

Review

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Ammonia emissions from croplands: processes, measurement, and mitigation

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Abstract

Croplands are the primary source of anthropogenic ammonia (NH₃) emissions, contributing significantly to soil nitrogen (N) loss and air pollution. In this review, we synthesize recent advancements in understanding cropland NH₃ emission processes, influential factors, measurement techniques, and mitigation strategies. We emphasize the critical, yet historically underestimated, biological sink provided by the crop canopy, which can recapture approximately 50% of soil-volatilized NH₃ following N fertilization. While current canopy exchange research has focused heavily on dryland crops, research quantifying NH₃ recapture by rice canopies remains severely lacking. Furthermore, we evaluate the efficacy of key mitigation strategies, including deep fertilizer placement, N rate optimization, post-fertilization irrigation, and the use of enhanced-efficiency fertilizers (EEFs), in reducing NH₃ emissions. We highlight the pressing need for integrated, multi-pollutant mitigation frameworks to prevent 'pollution swapping', in which NH₃ emission reductions inadvertently exacerbate emissions of other reactive N species, such as N₂O. Future research should focus on coupling low-cost, continuous monitoring technologies with artificial intelligence (AI) and satellite-based remote sensing, alongside the implementation of holistic governance, to move beyond single-pollutant control. Ultimately, a systems-level approach is essential to reduce NH₃ emissions, optimize N use efficiency, safeguard environmental quality, and ensure global food security.

Keywords: Cropland, Ammonia emission, Measurement methods, Canopy NH₃ exchange, Rice paddy fields, Co-mitigation

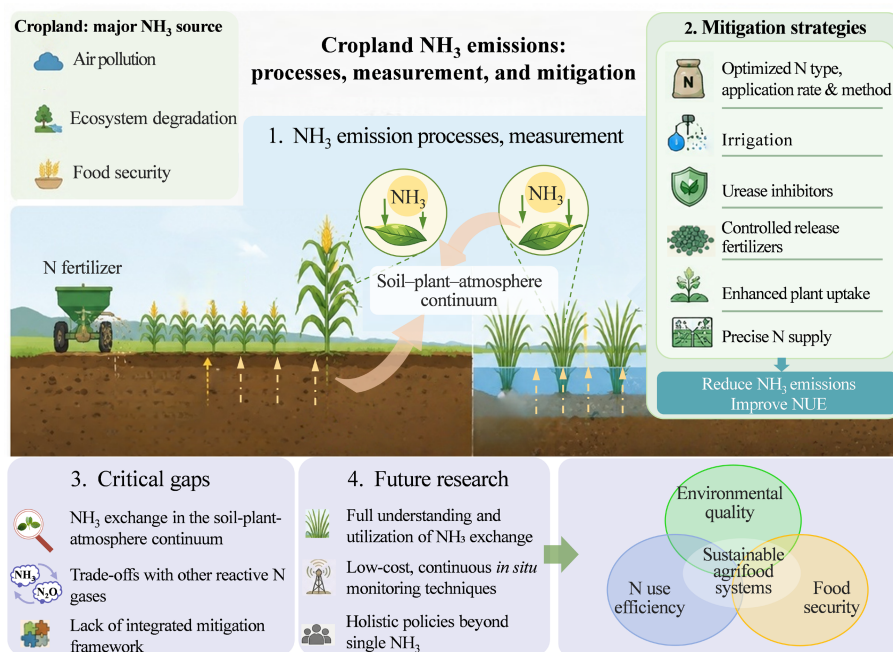
Highlights

- Cropland NH₃ emission processes, measurement, and management are reviewed.
- Crop canopy can recapture ~50% of emitted NH₃ following N fertilization.
- Assessment of NH₃ emissions should consider the entire soil–plant system.
- Co-mitigation strategies should address the reduction of multiple N gas emissions.

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Graphical abstract



Introduction

Ammonia (NH_3) emissions from agricultural activities, particularly from croplands, account for more than 35% of total global emissions^[1]. These substantial cropland NH_3 emissions trigger a cascade of negative environmental impacts. These include the formation of fine particulate matter ($\text{PM}_{2.5}$), which harms human health, as well as soil acidification, eutrophication of aquatic ecosystems, and biodiversity loss in natural ecosystems^[2–5]. From an agronomic perspective, NH_3 volatilization from croplands represents a significant loss of reactive nitrogen (N), undermining nitrogen use efficiency (NUE) and exacerbating environmental risks. Hence, accurately estimating and mitigating NH_3 emissions is crucial for achieving sustainable agriculture, improving air quality, and addressing climate change. Moreover, elucidating the mechanistic drivers of NH_3 emissions provides the fundamental scientific basis for developing evidence-based N management strategies that reconcile crop productivity with environmental protection.

Research on NH_3 emissions from applied N fertilizers in croplands spans over 70 years (Fig. 1), during which methodologies for measuring NH_3 emissions have evolved significantly. Early research primarily relied on chamber methods to detect NH_3 losses^[6–8]. As the demand for continuous field-scale monitoring grew, techniques evolved toward micrometeorological approaches, including the integrated horizontal flux (IHF) method, the aerodynamic gradient method (AGM), and the relaxed eddy accumulation (REA) method^[9–11]. Most recently, the field has advanced to high-frequency, non-intrusive measurements employing sophisticated techniques such as eddy covariance (EC)^[12] and the backward Lagrangian Stochastic (bLS) model^[13], enabling a more accurate characterization of dynamic emission fluxes.

In addition, significant advancements in NH_3 emission inventories, primarily through bottom-up estimates and top-down inversions, have been achieved. Traditional bottom-up approaches combine activity data with emission factors (EFs) derived from

empirical emission rates, field observations, or process-based modeling. Foundational databases such as EDGAR (Emissions Database for Global Atmospheric Research) are regularly updated to improve their spatiotemporal resolution and provide comprehensive global baselines^[14]. Since static bottom-up inventories often fail to capture rapid temporal fluctuations, recent studies have significantly refined NH_3 inventories using dynamic, meteorology-dependent process models that integrate high-resolution climate data and soil–plant system parameters^[15]. Additionally, incorporating bidirectional NH_3 exchange methodology holds great potential to improve traditional estimates, though large uncertainties remain^[16,17]. Concurrently, advancements in satellite remote sensing have revolutionized NH_3 estimates. Satellite-based instrumentation, such as CrIS and IASI, now provides high-resolution column densities of NH_3 . Satellite-derived top-down observations, coupled with network measurements of $\text{NH}_3/\text{NH}_4^+$ deposition, are increasingly used to calibrate and refine bottom-up inventories^[15,18].

More recently, artificial intelligence (AI) and machine learning (ML) have emerged as powerful tools to overcome limitations of traditional NH_3 estimation methods by capturing the complex, synergistic effects of meteorological factors and agricultural management practices. Data-driven algorithms process massive datasets to generate high-resolution NH_3 flux estimates and identify emission hotspots. Notably, Xu et al. developed ML models to generate global crop-specific EFs, demonstrating that optimizing fertilizer management can reduce NH_3 emissions by ~38% without altering total N inputs^[19]. However, a major limitation of AI approaches is their heavy reliance on the quantity and quality of training data. Future research should target coupling AI with process-based models and robust observational datasets to achieve both predictive accuracy and mechanistic interpretability.

At the same time, the paradigm of NH_3 emission control has shifted from solely an agronomic NUE concern to a dual objective of enhancing NUE while safeguarding air, water, and soil quality^[20]. The concept of minimizing NH_3 emissions has deep historical roots.

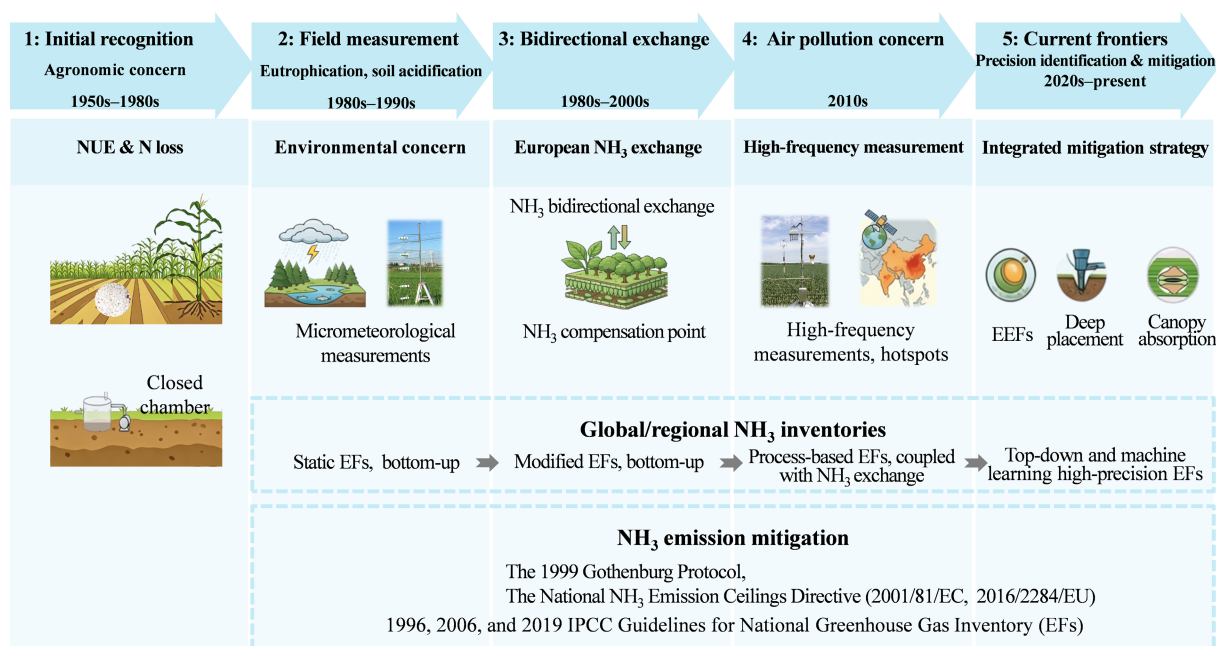


Fig. 1 An historical framework of research concerning NH₃ emissions from croplands. NUE-nitrogen use efficiency; EEFs-enhanced efficiency fertilizers; EFs-emission factors; EC-European Commission; EU-European Union; IPCC-Intergovernmental Panel on Climate Change.

Empirical knowledge from Chinese agriculture over 400 years ago recognized NH₃ as a 'fertilizer gas' and advocated for deep soil incorporation^[21], as documented in ancient agricultural texts: '深则肥气深入土中，徐徐讨力，且根派深远' (if fertilizer is applied deep into the soil, the 'fertilizer gas' penetrates the soil deeply, allowing nutrients to release gradually and promote extensive root development). Contemporary science has validated this ancient wisdom. Modern meta-analyses have demonstrated that deep placement of fertilizer can reduce NH₃ emissions by 48.0%. Furthermore, the adoption of enhanced-efficiency fertilizers (EEFs), such as controlled-release fertilizers and urease inhibitors (UIs), can significantly reduce NH₃ emissions by 56.8% and 53.1%, respectively^[22]. At a macro level, implementing an ambitious, integrated management framework encompassing all known mitigation practices could abate global cropland NH₃ emissions by up to 71%^[23].

In response to the escalating environmental burden, governments and international organizations have enacted policies to regulate excessive N fertilizer use and curb NH₃ emissions. For instance, the Gothenburg Protocol and the National NH₃ Emission Ceilings Directives (2001/81/EC, 2016/2284/EU) in the European Union set strict NH₃ reduction targets for member states. Similarly, China has launched action plans to cap synthetic fertilizer use and improve air quality, evolving from the 'Action Plan for Zero Increase in Fertilizer Use by 2020' (2015) to the 'Three-year Action Plan for Winning the Blue Sky War' (2018) and the 'Action Plan for Continuous Improvement of Air Quality' (2023).

Despite these research and policy advancements, critical knowledge gaps remain. These knowledge gaps include an incomplete mechanistic understanding of bidirectional NH₃ exchange processes, discrepancies in field-scale observations across different measurement methods, and a lack of integrated strategies to co-mitigate the loss of multiple reactive N gases. Bridging these gaps is essential for reconciling agricultural productivity with ecosystem health. Consequently, this review aims to critically synthesize the current literature on NH₃ emission processes across the

soil–water–plant–atmosphere continuum in croplands. Specifically, we analyze the underlying mechanisms and influencing factors, evaluate the main techniques for measuring NH₃ emissions, and assess the current mitigation strategies. Finally, we highlight key areas for future research. Overall, this review offers an integrated perspective on cropland NH₃ emissions, aiming to facilitate the development of robust N management strategies that enhance NUE, mitigate NH₃ emissions, and ultimately achieve agricultural sustainability.

Processes of NH₃ emissions across the soil–water–plant–atmosphere continuum

NH₃ emissions from croplands involve a complex, multi-step mass transfer process: the conversion of aqueous NH₄⁺ to dissolved NH₃ within the soil solution, the subsequent volatilization and diffusion of NH₃ across the soil–air interface, the emission from the soil, and the final transport through the plant canopy into the free atmosphere (Fig. 2).

The magnitude and direction of NH₃ flux are fundamentally governed by the concentration gradient and transport resistances between the emitting surface and the boundary layer. At the soil–atmosphere interface, the concentration gradient is driven by the total ammoniacal N pool and the thermodynamic equilibrium between NH₄⁺ and NH₃ in the soil solution, whereas transport resistances are primarily dictated by atmospheric turbulence^[24]. At the canopy–atmosphere interface, NH₃ exchange is a bidirectional process and is mainly governed by the NH₃ compensation point, which depends on plant type, growth stage, and N status^[25,26].

To assess these bidirectional fluxes and incorporate these processes into global or regional NH₃ emission evaluations, resistance-based models have been developed^[27,28]. Recent advances in these models have transitioned from initial static, empirical variables to process-based parameterizations of emission

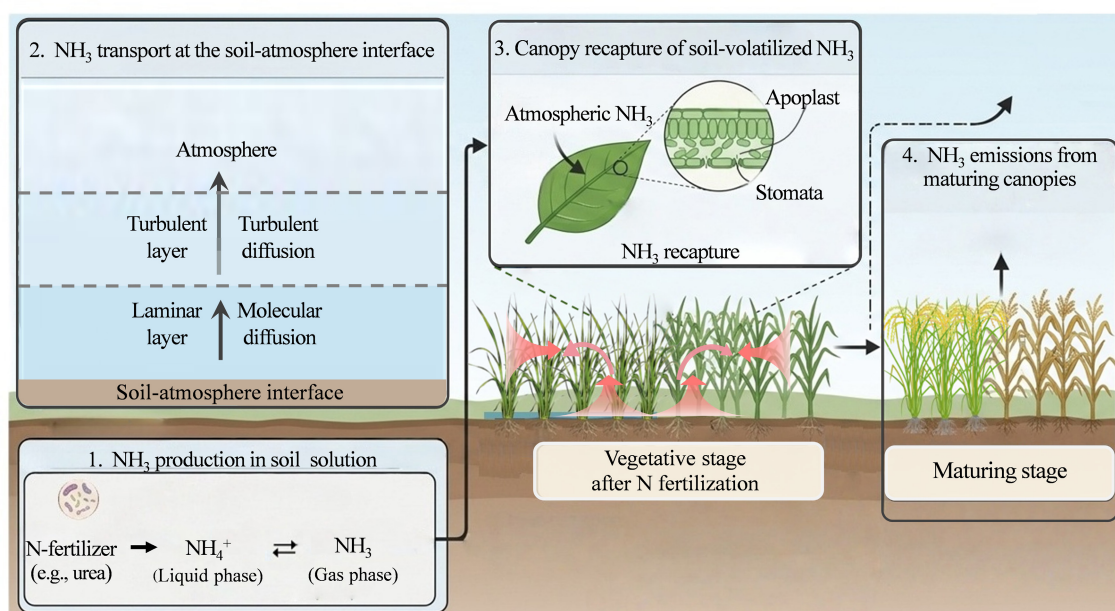
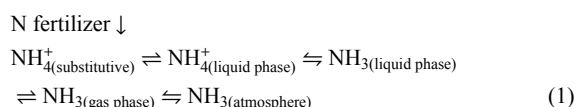


Fig. 2 Processes of NH_3 emissions across the soil–water–plant–atmosphere continuum.

potentials. Furthermore, the implementation of multi-layer canopy architectures into these models can capture in-canopy turbulence. Ultimately, the incorporation of these resistance models into regional chemical transport models (CTMs) has the potential to reduce uncertainties in global NH_3 inventories^[16,29,30].

The production of gaseous NH_3 in the soil solution

Following the application of NH_4^+ or urea-based N fertilizer to croplands, a series of physicochemical reactions occur at the soil–solution–gas interfaces. The chemical equilibrium equations governing NH_3 volatilization are as follows:



In dryland soil, the liquid phase refers to the soil solution^[31]. In flooded rice fields, the liquid phase corresponds to shallow floodwater, and the gas phase refers to the air above it^[24]. Factors that drive the above chemical equilibria to the right promote NH_3 volatilization^[31]. The equilibrium between NH_4^+ and NH_3 is regulated by pH and temperature, shifting to the right in environments with high pH and elevated temperatures. Specifically, following the application of urea ($\text{CO}[\text{NH}_2]_2$), the urease-catalyzed hydrolysis process produces NH_3 , NH_4^+ , and HCO_3^- . This reaction consumes H^+ , thereby raising soil pH and promoting NH_3 volatilization^[32].

Attention must be paid to NH_3 volatilization processes in rice paddy fields, which occupy approximately 11% of the global cropland area and where production is predominantly concentrated in South and East Asia. NH_3 volatilization in paddy fields differs fundamentally from that in dryland systems due to the presence of floodwater and underlying anaerobic conditions. Upon N fertilizer application, the lack of oxygen in the submerged soil layer suppresses nitrification, thereby maintaining high concentrations of NH_4^+ -N in the floodwater. Furthermore, paddy fields exhibit unique pH dynamics in floodwater driven by algal activity. During the daytime,

the intense photosynthetic consumption of dissolved CO_2 by algae drives the floodwater to highly alkaline levels (often exceeding pH 8.5 and occasionally reaching 9.0–10.0), despite the soil pH remaining at 5.5–6.0^[33,34]. This diurnal pH spike shifts the chemical equilibrium from aqueous NH_4^+ towards volatile NH_3 , triggering substantial pulses of NH_3 volatilization.

The transport of NH_3 at the soil–atmosphere interface

NH_3 transport at the soil–atmosphere interface primarily depends on two factors: the NH_3 concentration gradient between the soil surface and the atmosphere, and wind speed. A large concentration gradient is the primary driving force for volatilization, while high wind speed accelerates the removal of NH_3 from the boundary layer^[35]. The air above the soil surface consists of a laminar boundary layer topped by a turbulent layer. The NH_3 at the soil–air interface is transported across the laminar layer via molecular diffusion, and subsequently through the turbulent layer to the atmosphere via turbulent diffusion.

NH_3 exchange between the crop canopy and the atmosphere

Canopy recapture of soil-volatilized NH_3

Following N fertilizer application to croplands with an established canopy, the recapture of volatilized NH_3 by foliage plays a pivotal role in determining the magnitude of net atmospheric NH_3 emissions^[36,37]. The exchange of NH_3 between plant canopies and the atmosphere is inherently bidirectional. Plant canopies act as a sink for NH_3 when the ambient NH_3 concentration exceeds the NH_3 compensation point in the apoplast^[20,26]. This compensation point is directly determined by leaf temperature and the emission potential (Γ), defined as the ratio of NH_4^+ to H^+ concentration in the leaf apoplastic fluid^[38].

Based on apoplastic extraction methods, wild and semi-natural plants typically exhibit very low compensation points of 0.5–2.0 nmol/mol^[39,40], whereas fertilized crops generally display higher values of 2.0–10.0 nmol/mol^[41–43]. However, an exception is observed in rice leaves during the vegetative growth stage, where

NH₃ compensation points can be as low as 0.4–0.6 nmol/mol, even under adequate N fertilization. This anomalously low compensation point is attributed to a high density of chloroplasts, which facilitate rapid assimilation of NH₄⁺ in the mesophyll apoplast^[44].

Canopy absorption has been shown to exhibit a linear response to ambient NH₃ concentrations^[45]. Furthermore, in pasture or wheat fields, the canopy's capacity to absorb volatilized NH₃ increases with canopy height. For instance, the NH₃ emission reduction rate has been estimated at 2.5%–5.0% per cm of crop height^[46,47]. Mechanistically, the crop canopy alters the local microclimate, particularly by reducing wind speed, thereby prolonging the residence time of volatilized NH₃ and facilitating its recapture.

A substantial proportion of soil-volatilized NH₃ can be recaptured by the upper foliage, driving a significant internal NH₃ cycle within the canopy^[48]. Studies have demonstrated that a well-developed canopy can recapture over 50% of the NH₃ volatilized from the soil surface^[46,49,50]. However, such high recapture rates are not universally applicable across all ecosystems. While dense canopies like corn can absorb up to 70% of the volatilized NH₃^[36], efficiencies in other systems are often lower. For example, tomato canopies absorbed 24%–38% of the applied NH₃ after the flowering stage^[51], and coffee canopies reabsorbed 43% of enhanced soil-volatilized NH₃^[52].

Moreover, recapture efficiency varies considerably across plant growth stages and measurement techniques. In rice fields, at the early tillering stage, the canopy could only recapture 16.0% of the floodwater-volatilized NH₃. When evaluated with a portable NH₃ detector in a rice–wheat rotation, the rice and wheat canopy recaptured only 3%–5% of the soil-volatilized NH₃^[53]. In non-agricultural ecosystems, such as temperate grasslands or natural forests, recapture rates are highly dependent on canopy density and leaf area index^[54,55]. Overall, canopy recapture is governed by complex conditions, underscoring the need for ecosystem- and growth stage-specific parameterization.

Canopy NH₃ emissions

Whether a crop canopy emits NH₃ depends on the difference between the leaf NH₃ compensation point and the ambient NH₃ concentration^[56]. When the ambient levels fall below the NH₃ compensation point, NH₃ in the apoplast volatilizes through the stomata into the atmosphere. During leaf senescence or the post-anthesis period in cereals, the rapid degradation of *Rubisco* and other

proteins leads to a significant accumulation of NH₄⁺, triggering a surge in canopy NH₃ emissions^[57,58]. Generally, canopy NH₃ emission potential increases with N application rate, and accumulated NH₃ emissions over the growing season show a positive correlation with above-ground crop N content at anthesis^[10].

Measurement techniques for NH₃ emissions from croplands

Accurately measuring NH₃ fluxes is challenging due to the gas's high solubility, chemical reactivity, and spatiotemporal variability^[59]. Historically, methodologies have evolved from simple enclosure-based methods to sophisticated laser-based micrometeorological methods^[60,61]. These approaches can be broadly classified into indirect methods, chamber methods at the plot scale, and micrometeorological methods at the field scale (Fig. 3). Detailed technical descriptions and flux calculation equations for each technique are provided in the [Supplementary Text S1](#).

Indirect measurement methods

Indirect methods estimate NH₃ emissions by calculating the unaccounted-for N pool in the soil–plant system using mass balance, rather than directly capturing the emitted gas. However, this approach frequently overestimates NH₃ emissions^[62] because it inadvertently includes other N-loss pathways (e.g., denitrification). The accuracy can be improved by employing the ¹⁵N-tracing technique^[63].

Direct measurement methods

Direct measurement methods are currently the primary approaches used for monitoring NH₃ emissions and are broadly categorized into chamber methods and micrometeorological methods.

Chamber methods

Chamber methods, encompassing closed chambers, vented chambers, dynamic chambers, Dräger-Tubes, and wind tunnels, are primarily used for comparative studies of different treatments across small field plots.

Passive chambers (closed and vented) are inexpensive, easy to operate, and require no power supply. However, they drastically alter the internal microclimate (e.g., wind speed and temperature), which often leads to a substantial underestimation of NH₃ fluxes^[64].

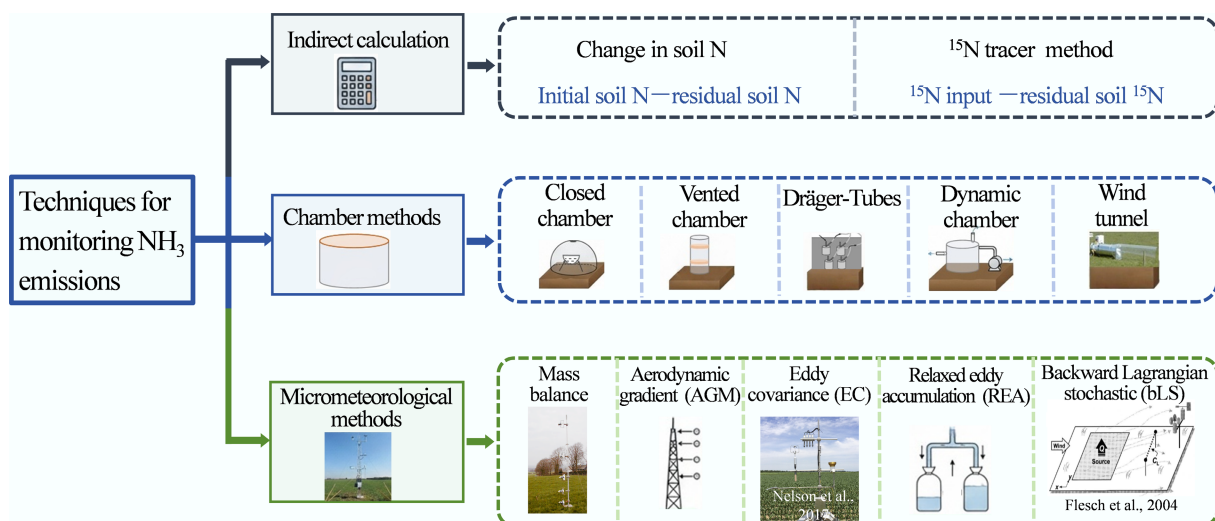


Fig. 3 Overview of techniques used to quantify NH₃ emissions from croplands.

Active chambers (dynamic chambers and Dräger-Tubes) require active pumping to maintain airflow. In dynamic chambers, air is drawn through at a constant rate, and the exhausted air passes through acid traps^[65]. A critical limitation here is that the estimated NH_3 flux is highly dependent on the air exchange rate^[66]. The Dräger-Tubes method is a portable variant in which ambient air is pulled through the chambers and analyzed instantly using colorimetric tubes^[67,68]. To improve accuracy, fluxes derived from Dräger-Tubes must be empirically calibrated using ambient wind speeds at a 2.0 m height^[69].

Wind tunnels utilize an automatic fan system to match the internal wind speed of a half-cylinder or rectangular tunnel to external environmental conditions. This method simulates field conditions and is suitable for small-scale, multi-treatment studies^[70,71]. However, the equipment is relatively complex, and it cannot simulate calm wind conditions or precipitation.

Micrometeorological methods

Micrometeorological methods are explicitly designed for large, open-field areas. Their significant advantage is that they are non-intrusive and integrate spatial heterogeneity, thereby providing representative field-scale flux measurements. However, they generally require large, uniform areas, stable meteorological conditions, and capital-intensive equipment.

The integrated horizontal flux (IHF) method is widely considered a standard micrometeorological method for measuring NH_3 emissions following fertilization^[72]. It calculates vertical NH_3 flux by integrating horizontal fluxes across a vertical cross-section of the plume^[62]. The invention of the passive Leuning sampler has greatly simplified its operation^[73].

The aerodynamic gradient method (AGM) and the relaxed eddy accumulation (REA) method are highly suitable for monitoring net bidirectional exchange (emission vs absorption) above crop canopies^[11,74]. AGM derives fluxes from vertical concentration profiles and turbulence information^[75,76], whereas REA segregates updrafts and downdrafts into separate reservoirs, avoiding the need for high-frequency gas analyzers^[11].

The eddy covariance (EC) method can quantify both NH_3 emissions and deposition fluxes by computing the covariance between simultaneous, high-frequency measurements of turbulent air movements and fast-response gas concentrations^[12].

The backward Lagrangian stochastic (bLS) model is a robust, flexible dispersion modeling approach that calculates NH_3 fluxes by simulating the backward trajectories of air parcels from downwind monitors back to the source area^[77]. When coupled with open-path lasers (OP-TDLAS), it enables instantaneous, continuous, and non-intrusive monitoring without perturbing natural microclimates. However, it becomes unreliable under low-turbulence conditions or extreme atmospheric stability^[13,78].

Comparative summary of measurement techniques

To provide a concise guide for selecting appropriate monitoring techniques, the spatial coverage, precision, cost, and suitability of the major NH_3 measurement techniques are summarized in Table 1.

Factors driving NH_3 emissions from croplands

NH_3 emissions from croplands are dynamically governed by the interplay among soil characteristics, environmental conditions,

management practices, and crop/microbial assimilation^[24,31,80] (Fig. 4). Soil properties dictate the internal thermodynamic and biochemical volatilization potential. Environmental factors act as external catalysts. Management practices determine the initial state and spatial distribution of the N source, and they also alter soil and environmental conditions.

Soil properties

Soil pH is the primary driver of NH_3 volatilization. Elevated soil pH exponentially increases the potential for NH_3 volatilization by accelerating the deprotonation of NH_4^+ to aqueous NH_3 ^[81]. Fertilizers such as urea inherently raise the local pH around the granule during hydrolysis, driving higher NH_3 losses^[82]. Soils with a high buffering capacity attenuate these localized pH spikes, thereby suppressing NH_3 emissions.

Cation exchange capacity (CEC), determined by clay mineralogy, soil texture, and soil organic matter (SOM) content, regulates NH_3 emissions by providing negatively charged sites. High-CEC soils electrostatically retain more NH_4^+ , effectively buffering changes in the soil solution and reducing the size of the N pool susceptible to volatilization^[83].

Soil urease activity is a key factor influencing NH_3 volatilization rates following urea application. The initial phase involves the catalytic hydrolysis of urea into ammonium carbonate by extracellular urease (optimum pH 7.0–9.0)^[84]. Synthesized by diverse soil bacteria and fungi, this enzyme's capacity is frequently evaluated using the abundance of the *ureC* gene as a molecular marker. Notably, crop residues harbor high urease activity, up to 20 times that of the underlying soil, exacerbating rapid hydrolysis of applied urea when residues remain on the soil surface^[85].

Soil nitrification, primarily driven by ammonia-oxidizing bacteria (AOB) and archaea (AOA), rapidly converts NH_4^+ into nitrite. When soil conditions favor the proliferation of AOB and AOA, the rapid consumption of NH_4^+ limits NH_3 volatilization. The intricate balance between *ureC*-mediated hydrolysis and *amoA*-mediated nitrification is crucial for managing the biological drivers of NH_3 dynamics.

Environmental conditions

Temperature: Post-fertilization temperature regulates NH_3 emissions through three mechanisms: (1) stimulating urease activity; (2) shifting the $\text{NH}_4^+/\text{NH}_3$ equilibrium towards gaseous NH_3 ; and (3) promoting the diffusion rates of urea, NH_4^+ , and NH_3 within the soil^[80,82].

Wind speed: High winds enhance NH_3 emissions by altering the NH_3 partial pressure gradient at the soil–atmosphere interface, swiftly removing emitted NH_3 to the atmosphere^[9,86]. However, this can be partially offset by wind-induced evaporative cooling, which lowers surface temperatures^[87]. This can also explain why NH_3 emission rates measured using dynamic chamber methods increase with higher air-exchange rates^[8,66]. The wind speed effect is modified by soil surface conditions. If there is tall and dense vegetation, the vegetation effectively slows down the wind and reduces the wind effect on NH_3 emissions.

Rainfall and irrigation: Light rain on moist soils without deep percolation accelerates urea hydrolysis, thereby exacerbating NH_3 emissions^[88]. Conversely, post-fertilization heavy rainfall or irrigation can leach surface-applied urea into deeper soil layers, promoting NH_4^+ adsorption and root uptake, thereby significantly suppressing NH_3 losses^[89,90].

Table 1 Comparison of major techniques measuring NH_3 emissions from croplands

Measurement technique	Spatial coverage	Precision	Cost and labor requirement	Suitability and limitation
Indirect methods	Plot to field scale	Low to medium (overestimates NH_3 losses. ^{15}N tracing improves accuracy)	Low to high cost (high for ^{15}N isotopes), high labor (soil sampling)	Suitable for estimating short-term losses under specific circumstances
Passive chambers (closed, vented)	Small plot scale (0.01–0.2 m^2)	Low (underestimates NH_3 fluxes by 26%–63% by dampening wind speed ^[13,79])	Very low cost, low labor, no power supply required	Ideal for relative comparisons among treatments in remote areas. Not suitable for absolute emission quantification
Active chambers (dynamic chambers, Dräger-Tubes)	Small plot scale (0.01–0.2 m^2)	Medium to high (highly depends on air exchange rate and calibration)	Medium cost, moderate labor; dynamic chambers require continuous power	Suitable for plot-scale treatment comparisons
Wind tunnels	Small plot scale (~1 m^2)	High (effectively simulates aerodynamic conditions)	High cost, complex equipment setup, requires continuous power	Suitable for plot-scale treatment comparisons. Cannot simulate calm winds
Integrated horizontal flux (IHF)	Field scale (15–50 m radius)	High (integrates spatial heterogeneity)	Medium cost, high labor (frequent sampler replacement and lab analysis)	Recommended standard for post-fertilization measurements in uniform, open fields
Aerodynamic gradient method (AGM)	Field scale (ha)	High (sensitive to atmospheric stability and NH_3 gradient)	Medium cost, high labor (depends on sampler type)	Suitable for bidirectional exchange in large, uniform ecosystems
Relaxed eddy accumulation (REA)	Field scale (ha)	Medium to high (provides time-averaged fluxes)	Medium cost, high labor (depends on sampler type)	Suitable for bidirectional exchange in large, uniform ecosystems
Eddy covariance (EC)	Field scale >(ha)	High (provides high-frequency temporal resolution)	High cost (requires fast-response laser spectrometers), high computational expertise	Ideal for continuous, real-time, and long-term monitoring of bidirectional fluxes
Backward Lagrangian stochastic model (bLS)	Field-to-farm scale	High (highly flexible source configuration)	High cost (if using open-path lasers), high computational expertise	Highly suitable for quantifying emissions from complex, distinct, or heterogeneous sources

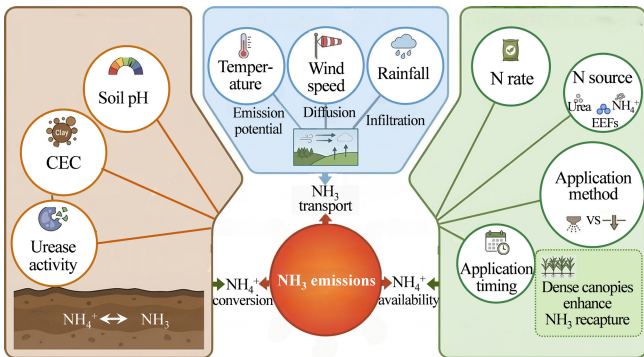


Fig. 4 Schematic diagram of factors modulating NH_3 emissions from croplands. CEC-cation exchange capacity; EEFs-enhanced efficiency fertilizers.

Fertilizer management practices

N fertilizer rate

NH_3 emissions frequently exhibit a nonlinear response to N application rates^[91,92]. When N inputs exceed the crop uptake capacity and soil's biochemical buffering thresholds, unassimilated NH_4^+ accumulates in the topsoil, triggering a surge in NH_3 volatilization.

N fertilizer type

Conventional urea exhibits high emission factors because its hydrolysis consumes H^+ , creating an alkaline microsite that favors NH_3 formation. In contrast, ammonium sulfate and ammonium nitrate generally produce lower NH_3 emissions, especially in neutral to acidic soils^[93]. Enhanced efficiency fertilizers (EEFs) are highly effective at mitigating NH_3 emissions. UIs (e.g., *N*-(*n*-butyl)thiophosphoric triamide [NBPT]) delay urea hydrolysis, minimize localized pH/NH_4^+ spikes, and reduce NH_3 emissions by 50%–54%^[22,94,95]. Alternatively, controlled-release fertilizers physically encapsulate urea, synchronizing the slow release of N with crop demand, thereby largely eliminating NH_3 emissions^[96].

Application method

Surface broadcasting of urea consistently yields the highest NH_3 losses, especially when applied over crop residues^[83,97] or in Asian paddy fields, where high temperatures and algal-induced pH spikes can drive losses by up to 46%–54% of applied urea-N^[34,79,86,98,99]. Conversely, deep placement (> 5–10 cm) or subsurface banding physically isolates the fertilizer from surface urease, wind, and heat. This globally recognized management practice effectively reduces NH_3 emissions by 35%–55%^[22,100,101].

Timing of application

In upland cropping systems, timing the application (if using broadcast application) before a heavy rainfall event to allow the urea to be washed into the soil will reduce NH_3 emissions. Splitting N applications to align with critical crop growth stages synchronizes nutrient supply with crop demand, preventing transient NH_4^+ accumulation in the topsoil^[102]. Furthermore, strategically timing the application of N when the crop canopy is fully developed and dense will allow the overlying foliage to recapture 30%–50% of the soil-volatilized NH_3 , thereby reducing net atmospheric emissions^[36,46,49].

Strategies for mitigating NH_3 emissions from croplands

A series of comprehensive reviews and meta-analyses have summarized strategies to reduce NH_3 emissions from croplands^[19,22,100,103–105]. However, because most field monitoring studies have focused on NH_3 fluxes from the soil surface, existing mitigation strategies primarily target the soil–atmosphere interface. Consequently, the role of the crop canopy, a critical component of the agroecosystem, in mitigating NH_3 emissions has historically received disproportionately limited attention.

Developing and implementing effective NH_3 mitigation strategies is essential for enhancing NUE in agriculture. Although NUE encompasses a wide array of definitions^[106], enhancing NUE, in the context of NH_3 mitigation, primarily refers to improving crop N

uptake. The synchronization of N supply with crop N demand is the most adoptable framework to mitigate NH₃ emissions. We summarize the emission reduction efficiencies of major mitigation strategies based on recent meta-analyses in Table 2. The integrated adoption of these strategies—ranging from rate optimization and deep placement to the adoption of EEFs, urea substitution, post-fertilization irrigation, split applications, and fertilizer amendments—offers a viable pathway to balance high crop productivity with a minimal environmental footprint (Fig. 5).

Optimizing the N application rate

Implementing site-specific N management to determine the optimum N application rate is the fundamental prerequisite for reducing NH₃ emissions without penalizing crop yield. Accurately determining optimal N rates remains an active research area, moving away from empirical estimations toward precision agriculture. Numerous quantitative models and approaches have been proposed to define the optimum N application rate for specific crop types and regions. Notable examples include the Regional Mean Optimal N approach (RMON)^[109], the theoretical N rate method^[110], the Stanford Theoretical Equation (STE)^[111], and integrated soil and crop testing approaches^[112].

Use suitable N fertilizer types to reduce NH₃ emissions

Different N fertilizers exhibit varying intrinsic potentials for NH₃ volatilization. Urea is highly susceptible to NH₃ loss because its rapid hydrolysis consumes H⁺, thereby increasing the microsite pH^[24,113]. Substituting urea with ammonium sulfate or ammonium nitrate, which

do not induce significant pH elevations, can substantially reduce NH₃ emissions, particularly in neutral or alkaline soils. This approach is strongly recommended in Europe's *Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions*^[114]. However, it is critical to note that ammonium sulfate and ammonium nitrate are generally unsuitable for flooded paddy fields, where enhanced urea formulations (e.g., controlled-release fertilizers or UIs) and deep placement remain the preferred options.

Deep placement of N fertilizers to reduce NH₃ emissions

Mechanically incorporating or banding fertilizer deep into the soil profile (e.g., > 5–10 cm) is consistently recognized as one of the most robust physical mitigation techniques^[19,22]. Deep placement protects the applied N fertilizer from atmospheric contact. More importantly, NH₃ produced within the soil profile encounters significant resistance to diffusion upward; it is intercepted, dissolved in the soil solution, and adsorbed by the soil's CEC. In paddy fields, this method is particularly effective because it isolates the fertilizer from floodwater, thereby bypassing NH₃ volatilization triggered by algal-driven pH elevations in floodwater.

Deep placement of urea below 10 cm, whether in paddy fields or dryland, can reduce NH₃ volatilization by up to 70%–90% compared to surface broadcasting^[115,116]. Mechanical side-deep placement of fertilizer has been shown to reduce NH₃ emissions by 30%–50%; the lower rate of reduction is due to some urea remaining exposed to the atmosphere or diffusing into the floodwater^[101,117,118]. Despite its high efficacy, the substantial labor and machinery costs associated with deep placement hinder its widespread adoption.

Post-fertilization irrigation to reduce NH₃ emissions

Irrigation immediately following N application is a highly effective operational strategy to reduce NH₃ emissions^[71]. Applying sufficient water post-fertilization through irrigation drives dissolved N deep into the rooting zone^[90]. Studies indicate that irrigation or rainfall exceeding 10 mm is the critical threshold for effectively suppressing NH₃ volatilization^[119].

Split application and enhancement of canopy recapture

Shifting a larger proportion of N fertilizer to mid-growth stages (e.g., panicle initiation) serves dual purposes. First, it synchronizes N supply with peak crop demand, minimizing the availability of substrate NH₄⁺ prone to volatilization^[112]. Second, applying N beneath a well-developed crop canopy reduces wind speed at the soil surface. Furthermore, the extensive leaf area acts as a biological sink, directly recapturing a substantial fraction of volatilized NH₃ through the stomata^[36,120].

However, it is imperative to highlight that current canopy recapture models rely predominantly on empirical data from dryland crops. The canopy recapture dynamics in paddy ecosystems differ fundamentally from those in drylands due to the distinct morpho-physiological traits of rice leaves^[44] and the exceptionally high NH₃ volatilization occurring above the floodwater. Consequently, quantifying canopy recapture in paddy systems represents a critical and unaddressed gap in current mitigation research.

Adoption of EEFs for reducing NH₃ emissions

Extensive research has validated the efficacy of UIs in delaying urea hydrolysis, thereby preventing rapid, localized pH increases and

Table 2 A summary of NH₃ emission reduction efficiencies for major mitigation techniques based on existing meta-analyses

Mitigation technique	Primary mechanism	Reduction efficiency (%)	Ref.
N rate optimization	Reduces substrate availability for NH ₃ emissions	30.7	[107]
Deep placement	Acts as a physical barrier; enhances soil adsorption	48.0	[22]
		54.7	[100]
		34.6	[107]
UIs	Delays urea hydrolysis to avoid rapid pH increases	53.1	[22]
		53.7	[100]
		50.0	[107]
		52.0	[95]
		56.8	[22]
Controlled-release fertilizers	Regulates N release to prevent high NH ₄ ⁺ concentrations	68.0	[100]
		60.8	[107]
		60.8	[107]
Nitrification inhibitors (NIs)	Inhibits nitrification, leading to NH ₄ ⁺ accumulation and increasing NH ₃ emission potential	−42.6*	[22]
		−38.0*	[100]
		−27.5*	[107]
Split applications of fertilizer	Avoids NH ₄ ⁺ accumulation and synchronizes N supply with crop needs	0	[22]
		23.6	[108]
		0	[100]
		31.7	[107]
Post-fertilization irrigation	Transports urea and NH ₄ ⁺ downward into the soil profile	38.8	[22]
		34.5	[100]
Substitution of Urea by ammonium sulfate or ammonium nitrate in drylands	Eliminates hydrolysis-induced pH increases	51.2–88.3	[22]
		63.5	[100]
Reducing basal fertilizer proportion	Avoids NH ₄ ⁺ accumulation	61.5	[107]
Delaying early tillering fertilizer	Enhances canopy NH ₃ recapture and root uptake of NH ₄ ⁺	31.0	[46]
Amendments	Promotes temporal adsorption of NH ₄ ⁺	31.4	[100]

* Negative values in association with NIs indicate an increase in NH₃ emissions.

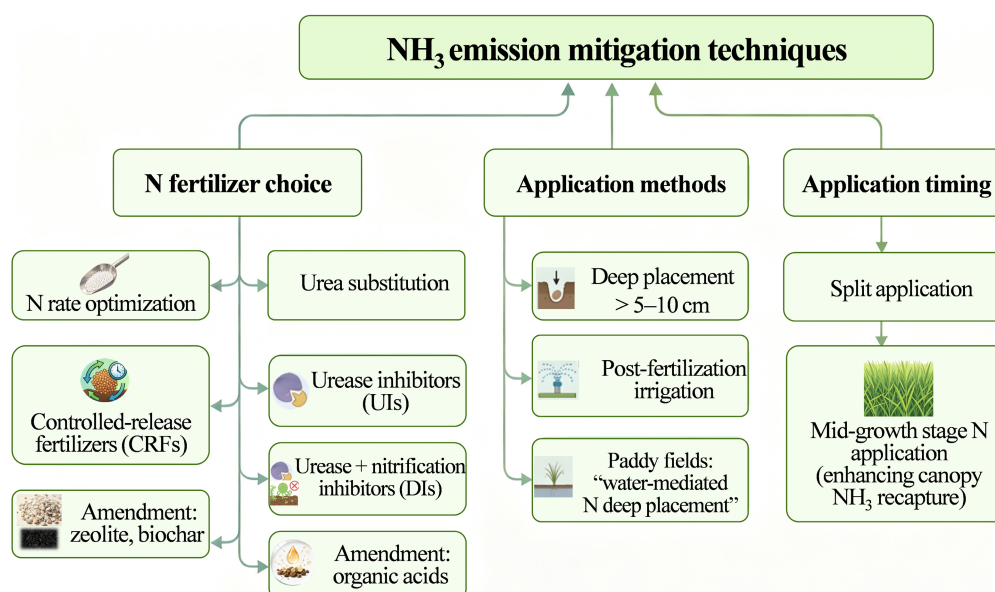


Fig. 5 Diagram illustrating cropland NH_3 emission reduction strategies.

subsequent NH_3 volatilization^[22,95,121,122]. Among commercially available UIs, NBPT is the most widely adopted due to its high efficiency at a low dosage. An NBPT application can reduce NH_3 fluxes from pastures by 40%–60%^[94]. In northern China, NBPT/NPPT (*N*-[*n*-propyl] thiophosphoric triamide) formulations decreased NH_3 emissions from maize and wheat fields by 65%–100%^[68].

Nevertheless, the efficacy of NBPT declines in paddy fields, resulting in an average reduction of 40%–50%. This diminished performance may be attributed to the anaerobic conditions caused by floodwater coverage, which hinder the essential oxidation of NBPT to its active form, NBPTO^[123].

Regarding NIs, while they successfully abate N_2O emissions, their suppression of nitrification prolongs the residence time of NH_4^+ in soils, inadvertently increasing the potential for NH_3 emissions^[124,125]. To counteract this, the co-application of NIs and UIs is recommended; however, determining their optimal ratios, elucidating synergistic mechanisms, and evaluating pollution trade-offs require further research.

Controlled-release fertilizers, such as polymer-coated urea, physically encapsulate the N core. By regulating N release in response to soil temperature and moisture, controlled-release fertilizers prevent sudden accumulation of high NH_4^+ concentrations. This can achieve substantial NH_3 reductions while synchronously matching plant N demand^[96]. However, the high price of controlled-release fertilizers hinders their widespread adoption.

Other amendments for reducing NH_3 emissions

Biochar has gained attention as a soil amendment for reducing greenhouse gas emissions, improving carbon sequestration, and enhancing soil fertility. Its porous structure and high surface area enable the adsorption of NH_4^+ ^[126]. However, because unmodified biochar is typically alkaline, the use of acidified or surface-modified biochar is recommended to prevent inadvertently raising soil pH^[127]. Additionally, when co-applied with fertilizers, amendments such as zeolite, pyrite, and organic acids have been shown to decrease NH_3 volatilization by 43.5%, 20.9%, and 15.9%, respectively^[100].

Areas for future research

Elucidating the role of the crop canopy in reducing cropland NH_3 emissions

The direction and magnitude of NH_3 exchange between crop canopies and the atmosphere represent one of the most profound uncertainties in understanding cropland NH_3 emissions. An accurate, integrated assessment of this bidirectional exchange is crucial for evaluating ecosystem-level NH_3 budgets and developing cost-effective mitigation strategies (Fig. 6). Due to methodological constraints, the vast majority of current field measurements, regional inventories, and mitigation evaluations focus almost exclusively on NH_3 volatilized from the soil or the floodwater surface^[19,91,92,128–130]. Although several advanced inventories have incorporated NH_3 compensation points, these models rely heavily on empirical values derived from dryland ecosystems in Europe and North America^[16,131,132], leaving rice-specific data remarkably scarce.

Determining the NH_3 compensation point of rice leaves is highly challenging compared to dryland crops due to the distinctive morpho-physiological traits, including pronounced surface hydrophobicity, restricted stomatal aperture, and a disproportionately high density of chloroplasts in the cell periphery^[44,133]. These factors complicate the precise quantification of the bidirectional NH_3 exchange in submerged paddy systems. Consequently, there remains a severe paucity of research on localized, growth-stage-specific parameters for canopy NH_3 exchange tailored to rice cropping systems.

Advancing NH_3 emission monitoring and estimation techniques

Current methodologies for quantifying cropland NH_3 emissions rely heavily on small dynamic or vented chambers designed to capture volatilization from the soil/floodwater surface^[44,117,124,134,135]. Consequently, continuous, *in situ* monitoring of NH_3 fluxes from the entire soil–water–plant–atmosphere continuum throughout the full growing season remains severely limited. While small chamber methods are

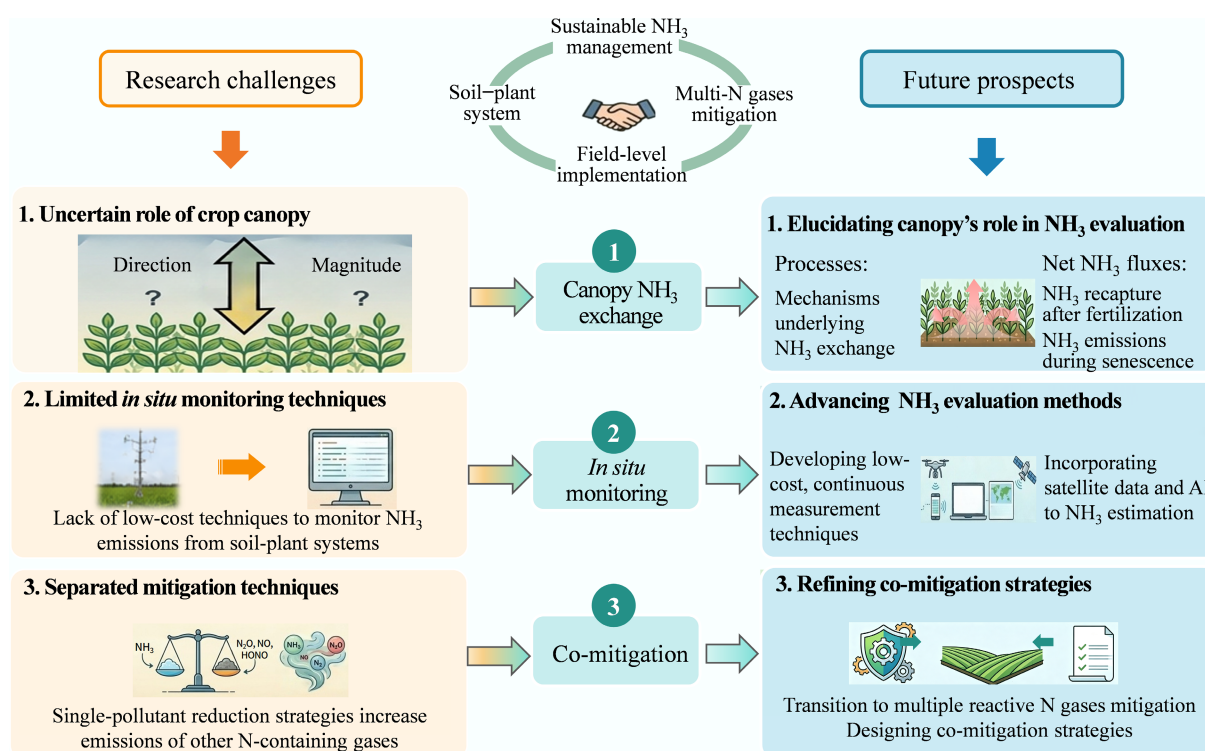


Fig. 6 Schematic diagram of the main research challenges and future prospects for research on cropland NH₃ emissions.

suitable for comparative evaluations of emission potentials among treatments, they fail to capture the actual net fluxes under natural field conditions. Therefore, developing and validating low-cost, highly automated micrometeorological techniques is urgently needed for ecosystem-scale measurements. Promising approaches include the deployment of miniaturized tunable diode laser absorption spectroscopy (TDLAS) and IoT-enabled electrochemical sensor networks.

Furthermore, to bridge the gap between plot-scale observations and regional inventories, future research should embrace emerging macro-scale technologies. While research on global and regional NH₃ inventories has advanced considerably, existing inventories continue to show substantial discrepancies (Supplementary Table S1) and are subject to certain uncertainties. Such limitations are primarily driven by field observations that generally overlook canopy NH₃ exchange, as well as the incomplete compilation of emission source activity data. Recent advancements in satellite-based remote sensing techniques offer vital top-down constraints for regional NH₃ estimation and validation. Concurrently, ML and AI algorithms are emerging as powerful tools to decipher the complex relationships between NH₃ emissions and multidimensional environmental/management drivers. Integrating continuous ground-based monitoring with satellite observations and AI-driven models will revolutionize the spatiotemporal prediction of cropland NH₃ emissions. It is hypothesized that coupling high-density ground data with satellite retrievals via AI can significantly reduce regional inventory uncertainties.

Integrated co-mitigation of multi-pollutants and smart governance

Cropland NH₃ management faces a complex environmental paradox: single-pollutant targeted reduction strategies often inadvertently trigger 'pollution swapping'—increasing the emissions of other reactive N gases. For example, N₂O, nitrogen oxides (NO_x), and nitrous

acid (HONO) are produced through interconnected biochemical pathways, making isolated mitigation approaches insufficient. For example, while NIs reduce N₂O production, they can alter soil pH and NH₄⁺ retention, inadvertently promoting NH₃ emissions^[124]. This demonstrates that addressing individual pollutants in isolation achieves limited environmental gains.

Transitioning to a co-mitigation framework that simultaneously addresses the mitigation of the entire suite of reactive N gases is essential. In terms of field management, priority should be given to practices that couple the deep placement of EEFs (e.g., dual inhibitors) as basal fertilization with variable-rate, precise N topdressing, guided by crop N status derived from canopy remote sensing. We hypothesized that this integrated co-mitigation strategy can simultaneously minimize the total reactive N gas footprint without compromising crop yield, thereby overcoming the 'pollution swapping' effect.

Beyond resolving outstanding scientific questions, future policy and governance development should transition from single-pollutant regulations to holistic N-loss accounting and market-driven governance. National NH₃ emission caps should be established synergistically with carbon neutrality goals, supported by financial mechanisms, such as a 'Nitrogen Credit Trading System' or the integration of N-surplus penalties into agricultural subsidies, to incentivize the adoption of low-emission technologies. At the management level, smart agriculture management platforms leveraging AI, big data, and sensors can enable real-time monitoring of soil-crop N dynamics, providing intelligent decision support for precise fertilization. Concurrently, systematic agricultural extension programs must be deployed to empower farmers with the skills required to operate smart equipment and implement precision N management. This integrated socio-technical approach will ensure the effective field-level execution of mitigation strategies, securing environmental sustainability without compromising food security.

Supplementary information

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Ethical statements

Not applicable.

Author contributions

The authors confirm their contributions to the paper as follows: Yuhua Tian: data curation, formal analysis, writing – original draft preparation, writing – review and editing, visualization; Lingyun Peng: data curation; Bin Yin: conceptualization; Chaopu Ti: conceptualization, methodology, writing – review and editing; Scott X. Chang: conceptualization, writing – review and editing. All authors reviewed the results and approved the final version of the manuscript.

Data availability

The datasets used or analyzed in the current study are available from the corresponding author upon reasonable request.

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Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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