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Review

Advances in Paper-Based Ammonia Sensors in Environment: Sustainable Materials, Nanotechnology Integration, and Smart Analytical Platforms

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Abstract: This review provides a comprehensive analysis of recent developments in sustainable paper-based sensors for ammonia detection, emphasizing their potential as low-cost, portable, and environmentally benign alternatives to conventional analytical techniques. It systematically evaluates principal sensing strategies including colorimetric, electrochemical, and chemiresistive modalities that utilize natural dyes, engineered nanomaterials, and conductive polymers to achieve enhanced sensitivity and rapid signal transduction. With operational lifespans of 30 to 45 days, colorimetric platforms based on plant extracts and anthocyanins can detect as little as 0.5 mg L^{-1} in aqueous medium, which makes them ideal for low-cost, disposable applications. WS_2–PANI hybrids and CNT/PPy/Pt are examples of chemiresistive nanocomposite sensors that exhibit ppb-level detection (down to 5 ppb) in gaseous environments, fast response–recovery periods (less than 45 s and about 80 s, respectively), and stability for more than 60 days in ambient humidity. Advances in fabrication methodologies such as additive manufacturing and three-dimensional microstructured platforms have facilitated the creation of mechanically flexible devices with capabilities for smartphone-based signal acquisition and real-time analytical performance across diverse application domains. These include environmental surveillance, food quality assessment, occupational safety, and clinical diagnostics, wherein sensor efficacy approaches or surpasses that of standard instrumentation. The review also addresses critical limitations such as analyte selectivity and temporal stability, and explores emerging directions involving integration with internet of things frameworks, use of fully biodegradable substrates, and simultaneous detection of multiple chemical targets. The collective progress reflects a paradigm shift toward the deployment of accessible and ecologically responsible sensing technologies aligned with global health and environmental sustainability objectives.

Keywords: paper-based sensors; ammonia detection; sustainable sensing; printed electronics; environmental monitoring

1. Introduction

The strong, colourless gas ammonia (NH_3) is used extensively in many different industries, such as food preservation, chemical processing, agriculture, and environmental monitoring. However, there are serious health and environmental problems due to the widespread use and unintentional release of NH_3. Common sources of ammonia emissions include the use of synthetic fertilizers, wastewater treatment, refrigeration systems, industrial activities employing ammonium-based compounds, and livestock waste [1,2]. NH_3 is a component of nitrogen pollution in environmental systems, which can cause eutrophication in aquatic habitats, which depletes oxygen and reduces biodiversity [3]. When inhaled by humans, NH_3 can induce respiratory and neurological distress and is harmful to aquatic organisms even at very low concentrations [4,5].

Ammonia is a crucial spoiling indication in the food sector, especially for items high in protein like meat and fish. The detection of volatile ammonia, which is released when microorganisms break down amino acids in perishable foods, is essential for quality assurance and shelf-life evaluation [6]. Similar to this, unchecked ammonia leaks in industrial settings provide serious concerns, such as flammability and long-term health issues, which is why strict monitoring procedures are required [7]. Moreover, NH_3 is a known biomarker in medical diagnostics; for example, high levels in urine or exhaled breath may be a sign of renal disease, Helicobacter pylori infection, or liver malfunction [8]. These diverse uses highlight how crucial it is to create ammonia detection devices that are quick, accurate, and sensitive.

The use of hazardous chemicals (such as mercury and phenol), complicated equipment, and high operating expenses are some of the disadvantages of conventional ammonia detection methods, such as Nessler's reagent and the phenate method, notwithstanding its sensitivity [9–11]. Furthermore, especially in contexts with restricted resources, these approaches are inappropriate for on-site or portable applications. This has led to the investigation of substitute sensor systems that are affordable, safe for the environment, and able to analyze data in real time.

Paper-based ammonia sensors are among the newer alternatives that have drawn a lot of interest because of their special blend of affordability, biodegradability, and accessibility. Because it is porous, flexible, and lightweight, paper makes a perfect substrate for fictionalization with conductive polymers, natural dyes, or nanomaterials [12–14]. By facilitating quick diffusion and contact with ammonia molecules, these structural characteristics improve sensitivity and reaction times. For instance, sensors that use polyaniline (PANI) films on paper substrates have shown effective room-temperature NH_3 detection with fast response and recovery duration [15–20]. MXene-coated origami paper and ternary nanocomposites integrated into filter paper have also demonstrated remarkable mechanical flexibility, environmental tolerance, and sensing capability over a wide range of concentrations [21–26].

Due to their environmentally friendly construction, which frequently uses green chemistry techniques and natural materials like anthocyanins or mango leaf extracts as pH-responsive indicators, paper-based sensors also fit in nicely with sustainable development goals [27]. Additionally, their decentralized and user-friendly deployment in environments like aquaculture farms, food packaging, and healthcare diagnostics is made possible by their interoperability with portable platforms like 3D-printed holders and smartphone-assisted colorimetric analysis [28]. Paper sensors are ideal for one-time use applications where cleanliness and contamination control are crucial because of their disposable nature, which also reduces electrical waste.

In conclusion, the invention of paper-based ammonia sensors offers a revolutionary method for NH_3 detection in the fields of biomedicine, industry, food, and the environment. By utilizing the natural qualities of paper and adding bio-derived indicators or functional nanomaterials, these sensors provide a viable, affordable, and efficient substitute for conventional techniques. The performance of printed electronics is continuously improved by developments in material science, opening the door for wider field deployment and commercialization.

This article attempts to give a systematic summary of current advancements in the field of sustainable and nanotechnology-enhanced paper-based ammonia sensors. The review emphasizes advances in sensor design, material integration, and fabrication techniques that improve sensitivity, selectivity, flexibility, and environmental compatibility, drawing on a broad spectrum of recent investigations. Sensors using nanomaterials like MXenes, carbon nanotubes, polyaniline composites, and metal-organic frameworks, as well as environmentally friendly materials such biodegradable substrates and plant-derived indicators, are given special consideration. The combined results highlight a paradigm shift towards disposable, affordable, and easy-to-use sensor platforms that can be used in industrial, food, biomedical, and environmental settings. With these developments, paper-based ammonia sensors are positioned as essential instruments in the future of decentralized monitoring technologies, reflecting an increasing trend towards fusing sustainability with high-performance sensing capabilities. Outlining current developments (2021–2024) in paper-based ammonia sensors, with an emphasis on performance improvements made possible by nanotechnology, is how this review fills in these knowledge gaps. Comparing material strategies, fabrication methods, and operational metrics—such as field-readiness levels, response/recovery times, stability, and limit of detection (LOD)—critically. Examining the possibility for practical deployment, including testing in intricate matrices such industrial air quality monitoring, hydroculture wastewater, and perishable food packaging. Providing practical insights for commercial translation by talking about cost-effectiveness, environmental impact, and regulatory compliance. Deciding on future research avenues, such as integrating AI and IoT, standardizing testing procedures, and designing next-generation sensors in an environmentally friendly manner.

2. Materials and Mechanisms for Ammonia Sensing

A number of transduction methods are used by paper-based ammonia sensors to transform chemical reactions with NH_3 into detectable signals. Electrochemical, chemiresistive, and colorimetric methods are the three main sensing concepts.

2.1. Colorimetric Sensing

Ammonia is detected via colorimetric sensors using discernible color variations brought on by pH changes or chemical reactions with NH_3. Usually, these sensors are functionalized using dyes that are sensitive to pH (such as methylene blue, anthocyanins, and bromothymol blue) and that change color when exposed to basic gases like ammonia. In aqueous and gaseous conditions, for instance, natural markers such anthocyanins that are derived from red cabbage, blueberries, or mango leaves have shown pH-responsive qualities that make them appropriate for ammonia detection [29]. Colorimetric sensors' main benefits are their affordability, ease of use, and visual detectability without the need for complicated equipment. The measurement of color changes is further improved by smartphone-assisted picture analysis, which makes analysis portable and real-time [28,30]. However, outside variables like ambient lighting, humidity, and sensor ageing can affect how reliable colorimetric responses are.

2.2. Electrochemical Sensing

Ammonia's redox activity at functionalized electrodes is the basis for electrochemical sensors' operation. Ammonia in these systems either donates or receives electrons at the electrode surface, resulting in detectable variations in impedance (electrochemical impedance spectroscopy), voltage (potentiometry), or current (amperometry). To create flexible electrochemical sensors, paper-based platforms have effectively combined printed interdigitated electrodes with conductive inks (such as charcoal, silver, or graphite) [31]. These sensors are capable of continuous monitoring, have great sensitivity and selectivity, and respond quickly. In recent years, conductive polymers such as polyaniline and transition metal dichalcogenide (e.g., WS_2) composites have been used to improve sensor performance at room temperature by increasing electron transport and surface reactivity [32–34]. Among the drawbacks are the possibility of electrode fouling and the requirement for reliable power sources in portable setups.

2.3. Chemiresistive Sensing

Chemiresistive sensors use changes in the electrical resistance of sensing materials when exposed to gas to detect ammonia. Charge transfer happens when NH_3 interacts with conductive or semiconducting materials (such as polyaniline, MXenes, ZnO, or carbon nanotubes), changing the resistance across the sensor. These alterations are tracked in real time and are associated with the concentration of ammonia [35].The ability to deposit chemiresistive chemicals directly onto paper substrates using methods like spray coating or in-situ polymerization makes this mechanism especially suitable for flexible and wearable formats. $Ti_3C_2T_X$ MXene or Zn-TPP-functionalized CNT sensors are proven to have excellent mechanical stability, wide detection ranges, and great sensitivity even when repeatedly bent and stretched [21,26,36]. Among the difficulties are baseline drift and selectivity problems, which can be lessened by surface functionalization and composite material techniques.

Each of these methods makes a distinct contribution to the ammonia sensing technologies landscape as a whole. Their incorporation into paper substrates and sustainable materials has increased the sensors' range of applications, especially in disposable and field-deployable forms.

2.3.1. Sustainable Materials

Integrating natural, biodegradable, and eco-friendly materials has been the main focus of recent developments in sustainable paper-based ammonia sensors. These materials have two advantages: they preserve or improve sensing performance while lowering the environmental impact of sensor production. Anthocyanins, plant extracts, and biodegradable paper substrates are three well-known types of sustainable functional materials.

Anthocyanins

Natural pH-sensitive pigments called anthocyanins are present in a variety of fruits and vegetables, including blackberries, blueberries, and red cabbage. These pigments are great choices for colorimetric ammonia sensing because they show clear color changes in response to pH changes. Anthocyanins change from reddish to greenish or bluish tones when exposed to NH_3, which raises the local pH and makes visual detection and measurement possible. By removing pigments from red cabbage and other fruits and immobilizing them on cellulose paper, Sun et al. and Stebbins et al. created anthocyanin-based paper sensors. At ammonia concentrations as low as 2 mg NH_3-N/L, these sensors showed a quick and noticeable color change, and a strong correlation with conventional spectrophotometric techniques was analyzed [37,38]. In addition to being sensitive and efficient, the anthocyanin-based sensors were also biodegradable and simple to make without the need of hazardous chemicals.

Plant Extracts

Eco-friendly paper-based ammonia sensors have also been developed using indicators derived from plants, such as anthocyanins. Mango leaf extract was used by S. Saborirad and his research group as a natural pH indicator, for instance. To produce a colorimetric sensor, the extract was immobilized on Whatman filter paper after being made under ideal aqueous conditions. The sensor showed a discernible color shift in response to ammonia gas produced by alkalinized liquids, which could be examined with a smartphone-based device. The device remained stable for up to 45 days in ambient circumstances, with a detection limit of 0.50 mg/L [39]. This method is a prime example of creating sustainable sensors using locally accessible, renewable resources.

Biodegradable Substrates

In the design of sustainable sensors, the paper substrate itself is crucial. In contrast to silicon-based substrates or traditional plastic, paper is abundant, biodegradable, lightweight, and compatible with low-energy manufacturing techniques. Standard paper substrates were used to fabricate a polyaniline (PANI)-based chemiresistive ammonia sensor, as shown by Gupta et al. (2023). The paper's porous nature allowed for quick gas diffusion in addition to providing mechanical support. The sensor performed well in a range of humidity levels and responded quickly and linearly to NH_3 concentrations between 12 ppm and 1000 ppm [40].

Sustainable materials were used in all of these instances to promote low-cost fabrication and real-time monitoring, which are critical for widespread use in environments with limited resources, in addition to making the sensors more environmentally friendly.

2.4. Nanomaterials and Interaction Mechanisms for Ammonia Sensing

Nanomaterials have been included into paper-based ammonia sensors more and more in recent years to improve performance attributes like sensitivity, selectivity, response time, and environmental stability. These nanostructured materials interact strongly with ammonia molecules through mechanisms like charge transfer, chemisorption, and acid-base proton exchange because of their large surface area, distinct electrical characteristics, and variable surface functions. Metal oxides (like ZnO and CuO), carbon nanotubes (like CNTs), two-dimensional layered materials (like WS_2 and MXene), and conducting polymers (like PEDOT:PSS and PANI) are examples of frequently used nanomaterials.

2.4.1. Zinc Oxide (ZnO)

The n-type semiconducting metal oxide zinc oxide (ZnO) is extensively studied. It interacts with ammonia through redox reactions involving oxygen species that are deposited on the surface. Oxygen molecules in ambient air are adsorbed onto the ZnO surface, where they seize free electrons to create O_2^- or O^- species. When exposed to ammonia, these oxygen species react with NH_3, which causes trapped electrons to return to the conduction band. This lowers the resistance of the sensor. The relatively high operating temperature of ZnO is a drawback, even with its advantageous electrical characteristics. It is therefore frequently utilised in hybrid setups with polymers or layered nanomaterials to facilitate room-temperature operation and enhanced selectivity [41].

2.4.2. Copper Oxide (CuO)

NH_3 molecules interact with the surface of copper oxide (CuO), a p-type semiconductor, to donate electrons, allowing for ammonia sensing. This causes resistance to rise in tandem with hole recombination [42]. Despite not being specifically covered in the docs that were provided, CuO is nevertheless an essential part of composite sensing films because of its complimentary sensing behavior when mixed with other materials.

2.4.3. Carbon Nanotubes (CNTs)

Chemiresistive ammonia detection is made possible by carbon nanotubes (CNTs), especially multi-walled types, which have superior electron mobility and surface reactivity. Ammonia molecules engage with CNTs by electron donation since they are electron givers. The p-type CNTs are de-doped as a result, and the resistance increases noticeably. A noteworthy study by Xiong and his group in the year 2022, where they used a composite of zinc-tetraphenylporphyrin (Zn-TPP) and carbon nanotubes (CNTs) made on paper utilising a wet papermaking and hot-pressing procedure to create a binder-free ammonia sensor. As a sensitiser, the Zn-TPP promoted hydrogen bonding and π–π conjugation with NH_3 molecules, improving responsiveness and selectivity [43].

2.4.4. Tungsten Disulfide (WS_2)

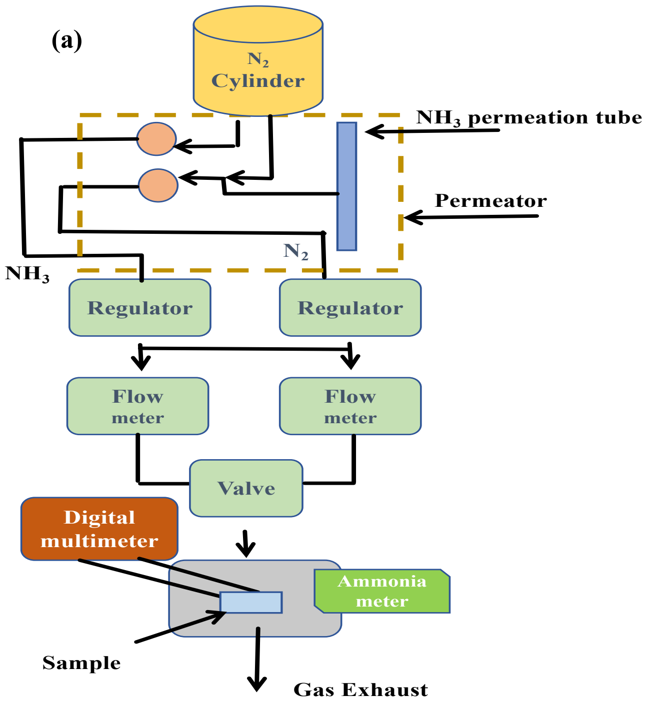
A two-dimensional material with a complex surface chemistry and a configurable bandgap, tungsten disulphide (WS_2) belongs to the transition metal dichalcogenide (TMD) family. The charge transfer interactions that WS_2 undergoes when exposed to ammonia alter its local electron density. WS_2 nanosheets and polyaniline (PANI) were combined by Kashyap et al. in the year 2024 [41], to create a flexible paper-based sensor. The resultant WS_2–PANI nanocomposite showed excellent mechanical stability under bending, a detection limit as low as 3 ppm, and quick reaction and recovery periods of 38 s and 58 s, respectively.

2.4.5 MXenes ($TiCT_X$)

MXenes are new 2D materials that combine high surface reactivity and metallic conductivity, especially TiC_2T_X. Strong chemisorption of NH_3 is made possible by their surface functional groups (-OH, -O, and -F), which modifies the surface potential and produces a detectable resistance change. A 3D origami paper-based NH_3 sensor with $Ti_3C_2T_X$ MXene distributed in gelatine was described by Wang and his research group in the year 2024 [44]. The sensor is appealing for transient and sustainable sensing applications because of its wide detection range (5–500 ppm), mechanical resilience, and complete biodegradability in 19 days in enzymatic media.

2.4.6. PEDOT:PSS

The conductive polymer PEDOT:PSS is renowned for its electrical stability and flexibility. Because of acid-base interactions, it develops when exposed to ammonia. By acting as a Lewis base and removing protons from the doped PEDOT chains and changing them into less conductive states, NH_3 lowers the conductivity of the material as a whole. PEDOT:PSS is frequently utilized in flexible sensor setups in conjunction with other nanomaterials, despite not being the primary emphasis of the literature that was uploaded. Figure 1a shows the schematic for testing PSS sensor performance in the gas phase, and Figure 1b shows charge transfer, de-protonation, or gas adsorption at the molecular level.



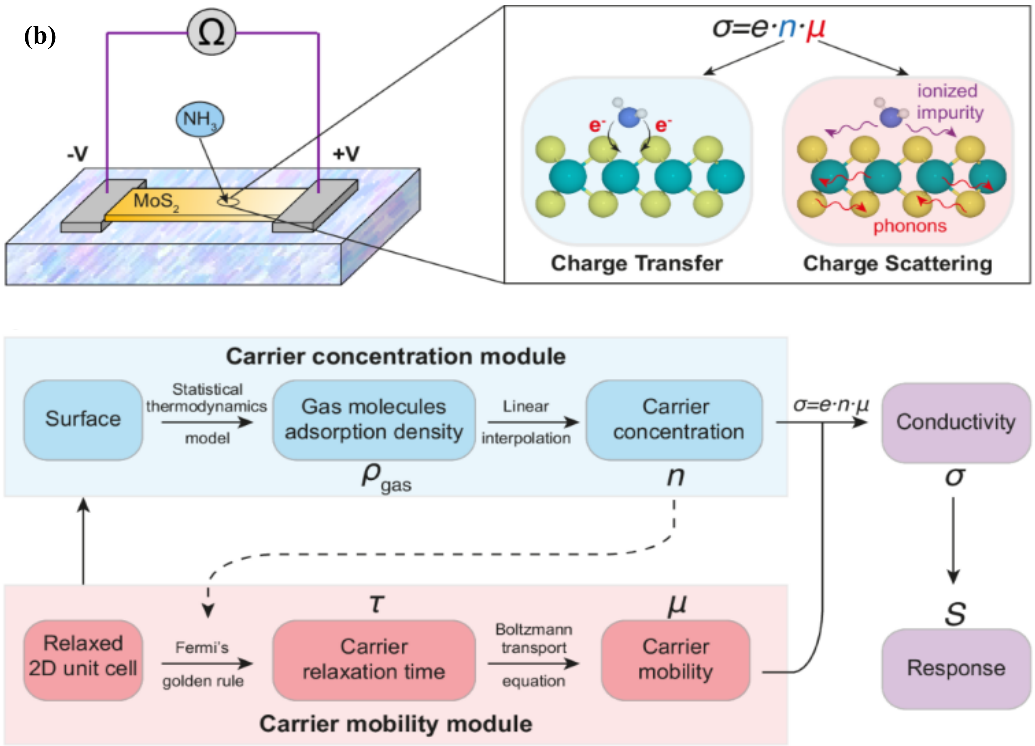


Figure 1. (**a**) Schematic representation of sensor for testing PSS sensor performance in the gas phase; and (**b**) charge transfer, de-protonation, or gas adsorption at the molecular level (Reproduced from Reference [45]).

2.4.7. Polyaniline (PANI)

One of the most researched conducting polymers in gas sensing is polyaniline (PANI). PANI has strong conductivity and is protonated in its emeraldine salt form. PANI de-protonates when exposed to ammonia, changing into its emeraldine base form, which has much less conductivity. Gupta et al. during 2023, achieved great sensitivity (response values of 3.60–9.33) and quick reaction times (9–30 s) across a wide range of NH_3 concentrations (12–1000 ppm) [40] by using a straightforward in-situ polymerization technique to deposit PANI on biodegradable paper substrates is shown in Figure 2. The summary of the mechanism is tabulated in the below Table 1.

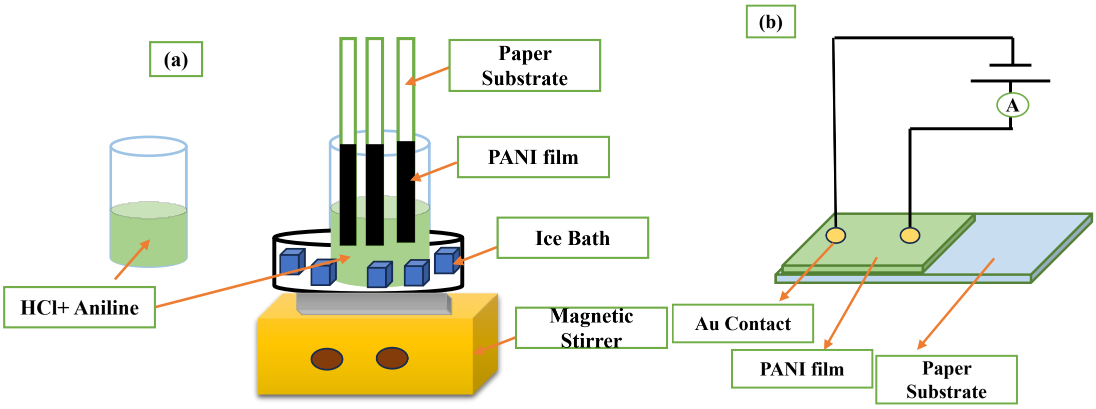


Figure 2. Schematic diagram of (**a**) In situ polymerization of PANI films over paper substrate and (**b**) Fabricated ammonia gas sensor with PANI film.

Relative performance provides the comparative analysis with advantages for different application platforms is shown in Table 2.

Table 1. Overview of several materials, their relationship to NH_3, and effect on sensor response.

Material	Type	Interaction Mechanism with NH_3	Effect on Sensor Response	Reference
ZnO	*n*-type SMO	NH_3 reduces surface-adsorbed oxygen → electron release	Decrease in resistance	[46]
CuO	*p*-type SMO	NH_3 donates electrons → recombines with holes	Increase in resistance	[47]
CNTs	Carbon nanomaterial	NH_3 donates electrons → de-dopes *p*-type CNTs	Increase in resistance	[48]
WS_2	2D TMD	Charge transfer from NH_3 alters electronic density	Variable; typically increased current	[49]
MXene ($Ti_3C_2T_X$)	2D carbide	Surface adsorption of NH_3 modifies conductivity	Decrease in resistance	[25]
PEDOT:PSS	Conducting polymer	NH_3 de-protonates PEDOT → reduces doping level	Decrease in conductivity	[50]
PANI	Conducting polymer	NH_3 deprotonates emeraldine salt → emeraldine base	Sharp increase in resistance	[51]

Table 2. comparative performance across several application platforms with respect to fabrication method, LOD, response characteristics, and benefits.

Platform	Sensing Stack & Fabrication	LOD	Response Features	Stability/Durability	Distinct Advantages	Reference
Food smart packaging	AJP carbon IDEs + carbon black on paper; photonic curing	3–12 ppm (gas)	Resistance change proportional to [NH_3]; robust at 75% RH	Tailored for packaging; label-like format	High-throughput printing; humidity-tolerant readout; packaging-ready	[50,52]
Environmental wastewater (dual-analyte)	Paper colorimetry in 3D-printed smartphone box	1.3 mg L^{-1} NH_3 (aq) LOD; simultaneous H_2S	Standardized imaging; good recoveries (91–105%)	Portable, field-ready module	Dual-analyte; smartphone quantification; treatment-plant workflows	[53]
Aquaculture water	Mango-leaf extract immobilized on paper + smartphone	0.50 mg L^{-1} NH_3 (aq) LOD; linear 1.7–10 mg L^{-1}	Naked-eye + quantitative imaging	≥45 days storage stability	Bio-derived, low-cost; farmer-friendly; field-deployable	[54]
Wearable/harsh handling	MWCNT/PPy/Pt on filter paper; twistable & water-tolerant (Du 2022)	5 ppb–60% *v*/*v* (gas)	Broad dynamic range; high selectivity; functional after immersion	Twistable (1080°) and 24 h water immersion tolerant	Best-in-class range; ruggedized paper sensor	[55]
Selective, flexible gas sensing	WS_2–PANI on paper with CEG electrodes	3 ppm (reported LOD)	Fast 38 s/58 s response/recovery; low VOC cross-talk	Bending-resilient	High selectivity at RT; low-power flexible device	[41]
Transient/green electronics	$Ti_3C_2T_X$ MXene/gelatin spray-coated origami	5–500 ppm (gas)	Spatial mapping & directionality; ~7% response at 50 ppm	Complete biodegradation ≈ 19 days; >1000 strain cycles; 50% stretch	Fully degradable, 3D mapping, mechanically robust	[44]
Mechanism-focused, RT operation	Zn-TPP/CNT binder-free paper	(RT sensing; selective)	162 s / 531 s response/recovery	Binder-free paper laminate	π–π/H-bonding boosted selectivity; RT operation	[43]
Low-cost polymer sensor	PANI on biodegradable paper	12–1000 ppm (gas)	Response time ≈ 9–30 s	Repeatable at RT	Inexpensive, fast RT response, simple chemistry	[40]
Aqueous lab assay (biodye)	Anthocyanin paper (Ul Haq 2021)	≈2 mg L^{-1} NH_3–N (aq)	Visual color shift; spectra-validated	Simple extraction chemistry	Ultra-low cost; educational/field kits	[56,57]

3. Sensor Design and Fabrication Strategies

Paper-based ammonia sensors' design and manufacturing process have a significant impact on their functionality and performance. Innovative manufacturing techniques including spray coating, 3D printing, and aerosol jet printing, along with sustainable substrates and nanomaterials, have made it possible to create flexible, wearable, and even biodegradable sensing platforms. Sensitivity, detection limits, and operational stability have significantly improved as a result of these advancements when paired with architectural advancements such as smartphone integration and origami-based structuring.

3.1. Fabrication Techniques

Paper-based ammonia sensors' cost-effectiveness, scalability, performance, and reproducibility are all directly impacted by the production process. Screen printing, dip coating, spray coating, aerosol jet printing (AJP), and 3D printing are the main methods investigated between 2021 and 2025.

3.1.1. Aerosol Jet Printing

A high-resolution, maskless deposition method that works well on flexible and uneven surfaces is aerosol jet printing. It makes it possible for functional inks to be directly patterned onto paper surfaces. In a work by Borghetti and his research group during 2022, carbon-based inter-digitated electrodes (IDEs) were deposited onto chromatographic paper using aerosol jet printing [50]. Flash lamp annealing was used for photonic curing after the procedure, which greatly shortened processing times without compromising substrate integrity. Under 75% relative humidity, the manufactured sensors revealed a resistance change of 12% even at the lowest measured concentration (3 ppm), and a proportional resistance drop with rising ammonia concentrations (3–12 ppm).

3.1.2. Spray Coating

A scalable and economical technique for evenly applying nanoparticles on flexible substrates is spray coating. Wang et. al. in the year 2024, created a 2D origami-based paper sensor and a 3D origami-based paper sensor using MXene/gelatin ink spray coating [44]. Under 50% strain, the sensor demonstrated mechanical compliance, and it continued to sense after 1000 stretching cycles. Between 5 and 500 ppm, it reacted favorably to NH_3, peaking at 7% at 50 ppm. Additionally, the sensor demonstrated its credentials as a high-performance and transient sensing platform by being completely degradable in enzymatic solutions in just 19 days.

3.1.3. 3D Printing

Sensor integration has been improved by the use of 3D printing technology, especially for portable platforms and support structures as shown in Figure 3. For the simultaneous detection of ammonia and sulphide in wastewater, Vargas-Muñoz et al. during 2023 created a colorimetric sensing device that can be used with a smartphone and is 3D printed. For quantitative investigation using smartphone imaging, a colorimetric paper sensor was incorporated within a sealed 3D-printed chamber with internal LED lighting and picture capturing alignment. With limits of detection (LODs) of 1.3 mg/L for ammonia, this platform provided excellent field-deployability and portability, making it useful for real-time monitoring in industrial and environmental applications [53].

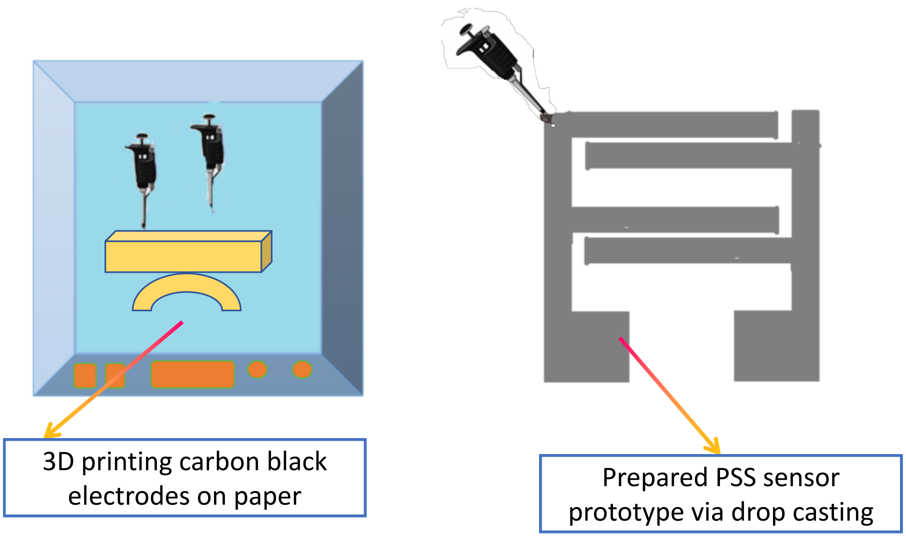


Figure 3. Schematic representation of PSS coated paper-based sensor fabrication using 3D printer.

Comparison of paper-based ammonia sensors synthesis methods with its scalability, cost, material quality, and application are shown in Table 3. Details of advantages, limitations, detection range, response time are shown in Supplementary Materials Table S1 in supporting documents.

The practical application of paper-based ammonia sensors in environmental monitoring, food packaging, aquaculture, and workplace safety requires reproducibility and long-term stability. The quantitative findings of recent research (2021–2024) are compiled here, along with performance under various environmental factors like humidity, mechanical deformation, and extended storage. The above table explains reproducibility and long-term stability of paper-based ammonia sensors in brief.

The stability duration of different paper-based ammonia sensors is shown using a graphical representation in Figure 4. The inexpensive cost and environmental friendliness of bio-derived colorimetric sensors are offset by their shorter shelf life and sensitivity to dampness. Adding stabilisers (such as chitosan or antioxidants) or packaging in inert pouches could increase the functional lifespan. Superior durability and reproducibility make nanocomposite-based chemiresistive sensors appropriate for multi-cycle use in a range of environmental situations.

Table 3. Comparison of the synthesis methods for paper-based ammonia sensors: Cost, scalability, material quality, and applicability.

Fabrication Technique	Reproducibility	Scalability	Cost per Sensor	Environmental Impact	Key References
Aerosol Jet Printing (AJP)	High precision and excellent batch-to-batch reproducibility	High, compatible with roll-to-roll (R2R) lines	Moderate (~$0.50–$1.00)	Low solvent waste; low-energy curing	[50]
Spray Coating	High, especially with automated deposition systems	Very high; supports industrial coating lines	Low (~$0.20–$0.50)	Minimal waste; eco-friendly inks possible	[44]
Dip Coating	Moderate; operator-dependent uniformity	Moderate; slow for mass production	Very low (<$0.10)	Green solvents feasible; low waste	[40]
Screen Printing	High; established for flexible electronics	High	Low (~$0.30–$0.70)	Moderate solvent use; recyclable substrates possible	[43]
3D Printing (FDM/SLA)	Good for prototyping; low reproducibility at scale	Low–moderate	Moderate (~$1.00)	Variable; depends on resin/polymers used	[53]

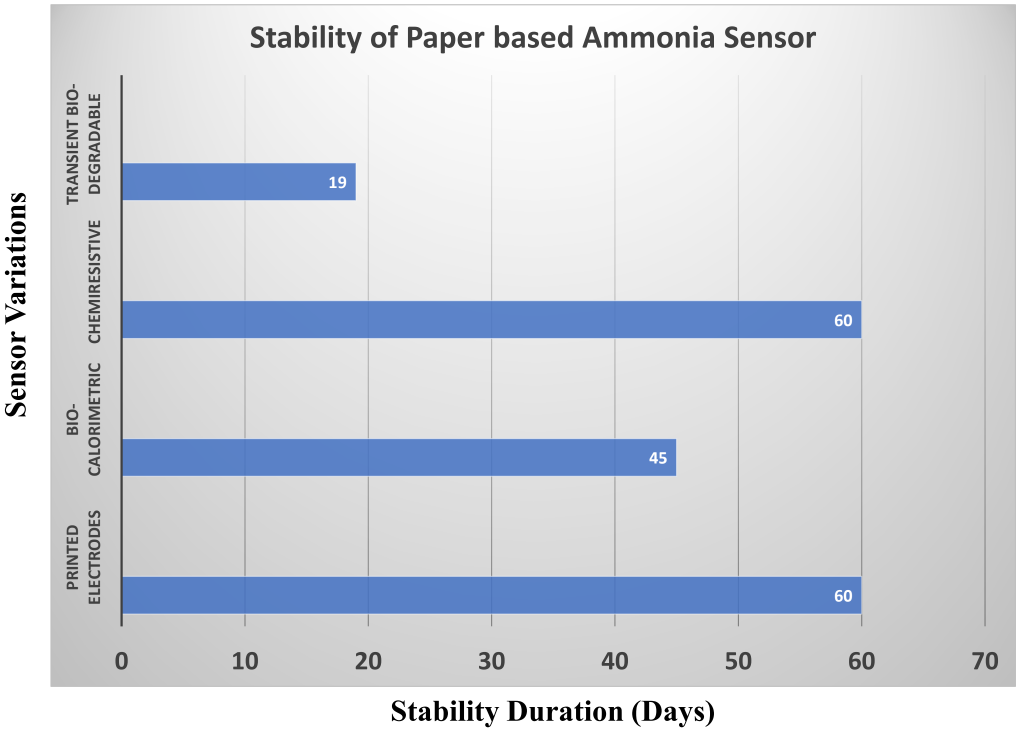


Figure 4. A timeline chart that compares the stability lifespan of various ammonia sensors that are based on paper.

For single-use applications where total degradation is desired after usage, transient devices offer a green option. In order to guarantee performance uniformity across all climates and storage settings, future research should concentrate on standardized stability testing, including accelerated ageing.

3.2. Innovations in Sensor Architecture

The manual drop-casting and dip-coating methods used in earlier reports (2016–2020) resulted in sensors with limited surface homogeneity, poor reproducibility, and scaling problems. Several performance improvements are provided by recent innovations (2021–2025): Greater reproducibility: By guaranteeing uniform active layer thickness and consistent conductivity, AJP and automated spray coating lower batch variability. Improved scalability: High-throughput roll-to-roll fabrication is now possible thanks to methods like screen printing and spray coating, which were not available in earlier research. Eco-friendly processing: Complementing green chemistry principles, the use of water-based inks, biodegradable substrates, and low-energy curing minimizes environmental impact. Advanced architectures: Origami-inspired 3D folding [44] and water-tolerant twistable platforms [55] offer mechanical flexibility and multifunctionality, promoting wearable and portable sensor designs.

3.2.1. Flexible and Wearable Designs

The inherent flexibility of paper has made it possible to develop wearable and foldable sensor devices. For example, Du et al. (2022) decorated filter paper with a ternary nanocomposite made of Pt nanoparticles, polypyrrole, and multiwalled carbon nanotubes to create a twistable and water-tolerant paper sensor. Ultrasensitive detection across a broad concentration range (5 ppb–60% *v*/*v* NH_3) was made possible by this method. Even after being submerged in water for 24 h, the sensors continued to function steadily even when they were folded and twisted up to 1080° [55].

3.2.2. Origami-Based Structures

Architectures inspired by origami and kirigami increase surface area and facilitate 3D sensing. In order to create 3D MXene origami structures, Wang et al. (2024) used mechanically assisted compressive buckling. This enabled the device to monitor ammonia content as well as its distribution and directionality. The functional use of NH_3 sensors is greatly increased by this structural innovation, especially in dynamic situations [44].

3.2.3. Smartphone-Integrated Systems

Real-time on-site analysis is made possible via smartphone integration, which eliminates the need for complex instrumentation. Both Nadi et al. (2024) and Vargas-Muñoz et al. (2023) used colorimetric systems that were based on smartphones [53,54]. The former involved a paper sensor based on mango leaf extract that changed color when exposed to NH_3. The color change was then measured using a smartphone app. With a detection limit of 0.5 mg/L and stability for up to 45 days, the approach proved suitable for field deployment in aquaculture settings [53,54].

3.3. Performance Factors

3.3.1. Sensitivity and Selectivity

Sensitivity and selectivity for NH_3 have been greatly boosted using sensors augmented with nanomaterials. According to Kashyap et al., the WS_2–PANI paper sensor, for instance, showed a high response even at 3 ppm of NH_3 and a low cross-sensitivity to other volatile organic compounds (VOCs) like ethanol and acetone [41]. Similar to this, Xiong et al. used hydrogen bonding and π–π interactions to obtain selectivity in their Zn-TPP/CNT sensor [43].

3.3.2. Detection Limits

For biological and environmental monitoring, low detection limits are crucial. Detection thresholds as low as 5 ppb were achieved by the sensors created by Du et al. and Wang et al., whereas colorimetric sensors integrated into smartphones reported LODs between 0.5 and 1.3 mg/L [44,55].

Paper-based ammonia sensors are now much more practical and perform better because to recent developments in fabrication techniques and sensor architecture. There are now more options for scalable, affordable, and environmentally friendly sensing solutions thanks to innovations like spray-coated nanomaterials, aerosol jet-printed electrodes, 3D-printed portable platforms, and smartphone-assisted quantification. These developments make it possible for sensors to be extremely sensitive, selective, and able to operate in challenging real-world settings in addition to being flexible and wearable. The major parameters of paper-based ammonia sensor are tabulated in the below Table 4.

3.4. Applications and Implementation in the Real World

Ammonia sensors have been adopted in a variety of real-world applications due to the increasing desire for affordable, portable, and sustainable sensors. Paper-based ammonia sensors have shown useful in fields like food spoilage detection, water quality monitoring, indoor air safety, and occupational hazard detection because of their adaptability, biodegradability, and compatibility with smartphone platforms. A comparative summary of different types of paper-based sensor with its parameters are shown in Table 5. Paper-based platforms are the least expensive choice, particularly for disposable and one-time use monitoring. The Nessler and ISE approaches increase operational complexity by requiring more chemicals and infrastructure. Because they are so portable and can often be analysed using just a smartphone camera, paper-based sensors are perfect for environments with little resources. Nessler and other traditional techniques are not appropriate for field deployment in the absence of portable kits. Compared to portable industrial electrochemical sensors, paper-based chemiresistive sensors achieve similar or quicker dynamics, whereas colorimetric forms lag significantly because of capillarity and passive diffusion. Traditional techniques, such as Nessler's reagent, are too sluggish for applications requiring real-time monitoring. Nessler and ISE approaches are still more sensitive than most paper sensors for aqueous systems, which makes them appropriate for trace-level detection in compliance monitoring. With detection limits as low as 5 ppb, considerably below occupational safety criteria (25 ppm, OSHA), sophisticated nanomaterial-enhanced paper sensors (e.g., Du et al., 2022) are on par with or better than traditional portable electrochemical sensors in gas-phase applications. Corresponding tables are shown in supporting document (Supplementary Materials Tables S2–S5).

Table 4. Essential elements for paper-based ammonia sensors.

Sensing Material	Substrate	Fabrication Method	LOD	Response Time	Recovery Time	Sensitivity	Operating Temp.	Reference
WS_2–PANI nanocomposite	Filter paper	Drop-casting	≈9 ppb	38 s	58 s	Strong response, high selectivity	Room temperature	[41]
PANI film	Biodegradable paper	In-situ polymerization	12 ppm	9–30 s (range)	Not stated	360–933% response (12–1000 ppm)	27 °C	[40]
Au@ZnO–rGO	Filter paper	Drop-casting	200 ppb	7 s	13 s	High response from 5 ppb to 60% *v*/*v*	Room temperature	[55]
Mango leaf extract	Whatman filter paper	Dipping + Colorimetry (Smartphone)	0.5 mg/L	~10 min	Not directly stated	Color change intensity vs. conc.	60 °C (optimal)	[54]
ZnTPP–CNT	Paper	Filtration + Hot pressing	100 ppb	20 s	25 s	19.76 (response value)	Room temperature	[43,56]
PANI–MWCNT	Paper	Aerosol jet printing + curing	0.5 ppm	13 s	18 s	Linear response from 3–12 ppm	25 °C ± 2 °C	[50,56]
PEI/Ag NPs on CNF	Paper	Dip-coating	1 ppm	<60 s	~90 s	Good selectivity to NH_3	Room temperature	[58,59]
PANI	Whatman filter paper	Immersion + drying	0.5 ppm	~60 s	~60 s	Visual color change	Room temperature	[60]
PANI–MoS_2	Filter paper	Drop-casting	1 ppm	40 s	50 s	Higher response than individual comps.	Room temperature	[56,61]
CuO@CNT	Paper	Hydrothermal + deposition	0.5 ppm	10 s	14 s	Good linearity in detection	Room temperature	[62,63]
$CH_3NH_3PbI_3$ (MAPI)	Cellulose paper	One-step solution dip-coating	<1 ppm	~10 s	~15 s	96% at 20 ppm	Room temperature	[64,65]
$CH_3NH_3PbBr_3$ (MAPB)	Cellulose paper	One-step solution dip-coating	<1 ppm	~10 s	~18 s	82% at 20 ppm	Room temperature	[64,66]
$CH(NH_2)_2PbI_3$ (FAPI)	Cellulose paper	One-step solution dip-coating	<1 ppm	~12 s	~20 s	65% at 20 ppm	Room temperature	[21,64,66,67]
$Ti_3C_2T_X$ MXene/gelatin	A4 paper	Spray coating + kirigami/origami (3D structure)	93.75 ppb	~240 s	~207 s	0.123%/ppm (5–50 ppm), 0.018%/ppm (50–500 ppm)	Room temperature	[44,63]
Bromothymol Blue (BTB)	Whatman filter paper	Paper disc impregnation + pervaporation in microplate	1.3 mg/L (~1.9 ppm)	5 min	Not specified	Linear range: 5–50 mg/L	Room temperature	[53,68]

Table 5. Specifications Depending on the type of paper-based sensor employed.

Metric	Paper-Based (Colorimetric)	Paper-Based (Nanocomposite/ Chemiresistive)	Nessler	ISE	Electrochemical Gas Sensors
Sensitivity (LOD)	Low–moderate (~0.5–2 mg/L aqueous; ~3–12 ppm gas)	High (5 ppb–3 ppm gas)	Very high (~10 ppb aqueous)	High (~50 ppb aqueous)	Moderate (~1 ppm gas)
Response Time	1–3 min	9–60 s	10–15 min	<1 min	10–60 s
Portability	Excellent	Excellent	Poor	Moderate	Good
Cost	Very low	Low	Moderate	Moderate	High
Re-usability	Mostly single-use	Reusable for multiple cycles	Single-use	Reusable	Reusable
Sustainability	High	High	Low	Low	Low

3.4.1. Food Spoilage Detection

A reliable indicator of protein deterioration in food items, especially in meat and seafood, is ammonia. Aerosol jet printed interdigitated electrodes and carbon black sensing layers were used by Borghetti et al. to create a paper-based ammonia sensor. The gadget, which was made for use in food packaging, showed a discernible drop in resistance as the ammonia concentration increased from 3 to 12 ppm. It also continued to work at high humidity

(75%), which replicated actual packaging circumstances. These characteristics highlight how the sensor might be used in smart packaging systems for real-time spoiling monitoring [50].

3.4.2. Wastewater and Aquaculture Monitoring

Due to fish waste and leftover feed, ammonia builds up in aquaculture systems and can be hazardous to aquatic life at concentrations as low as 0.5 mg/L. Using mango leaf extract as a natural ammonia indicator, Nadi et al. created a colorimetric paper sensor. The sensor showed a limit of detection (LOD) of 0.50 mg/L and functioned efficiently throughout a range of 1.70–10.00 mg/L when combined with a smartphone-based detection system. Because of its ability to stay steady for more than 45 days, the device has the potential to be used in rural areas with minimal resources [54].

This idea was expanded by Vargas-Muñoz et al. to a dual-analyte system for the simultaneous detection of hydrogen sulphide and ammonia in anaerobic digesters. The sensor demonstrated good recovery rates (91–105%) in actual wastewater samples and obtained a limit of detection (LOD) of 1.3 mg/L for ammonia using a 3D-printed chamber and smartphone-assisted colorimetric analysis. This makes it a desirable instrument for environmental monitoring and water treatment plants [53].

3.4.3. Indoor Air Quality and Workplace Safety

Ammonia is a dangerous gas that is commonly found in industrial environments; OSHA has set exposure limits of 50 parts per million. A very flexible, twistable paper-based sensor coated with a multiwalled carbon nanotube/polypyrrole/Pt nanocomposite was created by Du et al. to address this issue. Excellent stability under mechanical deformation and moist conditions was demonstrated by the device, which detected ammonia across a broad dynamic range (5 ppb to 60% *v*/*v*) [55]. According to Du and his research group, the sensor's capacity to adapt to curved surfaces and wearable formats, such as face masks, allows for real-time personal exposure monitoring.

A WS_2–PANI nanocomposite sensor was presented by Kashyap et al. on a flexible paper substrate, with negligible interference from ethanol and acetone and strong selectivity towards ammonia. The sensor supports applications in industrial safety and air quality surveillance with a bending stress resistance and a detection limit as low as 3 ppm [41].

3.4.4. Integration with Portable and Smartphone Platforms

Numerous researchers have concentrated on smartphone integration in order to improve accessibility and facilitate field diagnostics. Without the requirement for specialized equipment, Nadi et al. used cell phone imaging to analyze the colorimetric response of their mango-extract paper sensor [54]. A portable 3D-printed lightbox with controlled lighting was also developed by Vargas-Muñoz et al. to enable repeatable image collection and analysis [53]. A revolutionary development for portability and on-site quantification has been the integration of smartphone platforms: Colorimetric Platforms: For ammonia concentrations ranging from 0.5 to 10 $mg \cdot L^{-1}$, RGB-based analysis outperforms laboratory UV–Vis spectrophotometry in terms of accuracy by 90–95% [54]. Error margins are further reduced to less than 5% by using calibration algorithms and regulated lighting conditions.

Chemiresistive Platforms: Although smartphone-connected resistance readers have sensitivity levels that are comparable to those of benchtop multimeters, they have a small response recording lag (less than 2 s) when exposed to dynamic gases (Kashyap et al., 2024). A schematic diagram of the experimental setup for paper sensor using smartphone is shown in Figure 5 below.

A Bluetooth-enabled MXene origami sensor that transmits real-time data to smartphones was exhibited by Wang et al. (2024) as an example of an advanced IoT system. Although real-world industrial experiments are still unreported, field testing revealed a divergence of less than 3% from laboratory analyser's in controlled circumstances [44].

Although the performance difference between laboratory-grade instruments and portable smartphone-based platforms has been considerably reduced in recent studies, obtaining reliable, interference-free performance in complicated, variable field circumstances is still the next big step towards commercialization, shown in Table 6 below.

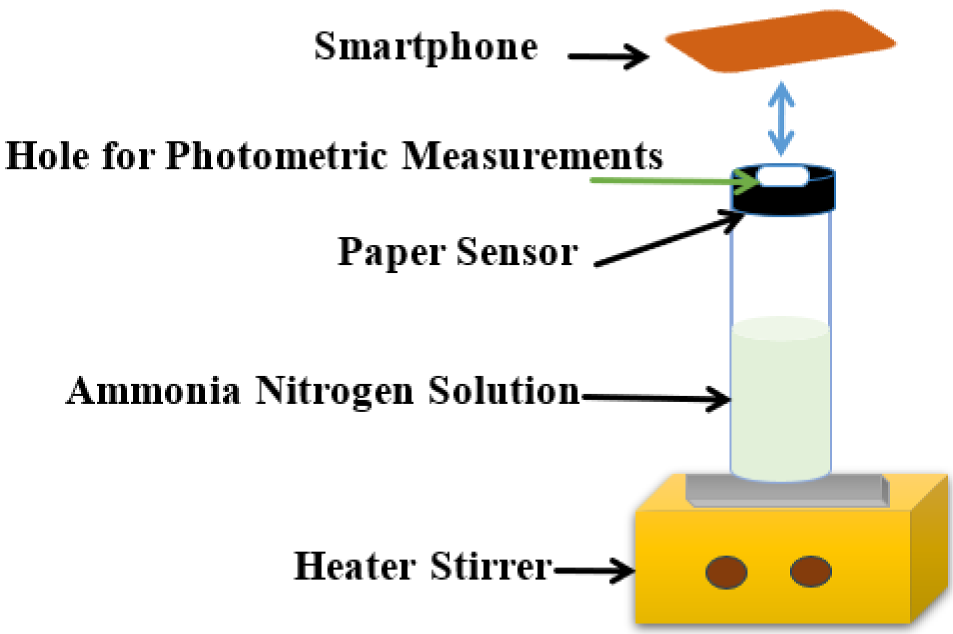


Figure 5. Schematic diagram of the experimental setup for paper sensor using smartphone.

Table 6. Gap analysis, present developments, and future research on field deployment, reliability, and smartphone integration.

Aspect	Current Status	Gap	Needed Advancements
Field Trials	Limited to pilot demonstrations (e.g., aquaculture, spiked food samples)	Lack of standardized protocols and large-scale testing	Multi-location trials; inter-laboratory validations
Long-Term Stability	30–60 days for most platforms	Drift under high humidity and cyclic stress unaddressed	Barrier coatings; encapsulation strategies
False Positives	Observed in VOC-rich or ion-contaminated samples	Insufficient selectivity and calibration	Surface functionalization; AI-driven correction
Smartphone Accuracy	~90–95% correlation with lab instruments	Performance varies with lighting and user error	Automated calibration and controlled lighting accessories

4. Challenges, Opportunities, and Future Directions

Compared to conventional gas detecting technologies, paper-based ammonia sensors have demonstrated great promise as accessible, affordable, and environmentally friendly substitutes. To enable widespread deployment and economic feasibility, a number of practical and technical obstacles still need to be overcome despite their proven potential. Concurrently, new fabrication techniques, digital integration, and developing materials offer intriguing opportunities for further study and implementation.

4.1. Advantages

Low cost, scaleable fabrication.

- Additive, maskless printing enables rapid electrode/sensing-layer patterning on paper with minimal material waste and compatibility with roll-to-roll lines ideal for smart packaging and disposable labels [57].
- Spray coating of functional inks yields uniform, conformal coverage over complex, folded paper architectures at low temperature [44].

Sustainability and end-of-life.

- Biodegradable substrates and transient architectures reduce e-waste; MXene/gelatin origami sensors degraded completely in enzymatic media within ~19 days [44].
- Bio-derived indicators enable green chemistry routes and facile disposal [54,56].

Mechanical compliance and field deployability.

- Paper’s inherent flexibility and porosity support twistable, foldable, and water-tolerant devices that maintain function after severe deformation and immersion [55].
- Smartphone integration delivers quantitative, on-site readouts without benchtop instrumentation [53,54].

Room-temperature operation and selectivity engineering.

- Chemiresistive nanocomposites operate at ambient conditions with tunable selectivity via acid–base and π–π interactions [41,43].

4.2. Current Limitations

Selectivity and cross-sensitivity are still major problems, particularly for sensors used in complex settings with humidity, acidic gases, or volatile organic compounds (VOCs). The majority of paper-based sensors continue to react to interfering species under ambient conditions, especially when colorimetric or non-functionalized sensing layers are used. This is despite some studies reporting improved selectivity through material design, such as the WS_2–PANI composite sensor by Kashyap et al., which showed good resistance to ethanol and acetone [41].

Long-term deployment is also constrained by environmental durability and sensor longevity. Exposure to light, oxygen, or microbes can cause natural markers like anthocyanin or plant extracts to degrade. Although longer duration and environmental resistance have not yet been investigated, Nadi et al. reported that their sensors based on mango leaf extract remained stable for 45 days while being stored [54]. According to Du et al., mechanical durability (such as twisting and immersion) can be developed; nevertheless, for dependable field use, moisture resistance and biodegradation stability need to be carefully matched [55].

Cross-comparability across various sensor systems is hampered by the lack of standardization in performance testing (such as LOD determination, humidity control, and interference testing). Although academic findings are encouraging, variable testing procedures and environmental restrictions make it unclear whether they can be replicated in industrial or regulatory settings.

4.3. Opportunities

Several technological and application-level opportunities are emerging to address current limitations:

Paper-based sensors can be integrated with Internet of Things (IoT) and artificial intelligence (AI) platforms to create intelligent, self-governing monitoring systems. Digital sensing platforms are built on smartphone-based systems, such as those created by Vargas-Muñoz et al. [53] and Nadi et al. [54]. Large-scale environnemental surveillance, predictive analytics, and improved accuracy can all be achieved by integrating AI-driven image analysis and cloud-based data aggregation.

One of the most important steps towards zero-waste diagnostics is the development of entirely biodegradable sensor systems. Wang et al. used a $Ti_3C_2T_X$ MXene/gelatin ink combination that broke down in 19 days in an enzymatic solution to demonstrate a totally transient sensor [44]. This strategy is in line with the objectives of the circular economy and green electronics, especially for single-use sensors used in food packaging, aquaculture, and agriculture.

Scalable manufacturing methods including screen printing, spray coating, and aerosol jet printing are making commercial scaling more and more possible. Borghetti et al. showed how aerosol jet printing may be used to create repeatable electrodes on paper at ambient temperature [50]. This allows for roll-to-roll manufacturing when paired with photonic curing. Paper-based ammonia sensors have emerged as sustainable, low-cost alternatives to conventional laboratory and industrial detection systems.

For aqueous systems, Nessler and ISE techniques still surpass most paper sensors in absolute sensitivity, making them suitable for trace-level detection in compliance monitoring. In gas-phase applications, advanced nanomaterial-enhanced paper sensors (e.g., Du et al., 2022) are comparable or superior to conventional portable electrochemical sensors, with detection limits as low as 5 ppb, well below workplace safety thresholds (25 ppm, OSHA).

4.4. Future Research Needs and Emerging Trends

Several crucial research fields must be prioritized as shown below:

- Multi-analyte sensing and real-time feedback systems: For industrial process control and environmental diagnostics, future designs should incorporate multi-functional sensing elements (such as those for pH, humidity, ammonia, and volatile organic compounds) with real-time wireless communication.
- Hybrid sensors that combine biological and nanomaterial components: By combining biosensing elements or enzymes with synthetic nanomaterials (MXenes, CNTs, WS_2), selectivity, sensitivity, and biocompatibility may be enhanced.
- Internationally recognized testing methodologies for LOD, reaction time, recovery, cross-sensitivity, and environmental stability must be established in order to receive regulatory approval and be adopted by the industry.
- Advanced data fusion and on-board computation: By integrating edge AI into micro-controllers or NFC modules, standalone sensors may be able to decipher data, spot trends, and send out alarms without the need for continual human intervention.

- Sensing in complex matrices: To reduce noise and improve target interaction, selective membranes or microfluidic filtration are needed for ammonia detection in high-protein foods, wastewater sludge, or exhaled breath. In next-generation designs, materials like molecular imprinted polymers, ion-selective layers, and hydrophobic coatings might become increasingly common.

In order for paper-based ammonia sensors to move from laboratory prototypes to widely used industrial and consumer instruments, standardization, field validation, and digital platform integration must be given top priority in research. Through material breakthroughs, scalable fabrication, and regulatory harmonization, these sensors can provide high-performance, biodegradable, and affordable solutions for the next generation of industrial, food, and environmental monitoring ecosystems.

Recent developments in paper-based sensors show strong trends toward AI/IoT integration, full biodegradability, and commercial scalability (Table 7). These trends indicate a shift from proof-of-concept prototypes to practical, regulatory-compliant devices, with several already piloted for real-world applications.

Table 7. Various trends of paper-based sensors with its feasibility, expected impact etc.

Trend	Expected Impact	Feasibility	Current Readiness Level (TRL)	Key Notes
AI/IoT Integration	Real-time, high-accuracy monitoring with predictive analytics	High (hardware is mature; software needs optimization)	TRL 5–6	Already piloted for aquaculture and packaging platforms
Fully Biodegradable Sensors	Zero-waste, eco-safe devices for disposable monitoring	High	TRL 4–5	MXene-gelatin and bio-based composites leading the field
Multi-Analyte Detection	Comprehensive sensing in complex matrices	Medium	TRL 3–4	Requires selective materials and AI-assisted analysis
Extended Stability (>90 Days)	Reliable long-term field use	Medium	TRL 3	Encapsulation and novel polymer matrices are promising
Commercial Scale-Up	Mass adoption in food, environmental, and industrial markets	High	TRL 6	Spray coating and AJP enable rapid upscaling
Standardized Calibration Protocols	Facilitates regulatory approval and cross-study comparability	High	TRL 4	Needs inter-laboratory collaborations

5. Conclusions

Even though paper-based ammonia sensors have previously demonstrated their promise in a variety of applications, overcoming urgent issues with selectivity, endurance, and reproducibility is necessary to move from laboratory proof-of-concept to reliable commercial devices. Nonetheless, these sensors are positioned to become essential instruments in environmental monitoring, public health, and smart packaging as a result of the confluence of smart manufacturing, nanotechnology, AI integration, and sustainable materials.

The usefulness and functionality of paper-based ammonia sensors have been greatly improved by recent developments in fabrication techniques and sensor architecture. Spray-coated nanomaterials, aerosol jet-printed electrodes, 3D-printed portable platforms, and smartphone-assisted quantification are examples of innovations that have made it possible to develop scalable, affordable, and environmentally friendly sensing technologies. These developments make it possible for wearable, flexible sensors that are also extremely sensitive, selective, and able to operate in challenging real-world settings.

The combination of digital connection, sustainable substrates, and nanotechnology is turning paper-based ammonia sensors from lab ideas into next-generation analytical instruments. Table 8 is typically a gap analysis for the paper based ammonia sensor from which the further future studies can be developed.

Large-scale validation, standardization, and regulatory alignment are essential for future success. Paper-based platforms can provide economical, portable, and environmentally friendly sensing solutions with focused investments and interdisciplinary partnerships, allowing for broad adoption in industrial safety, environmental monitoring, and international food security systems.

Table 8. Critical gap analysis for future research studies.

Challenge	Current Status	Required Action
Long-term stability	Most platforms <60 days	Develop barrier coatings and anti-fouling strategies for >90-day durability
False positives	High in VOC-rich or ion-contaminated matrices	Functionalize surfaces; integrate AI-driven correction algorithms
Standardization	Lack of universal testing protocols	Establish ISO-aligned calibration and validation standards
Scalability	R2R-compatible techniques exist but underused	Expand pilot manufacturing with automated quality control
Regulatory compliance	Early LCA and biodegradability data available	Align with FDA, EFSA, and OSHA for faster market approval

Supplementary Materials

The additional data and information can be downloaded at: https://media.sciltp.com/articles/others/2509251041501154/EESUS-2508000114-Supplementary-Materials.pdf.

Author Contributions

J.S: conceptualization, methodology; S.G.: data curation, writing-original draft preparation; C.M.H: supervision; J.S and C.M.H.: writing-reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

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