Review Article

Nitrogen Uptake and Use Efficiency of Aerobic Rice as Affected by Different Nitrogen Management: A Review

Abstract

A significant amount of the world's population relies heavily on rice, which is grown in both lowland and upland rice systems. Irrigated lowland rice systems account for over 76% of the world's rice production. Although the aerobic rice system can be viewed as a revolutionary substitute for conventional rice, increased nitrogen (N) losses and decreased N-use efficiency (NUE) have made it difficult for this novel method to be widely adopted. One of the most crucial ingredients in the cultivation of rice is nitrogen (N). Less than 50% of N is recovered in both lowland and highland systems. Soil erosion, volatilisation, leaching, and denitrification account for the majority of the loss of applied nitrogen. Consequently, it will be prudent to maximise the use of nitrogenous fertilisers in order to achieve high yields and maintain a level of production costs that can be sustained. For rice cultivation in the aforementioned scenario, nitrogenous fertiliser needs to be used more wisely and efficiently. This review focusses on the various production practices that can increase the efficiency with which N is used, such as liming acid soils, providing N at appropriate rates, using appropriate sources, applying N at the right time and method, rotating crops, using cover crops, implementing conservation tillage, planting N-efficient genotypes.

Keywords:*aerobic rice, rice ecosystems, nutrient use efficiency, nitrogen management, agronomic practices*

1. Introduction

In order to fulfil the future food demands of the expanding global population, rice (*Oryza sativa* L.) is regarded as a staple food for over half of the world's population. However, maintaining productivity amid resource constraint is difficult. Although rice is grown and consumed on every continent, the majority of it is grown and consumed in Asia, namely in China and India, which are the two largest producers and consumers of rice[1]. In addition, natives and immigrants from Asia, Africa, and South America consume enormous amounts of rice in North America and Europe. Studies have shown that in order to meet the demands of an expected rapidly growing population due to economic and industrial developments, as well as rapid population growth, global rice production will need to increase by approximately 20% by 2030 and 30% by 2050, at a rate of 0.6–1% increase annually [2]. For several years, agronomists have prioritised their study on examining different approaches to enhance rice grain production [3,4]. Given that the aerobic rice system may be viewed as a transformative substitute for conventional rice, increased nitrogen (N) losses and decreased N-use efficiency (NUE) have made it difficult for this novel method to be widely adopted[5]. Increased N levels are necessary for agricultural plants to go through regular growth and developmental cycles.

N is a mineral nutrient that is necessary for healthy plant development and metabolism since it is a major component of amino acids, nucleic acids, and many photosynthetic metabolites[6,7]. It has previously been estimated that 48% of the world's growing population could be met by N fertilisers (review the sentence, meaning not clear). However, uncontrolled and erratic N fertiliser soil application ~~amendment~~ has increased the environmental sustainability concerns associated with higher N losses through volatilisation or leaching, causing pollution in the environment due to greenhouse effects and accelerating the depletion of the ozone layer [8,9]. Although aerobic rice growth and yield are enhanced by excessive (high??, excessive would mean more than needed) N fertiliser application, environmental and economic sustainability are jeopardised. A number of environmental problems associated with increased nitrogen losses as nitrous oxide (N_2O), ammonia (NH_3), and nitrate (NO_3^-) have been brought to light by the irregular and uncontrolled use of N fertilisers[10]. This poses a threat to environmental sustainability because of the increased potential for global warming, ozone depletion, and eutrophication of water resources. Therefore, improving NUE in aerobic rice has emerged as a critical requirement for the creation of a long-term production system and predicts the economic return, is an important soil–plant interaction feature that has been studied for a long time (citation).

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Agronomic management approaches that are appropriate are necessary to achieve the efficient utilisation of synthetic N fertilisers, as irregular agricultural management practices contribute significantly to global anthropogenic emissions [11,12]. Ultimately, strategies and management regarding methods to get around this problem (such as scheduling fertiliser applications, deep placement fertilisation, slow-release fertilisation, mineralising organic amendments and soil organic matter, etc.) and matching biological demands (such as breeding for high NUE cultivars) to match the availability of N resources in order to maximise N retention in the soil and NUE of rice plants (FIND ME A VERB INTHIS LONG SENTENCE). This review examines the assessment of several agricultural and agronomic management strategies designed to lower elevated nitrogen losses while increasing the NUE and grain production in an aerobic rice system with minimal risks to the environment.

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2. Adopting aerobic rice system

About 30% of the freshwater on Earth is used by the flooded rice system, and over 45% of it is used in Asia [13]. Due to the accelerated demand for water from various sectors, freshwater resources are becoming more scarce, endangering the sustainability of conventional rice and making it more vulnerable to the effects of climate change. This necessitates the development of novel water-saving technologies through various modifications without compromising public health or environmental safety [14]. Traditionally, the rice-growing technique involves submerged circumstances, with standing water that is between 5 and 10 cm deep over the whole rice-growing season. Due to a lack of resources, including labour, electricity, and irrigation water, traditional rice farming is becoming more and more problematic.

For typical rice systems, puddling is an essential technique. However, it degrades the soil's structure, making it more difficult to prepare the land for subsequent crops that require more energy to achieve optimal soil tilth [15]. Consequently, these variables highlight how urgently traditional systems need to be modified through the introduction of water-saving techniques, including growing aerobic rice, which may function as an eco-efficient system by conserving natural resources without compromising grain output (Fig. 1).

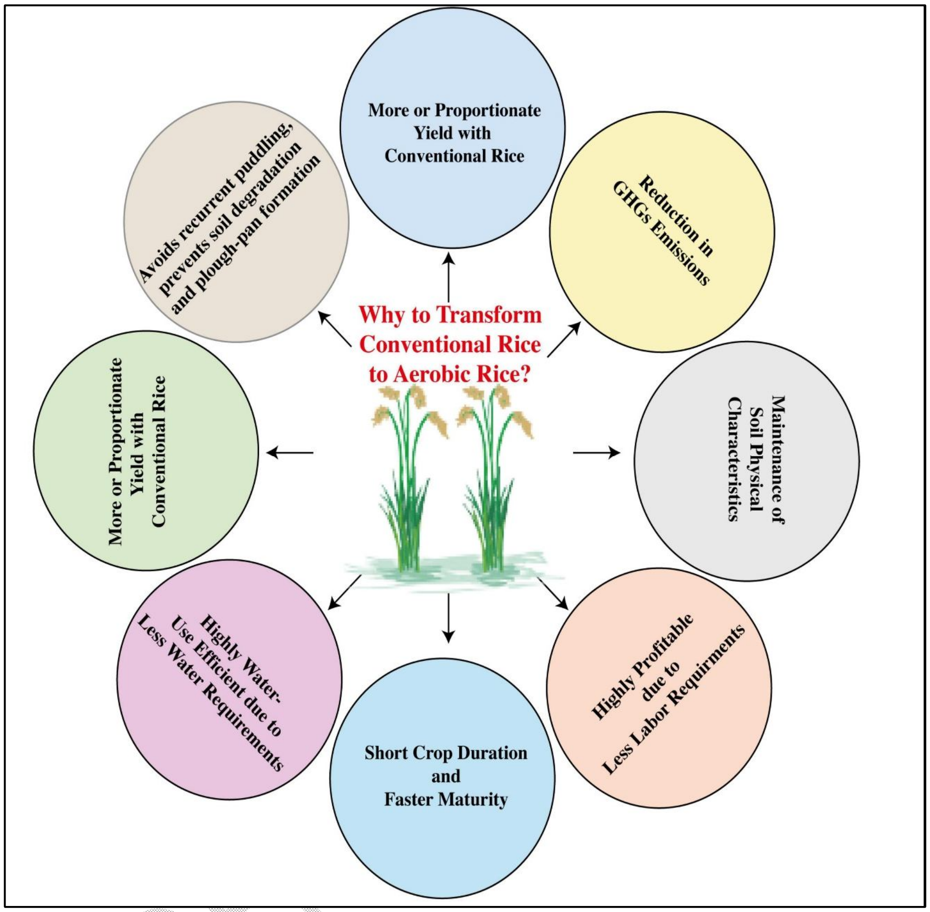

Fig. 1: Benefits of transformation of conventional rice to aerobic rice system

Source adapted from Joshi et al. [16]

Since rice naturally reacts negatively to drought, a decrease in irrigation supplies may result in a production fall [17]. Raised bed cultivation [13], the alternate wetting and drying system (AWD) [18], saturated soil culture [19], and the system of rice intensification (SRI) [20] are some of the modified technologies that have been developed in previous studies to reduce water application in rice systems. Due to the ongoing needs for puddling and soil saturation during crop growth, some of these are not water-use efficient and cannot receive a significant amount of water input. Rice is cultivated using the water-saving method of aerobic rice cultivation, which involves soil that is neither saturated nor puddled [16]. In addition to being adaptable in highland locations when additional irrigational water supplies are guaranteed, this modified method primarily targets irrigated lowland areas where irrigational water is insufficient for rice agriculture [21]. Early studies on aerobic rice technology reported grain yields of up to 6.5 t ha^{-1} with water savings of about 60% [22]. These results showed that aerobic rice cultivation could be a large-scale, sustainable method of producing rice in the face of finite natural resources and climate change.

2. Nitrogen (N) transformation in rice field

Rice plants in paddy fields receive fertilisation from N-containing substances mostly in the form of urea. The hydrolysis of urea produces ammonium (NH_4^+), which is then converted to NO_3^- in the oxic soil that surrounds the roots of the rice plants. Next, NO_3^- was incorporated into the oxidation of methane, denitrification, and anaerobic NH_4^+ oxidation (anammox) after diffusing to the underlying anoxic soil [23]. As soil particle surfaces are usually negatively charged, cations (such as NH_4^+) can be electrostatically attracted to them. Oxidising NH_4^+ to hydroxylamine (NH_2OH), nitrite (NO_2^-), and finally NO_3^- is the process of nitrification. Two classes of chemoautotrophic bacteria, namely those that oxidise ammonia and nitrite (AOB and NOB), catalyse these activities. The rate-limiting step is the oxidation of NH_4^+ to NH_2OH, which is catalysed by ammonia monooxygenase (AMO). From there, NH_2OH is oxidised to NO_2^- and subsequently to NO_3^- by nitrite oxidoreductase and hydroxylamine oxidoreductase, in that order [24]. Denitrification is the opposite process, wherein bacteria, fungi, and archaea decrease NO_3^- to NO_2^-, nitric oxide (NO), N_2O, and N_2. The environment will suffer from the partial decrease of NO_3^- to N_2O since N_2O is a greenhouse gas and has a global warming coefficient 300 times greater per molecule than CO_2, the primary ozone-destroying agent. Anammox, in which N_2 is released from NO_2^- and NH_3 by bacteria via the intermediates NO and hydrazine (N_2H_4), respectively, is another reduction of NO_3^- to NH_3 via NO_2^- under anaerobic or low-oxygen conditions known as dissimilatory nitrate reduction to ammonia (DNRA) [25].

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According to Schimel and Bennett [26], nitrogen mineralisation is the process by which organic matter is converted by microbial activities into inorganic molecules (firstly, NH_4^+). The rate of mineralisation is constrained by the depolymerisation of organic N, which releases organic N that is biologically available, such as amino acids. Microorganisms and plants can both absorb

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amino acids [27], however plants can only absorb most amino acid N after it has been converted to inorganic N [26]. In addition to nitrogen (N) taken by crop plants, a significant amount of N is retained in soil particles via mineralisation, which can release N for use in subsequent crop cycles, and is immobilised by soil microbes, resulting in N storage in soil organic matter pools [28]. There are several variables impacting oxidation/reduction processes in the complicated N cycle in rice fields [24] (Fig. 2). The amount, variety, and makeup of microbial communities—such as those made up of bacteria, archaea, and fungi—as well as their interactions with roots might influence how nitrogen is transformed in rice paddies [29]. According to Zhong et al. [30], the metagenomic analysis revealed that the soil from the high-yielding rice field has a higher abundance of genes involved in the nitrification process and more taxa with N metabolism functions. This promotes the effective transformation of NH_4^+ to NO_3^- in rice fields and stimulates high expression of NO_3^- transporters in plant roots. Soil microbiology is essential to the transformation of N in rice paddies.

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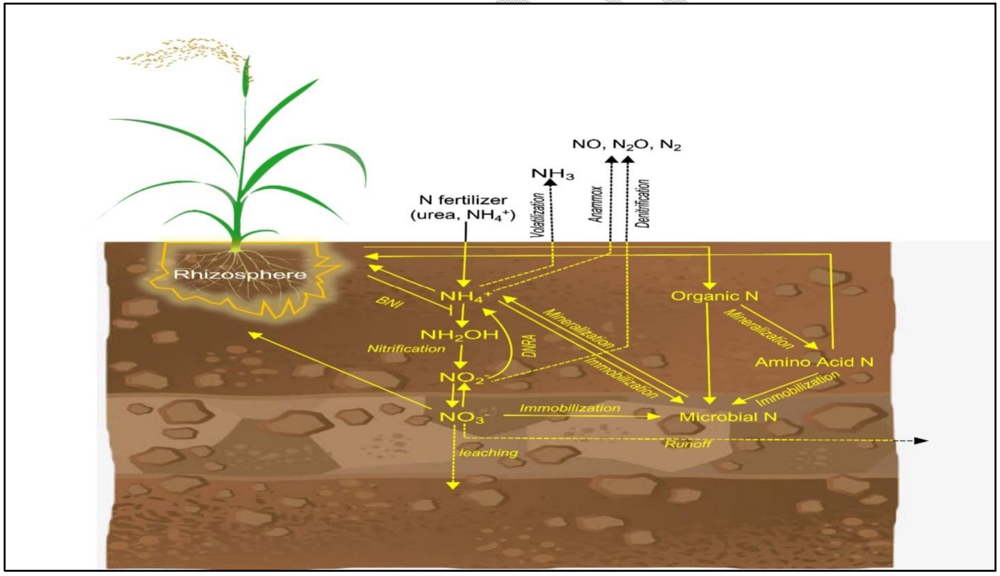

Fig. 2: Nitrogen (N) cycling in rice production system
Source adapted from Coskun et al. [24]

3. Nitrogen (N) losses from rice field

Deprotonation of NH_4^+ and volatilisation of NH_3 gas to the atmosphere account for the majority

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of nitrogen loss from paddy rice fields (globally, 10~~%~~–50% of applied fertilizer–N). A comparable amount (5.6~~%~~–50%) is lost through nitrification of N, which is followed by leaching and runoff because anion NO_3^- is poorly bound to soil. Denitrification (i.e., N_2, N_2O, and NOx to the ambient air) accounts for a relatively smaller portion (0.03~~%~~–0.68%) of nitrogen loss [31]. In soils and solutions, ammonia and NH_4^+ are in pH-dependent equilibrium, and volatilisation happens when there is an abundance of NH_4^+ in the soil and a high soil alkalinity (citation). Additionally, plants can release gaseous fluxes of NH_3, which are most common in plants with high N contents and mostly occur in rice between anthesis and maturity [32]. With very few exceptions, NO_3^- does not bind to soil after NH_4^+ transition to NO_3^-. As an anion, NO_3^- readily percolates through agricultural soil profiles and into groundwater. In soil, NO_3^- has a diffusion capacity that is 10–100 times greater than NH_4^+ [33]. Air pollution issues are exacerbated by the production and degradation of NO_3 by bacteria and archaea, which also releases additional NOx and N_2O, potent greenhouse gases.

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4. Nitrogen (N) uptake in aerobic rice ecosystem

The amount of N absorbed is measured as concentration, which is the amount of N in one unit of dry matter. N concentration in plants is often expressed as g kg^{-1} or as a percentage [34]. Concentration values are typically used to diagnosis plants for nutritional excess, shortage, or sufficiency. Nutrient concentrations from various agroecological zones can be extrapolated or utilised to diagnose nutritional problems in the same crop species. This is feasible because every element influencing nutrient availability depends on plant nutrient absorption. A measure of nutrient absorption is obtained by multiplying dry matter or grain yield by concentration; the result is given in accumulation or uptake units. For macronutrients, the unit of nutrient intake or accumulation in the field is kg ha^{-1}, whereas for micronutrients, it is g ha^{-1}. Nutrient absorption values are correlated with crop production levels and serve as helpful markers of the depletion of soil fertility. Dry matter accumulation was followed by nutrient accumulation patterns in agricultural plants, including rice [35]. Further nitrogen uptake and transformation are describing below.

Rice has the highest rate of N uptake, excluding K (citation). The two inorganic types of nitrogen that rice predominantly absorbs are NO_3- and NH_4^+~~-~~. Since the environment is anaerobic, NH_4^+ is typically thought of as the primary N type. Nevertheless, rice absorbs around 40% of the total

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N in the form of NO_3^- due to rhizosphere nitrification [36]. The absorption of nitrate has been well examined, and the associated rice transporters, such as the >80 nitrate transporter/peptide transporter (NRT1/PTR), 4 NRT2, and 2 nitrate assimilation related 2 (NAR2) members, have all been well-characterized. The first NO_3^- transporter with low affinity is OsNPF8.9 (OsNRT1) [37]. With the exception of NRT1.1, a dual affinity transporter, the majority of NRT1s exhibit poor affinity for NO_3^-[38]. High-affinity NO_3^- transporter genes were found in four NRT2 and two NAR2 genes. It was shown that nitrate transporters were effective in raising NUE. For example, up-regulated expression of OsNRT2.3b boosted grain output and NUE above wild type by 40% and enhanced the efficiency in NO_3^-, NH_4^+, P, and Fe absorption [39]. While NH_4^+ has long been thought to be the primary N absorption mechanism for rice plants, not much progress has been made in understanding NH_4^+ transporters [40].

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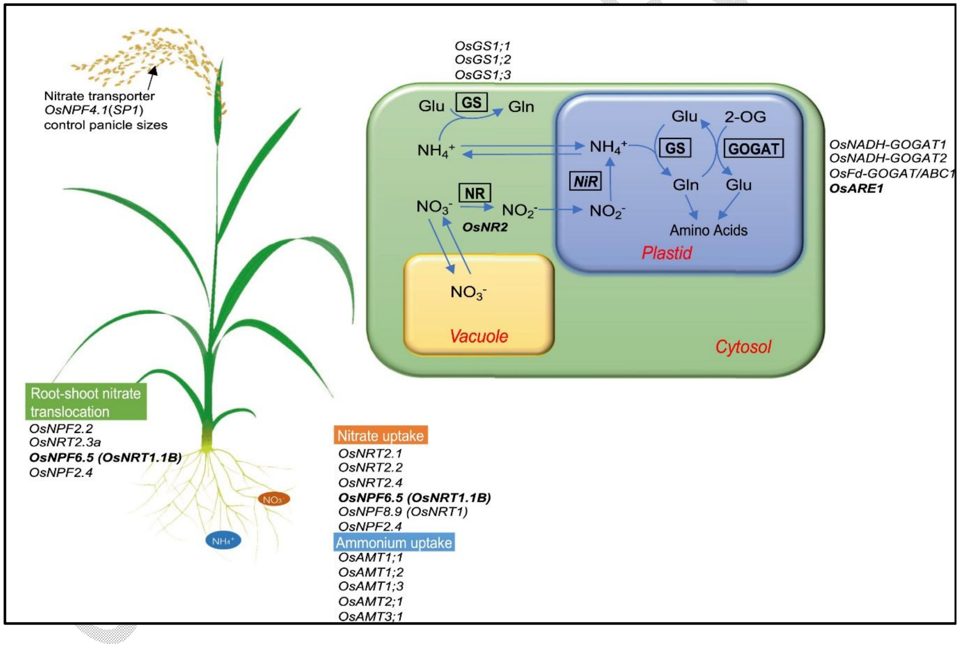

Fig. 3: Schematic illustrating the nitrate and ammonium assimilation and metabolism in plants. Source adapted from Li et al. [40]

According to Li et al. [40] (2017), rice possesses at least 12 putative NH_4^+ transporters (AMTs). Ragel et al. [41] suggest that overexpressing OsAMT1;1 might enhance NH_4^+, particularly in situations where NH_4^+ levels are inadequate. The simultaneous activation of Glutamate

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synthetase 1 (OsGOGAT1) and OsAMT1/2 boosted the plant's ability to withstand N restriction and improved N remobilization and NH_4^+ absorption overall [42]. Nevertheless, in contrast to the advancements in NO_3^- transporter research, the effectiveness of the NH_4^+ transporter has not been as successfully improved [42]. After rice plants ingest NO_3^-, nitrate reductase (NR) in the cytoplasm converts it to NO_2^- first. Next, nitrite reductase (NiR) transfers NO_2^- to the plasmids, where it is further reduced to NH_4^+ (Fig. 3). In the GS–GOGAT cycle, glutamine synthetase (GS) and GOGAT transform inorganic NH_4^+ into glutamine. There are two types of GOGAT, ferredoxin-dependent (Fd-GOGAT, OsFd-GOGAT) and NADH-dependent (NADH-GOGAT, OsNADH-GOGAT1, and OsNADHGOGAT2) enzymes with varying electron donor specificity, and three GS isoforms (OsGS1;1, OsGS1;2, and OsGS1;3) [43].

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5. Nitrogen use efficiency (NUE) in aerobic rice ecosystem

The complicated feature of NUE is influenced by several chemical and metabolic routes as well as environmental factors [44]. Various agricultural main research wings have varied definitions of NUE. For example, plant physiologists consider numerous processes in the management of nitrogen, such as absorption, assimilation, allocation, and remobilization of nitrogen, which is particularly evident during leaf senescence [22]. Additionally, they split the NUE according to the several N cycle components, including N intake, N assimilation, N allocation, and N remobilization [45]. Grain yield equivalent to the entire quantity of accessible N from soil, including N fertiliser treatment, is what agronomists refer to as the NUE [46]. All agricultural experts worldwide concur that NUE is made up of two essential components that are readily evaluated in both controlled and field settings: the N uptake efficiency and the N utilisation efficiency [47]. N utilisation efficiency is the native ability of the plant to use the absorbed N, facilitating absorption and remobilization to create end harvest products. On the other hand, N uptake efficiency is the total capability to absorb, or uptake, N given from soil N pools.

The best way to characterise N absorption efficiency is as the best possible balance between N remobilization and assimilation efficiencies [47]. In the meantime, N remobilization efficiency is determined by the total amount of N that is remobilised between the source and sink tissues, whereas N assimilation efficiency is defined as the overall capacity for the assimilation of inorganic N to manufacture amino acids and various other essential N-containing molecules [48]. According to Ierna and Mauromicale[49], each component of NUE is associated with a variety of complicated features, such as root morphological parameters, leaf senescence, N remobilization, and the ability to take accessible N from soil N pools. Enhanced N absorption and remobilization, enhanced N intake by various genetic alterations, and their control are the key drivers that can improve NUE. Furthermore, to raise NUE, a mix of agronomic techniques and traditional breeding methods is essential (citation).

5.1Important elements for improving Nitrogen use efficiency (NUE)

To meet the future food needs of the anticipated population growth, improvements in NUE under aerobic rice systems and other non-N_2 fixing crops are needed. These improvements can be made through other crops, irrigation, and fertiliser management techniques, as well as improved and modified N-use efficient varieties [50]. The use of controlled-release N fertilisers, urease inhibitors for synthetic N fertilisers, crop variety management in terms of water and NUE, plant N uptake management, irrigation techniques, fertiliser input management, and other agronomic integrative crop management approaches are some of the management practices that are focused(see spelling elsewhere) on improving plant N uptake and NUE [51]. Research on NUE has shown that it is primarily related to the kind and application of fertiliser inputs, irrigation techniques, soil N availability, and plant N absorption [52]. The linked management strategy, which combines irrigation and nitrogen control, is a widely used and environmentally sustainable technology in contemporary agriculture that may maintain rice output in the face of limited water resources while maintaining environmental sustainability. When N and irrigational managements are combined, N losses and fertiliser application rates are decreased, and NUE and irrigational water inputs are improved by over 20% [53]. Consequently, raising the total NUE in aerobic rice systems requires a thorough comprehension and assessment of all the aforementioned parameters influencing NUE and their management.

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6. Agricultural Nitrogen (N) management for aerobic rice ecosystems

Since the amount of N harvested in grains and soil N pools varies between intensive and extensive approaches, agricultural management aiming to increase NUE without compromising crop productivity should be in accordance with local soil and climatic conditions. This could involve intensive and extensive soil and crop residue management practices [54]. Tillage practices present another difficulty for aerobic rice systems. While successive no-tillage or regular tillage methods led to higher N- and water-use efficiencies, they also increased crop competition because of increased weed invasion [55]. Therefore, for increased NUE and crop production in aerobic rice systems, integrated crop management strategies together with sophisticated irrigation control techniques are needed. In the section that follows, a few agricultural management techniques to raise NUE are covered.

6.1 Site-specific nutrient management

A strategy known as "site-specific nutrient management" (SSNM) was developed in recent decades with the goal of producing fertiliser recommendations that are particular to a given field and improving the nutrient-use efficiency of important nutrients like phosphorus (P), potassium (K), and nitrogen (N) [56]. In order to synchronise nutrient provision and demand based on differences in plant requirements, indigenous nutrient provision, and nutrient recovery from applied fertilisers and other resources, the SSNM is a dynamic, typically plant-based, soil and crop growth season-specific nutrient management approach. Increasing nutrient-use efficiency is the main goal of SSNM in order to boost crop yields and local farmers' economic outputs [57]. For smallholder rice farmers in Asia, where field occupations are typically small with ~~and there are~~ significant spatial variations in soil nutrient status and management, SSNM was first developed. This method of managing nutrients is primarily predicated on the idea of estimating nutrient requirements through the comparison of the total amount of nutrients needed to achieve a given crop's production target and the native supply of that particular nutrient [58]. Therefore, by adjusting the time of N fertiliser ~~amendment~~ application to meet the plant's prospective N requirements, this technique might promote the optimal use of N fertilisers in aerobic rice systems, enhance NUE, and prevent environmental concerns [57].

6.2 Integrated nutrient management strategies

To improve N recovery and NUE, integrated nutrient management (INM) entails making the best and most balanced use of naturally occurring N components, such as plant wastes, organic manures, biological N fixation, mineral N fertilisers, and their complementing interacting pathways [59]. The enhancement of the physico-chemical properties of the soil [60] or the improvement of plant root growth and the supply of necessary N along with other micronutrients [61] are the two main causes of the beneficial effects of the INM approach, which involves the mixed use of organic (such as biochar, manures, and compost) and inorganic N resources. To fully capitalise on the beneficial effects that are essential to raising net economic returns to farmers in terms of targeted production while preserving soil quality and raising NUE, it is imperative that the interacting pathways under INM be adequately evaluated and understood. A notable rise in crop yield and NUE may result from the complementing interactions between N from synthetic and non-synthetic fertilisers and other micronutrients. Therefore, improved NUE, reduced environmental hazards, and higher aerobic rice production will result from the wise and balanced use of N fertilisers from all available resources (organic and inorganic) through INM approaches. This will help ensure rice sustainability in the future even in the face of resource scarcity due to climate change.

6.3 Incorporation of enhanced use efficiency N fertilizers (harmonise spelling)

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As of right now, a number of fertiliser products are useful because they may increase the NUE of applied N fertilisers by reducing N losses associated with the rice production system. The main characteristics of these fertiliser products are their ability to either slow down the rate at which N is released or to interfere with N transformation pathways in order to minimise N losses. N fertilisers with regulated and slow release have a crucial role in mitigating different types of nitrogen losses, which in turn affects recovery and availability of nitrogen [62]. NO_3^- containing N fertilisers are more prone to leaching than NH_4^+ containing fertilisers, whereas the former is more vulnerable to volatilisation loss under alkaline soil conditions. A variety of commercially available slow- and controlled-release nitrogen fertilisers can be used in conjunction with possible mitigation techniques to improve NUE and decrease N losses, ultimately leading to a sustainable agricultural production system [63]. Because of their ability to postpone N release patterns, these slow- and controlled-release N compounds can enhance the synchronisation between soil N supply and plant N requirements, hence reducing N losses. Furthermore, commercial urea coated with neem(scientific name) can be extensively employed in aerobic rice systems because to(because of, due to) its proven slow-release N fertiliser properties in South Asia [64]. Measures that can increase the use of these compounds are necessary because of the higher manufacturing costs and restricted availability of such controlled-release N fertilisers, which make their broad use difficult.

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6.4 Residue management

The primary source and sink for the C and N cycles are crop wastes. By first converting nitrogen into inorganic forms and then mineralising it at later phases of crop growth when crop need for nitrogen becomes significant, the incorporation of crop wastes into the soil assures that the plants will have access to nitrogen for a longer length of time. Furthermore, because soil microorganisms temporarily immobilise nutrients released into the soil and preserve them in slowly accessible forms, including crop leftovers into the aerobic rice system may be advantageous [54]. It has previously been shown that plant residues from a variety of cereals can guarantee the provision of N between 40 and 100 kg ha^{-1} $season^{-1}$ and help the soil system accumulate organic C, which enhances the NUE and soil N pool even more [65]. Legumes have a high N content and lower C/N ratios than cereals, therefore adding them to the aerobic rice system can be a useful way to increase soil N pools [66]. Furthermore, half of the total quantity of N would be accessible for plant absorption after two months of residue integration due to the faster rates of mineralisation of legume plant residues [67,68].

6.5 Green manuring

Numerous legume crops possess an exceptional ability to fix atmospheric nitrogen, making them suitable for use in green manuring within aerobic rice systems [69]. According to Sharma et al. [70], in order for legume crops to be considered superior for green manuring, they need to have certain key characteristics. These include the ability to produce large amounts of dry matter quickly and easily, the potential to fix atmospheric free nitrogen, the ability to grow quickly and shorter growth durations for easy settlement into an intensive cropping system, and the cultivation of minimal land management practices. However, the quality and amount of residues available, soil characteristics, microbial diversity and activity, soil moisture content, and atmospheric factors all have a major role in the positive effects and effectiveness of legumes as green manures. To improve N recovery and total NUE, it is therefore essential to cultivate crops in a recurrent succession on the same plot of land and to properly rotate legumes with aerobic rice systems. It has been discovered that legume crops have the ability to lessen the requirement for subsequent crops in the rotation system (citation). Additionally, by increasing total carbon stocks, which in turn increases plant availability of N, narrow C:N ratios of legume residues can improve the physical, chemical, and biological properties of the soil [71].

6.6 Precision farming

In order to maximise net profits, crop production, resource efficiency, and system sustainability in terms of quality and quantity, precision farming is an information- and technology-based farm input management system that focusses (check and adjust spelling elsewhere) on the use of cutting-edge technologies and principles in identifying, analysing, and managing spatial and temporal variabilities associated with all characteristics of crop production systems [72-74].According to Yousefi and Razdari [75], one important way to increase the NUE under varying climatic conditions is to measure variabilities in the field with respect to the availability of N for plant uptake and apply the optimal dose of N fertilisers at the right time by using technologies like rate applicator, remote sensing, geographic information system (GIS), and global positioning system (GPS). In order to assess a crop's need for more N, modern crop management systems can also make use of local or distant N sensors. Consequently, increasing the NUE in intensive agricultural systems may benefit from the application of the aforementioned technology and precision agricultural techniques.

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7. Climate Change: Context and challenges in Aerobic rice production

There is evidence of climate change, which has an effect on ecosystems, the population, and livelihoods [76]. Climate change poses significant developmental issues for the global society due to its extensive effects, especially for the impoverished and people in developing and underdeveloped nations that depend on natural resources [77]. Communities are affected by the global phenomena of climate change in different ways within and across nations [78]. In a nation, the impoverished, politically disenfranchised and marginalised communities, and those with the least resources are the most likely to be negatively impacted by climate change and are also the least likely to diversify their sources of income [79]. The mean earth surface temperature has been rising since the start of the 19th century due to anomalies and unevenness in the variabilities of climatic components (citation). The data from the Intergovernmental Panel on Climate Change (IPCC) annual report 6 (AR6) working group I (WGI) report show that, based on projected temperature fluctuations over the last few decades, the global atmospheric temperature has risen by 1.09°C since the 1950s. The majority of this temperature change was observed in the last 30 years of the 19th century [80]. There are three main causes that are known to contribute to climate change: land-use changes, human-induced factors like greenhouse gas emissions (GHGs), and natural fluctuations.

Assessments of future climate change indicate that extreme weather events, temperature variations, and precipitation intensity, frequency, and patterns will all increase in severity in the years to come [81]. Concurrently, it has been predicted that increased oceanic absorption of CO_2 will cause the earth's surface temperature to rise more slowly than that indicated by climate model estimates [82]. Therefore, there are a number of errors in the patterns, frequency, and intensity of precipitation due to the climate models' inability to accurately estimate the hydrological cycle over the tropical areas [83]. One of the environmental factors that determines whether a crop plant will succeed or fail is the climate. It supports and is crucial to both short- and long-term crop planning, especially in the case of climatic disasters or altered weather patterns.

Uneven and unstable climate variations have put the world's rice crop in jeopardy, especially in Asia. Rice production and climate change are strongly related since the flooded rice system adds to greenhouse gas emissions and increases global warming, which in turn affects the rice agriculture system. The Food and Agriculture Organisation (FAO) forecasts that in order to achieve food security goals in the face of resource scarcity, rice production must rise by 40% by the end of the 2030s [84]. If this increase in food is achieved using the least amount of environmentally friendly practices, environmental pollution problems might get worse. One of the primary causes of greenhouse gas emissions is thought to be ice grown in traditional flooding settings [85]. In light of the impending shortage of resources and the need to reduce methane (CH_4) emissions [86], a number of transformations have been implemented for the production of rice. However, these changes come with a number of environmental risks because of the substantial losses of nitrogen through volatilisation and leaching.

Generally speaking, the conventional rice system produces higher greenhouse gas emissions. However, when the conventional system is modified to meet food security goals and increase the sustainability of rice production in the face of limited natural resource availability, high nitrogen losses result from the intermixing of nitrification and denitrification processes [79]. Therefore, it is required to modify the traditional rice system or replace it with an aerobic rice system in order to reduce greenhouse gas emissions and meet future food requirements in the face of resource constraint [87]. However, widespread adaptation of aerobic rice necessitates research and evaluation of modifications in the N cycle pathways and microbial abundance and functioning under the aerobic rice system through agronomic management approaches due to high N losses and environmental pollution issues.

8. Future thrust

In order for the aerobic rice system to be widely adapted, study on the ways in which the interaction activities of microbial communities—such as nitrifiers, denitrifiers, and ammonia oxidizers—change under different soil conditions is required on a global scale. One of the main issues facing the aerobic rice system at the moment is our incomplete knowledge of the interactions between various microbial populations when implementing N fertiliser control strategies.Furthermore, while implementing any agronomic management practices, there is still little ability to interactively evaluate changes in the abundance, diversity, and functioning of microbial communities in both space and time under aerobic soil conditions.Agronomic management practices for aerobic rice systems that incorporate NUE-boosting while N-reducing N losses may have an effect on the quantity and activity of soil microbial communities as well as biochemical characteristics. Therefore, more research on aerobic rice systems is urged, with an emphasis on designing experiments that evaluate changes in the variety and activity of microbial communities, plant N needs, and N management strategies in an interactive manner. This will increase our knowledge and comprehension of the ways that various agronomic N management techniques affect the quantity, diversity, and activities of soil microbial communities. This knowledge and comprehension may then be used to improve NUE and lower N losses for increased grain yield and environmental safety.

9. Conclusion

Crops depend on nitrogen, and adding it to aerobic rice production systems is crucial to boosting crop yield and keeping up with the growing human population. A significant amount of the nitrogen (N) that is applied to rice, however, is lost to the environment, which causes a number of issues. Although the absorption and transformation of nitrogen in the rice ecosystem is complicated and involves a wide range of entities and participants, there are several chances for N management intervention. In aerobic rice systems, providing the ideal conditions and making agronomic modifications to account for N losses can help close the production gap between traditional and conventional rice systems. When switching from an anaerobic to an aerobic rice system, there is a risk of substantial nitrogen losses because of changes in soil nitrogen pools, water availability, and microbial activity. In order to achieve widespread adoption of the aerobic rice system, rice cultivars that exhibit improved root characteristics for improved nitrogen uptake and utilisation, improved yield traits for lowland cultivars, and improved water stress tolerance traits for upland cultivars must be introduced. To sustain grain yield and ensure environmental sustainability in the face of future projected climate change and input scarcity, research-based evaluation of agronomic management measures for aerobic rice systems is required to decrease N losses and increase NUE.

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