puchalski, M. A., M. E. Sather, J. T. Walker, C. M. Lehmann, D. A. Gay, J. Mathew and W.

866 P. Robarge, 2011. Passive ammonia monitoring in the United States: Comparing three

867 different sampling devices. Journal of Environmental Monitoring 13(11): 3156-3167.

868 Pushkarsky, M., M. Webber and C. Patel, 2003. Ultra-sensitive ambient ammonia detection

869 using CO 2-laser-based photoacoustic spectroscopy. Applied Physics B 77(4): 381-385.

870 Reche, C., M. Viana, M. Pandolfi, A. Alastuey, T. Moreno, F. Amato, A. Ripoll and X. Querol,

871 2012. Urban NH3 levels and sources in a Mediterranean environment. Atmospheric

872 Environment 57: 153-164.

873   Reidy, B., B. Rhim and H. Menzi, 2008. A new Swiss inventory of ammonia emissions from

874   agriculture based on a survey on farm and manure management and farm-specific model

875   calculations. Atmospheric Environment 42(14): 3266-3276.

876   Rosenstock, T. S., E. Diaz-Pines, P. Zuazo, G. Jordan, M. Predotova, P. Mutuo, S.

877   Abwanda, M. Thiong'o, A. Buerkert and M. C. Rufino, 2013. Accuracy and precision of

878   photoacoustic spectroscopy not guaranteed. Global Change Biology 19(12): 3565-3567.

879   Rostami, M., S. Monaco, D. Sacco, C. Grignani and E. Dinuccio, 2015. Comparison of

880   ammonia emissions from animal wastes and chemical fertilizers after application in the soil.

881   International Journal of Recycling of Organic Waste in Agriculture 4(2): 127-134.

882   RoTAP., 2012. Review of Transboundary Air Pollution (RoTAP): Acidification,

883   Eutrophication, Ground Level Ozone and Heavy Metals in the UK: Summary for Policy

884   Makers, Centre for Ecology & Hydrology.

885   Sather, M. E., J. Mathew, N. Nguyen, J. Lay, G. Golod, R. Vet, J. Cotie, T. Hertel, E. Aaboe

886   and R. Callison, 2008. Baseline ambient gaseous ammonia concentrations in the Four

887   Corners area and eastern Oklahoma, USA. Journal of Environmental Monitoring 10(11):

888   1319-1325.

889   Schilt, S., L. Thévenaz, M. Niklès, L. Emmenegger and C. Hüglin, 2004. Ammonia

890   monitoring at trace level using photoacoustic spectroscopy in industrial and environmental

891   applications. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 60(14):

892   3259-3268.

893   Schroeck, A. M., V. Gaube, E. Haas and W. Winiwarter, 2019. Estimating nitrogen flows of

894   agricultural soils at a landscape level–A modelling study of the Upper Enns Valley, a long-

895   term socio-ecological research region in Austria. Science of The Total Environment 665:

896   275-289.

897   Shankar, P. and J. B. B. Rayappan, 2015. Gas sensing mechanism of metal oxides: The role

898   of ambient atmosphere, type of semiconductor and gases-A review. Sci. Lett. J 4: 126.

899   Sheikh, I., S. Nissa, B. Zaffer, K. Bulbul, A. Akand, H. Ahmed, D. Hasin, I. Hussain and S.

900   Hussain, 2018. Ammonia production in the poultry houses and its harmful effects.

901   International Journal of Veterinary Sciences and Animal Husbandry 3(4): 30-33.

902   Sheppard, L. J., I. D. Leith, T. Mizunuma, J. Neil Cape, A. Crossley, S. Leeson, M. A. Sutton,

903   N. van Dijk and D. Fowler, 2011. Dry deposition of ammonia gas drives species change

904   faster than wet deposition of ammonium ions: evidence from a long-term field manipulation.

905   Global Change Biology 17(12): 3589-3607.

906   Sigrist, M. W., 2015. Mid-infrared laser-spectroscopic sensing of chemical species. Journal

907   of Advanced Research 6(3): 529-533.

908   Silva, S. O., R. Magalhães, M. Marques and O. Frazão, 2016. New advances in fiber cavity

909   ring-down technology. Optics Laser Technology 78: 115-119.

910   Singles, R., M. Sutton and K. Weston, 1998. A multi-layer model to describe the atmospheric

911   transport and deposition of ammonia in Great Britain. Atmospheric Environment 32(3): 393-

912   399.

913   Sintermann, J., C. Ammann, U. Kuhn, C. Spirig, R. Hirschberger, A. Gärtner and A. Neftel,

914   2011. Determination of field scale ammonia emissions for common slurry spreading practice

915   with two independent methods. Atmospheric Measurement Techniques 4(9): 1821-1840.

916   Sommer, S. G., J. E. Olesen and B. T. Christensen, 1991. Effects of temperature, wind

917   speed and air humidity on ammonia volatilization from surface applied cattle slurry. The

918   Journal of Agricultural Science 117(1): 91-100.

919   Šraj, L. O. C., M. I. G. Almeida, S. E. Swearer, S. D. Kolev and I. D. McKelvie, 2014.

920   Analytical challenges and advantages of using flow-based methodologies for ammonia

921   determination in estuarine and marine waters. TrAC Trends in Analytical Chemistry 59: 83-

922   92.

923   Strömberg, N. and S. Hulth, 2001. An ammonium selective fluorosensor based on the

924   principles of coextraction. Analytica Chimica Acta 443(2): 215-225.

925 Sun, K., L. Tao, D. J. Miller, M. A. Zondlo, K. B. Shonkwiler, C. Nash and J. M. Ham, 2015.

926 Open-path eddy covariance measurements of ammonia fluxes from a beef cattle feedlot.

927 Agricultural and Forest Meteorology 213: 193-202.

928 Sutton, M., Y. Tang, B. Miners and D. Fowler, 2001. A new diffusion denuder system for

929 long-term, regional monitoring of atmospheric ammonia and ammonium. Water, Air and Soil

930 Pollution: Focus 1(5-6): 145-156.

931 Tang, Y., J. Cape and M. Sutton, 2001. Development and types of passive samplers for

932 monitoring atmospheric NO2 and NH3 concentrations. The Scientific World Journal 1: 513-

933 529.

934 Tang, Y. S., U. Dragosits, N. van Dijk, L. Love, I. Simmons and M. A. Sutton, 2009.

935 Assessment of ammonia and ammonium trends and relationship to critical levels in the UK

936 National Ammonia Monitoring Network (NAMN). Atmospheric Ammonia, Springer: 187-194.

937 Tang, Z., J. Yang, J. Yu and B. Cui, 2010. A colorimetric sensor for qualitative discrimination

938 and quantitative detection of volatile amines. Sensors 10(7): 6463-6476.

939 Tanguy, N. R., M. Thompson and N. Yan, 2018. A review on advances in application of

940 polyaniline for ammonia detection. Sensors and Actuators B: Chemical 257: 1044-1064.

941 Tavoli, F. and N. Alizadeh, 2013. Optical ammonia gas sensor based on nanostructure dye-

942 doped polypyrrole. Sensors and Actuators B: Chemical 176: 761-767.

943 The Royal Society, 2018. The impact of ammonia emissions from agriculture on biodiversity.

944 RAND Europe. S. Guthrie, S. Giles, F. Dunkerley et al. Cambridge, UK.

945 Thöni, L., P. Brang, S. Braun, E. Seitler and B. Rihm, 2004. Ammonia monitoring in

946 Switzerland with passive samplers: patterns, determinants and comparison with modelled

947 concentrations. Environmental Monitoring and Assessment 98(1-3): 93-107.

948 Timmer, B., W. Olthuis and A. Van Den Berg, 2005. Ammonia sensors and their

949 applications—a review. Sensors Actuators B: Chemical 107(2): 666-677.

950   Toda, K., J. Li and P. K. Dasgupta, 2006. Measurement of ammonia in human breath with a

951   liquid-film conductivity sensor. Analytical chemistry 78(20): 7284-7291.

952   UK_Government, 2019. The Environmental Permitting (England and Wales) Regulations.

953   from http://www.legislation.gov.uk/.

954   United Nations, E. a. S. C., 2014. Convention on Long-range Transboundary Air Pollution:

955   Guidance document on preventing and abating ammonia emissions from agricultural

956   sources.

957   USHHS, 2004. U.S. Department of Health and Human Services. Toxicological Profile For

958   Ammonia. Agency for Toxic Substances and Disease Registry. P. H. Service. US, U.S.

959   DEPARTMENT OF HEALTH AND HUMAN SERVICES.

960   Vaddella, V., P. Ndegwa, H. Joo and J. J. J. o. e. q. Ullman, 2010. Impact of separating dairy

961   cattle excretions on ammonia emissions. 39(5): 1807-1812.

962   Valente, I. M., H. M. Oliveira, C. D. Vaz, R. M. Ramos, A. J. Fonseca, A. R. Cabrita and J. A.

963   Rodrigues, 2017. Determination of ammonia nitrogen in solid and liquid high-complex

964   matrices using one-step gas-diffusion microextraction and fluorimetric detection. Talanta

965   167: 747-753.

966   Van Damme, M., L. Clarisse, S. Whitburn, J. Hadji-Lazaro, D. Hurtmans, C. Clerbaux and

967   P.-F. Coheur, 2018. Industrial and agricultural ammonia point sources exposed. Nature

968   564(7734): 99.

969   Van der Heyden, C., E. Brusselman, E. Volcke and P. Demeyer, 2016. Continuous

970   measurements of ammonia, nitrous oxide and methane from air scrubbers at pig housing

971   facilities. Journal of Environmental Management 181: 163-171.

972   Vantieghem, P., D. Maes, A. Kaiser and T. Merckx, 2017. Quality of citizen science data and

973   its consequences for the conservation of skipper butterflies (Hesperiidae) in Flanders

974   (northern Belgium). Journal of Insect Conservation 21(3): 451-463.

975 Velthof, G., C. Van Bruggen, C. Groenestein, B. De Haan, M. Hoogeveen and J. Huijsmans,

976 2012. A model for inventory of ammonia emissions from agriculture in the Netherlands.

977 Atmospheric Environment 46: 248-255.

978 Vieno, M., M. Heal, S. Hallsworth, D. Famulari, R. Doherty, A. Dore, Y. Tang, C. Braban, D.

979 Leaver and M. Sutton, 2014. The role of long-range transport and domestic emissions in

980 determining atmospheric secondary inorganic particle concentrations across the UK.

981 Atmospheric Chemistry Physics 14(16): 8435-8447.

982 Waldrip, H., N. Cole and R. Todd, 2015. Nitrogen sustainability and beef cattle feedyards: II.

983 Ammonia emissions. The Professional Animal Scientist 31(5): 395-411.

984 Wang, S., J. Nan, C. Shi, Q. Fu, S. Gao, D. Wang, H. Cui, A. Saiz-Lopez and B. Zhou, 2015.

985 Atmospheric ammonia and its impacts on regional air quality over the megacity of Shanghai,

986 China. Scientific Reports 5: 15842.

987 Wathes, C. M., T. G. Demmers and H. Xin, 2003. Ammonia concentrations and emissions in

988 livestock production facilities: guidelines and limits in the USA and UK. 2003 ASAE Annual

989 Meeting, American Society of Agricultural and Biological Engineers.

990 Webber, M. E., T. MacDonald, M. B. Pushkarsky, C. K. N. Patel, Y. Zhao, N. Marcillac and

991 F. M. Mitloehner, 2005. Agricultural ammonia sensor using diode lasers and photoacoustic

992 spectroscopy. Measurement Science Technology 16(8): 1547.

993 Weeser, B., J. S. Kroese, S. Jacobs, N. Njue, Z. Kemboi, A. Ran, M. Rufino and L. Breuer,

994 2018. Citizen science pioneers in Kenya–A crowdsourced approach for hydrological

995 monitoring. Science of The Total Environment 631: 1590-1599.

996 Wilson, L., P. Bacon, J. Bull, U. Dragosits, T. Blackall, T. Dunn, K. Hamer, M. Sutton and S.

997 Wanless, 2004. Modelling the spatial distribution of ammonia emissions from seabirds in the

998 UK. Environmental Pollution 131(2): 173-185.

999   Wolseley, P. A., P. W. James, M. R. Theobald and M. A. Sutton, 2006. Detecting changes in

1000   epiphytic lichen communities at sites affected by atmospheric ammonia from agricultural

1001   sources. The Lichenologist 38(2): 161-176.

1002   Zhang, D., Z. Wu, P. Li, X. Zong, G. Dong and Y. Zhang, 2018. Facile fabrication of

1003   polyaniline/multi-walled carbon nanotubes/molybdenum disulfide ternary nanocomposite and

1004   its high-performance ammonia-sensing at room temperature. Sensors and Actuators B:

1005   Chemical 258: 895-905.

1006   Zhang, Y. and L.-T. Lim, 2018. Colorimetric array indicator for NH3 and CO2 detection.

1007   Sensors and Actuators B: Chemical 255: 3216-3226.

1008   Zhao, L., R. Manuzon, M. Darr, H. Keener, A. J. Heber and J.-Q. Ni, 2009. Ammonia

1009   emissions from a commercial poultry manure composting facility. Livestock Environment VIII,

1010   31 August–4 September 2008, Iguassu Falls, Brazil, American Society of Agricultural and

1011   Biological Engineers.

1012

1013