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Biomass addition and nitrogen mineralisation in wetland paddy soils: A review

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Abstract

Wetland paddy soils play a critical role in supporting global rice production, but their longterm viability is at risk due to nutrient depletion, poor nitrogen (N) management, and increasing greenhouse gas (GHG) emissions. Nitrogen is the primary limiting nutrient in wetland rice ecosystems, and its transformation through processes such as ammonification, nitrification, denitrification, dissimilatory nitrate reduction to ammonium (DNRA), and anaerobic ammonium oxidation (anammox) affects both nitrogen availability to crops and environmental outcomes. These microbial processes are influenced by factors such as soil redox potential, pH levels, organic matter content, temperature, and water management practices. The incorporation of biomass in the form of crop residues, green manures such as *Sesbania aculeata*, Azolla, and cyanobacteria, together with integrated nutrient management (INM), can significantly increase soil organic carbon, enhance microbial activity, and synchronize nitrogen release with crop demand. Advanced fertilisation strategies, including split application, controlled-release urea, deep placement of urea super granules, and nitrification inhibitors, improve nitrogen use efficiency while reducing nitrogen losses and greenhouse gas emissions. This review synthesises current knowledge on nitrogen dynamics, microbial ecology, biomassmediated nitrogen cycling, and nutrient management in wetland paddy soils, and identifies future research priorities for improving nitrogen use efficiency and sustainable rice production.

Keywords: Nitrogen mineralization, wetland rice, biomass addition, green manure, nitrogen use efficiency, greenhouse gas emissions, paddy soil

1. Introduction

Wetlands occupy approximately 6–9% of the Earth's land area and provide vital ecosystem services, including carbon sequestration, flood control, water purification, and biodiversity conservation (Davidson, 2014) ^[1]. Among these, wetland paddy ecosystems are of particular importance because they support global rice production. Paddy soils are characterized by prolonged flooding resulting from bunding and puddling, creating unique physicochemical conditions that strongly influence microbial activity, nitrogen (N) cycling, and soil carbon dynamics (Haefele, 2023) ^[2]. Nitrogen is the primary nutrient limiting rice production worldwide, with indigenous soil nitrogen mineralization supplying nearly 50–66% of crop N uptake in many wetland rice systems (Sahrawat, 2009) ^[3]. Unlike upland soils, flooded paddy soils are predominantly anaerobic, where ammonium (NH₄⁺) serves as the major plant-available nitrogen form. Nitrogen availability is governed by interconnected microbial processes, including mineralization, nitrification, denitrification, dissimilatory nitrate reduction to ammonium (DNRA), and anaerobic ammonium oxidation (anammox), which regulate nitrogen retention, transformation, and loss (Gu and Yang, 2022; Keeney and Sahrawat, 1986; Ishii *et al.*, 2011) ^[4, 5, 6, 7]. These processes influence both crop productivity and environmental outcomes through nitrogen losses and greenhouse gas emissions (Qian *et al.*, 2023) ^[8]. Improving nitrogen use efficiency through sustainable management practices has become increasingly important for maintaining rice productivity while minimizing environmental impacts. This review synthesizes current knowledge on nitrogen dynamics in wetland paddy soils, the microbial processes governing nitrogen mineralization, the role of biomass addition in improving soil fertility and nitrogen availability, and recent advances in nitrogen management strategies for sustainable rice production.

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2. Nitrogen dynamics in wetland paddy soils

2.1 Nitrogen inputs

Nitrogen enters wetland paddy soils through both natural and anthropogenic sources, replenishing the nitrogen removed through crop uptake and various loss pathways. The principal nitrogen inputs include inorganic fertilizers, biological nitrogen fixation, organic amendments, and atmospheric deposition, all of which contribute to maintaining soil fertility and sustaining rice productivity.

2.1.1 Fertilizer application

Inorganic fertilizers constitute the principal external source of nitrogen in wetland paddy cultivation. Ammonium-forming fertilizers such as urea remain the most widely used nitrogen source because they are particularly suited to flooded rice soils, where ammonium (NH_4^+) is the stable and predominant form of mineral nitrogen. Other nitrogen fertilizers, including ammonium sulphate and controlled-release fertilizers, are also used to improve nitrogen availability and enhance nitrogen use efficiency under submerged conditions (Alam *et al.*, 2023) ^[9].

2.1.2 Biological nitrogen fixation

Biological nitrogen fixation contributes substantially to the nitrogen economy of flooded paddy soils by converting atmospheric nitrogen (N_2) into plant-available forms through diazotrophic microorganisms. The floating aquatic fern *Azolla*, in symbiosis with the cyanobacterium *Anabaena azollae*, together with free-living blue-green algae (cyanobacteria), can supply significant quantities of biologically fixed nitrogen, thereby reducing dependence on synthetic nitrogen fertilizers (Kalidurai and Kannaiyan, 1991; Iniesta-Pallarés *et al.*, 2021) ^[10, 11].

2.1.3 Organic amendments

Organic amendments, including crop residues, farmyard

manure, green manures, bone meal, and fish meal, provide an additional source of nitrogen to flooded soils. Unlike inorganic fertilizers alone, these amendments also increase soil organic carbon, stimulate microbial activity, and improve soil fertility through the gradual mineralisation of organic nitrogen into plant-available forms (Alam *et al.*, 2023) ^[9].

2.1.4 Atmospheric deposition

Atmospheric deposition through rainfall and irrigation water contributes small quantities of nitrogen to wetland paddy soils. Although this input is generally minor compared with fertilizer application and biological nitrogen fixation, it provides a continuous background source of nitrogen that supplements the overall nitrogen budget of flooded rice ecosystems.

2.2 Nitrogen transformations

Plants absorb nitrogen primarily as nitrate (NO_3^-) and ammonium (NH_4^+). Under the anaerobic conditions of flooded paddy soils, limited nitrification promotes the accumulation of NH_4^+ making it the predominant form of mineral nitrogen and the preferred nitrogen source for rice plants (Ameen *et al.*, 2021) ^[12]. Although NH_4^+ is assimilated more efficiently than NO_3^- excessive concentrations may impair plant growth, whereas the presence of NO_3^- can alleviate ammonium toxicity (Gu and Yang, 2022; Hou *et al.*, 2021) ^[4, 13, 7]. In flooded paddy soils, nitrogen occurs mainly as organic nitrogen, NH_4^+ , NO_3^- , NO_2^- , and dissolved gaseous forms, whose interconversion is regulated by a series of microbially mediated transformation processes under alternating oxic–anoxic conditions. These interconnected processes, including ammonification, nitrification, denitrification, dissimilatory nitrate reduction to ammonium (DNRA), and anaerobic ammonium oxidation (anammox), determine nitrogen availability, retention, and loss in submerged rice ecosystems (Ding and Yu, 2025) ^[14].

Table 1: Nitrogen transformation processes in the soil

Process	Description	Conditions	Main Microorganisms / Enzymes	Significance
Ammonification	Breakdown of organic nitrogen compounds into ammonium (NH_4^+).	Aerobic or anaerobic	Heterotrophic microbes	First step in nitrogen recycling from organic matter
Mineralization	Microbial conversion of organic nitrogen to inorganic forms like NH_4^+ . Often includes ammonification.	Mostly aerobic	Bacteria and fungi	Supplies plant-available N; driven by organic matter decomposition
Immobilization	Uptake of inorganic N (NH_4^+ or NO_3^-) by microbes for growth.	Aerobic or anaerobic	Soil microbes	Temporarily reduces available N to plants; contributes to soil N storage
Nitrification	Stepwise oxidation of NH_4^+ to NO_2^- and then to NO_3^-	Aerobic (oxic zones)	AOB (Nitrosomonas), NOB (Nitrobacter); AMO enzyme	Produces NO_3^- for plant uptake; precursor for N losses via denitrification
Denitrification	Stepwise reduction of NO_3^- to NO_2^- , NO, N_2O , and N_2 under low oxygen.	Anaerobic (anoxic zones)	Denitrifying bacteria, fungi, archaea	Removes excess nitrate; can lead to N_2O emissions
DNRA	Reduction of NO_3^- to NH_4^+ instead of N_2 .	Strongly anaerobic, high C	DNRA bacteria (Shewanella, Geobacter)	Retains N in the system; competes with denitrification
Anammox	Anaerobic ammonium oxidation: NH_4^+ and NO_2^- to N_2 gas.	Strictly anaerobic	Anammox bacteria (Brocadia, Kuenenia)	Removes fixed N; efficient under anaerobic conditions without organic carbon

2.2.1 Ammonification

Ammonification is the microbial conversion of organic nitrogen compounds into ammonium (NH_4^+), representing the first step in nitrogen mineralization. Under flooded conditions, anaerobic microorganisms decompose soil organic matter, resulting in the

accumulation of NH_4^+ , which serves as the principal source of mineral nitrogen for rice plants. The predominance of anaerobic conditions in submerged soils makes ammonification the dominant nitrogen transformation pathway, supplying substrate for subsequent microbial processes.

2.2.2 Nitrification

Nitrification is restricted to the aerobic microsites of flooded paddy soils, including the thin oxidised surface layer, floodwater, and oxygenated zones surrounding rice roots. The process is initiated by ammonia-oxidizing bacteria (AOB), with ammonia monooxygenase (AMO) catalysing the rate-limiting step, making it a key regulator of nitrification under submerged conditions (Ishii *et al.*, 2011) ^[6].

2.2.3 Denitrification

Denitrification is the major pathway of nitrate loss in flooded paddy soils under anaerobic conditions. Incomplete reduction results in the accumulation of nitrous oxide (N₂O), a potent greenhouse gas with a global warming potential approximately 300 times greater than that of CO₂ over a 100-year period, contributing to both nitrogen loss and climate change (Qian *et al.*, 2023) ^[8].

2.2.4 Dissimilatory nitrate reduction to ammonium (DNRA) and anaerobic ammonium oxidation (Anammox)

DNRA and anammox are alternative microbial pathways that regulate nitrogen retention and removal in flooded paddy soils under anaerobic conditions. Unlike denitrification, DNRA conserves nitrogen within the soil by reducing NO₃⁻ to NH₄⁺, thereby retaining plant-available nitrogen. In contrast, anammox directly converts NH₄⁺ and NO₂⁻ to N₂ via hydrazine (N₂H₄) as a key intermediate, resulting in permanent nitrogen removal from the system (Ishii *et al.*, 2011) ^[6]. Stable isotope studies have shown that denitrification remains the dominant nitrogen loss pathway, accounting for 82–85% of total N₂ production, whereas anammox contributes 15–17%. Denitrification predominates at soil depths of 60–80 cm, while anammox is more active in the upper soil layers. Under controlled fertilization, continuous flooding minimized total nitrogen loss compared with other irrigation regimes (Abid *et al.*, 2024) ^[15].

2.2.5 Rhizosphere processes

The rice rhizosphere plays a critical role in regulating nitrogen transformations under flooded conditions. Radial oxygen loss from rice roots creates localized aerobic microsites within the predominantly anaerobic soil matrix, enabling nitrification to occur adjacent to denitrification zones. This close spatial coupling enhances nitrogen cycling and supports the coexistence of diverse microbial communities responsible for nitrification, denitrification, DNRA, and anammox (Ishii *et al.*, 2011) ^[6]. The rhizosphere therefore acts as an important interface controlling nitrogen availability and transformation in submerged paddy soils.

2.3 Nitrogen loss pathways

Nitrogen losses in flooded paddy soils reduce nitrogen use efficiency, lower crop productivity, and contribute to environmental pollution. The major nitrogen loss pathways include ammonia volatilisation, leaching and runoff, denitrification, and nitrogen removal through crop harvest.

2.3.1 Ammonia volatilisation

Ammonia volatilisation is one of the major nitrogen loss pathways in flooded paddy soils, particularly following surface application of urea. Under alkaline floodwater conditions, especially when algal photosynthesis increases the pH, ammonium (NH₄⁺) is converted to gaseous ammonia (NH₃), which escapes into the atmosphere. The magnitude of ammonia

loss is influenced by floodwater pH, temperature, wind speed, and water depth (Sahrawat, 2009) ^[3].

2.3.2 Leaching and runoff

Although nitrate concentrations are generally low in submerged soils because of limited nitrification, nitrate that escapes denitrification may be transported through leaching into groundwater or lost through surface runoff. The extent of these losses is largely governed by irrigation practices, rainfall, and water movement within the soil profile (Abid *et al.*, 2024) ^[15].

2.3.3 Denitrification losses

Denitrification is an important pathway of nitrogen loss under anaerobic conditions, during which nitrate is sequentially reduced to nitrous oxide (N₂O) and dinitrogen (N₂). While N₂ is an environmentally benign end product, incomplete denitrification results in the emission of N₂O, a potent greenhouse gas with a global warming potential approximately 300 times greater than that of CO₂ over a 100-year period, thereby contributing to climate change as well as reducing nitrogen availability for crops (Qian *et al.*, 2023) ^[8].

2.3.4 Harvest removal

Nitrogen absorbed by rice plants is exported from the field during harvest in the form of grain and straw. Unless crop residues are incorporated back into the soil, this represents a permanent removal of nitrogen from the system, necessitating replenishment through fertilizer application, biological nitrogen fixation, or organic amendments to sustain soil fertility and crop productivity.

2.4 Soil-Water-plant interactions

Nitrogen dynamics in flooded paddy soils are closely regulated by interactions among the soil, water, and rice plants. Flooding creates unique physicochemical conditions that influence nitrogen transformations, nutrient availability, and microbial activity. The principal factors governing these interactions include redox dynamics, soil pH, root-mediated processes, and the structure of the soil microbial community.

2.4.1 Redox dynamics

Flooding creates distinct oxic–anoxic redox gradients that govern nitrogen transformations in paddy soils. Ammonification, immobilisation, and denitrification predominate in the anaerobic bulk soil, whereas nitrification is confined to the thin oxidised surface layer and oxygenated microsites surrounding rice roots (Keeney and Sahrawat, 1986; Nurulhuda *et al.*, 2017) ^[5,16]. Nitrate produced in aerobic zones readily diffuses into adjacent anaerobic soil, where it is denitrified, contributing to nitrogen loss. Water management modifies these redox conditions by altering soil aeration; alternate wetting and drying (AWD) periodically introduces aerobic conditions that reduce denitrification and improve nitrogen use efficiency compared with continuous flooding (Aioub *et al.*, 2024) ^[17].

2.4.2 pH Gradients

Soil pH strongly influences nitrogen transformations by regulating microbial activity and the stability of nitrogen species. Acidic conditions suppress autotrophic nitrifiers, whereas neutral to slightly alkaline conditions promote nitrification and organic nitrogen mineralisation, with net mineralisation decreasing by 75–76% at pH 5.5 compared with pH 6.3–7.7 (Meng *et al.*, 2023) ^[18]. Under alkaline floodwater

conditions, elevated pH favours the conversion of ammonium (NH_4^+) to gaseous ammonia (NH_3), increasing ammonia volatilisation, which is further influenced by temperature, wind speed, and floodwater depth (Sahrawat, 2009) [3].

2.4.3 Root exudates and oxygen release

Rice roots modify the flooded soil environment through radial oxygen loss, creating localized aerobic microsites within the predominantly anaerobic soil matrix. These oxygenated zones support nitrifying microorganisms adjacent to denitrifiers, thereby facilitating coupled nitrification–denitrification over short spatial scales (Ishii *et al.*, 2011) [6]. Rice root exudates also influence rhizosphere microbial activity by supplying carbon compounds and, in some rice genotypes, exhibiting biological nitrification inhibition (BNI) activity that can suppress soil nitrification and improve nitrogen retention (Pariasca Tanaka *et al.*, 2010; Coskun *et al.*, 2017) [19, 20].

2.4.4 Microbial community structure

The physicochemical gradients created by flooding shape the composition and function of microbial communities responsible for nitrogen cycling. Distinct functional groups, including ammonia-oxidising archaea (AOA), ammonia-oxidising bacteria (AOB), denitrifiers, DNRA bacteria, anammox bacteria, and diazotrophs, occupy specific ecological niches along the redox gradient. Their interactions regulate nitrogen retention, transformation, and loss, ultimately determining nitrogen availability and ecosystem functioning in flooded paddy soils (Ding and Yu, 2025) [14].

2.5 Management strategies

Efficient nitrogen management in wetland paddy soils aims to synchronize nitrogen availability with crop demand while minimizing nitrogen losses through volatilisation, denitrification, and leaching. This is achieved through appropriate fertilizer management, integrated nutrient management, optimized water management, and emerging precision technologies that improve nitrogen use efficiency and support sustainable rice production (Kamuruzzaman *et al.*, 2024) [21].

2.5.1 Fertilizer timing and placement

Appropriate fertilizer timing and placement are essential for maximizing nitrogen use efficiency in flooded rice. Practices such as split nitrogen application, deep placement of urea, and the use of coated or controlled-release fertilizers improve synchrony between nitrogen availability and crop demand while reducing nitrogen losses through volatilisation and denitrification (Kamuruzzaman *et al.*, 2024) [21].

2.5.2 Integrated nutrient management

Integrated nutrient management combines inorganic fertilizers with organic sources such as farmyard manure, green manure, crop residues, and biofertilizers to provide a balanced nutrient supply. This approach enhances nitrogen use efficiency, improves soil fertility, and promotes long-term soil health while reducing dependence on synthetic nitrogen fertilizers (Alam *et al.*, 2023) [9].

2.5.3 Water management

Water management is an important component of nitrogen management in paddy soils. Practices such as alternate wetting and drying (AWD) regulate soil aeration, influence nitrogen transformations, and improve nitrogen use efficiency when

integrated with appropriate fertilizer management. (Islam *et al.*, 2018) [22].

2.5.4 Innovative practices

Emerging technologies are improving nitrogen management in rice production. Precision farming tools enable site-specific fertilizer application, while stable nitrogen isotope techniques provide valuable insights into nitrogen transformation pathways and losses under field conditions (Abid *et al.*, 2024) [15]. In addition, industrial by-products such as liquid organic fertilizer recovered from monosodium glutamate (MSG) wastewater have shown potential to partially replace chemical nitrogen fertilizers, improving nitrogen use efficiency while reducing reactive nitrogen losses and maintaining rice yield (Li *et al.*, 2022) [23].

2.6 Environmental impacts

Nitrogen dynamics in flooded paddy soils influence not only crop productivity but also environmental sustainability. Improper nitrogen management can contribute to greenhouse gas emissions, water pollution, soil degradation, and reduced resilience of rice production systems to climate change.

2.6.1 Greenhouse gas emissions

Nitrogen transformations in paddy soils contribute to greenhouse gas emissions, particularly through nitrification and denitrification. Incomplete denitrification results in the release of nitrous oxide (N_2O), a potent greenhouse gas with a high global warming potential, while continuous flooding generally favours methane (CH_4) production under anaerobic conditions (Qian *et al.*, 2023; Hafif *et al.*, 2024) [8, 24].

2.6.2 Water pollution

Nitrogen losses through nitrate leaching and surface runoff contribute to water pollution by increasing the risk of eutrophication in surrounding aquatic ecosystems. Excessive nitrogen loading can impair water quality and negatively affect ecosystem health, highlighting the importance of efficient nitrogen management.

2.6.3 Soil health

Long-term reliance on inorganic nitrogen fertilizers alone may adversely affect soil microbial diversity and biological soil health. In contrast, integrated nutrient management practices that combine organic and inorganic nutrient sources help maintain soil fertility, enhance microbial activity, and support sustainable crop production (Nayak *et al.*, 2025) [25].

2.6.4 Climate resilience

Improving nitrogen use efficiency through sustainable nitrogen and water management enhances the climate resilience of wetland rice systems. Nitrogen transformations influence greenhouse gas emissions, water quality, soil health, and ecosystem sustainability. The magnitude of these impacts depends on nitrogen management and water regime (Islam *et al.*, 2018; Hafif *et al.*, 2024) [22, 24].

3. Microbial ecology of nitrogen mineralization in paddy soils

In rice paddy soils, a variety of microorganisms drive nitrogen transformations. Ammoniaoxidizing archaea (AOA) associated with Thaumarchaeota and bacterial species like Nitrosomonas and Nitrospira represent major nitrifying microorganisms, and they are especially crucial in low-oxygen, submerged

environments (Ishii *et al.*, 2011) ^[6]. While anammox is mostly carried out by *Brocadia* and similar taxa, denitrifiers include genera like *Pseudomonas*, *Paracoccus*, and *Alcaligenes*. *Nitrospira* species are important nitrite-oxidizing bacteria (NOB) that catalyse the second step of nitrification (Ishii *et al.*, 2011) ^[6].

Nitrogen fixation and dissimilatory nitrate reduction to ammonium (DNRA) are the principal biological processes contributing to ammonium generation in paddy soils. In paddy soils, Wang *et al.* (2025) ^[26, 27] identified important heterotrophic bacterial groups involved in these pathways. According to Wang *et al.* (2025) ^[26, 27], Geobacteraceae were enriched under N_2O - and N_2 -amended conditions, Bacillaceae were enriched under NO_3^- - and N_2 -amended conditions, and Anaeromyxobacteraceae were enriched under NO_3^- - and N_2O -enriched conditions.

Table 2: Key heterotrophic microbial families involved in ammonium generation in paddy soils (Wang *et al.*, 2025) ^[26, 27]

Microbial Family	Functions in Nitrogen Cycling
Geobacteraceae	Nitrogen fixation; DNRA; Denitrification
Bacillaceae	Nitrogen fixation
Pseudomonadaceae	Nitrogen fixation; Denitrification
Rhodocyclaceae	Nitrogen fixation; Denitrification
Sulfurospirillaceae	Nitrogen fixation; DNRA; Denitrification
Clostridiaceae	Nitrogen fixation; DNRA; Denitrification
Anaeromyxobacteraceae	DNRA

Soil acidification suppresses autotrophic nitrifiers (AOB and AOA), thereby altering the composition and activity of microbial communities involved in nitrogen transformations. In contrast, neutral to alkaline conditions promote efficient autotrophic nitrification, greater nitrate production, and enhanced microbial-mediated organic nitrogen mineralization. In Zhejiang Province, China, Meng *et al.* (2023) ^[18] showed that net nitrogen mineralization decreased by 75-76% at pH 5.5 compared with soils at pH 6.3-7.7, demonstrating the strong regulatory influence of soil pH on nitrogen availability.

4. Factors influencing nitrogen mineralization

Nitrogen mineralization in wetland paddy soils is regulated by the interaction of environmental and edaphic factors. Soil organic matter (SOM) is a major determinant, as higher soil organic carbon provides substrates for microbial decomposition and nitrogen release (Sahrawat, 2006) ^[28]. Organic materials with low carbon-to-nitrogen (C:N) ratios favour net

mineralization, whereas high C:N ratios promote nitrogen immobilization (Alam *et al.*, 2023) ^[9]. Soil texture, cation exchange capacity (CEC), calcium, and exchangeable bases improve nutrient retention, stabilize soil pH, and support microbial activity (Yeasmin *et al.*, 2012) ^[29]. Temperature accelerates microbial metabolism and nitrogen mineralization, while flooding creates anaerobic conditions that suppress nitrification and promote ammonium accumulation (Bhuiyan *et al.*, 2023) ^[30]. Soil moisture also regulates nitrogen transformations; excessive moisture favours denitrification and N_2O emissions, whereas moisture deficiency restricts microbial activity. Maintaining optimum soil moisture and pH can therefore reduce nitrogen losses and improve nitrogen availability (Fu *et al.*, 2025) ^[31].

5. Greenhouse gas emissions and water management in paddy soils

Rice cultivation is a significant agricultural source of greenhouse gas emissions, particularly methane (CH_4) and nitrous oxide (N_2O), because water management regulates soil redox conditions and the microbial processes responsible for their production (Hafif *et al.*, 2024) ^[24]. Under continuously flooded conditions, prolonged anaerobic conditions promote methanogenesis, resulting in high CH_4 emissions, a greenhouse gas with a global warming potential approximately 34 times greater than CO_2 over a 100-year period (Qian *et al.*, 2023) ^[8]; Cai *et al.*, 2012) ^[32]. During alternate wetting and drying (AWD), soil aeration stimulates nitrification, while subsequent rewetting promotes denitrification, increasing the potential for N_2O emissions (Islam *et al.*, 2018) ^[22]. Thus, irrigation regime determines the trade-off between CH_4 and N_2O emissions.

6. Nitrogen nutrition and fertilization strategies in wetland rice

Efficient nitrogen fertilization is essential because the natural supply of plant-available nitrogen is often insufficient to meet the demand of high-yielding rice crops (Shrestha *et al.*, 2022) ^[33]. Since ammonium is the predominant nitrogen form under anaerobic conditions, urea remains the principal fertilizer source for flooded paddy soils (Alam *et al.*, 2023) ^[9]. Fertilizer source, application timing, placement method, and integration with biological inputs largely determine nitrogen use efficiency. Table 3 summarizes the major nitrogen fertilization strategies used in wetland paddy cultivation.

Table 3: Nitrogen fertilizer strategies for wetland paddy cultivation (Alam *et al.*, 2023; Kamuruzzaman *et al.*, 2024) ^[9, 21]

Fertilizer/Strategy	Description	Key Benefits	Reported Outcomes
Controlled-Release Urea (CRU)	Slow-release fertilizers that match N release with crop demand	Improves NUE and reduces N losses	NUE increase by 3-18%; ammonia volatilization reduced by 20-43%
Deep Placement Fertilizers (e.g., urea super granules)	Fertilizer placed 8-12 cm below surface to minimize losses	Enhances N uptake and reduces volatilization	Yield increases up to 82%; >90% reduction in ammonia volatilization vs surface application
Nitrification Inhibitors (e.g., DMPP, DCD)	Compounds that slow conversion of NH_4^+ to NO_3^-	Reduces denitrification and nitrate leaching	Prolongs N availability; enhances grain yield and NUE
Split Application and Timing	N applied in phases (planting, tillering, panicle initiation)	Matches N supply with crop demand	Consistent increase in yield and NUE; reduces excess loss
Integrated Organic and Biological Sources (green manures, Azolla, biofertilizers)	Partial replacement of inorganic N with organic/bio-N sources	Enhances sustainability and soil health	Improved NUE and sustainability; most effective when integrated with inorganic N

Kamuruzzaman *et al.* (2024) ^[21] reported that deep placement of urea super granules (USG) in Bangladesh calcareous soils improved rice yield (5.22%), nitrogen use efficiency (13%), agronomic efficiency (20%), and nitrogen recovery (19%) compared with conventional urea, while reducing nitrogen input by 8% without yield loss. Biofertilizers also complement mineral fertilisers by enhancing nitrogen availability. *Azolla* can reduce synthetic nitrogen requirements by 15–30% through biological nitrogen fixation (Alam *et al.*, 2023) ^[9], while cyanobacteria and *Sesbania* contribute additional nitrogen inputs (Kalidurai and Kannaiyan, 1991) ^[10]. Locally adapted cyanobacterial inoculants and biofertilizers have improved rice productivity while reducing mineral nitrogen use and nitrogen losses (Iniesta-Pallarés *et al.*, 2021; Hu *et al.*, 2024) ^[11, 34, 35].

7. Biomass addition and its effects on nitrogen availability in paddy soils

7.1 Sources and nitrogen content of organic biomass

Organic biomass inputs, including crop residues, manures, and green manures, regulate nitrogen availability in flooded paddy soils by influencing residue decomposition, microbial activity, and the mineralization of organic nitrogen into plant-available forms (Alam *et al.*, 2023) ^[9]. Residue quality, particularly the C:N ratio, strongly influences decomposition and nitrogen mineralization, with leguminous residues decomposing rapidly because of their high nitrogen content and low C:N ratio (Zhou *et al.*, 2020) ^[36]. Combining nitrogen-fixing biomass such as *Sesbania aculeata* and *Azolla* with inorganic fertilizers stimulates microbial activity, accelerates residue decomposition, and enhances nitrogen mineralization in paddy soils (Philip and Kumar, 2018) ^[37].

7.2 Nitrogen mineralization patterns from different biomass sources

7.2.1 Role of substrate quality: C:N ratio and lignin content

Nitrogen mineralization from organic biomass is primarily governed by residue quality, particularly the C:N ratio and lignin content. High C:N residues promote temporary nitrogen immobilization, whereas low C:N materials such as leguminous green manures decompose rapidly and release nitrogen (Chen *et al.*, 2020) ^[38]. Residue quality is further influenced by elemental composition, cellulose, lignin, and particle size (Adhikari *et al.*, 2024). Root residues mineralize more slowly than shoots because of their higher lignin:N ratio (Srinivas *et al.*, 2020) ^[39].

Under continuous flooding, anaerobic decomposition forms phenolic-lignin compounds that stabilize nitrogen in resistant forms, reducing its availability (Olk *et al.*, 2006) ^[40].

7.2.2 Mineralization patterns of cow manure and rice bran in flooded paddies

Sekiya *et al.* (2026) ^[41] reported that 14–42% of nitrogen from rice bran and cow manure was mineralized, with over 88% taken up by rice plants. Rice bran released nitrogen rapidly, whereas cow manure provided a slower, sustained supply, resulting in better synchrony between nitrogen availability and crop demand.

7.2.3 Leguminous green manure: Chinese milk vetch (*Astragalus sinicus*)

Chinese milk vetch (*Astragalus sinicus* L., CMV) is a widely studied leguminous green manure for improving paddy nitrogen dynamics. Wang *et al.* (2025) ^[26, 27] reported that CMV, alone or combined with chemical fertilisers, significantly enhanced potential nitrogen mineralisation (PNM) and nitrification (PNA) compared with chemical fertilisers alone. PNM was

positively associated with rice yield, nitrogen uptake, soil nitrogen status, microbial biomass, and beneficial bacterial groups involved in nutrient cycling. Co-application of CMV with fertilisers also improved microbial functional processes by enhancing mineralisation and nitrate assimilation while suppressing nitrification (Liu *et al.*, 2023) ^[42]. Green manure application can replace 20–40% of mineral nitrogen fertilizer while maintaining rice yield by sustaining nitrogen mineralization and reducing nitrogen losses (Yang *et al.*, 2022; Liu *et al.*, 2023) ^[7, 42].

7.2.4 Potentially mineralizable nitrogen (PMN) fractions

Kumar *et al.* (2024) ^[43] identified two potentially mineralizable nitrogen (PMN) pools under integrated nutrient management: a fast-mineralizing pool (PMN-I) associated with improved short-term nitrogen availability and a stable pool (PMN-II) contributing to long-term nitrogen storage. Organic amendments increased microbial biomass carbon (43%) and nitrogen (41%) compared with sole inorganic fertilization.

7.2.5 Rice straw and azolla combined application

Co-application of rice straw and *Azolla* improved net nitrogen balance, agronomic nitrogen use efficiency, and soil organic carbon by offsetting the high C:N ratio of straw with the low C:N ratio of *Azolla*. This combination improves nitrogen mineralization and crop nitrogen availability (Marzouk *et al.*, 2024) ^[44].

7.3 Combined green manure and crop residue management

7.3.1 Synergistic effects on soil nitrogen supply and rice yield

Chen *et al.* (2024) ^[45] demonstrated that combining green manure with straw enhanced residue decomposition, microbial activity, and nitrogen mineralization, thereby improving soil fertility and rice productivity. However, these organic inputs also increased methane emissions, with straw showing a stronger effect. The study highlights the importance of balancing biomass decomposition with greenhouse gas mitigation through appropriate residue and water management.

7.3.2 Green manure cover combined with optimal water management

Gao *et al.* (2025) ^[46] reported that water regime regulated green manure decomposition, increasing indigenous soil nitrogen use by 31–42%. Although continuous flooding increased CH₄ emissions, integrating green manure with AWD sustained biomass-derived nitrogen release while reducing global warming potential.

7.3.3 Covering green manure and soil nitrogen cycling

Li *et al.* (2025) ^[47] reported that surface application of green manure enhanced soil nitrogen supply by stimulating microbial amino acid turnover, increasing nitrogen mineralization, and improving NH₄⁺-N availability. It also increased rice utilization of indigenous soil nitrogen by 31–42%, offering a practical alternative where green manure incorporation is constrained.

7.3.4 Green manure substitution and soil mineral nitrogen dynamics

Cao *et al.* (2021) ^[48] reported that green manure substitution increased soil mineral nitrogen (27.4–94.9% at jointing and 1.0–45.0% at maturity) and crop nitrogen uptake (18.4–62.2%) compared with sole chemical fertilization. These changes

improved synchronization between mineral nitrogen release and crop demand while reducing nitrate losses.

7.3.5 Straw Return combined with nitrogen management: GHG trade-offs

Hu *et al.* (2024) ^[35, 34] reported that the CH₄ emission penalty associated with straw return was reduced when combined with lower nitrogen inputs and mid-season drainage. Soil pH, organic carbon, and total nitrogen influenced residue decomposition and nitrogen dynamics, highlighting how residue decomposition influences both nitrogen mineralization and greenhouse gas production.

7.3.6 Milk vetch combined with chemical fertilizer in double-rice systems

In double-cropping rice systems throughout southern China, Fan *et al.* (2023) ^[49] assessed Milk vetch (*Astragalus sinicus* L.) in conjunction with reduced chemical fertiliser and discovered that this combination concurrently increased rice yield and nitrogen, phosphorus, and potassium use efficiency. Following the addition of green manure, the keystone microbial taxa shifted from nitrogen-fixing and oligotrophic microorganisms to copiotrophic carbon degraders and nitrifiers/denitrifiers. This indicates that green manure reshapes microbial communities to promote residue decomposition and nitrogen mineralization (Fan *et al.*, 2023) ^[49].

7.4 Long-term integrated nutrient management

7.4.1 Long-term INM and soil health

Long-term incorporation of organic biomass through integrated nutrient management (INM) enhances residue decomposition, microbial biomass, enzyme activity, and potentially mineralizable nitrogen, thereby sustaining nitrogen mineralization over successive cropping cycles. Nayak *et al.* (2025) ^[25] reported higher microbial biomass carbon, enzyme activity, microbial diversity, and Biological Soil Health Index (BSHI) under long-term INM, while Kumar *et al.* (2024) ^[43] observed significant increases in nitrogen-cycling enzyme activities, microbial biomass carbon (43%), microbial biomass nitrogen (41%), and potentially mineralizable nitrogen (PMN), indicating enhanced microbial-mediated nitrogen cycling. Similarly, Panda *et al.* (2022) ^[50] demonstrated that integrating cow dung or poultry litter with balanced fertilizers improved soil physical properties and soil quality in tropical rice–rice systems compared with long-term inorganic fertilization. Collectively, these studies demonstrate that sustained biomass incorporation maintains long-term nitrogen mineralization while improving soil biological fertility.

7.4.2 Long-term INM, carbon sequestration and climate resilience

Long-term INM also enhances carbon sequestration and improves the environmental sustainability of rice-based agroecosystems. Sharma *et al.* (2025) ^[51] reported that 38 years of INM in a rice–wheat system increased soil organic matter, stable carbon fractions, soil aggregation, and carbon sequestration relative to sole organic or inorganic fertilization. Likewise, Borah *et al.* (2024) ^[52] observed higher NH₄⁺-N availability, lower NO₃⁻-N concentrations, increased soil carbon fractions, and moderated CH₄ and N₂O emissions under long-term INM, demonstrating greater agroecosystem resilience and improved nutrient use efficiency. Overall, long-term INM maintains soil productivity while strengthening

carbon storage, reducing environmental impacts, and enhancing the sustainability of rice production systems.

8. Future prospects

Wetland paddy systems face increasing challenges from declining soil organic matter, water scarcity, rising production costs, and the need to reduce greenhouse gas emissions. Future research should focus on improving the mechanistic understanding of nitrogen transformations under fluctuating redox conditions, particularly the interactions among denitrification, dissimilatory nitrate reduction to ammonium (DNRA), and anammox, to enhance nitrogen retention and reduce reactive nitrogen losses. Greater emphasis should be placed on biological inputs such as lignocellulose-degrading fungi, diazotrophs, and nitrogen-fixing cyanobacteria, which can enhance residue decomposition, nutrient cycling, and soil health. Optimizing biomass management through strategic combinations of high and low C residues, together with appropriate timing and placement, can better synchronize nitrogen release with crop demand. Integrating water-saving irrigation with optimized nitrogen management remains essential for improving nitrogen use efficiency (NUE), sustaining productivity, and mitigating greenhouse gas emissions. Long-term, multi-location field studies are needed to evaluate these practices across diverse agroecological conditions. In addition, precision nutrient management technologies, including sensor-based diagnostics and decision-support tools, combined with supportive policies promoting biomass recycling, green manures, and low-emission practices, will be critical for advancing sustainable and climate-resilient rice production.

9. Conclusion

Wetland paddy soils represent one of the world's most agriculturally important and biogeochemically complex agroecosystems. Nitrogen, the most limiting nutrient for rice production, undergoes a series of changes controlled by the anaerobic conditions that occur during flooding, leading to ammonium as the predominant plant-available form while also creating pathways for nitrogen losses through gaseous emissions and greenhouse gas production.

The foundation of sustainable nitrogen management in wetland paddy systems continues to be biomass addition, whether through *in situ* green manuring with leguminous species, crop residue incorporation, farmyard manure application, or the cultivation of biofertilizers like *Azolla* and nitrogen-fixing cyanobacteria. Organic inputs maintain or increase rice productivity while lowering reliance on synthetic fertilisers via increasing soil organic carbon, enzymes involved in the nutrient cycle, and synchronising nitrogen release with crop demand. In a variety of soil types and cropping systems, integrated organic-inorganic nutrient management has been shown to be superior to either sole organic or sole inorganic approaches. This is particularly relevant to the tropical humid rice-growing regions of South and Southeast Asia.

Advanced fertilization technologies, including deep placement of urea super granules, controlled-release fertilizers, and nitrification inhibitors further improve nitrogen use efficiency by reducing the temporal mismatch between nitrogen supply and crop demand and by limiting the substrate available for denitrification and ammonia volatilization. These technologies are most effective when deployed within an integrated management framework that also encompasses judicious water

management, appropriate tillage and timely organic input incorporation.

Sustained organic matter inputs are essential for the long-term resilience and stability of paddy soil health. Regardless of the short-term productivity gains, sole chemical fertilisation gradually depletes microbial biomass, lowers enzyme activity, and destabilises soil carbon stores, all of which compromise the soil's ability to supply nitrogen on its own. In contrast, long-term integrated nutrient management maintains microbial diversity and function, promotes the formation of stable carbon fractions that provide thermal and hydrological resilience, and stabilises and often improves the biological soil health index. In wetland rice agriculture, achieving food security, economic sustainability, and environmental responsibility necessitates shifting from a sole focus on yield maximisation to a systems-level optimisation that strikes a balance between productivity, soil health, and climatic effect. The most viable and realistic approach to achieving this objective throughout Asia's varied paddy landscapes is the combination of site-specific biomass management, precision nutrient management, and ecologically conscious water management.

10. References

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