

Current Research on Gaseous Ammonia Detecting and Capture Technologies

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Abstract

Ammonia is currently widely used for fertilizers, and it continues to grow as a potential green fuel source or hydrogen carrier which may result in growing ammonia emissions. Increasing anthropogenic ammonia emissions raises concerns such as disrupting the global nitrogen cycle and negating the greenhouse gas reduction. This review article outlines and compiles recent studies on gaseous ammonia detecting and absorption/adsorption, which could alert or reduce rogue emissions, i.e., unintended releases of ammonia. Different sensors and their characteristics are outlined with a focus on the more popular chemoresistive technologies. Several absorption/adsorption methods for ammonia capture using metal-organic frameworks (MOFs) and deep eutectic solvents (DESs) are described and certain research highlighted.

Highlights

- Several chemoresistive style gas sensors show <1 ppm LOD and fast response times (< 1 min)
- New class of DES V show promising absorption capabilities for ammonia
- Computational screening allows the wide field of potential absorbents/adsorbents to be narrowed down to higher potential value options

Keywords

Ammonia; Gas sensor; Metal-Organic Frameworks (MOFs); Deep Eutectic Solvents (DES); Adsorption capacity; Absorption;

Background

Ammonia has been applied in agriculture as a binding site for atmospheric nitrogen to supply nitrogen to crops and is proposed for use as a carbon-free fuel, a hydrogen carrier and an energy vector [1]. Integrating ammonia's use in different sectors was found to be a profitable pathway to use low-carbon ammonia for decarbonization [2]. However, ammonia is also very disruptive to ecosystems being toxic to organisms and causing eutrophication in surface water [3,4]. Ammonia is abundant in a variety of bioprocesses and the atmosphere where it can react to create the toxic ammonium, nitrous oxides (N₂O) and nitrate. N₂O is a potent greenhouse gas that offsets the reduction in greenhouse gases going from carbon-based fuels to ammonia provides [5]. Additionally, particulate matter 2.5 (PM 2.5) are fine particles less than 2.5 microns wide, in which nitrates make up a large portion of this classification. As ammonia is a large contributor to the formation of nitrate; the rapidly growing gaseous ammonia

emissions could increase the amount of PM 2.5 in the air [6]. As the ammonia industry continues to grow with its variety of uses and decarbonization potential, the mitigation and remediation strategies for atmospheric ammonia must grow as well [5]. A variety of technologies have been developed to detect, separate and capture ammonia from leakage, rogue or fugitive emissions, combustion flue gas, and even directly from the atmosphere. This work focuses on recent studies regarding ammonia detection and capture, readers are recommended to visit highlighted reviews that are more comprehensive and cover a further depth of history [7**,8*,9*,10**].

Ammonia Detecting

Ammonia is found to be pungent and noticeable by human smell at about 20 ppm and an occupational hazard at 25 ppm [11]. It quickly becomes impairing at 400 ppm and increasingly fatal beyond 3000 ppm. Ammonia sensing devices are used in many different fields with several intended for indoor use for health and safety [12]. The automotive industry tests vehicles for emission regulation and the health industry uses sensors for breath analysis [9**]. As production of ammonia grows, the need to detect rogue emissions from sites grows concurrently.

Rogue emissions are unintended releases of gaseous pollutants through undetected leaks in the system or pipe failures. They can be environmentally detrimental based on two major characteristics. Firstly, rogue emissions can be very low in concentration, but constantly emitted by a plant for an extended period, resulting in a large total loading into the atmosphere. Secondly, a large amount can escape from a plant unknowingly as ammonia is colourless and only perceptible to humans by odour [13]. Therefore, it is critical to have low limit of detection (LOD) sensors assisting in the first case and quick responding sensors in the second case. Response time is heavily affected by the concentration of the target gas being detected, relative humidity and other environmental factors [14]. Sensors should be tested in similar conditions to where they will be employed for optimal results.

Many recently studied sensors with their response time and LOD are listed in Table 1 below.

Chemoresistive Sensors

Chemoresistive sensors work on the principle that semiconductors have varying resistances and thus conductivity as the target gas adsorbs onto them. At the initial state, oxygen is adsorbed onto the sensor; when the target gas (e.g., ammonia) comes into contact, adsorbed oxygen is replaced by the target gas molecules, resulting in a change in resistance to detect the target gas [12]. Chemoresistive sensors depend on adsorption which is why metals, organic materials and metal-organic frameworks (MOFs) are all studied. Doping is a common technique to increase the performance of chemoresistive sensors by creating impurities which increases the amount of adsorption sites, resulting in a higher detection of the target gas [12]. Nanostructures such as carbon nanotubes are used to increase the adsorption area as well [15].

Metal oxide semiconductor (MOS) gas sensors are widely used due to their ease of production, reliability and fast response times. MOS gas sensors work most optimally in high operating temperatures up to 600°C making them ideal in ammonia production facilities [9,16]. However, their selectivity is not high [9,10,17]. Boomashri et al. [18] worked on a 2% antimony doped tin oxide sensor, which was able to detect ammonia concentrations down to 50 ppm with a response time of 42 seconds. Thomas et al. [19] studied a nanostructure of ZnO with a lower detection range of 5-100 ppm and a response time of 36 seconds at 5 ppm. Agrawal et al. [17] however found that their ZnO sensor was only ~179% more selective to ammonia gas than to carbon monoxide.

Organic semiconductor (OSC) gas sensors work similarly to MOS sensors. Their interactions with gas molecules cause a shift of electrons affecting the concentration of carriers in the sensor [20*]. They tend

to be cheaper compared to their metal oxide counterparts as well as performing well at room temperatures [21]. Yet these benefits are held back by their weak mechanical strength [10**].

Yan et al. [14] created a chemoresistive gas sensor using a MOF of ZIF-8 with carbon nanotubes (ZIF-8/CNT) to develop a sensor with strong resistance to humidity. Ammonia response only begun to falter at 90% relative humidity.

Field-Effect Transistor Sensors

Field-Effect Transistor (FET) sensors can be composed of metal, organic or polymer variants. They operate by having a sensing material as a gate and lowering the threshold voltage when the target gas adsorbs onto the material [22**]. Their excellent stability and low power consumption make them suitable in many fields such as medical diagnostics and industrial safety [8*,22**]. Verma et al. [21] designed an OSC ammonia sensor using P3HT (Poly(3-hexylthiophene-2,5-diyl))/GO (Graphene Oxide) for use in the poultry industry. The sensor was found to respond to very dilute concentrations down to 0.278 ppm with a response time of 44 seconds. The selectivity of the sensor is highly dependent on the characteristics of the metal oxide or organic compound used [10**].

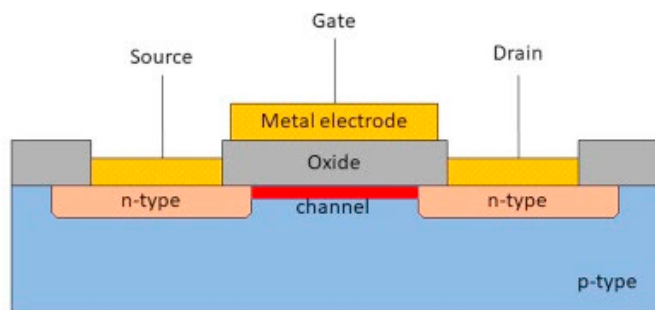


Figure 1. Typical configuration of a MOSFET gas sensor. Electrons try to pass from the source to drain but are trapped by adhered oxygen atoms on the oxide. Ammonia replaces the oxygens freeing the electrons to complete the circuit (Kwak D et al. *Talanta*, 204 (2019) 713–730 © 2019 Elsevier B.V.) [10**].

Quartz Crystal Microbalance Sensors

Quartz Crystal Microbalance (QCM) sensors have become a highly recognized type of detection mechanism used in various analytical and biochemistry fields due to their simple structure and low cost. They operate based on the piezoelectric effect of quartz crystals. A quartz crystal is placed between two electrodes, where it generates vibrations due to the electric field. These vibrations are highly sensitive to changes in small amounts of mass. QCM sensors, when doped with a compatible material, tend to be highly selective towards specific gasses [23*]. Zhang et al. [16] compare their Ti_3C_2Tx QCM sensor to other chemoresistive sensors with the same alloy. They found tremendous success in the lower level detection limit at 0.01ppm with their QCM sensor.

Optical Sensors

Optical sensors work on the principle that the adsorbed gas changes the optical properties of the sensing layer such as the refractive index or light absorbance [24]. Optical sensors use fiber cables to transmit light instead of electrical signals which can be safer in environments with explosive or flammable gasses [25]. The change in optical property can be determined by the transmitted light allowing for the amount of adsorbed gas to be calculated [26*,27]. They are highly selective with great sensitivity; however, the major limiting factor is the use of a laser which requires high currents and is sensitive to variations in the current [10**]. Other disadvantages include the inability for miniaturization and a high cost to manufacture [22**].

Table 1. Recently studied sensors for gaseous ammonia.

Name	Type of Sensor	Tested Detection Range (ppm)	Tested Temperature Range (K)	Limit of Detection (ppm)	Response Time @ detected concentrations (secs)	Source
SnO ₂ : 2% Sb dope	Chemoresistive	50-250	293	--	42 @ 250ppm	[18]
Thin film ZnO	Chemoresistive	10-70	353 – 553 Ideal: 453	10	112 @ 30ppm	[17]
ZnO nanostructure	Chemoresistive	5-100	623	5	36 @ 5ppm 29 @ 100ppm	[19]
WO ₃	Chemoresistive	0.5-100	523-648 Ideal: 573	0.04955	52 @ 30ppm	[28]
ZIF-CNT ¹	Chemoresistive	25-250	298-383 Ideal: 298	0.208	120 @ 25-250ppm	[14]
PAPYP ²	Chemoresistive	0 – 20	298-338 Ideal: 298	0.05	136 @ 1ppm	[29]
Polyaniline-Ag	Chemoresistive	1-200	298	1	100 @ 1ppm 30 @ 100ppm	[30]
Bis-Phenylalanine Naphthalene Diimide	Chemoresistive	2-50	297-299	2	15.3 @ 50ppm	[31]
Graphene: 7.5% F dope	Chemoresistive	0.5-10	293	0.064	380 @ 10ppm	[32]
NiO (spherical sheets)	Chemoresistive	1-20	423	--	136.5 @ average	[33]
NiO (porous sheets)	Chemoresistive	1-20	303-473 Ideal: 423	--	108.5 @average	[33]
Carbon Nanotubes (AuNPs sputtered)	Chemoresistive	0-10	298, 413 Ideal: 413	0.5	12 @ 1ppm	[15]
Carbon Nanotubes (AuNPs chemically impregnated)	Chemoresistive	0-10	298, 413 Ideal: 413	--	25 @ 1ppm	[15]
P3HT:GO ³	FET	0-80	298	0.278	44 @ 80ppm	[21]
TIPS-pentacene ⁴	FET	1	298, 353 Ideal: 353	--	26 @ 1ppm	[34]

Polyacrylic Acid:Polyaniline	Optical	0-300	298	--	100 @ 150ppm	[24]
Ti ₃ C ₂ Tx-S	QCM	0.01 – 100	297-299	0.01	33 @ 0.1ppm	[16]
PSS/ZIF-C/PANI ⁵	QCM	1-50	298	1	28 @ 10ppm	[35]

1: Zeolitic Imidazolate Framework-8/Carbon Nanotube

2: Poly(aniline-co-pyrrole) on flexible porous polyvinylidene fluoride based sensitive membrane

3: Poly(3-hexylthiophene-2,5-diyl)/GO (Graphene Oxide)

4: 6,13-Bis(triisopropylsilylethynyl) pentacene

5: PSS: Poly (sodium 4-styrenesulfonate), ZIF-C: ZIF-8 derived porous carbon, PANI: Polyaniline

Ammonia Capture

Gaseous ammonia capture can be separated into two major categories: absorption into a liquid phase or adsorption onto a typically acidic surface. Depending on the circumstance, the sorbent may require different properties [9**]. For example, the selectivity of ammonia over water vapour will be important in coastal regions but less prioritized in more arid contexts [14]. Nowrin et al. [36] highlight that in ammonia production facilities, ammonia separation techniques are often used to treat the effluent stream allowing for unreacted inputs to be recycled which can result in higher production rates. This results in the need for desorption to be easily achievable and high thermal stabilities of the capture medium [37].

In the contexts of atmospheric capture, the need for fast adsorption rates are ideal for large rogue emissions. In this review, the ammonia capture capacities of different sorbents were summarized, while capture rate and regenerative stability are noted where available. Capture rate is denoted by the time it takes for equilibrium to be reached or until near full penetration occurs in a breakthrough curve. Regenerative stability is often measured by the portion of the capacity after successive runs.

Another extensively researched method of ammonia capture is membrane separation. It is commonly used in wastewater treatments, where high concentrations of ammonia exist, for the purification of water as well as the recovery of ammonia. There has been some recent work on the degradation of gaseous ammonia using membranes [38]. Membrane separations are an excellent method of ammonia capture in industrial processes, however currently lack the potential to capture rogue emissions. Readers are recommended to read the following sources for a more in depth study on membrane separations in industry [38,39,40].

This work will focus on the previously mentioned two major categories of absorption and adsorption. Table 2 below this section highlights several different sorbents with their ammonia capacity from recently studied literature.

Liquid Absorbents

Ammonia's high solubility in water makes it seem the obvious absorbent of choice. However, the high-pressure requirements for absorption and the high heat capacity of water for desorption is energy intensive offsetting the potential green house gas emissions reduction of the captured ammonia [7**,41*,42].

Ionic Liquids

Ionic liquids (ILs) are solvents comprised solely of anions and cations and have been historically considered for gas adsorption [7**]. They often show incredible potential for ammonia absorption, but many recent literature studies report that they are expensive and difficult to synthesize compared to other sorbents [7,43,44,45*].

Sun et al. [46] synthesized triazole cation-functionalized ionic liquids (TCFILs) by introducing protic sites on triazole based ionic liquids. These ionic liquids were able to achieve high ammonia absorption capacities up to 21.4 mmol/g and with an absorption duration of approximately an hour. A stability analysis was conducted for 5 absorption/desorption cycles and no decrease in adsorption capacity could be noticed.

Deep Eutectic Solvents

Deep Eutectic Solvents (DESs) are an emerging sorbent chemical equivalent to ionic liquids for the adsorption of ammonia [47]. DESs are liquid mixtures that form hydrogen bonds to reduce the melting

point of the mixture compared to the ionic bonding the ions would form naturally causing a eutectic solvent [48]. They are often characterized by their hydrogen-bonded donator (HBD) and hydrogen-bonded acceptor (HBA). DESs are heavily desired due to their thermal stability, relative low cost and ease of regeneration through simple processes such as pressure swinging [45*].

A recent study by Kazarina et al. [45*] investigated ammonia absorption using ammonium salt with different ethyl substitutes along with ethylene glycol. They found that more hydroxyl groups lowered the Henry's law constant (resulting in more solubility of dilute gasses) and vice versa for ether groups.

Cheng et al. [49] studied the use of metal chlorides to provide additional weak acidic sites for interactions with ammonia. They synthesized DESs by varying ratios of EaCl (ethylamine hydrogen chloride), glycol and several metal chlorides. The absorption results were impressive even at lower pressures boasting a 10.24 mmol/g at 6.8 kPa with one of their CoCl₂ DES.

A novel subgroup of DES is recently being investigated deemed Type V DESs [50**]. The key difference between Type V and the other four categories of DESs is the detail that Type V do not have ionic components in either substance. The lack of ionic components leads to less viscous solutions with strong deviations from ideality that are easily regeneratable by evaporation [50**,51]. Zhou et al. [44] reports a Type V DES 3-hydroxypyridine/phenol (molar ratio of 1:5) that can absorb 10.00 mmol/g at 1 bar. This is a large improvement compared to other recent DESs in literature.

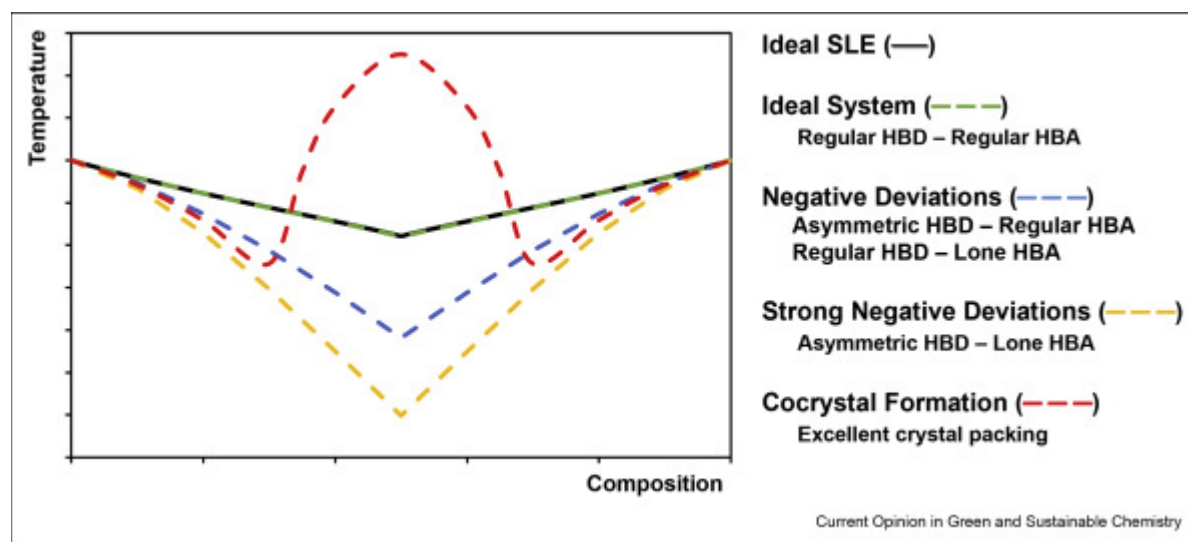


Figure 2. Solid-liquid phase diagrams of ideal and non-ideal systems. Type V DESs consist of an asymmetric hydrogen-bonded donator and a lone hydrogen-bonded acceptor which create a strong negative deviation from ideality (Abranches et al. Current Opinion Green and Sustainable Chemistry, 35 (2022) 100612 © 2022 Elsevier B.V.) [50**].

Solid Adsorbents

Solid state materials such as metal halides, zeolites and metal-organic frameworks (MOFs) can be employed to absorb select atmospheric gasses. They typically operate in a pair of columns, one for adsorption and one for desorption [7**]. Metal adsorbents are often introduced to porous materials to increase their adsorption capacities via Lewis acid-base interactions [43]. The large surface area of metal adsorbents incorporated into porous materials allows for high adsorption capacities, and the lack of volatility and viscosity issues make them a prime field to look into for the future of ammonia capture [7**]. Zeolites are a traditional adsorbent in separation processes of ammonia production due to their high

thermal stability; however, metal halides and MOFs have been more recently studied because of their suitability outside of the high temperature and pressure scenarios in ammonia production [52].

Metal Halides

Metal halides are reported to be cheap and easily synthesized compared to other adsorbents, which has caused widespread adoption of their use. However, their major downside is that pure metal halides have quite slow adsorption rates [7**, 53*].

A few-layered hexagonal boron nitride (h-BN) has been synthesized for the adsorption of ammonia in the Haber-Bosch process [41*]. The metal halide was found to have an excellent thermal stability and an ammonia adsorption capacity of 8.67 mmol/g at 1 bar, 313.2K. After multiple regenerative cycles, the capacity of adsorption was found to not noticeably change resulting in a very long lasting and stable adsorbent.

Shen et al. [54] investigated the use of chemically impregnating silicon into different chlorides to improve adsorption capacities. The use of silicon kept the adsorption capacity relatively the same or improved. It was also found that CuCl_2 had considerable stability in its adsorption capacity thermally.

To speed up the sorbent material discovery, a machine learning tool was developed to design mixed metal halides based on their desorption energies and other thermodynamic properties. The mixed metal halide $\text{Mg}_x\text{Ca}_{(1-x)}\text{Cl}_y\text{Br}_{(2-y)}$ where $x: 0-1$ & $y: 0-2$ was investigated; however, future research into other transition metals are also considered [53*].

Metal Organic Frameworks

Metal-organic frameworks (MOFs) are heavily investigated to find an appropriate combination of an inorganic metal cluster and organic linker to bind with ammonia. There are also some developments on using different nanostructures to increase the surface area of adsorption. Depending on the field, the presence of certain chemicals can be heavily disadvantageous. For example, MOFs containing chlorine are corrosive to the metal structure of many processing plants and heavy metals are toxic to agricultural systems [55,56]. The high customizability of MOFs allows researchers to circumvent certain chemicals dependent on their applications. Along with typically excellent stability and recyclability, MOFs are a premier adsorbent being researched [57**].

Two MOFs with zinc as the metal cluster zinc-trimesic acid (ZnTA) and 2-methylimidazole zinc salt (ZIF-8) were explored for ammonia adsorption in agricultural practices. They were found to have adsorption capacities of 11.37 mmol/g and 1.26 mmol/g respectively at 298K and 1 bar [55]. A later study by the same group looked at Bistrichloromethylcarbonate (BTC, Triphosgene) as a linker to different metal clusters. ZnBTC, FeBTC and CuBTC exhibited capacities of 11.33, 9.5 and 23.88 mmol/g at 1 bar [57**].

Computational screening of MOFs has been completed via Grand Canonical Monte Carlo simulations by Zhu et al. [58]. Several candidates for further research were discovered based on adsorption capacity and selectivity. Some of the top MOFs with excellent adsorption capacities are shown in Table 2.

Other adsorbents

Xerogels are the solid result of unconstrained shrinkage by evaporation of a gel [59]. Hu et al. [60**] look into a sulphur-based silica xerogel (MPTS-X) for the capture of atmospheric ammonia. The SO_3H -modified silica xerogel was prepared using different volume ratios (X) of Mercaptopropyl trimethoxy silane (MPTS-X). It was noted that as more MPTS was added, the shrinkage of the xerogel increased resulting in smaller pores. The chemistry behind the greater adsorption capacity is that the $-\text{SO}_3\text{H}$ acidic

sites create stronger bonds than the hydrogen bonding process of the unmodified Si-OH in MPTS-0. MPTS-1 had a breakthrough point at 10 hours in 50 ppm, 298K conditions with a 95% saturation capacity of 1.4 mmol/g. After 5 regenerative cycles, MPTS-1 kept at about 80% of the saturation capacity. In a field test with 2 ppm ammonia, MPTS-1 was able to reduce the initial concentration to 55% in approximately 110 mins.

Table 2. Recently studied materials for adsorption and absorption of ammonia.

Name	Capture Mechanic	Testing Conditions		Tested Regeneration	Capacity (mmol/g)	Comment on Capture Rate	Source
Liquid Absorbents							
[Li-TEG][Tf2N] ¹	IL	T = 313.2K P = 102.5 kPa	Bubbled pure NH ₃ with magnetic stirrer	Similar capacities were met for 8 consecutive runs	7.685 ²	--	[61]
[1, 2, 3-TrizH ₂][NO ₃] ₂ ³	TCFIL	T = 303K P = 1 bar	3g of TCFIL was place in a bottle controlled by thermostatic water bath with pure NH ₃ gas bubbling at 150ml/min	Stable capacities for 5 consecutive runs	21.4	60 mins to equilibrium	[46]
[1, 2, 4-TrizH ₂][NO ₃] ₂ ³				--	21.2	60 mins to equilibrium	[46]
[1, 2, 3-TrizH ₂][CF ₃ SO ₃] ₂ ³				--	17.6	20 mins to equilibrium	[46]
[1, 2, 4-TrizH ₂][CF ₃ SO ₃] ₂ ³				--	16.7	20 mins to equilibrium	[46]
MgCl ₂ /Res/EG (0.1:1:2) ⁴	DES	T = 313.2K P = 1 bar	8g of DES was bubbled with NH ₃ -N ₂ mixed gas at 60 cm ³ /min	Stable capacities for 6 consecutive runs	12.12	60 mins to equilibrium	[43]
3,4-DHBA/EG (1:3) ⁵	DES	T = 298.2K P = 1 bar	Test was complete in stainless steel tank with magnetic stirrer and pure NH ₃	3,4-DHBA/EG (1:6) was found to be stable with 6 consecutive runs	11.69	--	[48]
DES 1 ⁶	DES	T = 313.2 K P = 101 kPa	A high-pressure equilibrium cell was used to determine Henry's Law Constant and other thermodynamic properties	--	3.640	--	[45*]
DES 2 ⁶				--	4.295	--	[45*]
DES 3 ⁶				--	2.861	--	[45*]
DES 4 ⁶				--	3.081	--	[45*]
EaCl + CoCl ₂ + Gly (1:0.75:3)	DES	T = 298.2K P = 103.0 kPa	Test was complete in stainless steel tank with magnetic stirrer and pure NH ₃	Capacity reduced by about 15% after the first run then remained stable for 8 runs	17.55	Less than 200 secs to equilibrium	[49]
3-hydroxypyridine/phe nol (1:5)	DES V	T = 298.15K P = 1 bar	NH ₃ was bubbled at 60 cm ³ /min	Capacity is stable for 5 consecutive runs	10.00	~160 mins to equilibrium	[44]

Solid Adsorbents

h-BN ⁷	Metal Halide	T = 313.2K P = 1 bar	Adsorption isotherms were measured using a NH ₃ stream. Mixed gas samples were found to have little impact on the adsorption capacity.	Capacities is stable for 5 consecutive runs	8.67	~125 mins to fully penetrate on breakthrough curve	[41*]
CuCl ₂	Metal Halide	T = 298K P = 1 bar	A fixed bed reactor was used with a 100ml/min pure NH ₃ stream at varying temperatures.	--	39.3 ⁸	Adsorption was completed by 20 mins	[54]
CuCl ₂ : Silicon				--	37.6 ⁸		[54]
MnCl ₂		T = 308K P = 1 bar		--	24.7 ⁸		[54]
MnCl ₂ : Silicon				--	31.7 ⁸		[54]
CaCl ₂		T = 298K P = 1 bar		--	22.3 ⁸		[54]
CaCl ₂ : Silicon				--	25.2 ⁸		[54]
MgCl ₂		T = 303K P = 1 bar		--	22.4 ⁸		[54]
MgCl ₂ : Silicon				--	27.6 ⁸		[54]
CuCyhd	MOF	T = 298K P = 1 bar	Adsorption isotherms collected by a gas adsorption analyzer	Specific regeneration tests were not completed however stability at variable temperature and pressures were	17.5	--	[56]
Zinc-Trimesic Acid	MOF	T = 298K P = 1 bar	Adsorption was measured with a 4:1 (v:v) mix of NH ₃ and H ₂ O	--	11.37	--	[55]
ZIF-8				--	1.26	--	[55]
ZnBTC	MOF	T = 323K P = 1 bar	Adsorption was measured with pure NH ₃ and selectivity with 4:1 (v:v) mix of NH ₃ and H ₂ O	--	11.37	--	[57**]
FeBTC				--	9.5	--	[57**]
CuBTC				--	23.88	--	[57**]
CaH ₄ (C ₂ O ₄) ₄	MOF	T = 298K P = 1 bar	Simulated with 1% mol NH ₃ and varying amounts of N ₂ and H ₂ .	Indicate that regenerative ability will be researched in future studies	18.33	--	[58]
MgH ₄ (C ₄ O ₃) ₂					16.49	--	[58]
SrH ₄ (C ₂ O ₄) ₄					15.60	--	[58]
MPTS-0 ⁹	Xerogel	T = 298K P = 1 bar	Static adsorption tests were completed with pure NH ₃ . A	--	3.19	~80 mins for 95% breakthrough	[60*]

MPTS-0.5 ⁹			3m ³ field test was also conducted.	--	6.79	~130 mins for 95% breakthrough	[60*]
MPTS-1.0 ⁹				Capacity reduced by about 20% after the first run then remained stable for 5 runs	7.00	~155 mins for 95% breakthrough	[60*]
MPTS-1.5 ⁹				--	6.99	~180 mins for 95% breakthrough	[60*]
MPTS-2.0 ⁹				--	6.14	~180 mins for 95% breakthrough	[60*]
MPTS-3.0 ⁹				--	6.25	~95 mins for 95% breakthrough	[60*]
Polyaniline (PANI)	Organic Polymer	Not Noted	A fixed bed reactor with 0.5g of adsorbent with a 100L/min pure NH ₃ stream at concentrations (35-150ppm) was used.	--	3.602	35 mins to equilibrium	[62]
PANI-Clay	Organic Polymer	Not Noted		--	4.323	~60 mins to equilibrium	[62]

1: Lithium-TriEthylene Glycol + bis(trifluoromethanesulphonyl)imide

2: Converted from mol/mol basis

3: Triz: Triazole

4: Res: Resorcinol, EG: Ethylene Glycol. (0.1:1:2 molar ratio)

5: DHBA: Dihydroxybenzoic Acid

6: These are all N-substituted ammonium salts with ethylene glycol. See paper for specific structure.

7: Hexagonal Boron Nitride

8: Converted from g/g basis

9: Silica based xerogel with varying volume ratios of Mercaptopropyl Trimethoxy Silane

Concluding Remarks

Ammonia's vast uses highlight it as one of the most important chemicals, and its significance will grow in the future. However, its human toxicity and environmental distress instigate a more diligent environmental regulation system for ammonia emissions. In this review article, we focus on the detection and capture of gaseous ammonia to reduce the potential environmental impacts associated with rogue emissions when scaling up ammonia applications.

A majority of ammonia gas sensors are chemoresistive style sensors. Research is primarily based on different doping techniques, coating mechanisms and nanostructures to increase surface area without compromising structural integrity and thermal stability. Many are capable of detecting emissions below 1 ppm of ammonia. Several of the sensors have response times less than 1 minute; however, several environmental factors such as the tested concentrations impact this response. Fast reacting sensors that detect low concentrations of ammonia will be needed in rogue emission response scenarios.

For capturing gaseous ammonia, metal halides and ionic liquids both have high adsorption capacities that are appealing but the slow adsorption rates do not make them ideal for rogue emission capture. The high designability of MOFs and DES have recently made them a very popular research field for ammonia capture. Research is mostly on functional group substitutions in MOFs and DES. Computational screening methods have also gained some traction to determine where research should be focused. Apart from lab tests, field results for the capture of trace ammonia will also be needed to validate the performances of the developed ammonia sorbents.

Declaration of interests

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This is an outstanding review article that is comprehensive in several different types of sorbent materials. Less commonly used materials such as zeolites are described within.

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