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A review for nitrogen application in Malaysian rice production

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Abstract

Nitrogen (N) fertiliser plays a vital role in achieving high rice yields, but its inefficient use remains a major challenge in Malaysian rice production. This review synthesises findings from research studies, field trials and policy documents to evaluate the effectiveness of split N-splitting applications, as compared to the current Department of Agriculture (DOA) recommendations with alternative strategies and highlight the environmental and economic risks associated with excessive N use. Based on our analysis, a three-way split applying 20% of total N at the 3-leaf stage, 30% at active tillering and 50% at panicle initiation provides the best balance between crop demand, uptake efficiency and environmental protection for medium-maturity varieties such as MR 315. This targeted approach significantly improves grain yield and nitrogen use efficiency while reducing losses through leaching and volatilisation. While DOA guidelines have taken important steps by promoting split applications, recent evidence suggests that further refinement particularly in adjusting early-stage N rates, could enhance synchrony with crop uptake patterns and reduce avoidable losses. Alternative strategies such as Site-Specific Nutrient Management, enhanced-efficiency fertilisers and the 4R nutrient stewardship framework (Right Source, Right Rate, Right Time, Right Place) offers more flexible and sustainable solutions. This review proposes a revised fertilisation schedule that prioritises panicle initiation as a critical stage for N application. By integrating agronomic evidence with policy and economic considerations, we advocate for adaptive, efficiency-driven N management to enhance productivity, reduce environmental risks and support long-term sustainability in Malaysian rice systems.

Keywords: *nitrogen, fertilisation, nutrient use efficiency, yield, rice*

Introduction

Rice is a staple food for Malaysians. In terms of rice industry productivity, Malaysia consumed approximately 2.69 million mt of rice in 2020, yet domestic production met only about 70% of this demand (Zakaria & Ghani, 2022). Consumption is expected to increase by 1.6% annually, driven by population growth, while production trends remain stagnant. For instance, rice production declined from 2.35 million mt in 2019 to 2.34 million mt in 2020, reflecting a 1.2% decrease/year (Zakaria & Ghani, 2022). Recent estimates by the USDA shows further strain on Malaysia's rice sector, with total milled rice production forecasted at only 1.75 mt, cultivated across 660,000 ha with an average yield of 4.08 t/ha (USDA 2024). These figures highlight an ongoing shortfall in supply relative to rising demand, reinforcing Malaysia's continued dependence on rice imports and the urgent need for improved production strategies. Various efforts and government interventions in the paddy and rice industries have been undertaken to ensure food security and farmer welfare (Rosnani et al. 2015). However, rice market shortages may occur in the future due to rising demand and declining supply. The only way to solve the shortage is to increase rice production. If the country continues to rely on imported rice for supply in the future, this will have a negative impact on the local rice industry and the value of the Ringgit against other currencies (Rajamoorthy et al. 2015). Nitrogen fertiliser is essential for achieving high rice yields, but its use in Malaysia is increasingly associated with several key challenges that hinder productivity. The first major challenge is low nitrogen use efficiency (NUE), where only a small portion of the nitrogen applied is taken up by

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rice plants, while the rest is lost to the environment. This inefficiency often results from poor fertiliser management practices, such as incorrect timing, over-application and use of unsuitable fertiliser types (Wang et al. 2022; Yuan et al. 2024). Tropical conditions with heavy rainfall also exacerbate losses through leaching and runoff. Studies have shown that NUE in rice systems is typically below 50%, indicating that more than half of the N applied does not benefit the crop (Dobermann & Fairhurst, 2000). The second challenge involves environmental losses, where unused N contributes to serious ecological issues. Nitrogen losses from agriculture, particularly through emissions to air and water, have significant negative effects on both human health and ecosystem functions. Agricultural N emissions, such as ammonia (NH_3) and nitrogen oxides (NO_x), contribute to air pollution, which affects respiratory health and reduces biodiversity, while N runoff pollutes water sources, impacting aquatic life and drinking water quality (Viancelli & Michelon, 2024; Wyer et al. 2022). Despite these challenges, N fertilisers remain essential for global food production, especially with the growing population expected to reach 10 billion by 2050. However, improving NUE across the agricultural supply chain is crucial to minimising these harmful impacts (Vries 2021). The third challenge is the economic impact of these inefficiencies. During the 2021 – 2022 period, the global spike in fertiliser prices raised concerns that reduced fertiliser application would lead to lower crop yields, rising food prices and heightened food insecurity worldwide. Despite fears of significant reductions in fertiliser use, global demand only fell modestly during the 2022 – 2023 cropping cycle, as many commercial producers absorbed the rising costs due to favourable harvest prospects and strong market prices (Vos et al. 2025). However, this global trend masks unequal impacts across regions. In Malaysia, rice cultivation remains heavily dependent on subsidised fertiliser, making the sector particularly sensitive to price volatility. In many cases, farmers may be unable to apply additional fertiliser to meet the actual nutrient requirements of their rice crops due to rising costs. As a result, any inefficiency in fertiliser use becomes even more economically damaging, as farmers are paying more while potentially achieving less in return. Without targeted support or improvements in nutrient use efficiency, these challenges could widen existing production gaps and undermine national food security goals. In Malaysia, these challenges contribute to a worrying trend of declining rice production and increasing reliance on imports (Hasbullah et al. 2021). Overall, poor N management not only harms the environment but also threatens the economic sustainability of rice farming and national food security.

According to Makhtar et al. (2022) to ensure that Malaysia's rice industry does not become too dependent on rice imports, rice grain yield, cultivation hectares, and the food consumer price index are the factors that influence short-term rice production. In addition, a study conducted by Solaymani (2023) found that in the long run, an increase of one percent in the harvested area is linked to an increase of 1.65% in rice production in Malaysia. While expanding the cultivated area can contribute to higher production in the short term, Malaysia's limited arable land and environmental sustainability concerns restrict this option. Therefore, improving rice yields through enhanced agronomic practices particularly efficient N management via approaches such as the 4R framework and Site-Specific Nutrient Management (SSNM), offers a more sustainable and scalable strategy for increasing production (Chivenge et al. 2021; Lyu, 2024). This distinction highlights the critical importance of optimising fertiliser use to close the yield gap without depending on land expansion. In Indonesia, several studies have demonstrated that increasing seed density, fertiliser application, pesticide use and labour inputs positively impact rice production. For example, Rasyid et al. (2016) reported that the combined use of these inputs enhances soil nutrient availability, reduces crop losses due to pests, and improves overall yield. Further studies by Kasmin & Kartomo, (2020); Siagian et al. (2020); Elvina et al. (2023) and Yardha et al. (2021) confirm these findings, highlighting that optimised input management plays a crucial role in improving rice productivity in various Indonesian regions.

In various rice-growing regions beyond Southeast Asia, land area and fertiliser application consistently emerge as key determinants of rice yield. For instance, in Zambia's Western Province, Musaba and Mukwalikuli (2019) found that increasing land size, seed use, agrochemical input (including fertilisers) and labour contributed to rice production gains of 0.424%, 0.487%, 0.305% and 0.162%, respectively, with land and input use having the most substantial effects. Similarly, in the Philippines, expanding land area and applying urea fertiliser were among the most significant contributors to increased rice productivity (Jennifer Madonna, 2023) along with pesticide application and access to irrigation (German et al. 2022). A study in Tanzania's Mbeya Region further reinforces the importance of land-related and agronomic variables. While socio-demographic factors such as household gender and marital status also influenced rice yields, farm size and labour availability were among the most impactful contributors. Additionally, environmental conditions such as rainfall variability and pest outbreaks played important roles (Kulyakwave et al. 2022). Taken together, these findings support the central argument that land area and fertiliser application, particularly N-based inputs, are common and critical factors influencing rice yield across diverse agroecological contexts. However, given the constraints on land expansion and the environmental risks of excessive N use, optimising fertiliser management, especially N, is essential for sustainably maximising rice productivity. However, land expansion alone does not guarantee increased rice productivity, as the yield potential of new or existing fields is heavily dependent on soil quality. Fertiliser application, particularly N, plays a critical role in maintaining soil fertility and enhancing nutrient availability, which directly influences crop growth and yield outcomes. Studies have shown that key soil parameters such as bulk density, soil porosity, organic carbon content, nutrient element concentrations and aggregate stability are essential in determining the overall productivity of rice systems (Dorairaj & Govender, 2023).

While Malaysia has achieved modest gains in rice production through intensified N fertiliser use despite stagnant harvested areas (Firdaus et al. 2020), this approach presents environmental challenges. Excessive N application can lead to significant losses through volatilisation, leaching and runoff, contributing to air and water pollution, soil acidification and greenhouse gas emissions (Chivenge et al. 2021). To mitigate these issues, enhancing NUE is crucial. The 4R Plus nutrient management strategy, which involves applying the right source of nutrients at the right rate, right time and right place, could offer a comprehensive approach to improve NUE and environmental sustainability (Upadhaya et al. 2023). Implementing practices such as site-specific nutrient management, controlled-release fertilisers and the integration of organic inputs like poultry compost has been shown to enhance soil health, reduce N losses and maintain or even increase rice yields (Chivenge et al. 2021; Farooq et al. 2024). These strategies underscore the importance of optimising fertiliser use to achieve sustainable rice production without expanding cultivated land.

Input subsidies, such as fertiliser, help to maintain rice productivity. The Malaysian rice industry has always received special treatment due to its social, political and economic importance (Ramli et al. 2012; Dorairaj and Govender, 2023). To safeguard national food security and ensure the welfare of rice farmers, the government has implemented various policy measures, including fertiliser subsidies and guaranteed minimum prices. These incentives are designed to boost productivity and income among smallholder farmers (Hairazi et al. 2022), reflecting the industry's central role in national stability and rural livelihoods. As noted by Dorairaj and Govender (2023), the rice sector in Malaysia is heavily regulated and subsidised as it is viewed as vital to both food security and political stability. However, recent studies highlight that excessive N fertiliser use has major environmental impacts, contributing to climate change, air and water pollution and biodiversity loss. It accounts for around 5% of global greenhouse gas emissions, primarily due to N surpluses in agricultural fields (Li et al. 2024). These surpluses, defined as the gap between nitrogen inputs and outputs, are a key indicator of pollution. South Asian cereal production is a global hotspot for such surpluses due to inefficient fertiliser use, leading to both environmental harm and heavy fiscal burdens from government subsidies. For instance, India allocated US$16 billion for urea subsidies in 2023/2024 (Coggins et al. 2025). To address this, there is growing emphasis on enhancing NUE through precision nutrient management strategies such as controlled-release fertilisers, which have been shown to maintain or improve yields while minimising nutrient losses (Chen et al. 2008). These approaches support more sustainable intensification of rice farming, ensuring that subsidies contribute not only to productivity but also to long-term soil and environmental health.

In Malaysia, lowland rice farmers receive subsidised fertilisers through two main government schemes; *Skim Baja Padi Kerajaan Persekutuan* and *Skim Insentif Pengeluaran Padi.* Under these programs, they are provided with 80 kg of Urea (46% nitrogen), 240 kg of compound fertiliser 17.5:15.5:10 NPK ratio (Padi 1) or compound fertiliser with a 17:20:10 (Padi 2). Additionally, they receive 150 kg of NPK fertiliser with a 17:3:25:2 MgO formulation (Padi 3) (Hairazi et al. 2022; Rubiah et al. 2022). Since fertiliser is subsidised, in the 4R program, farmers do not have the option of *right source* and *right rate*, while *right place* is a common practice. Because fertilisers are subsidised, farmers have limited control over selecting the right source and right rate of nutrients, the two key principles of the 4R nutrient stewardship framework, which promotes the right source, rate, time and place. While the right place is generally practised, fertiliser application at the right time remains inconsistent and poorly synchronised with the crop's nutrient demand. Despite extensive research on rice productivity, there remains a critical gap in N fertilisation strategies, particularly in applying precision approaches like the 4R framework. Due to the constraints imposed by the current fertiliser subsidy system, NUE in Malaysian rice farming is believed to be relatively low. This inefficiency due to the widespread use of uniform fertiliser types and rates, regardless of crop stage, soil conditions or variety-specific needs. As a result, a significant portion of applied N is lost through leaching, volatilisation, runoff and denitrification. Although exact figures for NUE in Malaysia are limited, global estimates in similar wetland rice systems typically range between 40%, suggesting a comparable trend may be occurring locally (Alam et al. 2023). This inefficiency leads to substantial N losses, causing environmental damage to soil, water, and air and threatening ecosystem health. Moreover, the practice of SSNM, which adapts fertiliser application to local field conditions and crop variety needs, is still underexplored and not incorporated into current national fertiliser programs. Globally, efforts to enhance NUE have successfully integrated agronomic, physiological and molecular approaches, including improved crop varieties, organic fertilisation and conservation practices such as no-till farming. These strategies reduce dependence on synthetic fertilisers while maintaining yields. This review therefore seeks to explore how N application, particularly the right time and right rate, can be more effectively implemented in Malaysia's rice farming systems. It also aims to assess how these strategies align with existing local rice varieties to support more efficient and sustainable nitrogen management. A comprehensive approach that integrates 4R principles with site-specific practices and aligns with national agricultural policies is essential to improving productivity while ensuring environmental sustainability.

Materials and method

This narrative review synthesises findings from 25 unique, peer-reviewed research articles and official agricultural reports related to nitrogen fertilisation in Malaysian rice production. To ensure a comprehensive and reliable evidence base, literature was identified through structured searches of major academic databases, including Google Scholar, ScienceDirect, Scopus and Web of Science. The search strategy employed a combination of targeted keywords and Boolean operators such as "*nitrogen use efficiency*," "*split nitrogen application*," "*4R nutrient stewardship*," "*site-specific nutrient management*," and "*rice yield Malaysia*." Following the initial database search, titles and abstracts were screened to assess their relevance to the scope of this review. Studies were selected for inclusion if they focused on nitrogen fertiliser use in rice cultivation, addressed agronomic practices relevant to Southeast Asia, particularly Malaysia and provided empirical data or policy-related insights. The selected studies were then reviewed in full and relevant data were extracted and synthesised according to key thematic areas. These themes included nitrogen application timing, fertiliser management strategies, nitrogen use efficiency (NUE) and policy implications associated with fertiliser subsidies and sustainable practices. The findings were organised to reflect the agronomic, physiological and environmental dimensions of nitrogen management in Malaysian rice systems, enabling a comprehensive understanding of current practices, challenges and opportunities for improvement.

Nitrogen management for rice

Fertilisers play a vital role in global food crop production, with N being the most essential nutrient for rice. To improve rice grain production and NUE, various research studies have investigated the effects of split N at critical growth phases. Unlike typical single or two time applications, split N application systems try to coordinate N availability with the physiological need of the rice plant. This technique has been widely regarded as effective in improving chlorophyll content, biomass accumulation and grain filling, particularly when applied during early vegetative growth, tillering, panicle initiation and occasionally flowering stages (Vinod & Heuer, 2012; Kamruzzaman et al. 2013; Singh et al. 2014; Hamani et al. 2023; Li et al. 2024). Given the variability in agronomic circumstances, cultivar responses and fertiliser regimens, there is no one-size-fits-all solution. However, similar themes have emerged from recent studies that might guide context-specific recommendations. Several studies throughout tropical and subtropical rice systems, including those relevant to Malaysia, with specific rates and timing suited to crop phenology and climatic circumstances. *Table 1* presents N management guidelines from selected published studies that have shown considerable gains in grain production through deliberate N splitting. The table emphasises the number of splits, total N rate, timing of treatment and observed outcomes in terms of yield. This synthesis provides a valuable comparison framework to discover successful N scheduling options and highlights the importance of stage-specific fertilisation as a tool for sustainable rice intensification. In rice cultivation, NUE remains a major challenge, with typical efficiencies ranging between 20 – 40%, often due to poor timing and over-application (Alam et al. 2023). In fact, fertilisers are estimated to sustain 40 – 60% of all agricultural production today (Johnston & Bruulsema, 2014). However, inefficient and imbalanced global N use has led to environmental degradation, nutrient runoff and disruption of soil nutrient ratios, particularly N, which threatens ecosystem health and biodiversity. Over application in some regions and underuse in others also reflect significant global disparities in fertiliser access and management (Penuelas et al. 2023). Applying N at the right rate and right time is essential for improving NUE and reducing N losses through leaching, volatilisation and denitrification. Precision N management strategies such as split applications timed to crop growth stages, slow- and controlled-release fertilisers, urease and nitrification inhibitors and SSNM have been shown to enhance N uptake while minimising environmental impact (Jat et al. 2012; Shrestha et al. 2022; Alam et al. 2023; Kamuruzzaman et al. 2024; Kumar et al. 2025; Tiwari et al. 2025). These practices align fertiliser application with the rice plant's physiological demand, ensuring optimal nutrient availability and improving overall productivity. Adopting the 4R nutrient stewardship framework, applying the right nutrient source at the right rate, at the right time and in the right place has been widely recommended to optimise crop uptake, improve NUE and address the twin goals of food security and environmental sustainability (Penuelas et al. 2023).

Based on earlier research, N is a key component of chlorophyll, the pigment that captures light energy during photosynthesis. Adequate N availability stimulates the formation of chlorophyll molecules, which improves the plant's ability to absorb light energy. Adequate N supports overall plant growth, including the formation of leaves in rice plants. More leaves result in a greater leaf area index (LAI), which correlates directly with higher potential photosynthetic rates and ultimately, grain yield (Zhang et al. 2020; Peng et al. 2021; Fathi 2022; Zhou et al. 2023). Chloroplasts are where the intricate photochemical and metabolic processes of photosynthesis take place. Rice production is determined by the relationship between the resources absorbed by the crop and their efficiency of use. Given that biomass growth is primarily fueled by light through photosynthesis, improving photosynthetic processes is regarded as a critical pathway to increasing crop yields, including rice (Xiong 2024). Recent research has increased the understanding of optimal N scheduling, precision fertilisation and NUE in rice agriculture, particularly in the setting of split N applications. Precision N management solutions, such as the SPAD chlorophyll meter and Nutrient Expert® systems (NE), have shown considerable gains in yield and NUE. For instance, SPAD and NE based N scheduling boosted grain output by 9.2% and N uptake by 22.1% compared to standard techniques (Pratap et al. 2024). Islam et al. (2009) found that splitting N applications (*Table 1*) had a significant contribution to rice grain yield by improving the leaf chlorophyll content in Bangladesh. Sonboir et al. (2020) mentioned that an increase in leaf area could maximise the interception and absorption of the wavelength of light required for photosynthesis, and more chlorophyll content resulted in higher dry matter accumulation, which increased N absorption. As a result, the grain and straw yield of rice grown in vertisol soil of the Chhattisgarh Plains agroclimatic zone increased by splitting the N application. In addition, Abd El-Megeed & El-Habet, (2020) indicated that the geometric structure of the transplanting method, which allows light to penetrate rice rows and hills, resulted in a greater amount of photosynthetic rate, which increased the number of filled grains, panicle weight and grain production, but this could only be done with suitable N timing, which gave the highest N uptake. Split N treatments, especially those separated into three or more equal doses throughout critical phenological stages (basal, tillering and panicle initiation), were consistently associated with increased agronomic performance. Equal three way splits raised yield by 30 – 38% and improved NUE measures such as agronomic efficiency and partial factor productivity (Sajjad et al. 2025). In drought prone locations, a three way split of 46 kg N/ha applied during early tillering, panicle initiation and flowering significantly enhanced chlorophyll content and grain yield compared to single or two-way applications (Uddin & Rahman, 2024). In Malaysian rice systems, the time and frequency of N application were particularly essential. One study employing the rice cultivars MR 219 and MR 232 employed a total of 135 kg N/ha, with 75 kg N/ha applied in two splits during the vegetative stage (15 and 35 days after sowing), followed by 60 kg N/ha applied at panicle initiation. Application at 55 DAS resulted in significantly increased chlorophyll content and grain yield, but a delay to 65 DAS led to yield decreases of up to 39% (Bah et al. 2009). In addition, SPAD-based real-time N management with a threshold of ≤ 38 utilised to trigger topdressings of 20 kg N/ha at several growth stages achieved an 8% increase in grain yield and a 43% improvement in NUE, while reducing total N input by 18% (Ghosh et al. 2023). However, while N is crucial for improving photosynthesis and grain yield, reaching the greatest photosynthetic efficiency needs precise timing of management. Therefore, optimal N management tactics must be adjusted to specific rice growth stages to enhance crop output. Collectively, recent findings emphasise that not only the timing but also the number and proportion of N applications across key phenological stages, particularly early vegetative growth, tillering, panicle initiation and flowering, are critical for optimising chlorophyll content, grain yield and nitrogen use efficiency in rice cultivation systems. Therefore, to optimise chlorophyll content, photosynthesis and grain yield, rice farmers should apply N in three to four strategic splits: at early vegetative growth (basal), mid-tillering, panicle initiation (around 55 DAS) and optionally at flowering, adjusted by SPAD readings or real-time crop conditions. This technique enables synchronised N availability with plant demand, leading to increased nitrogen use efficiency, especially in different agro-ecological regions such as Malaysia.

Farmers use vast amounts of N fertiliser in rice fields to maximise output, yet the crop only absorbs 20 – 50% of the N. Nitrogen utilisation efficiency is low, with a global average partial factor of productivity N (PFP N) of approximately 40 kg grain/kg N and this is largely due to farmers using huge amounts of N fertiliser during the early phases of growth, when the rice plants' root systems have not fully grown (Chivenge et al. 2021). A key reason for this inefficiency is the over application of N during early growth stages when rice root systems are immature and unable to adequately absorb the nutrient. This poor coordination between N availability and plant demand leads to considerable N losses through volatilisation, leaching, denitrification and surface runoff. For instance, ammonia volatilisation alone can account for up to 75% of total N losses, followed by runoff (16 – 23%) and leaching (7 – 9%), with total losses ranging from 38 to 114 kg N/ha depending on fertiliser type and timing (Chen et al. 2021). The worry surrounding too early N application and its inefficiency due to underdeveloped root systems is particularly applicable to the Malaysian rice producing scenario. According to the Rice Check recommendations published by Malaysia's Department of Agriculture (DOA), N application is indicated predominantly at the three-leaf stage and active tillering stage, which together account for a major fraction of the total N applied. Under the current subsidy plan, roughly 61.3 kg N/ha, or 58% of the total required N, is applied within these early vegetative phases. While this method is designed to stimulate initial plant establishment, it may also accidentally contribute to N losses if the crop's root system is not yet adequately established to take the applied N efficiently. These losses diminish the N availability during important growth stages like tillering, panicle initiation and grain filling, when demand is highest. Notably, rice plants with increased N uptake capacity, characterised by longer root length, bigger volume, higher root density and extended surface area, demonstrate significantly greater grain yield and NUE (Zhang et al. 2023). Enhancing root growth is thus crucial to boosting N acquisition and absorption efficiency. It has been demonstrated to decrease N losses and increase synchrony between supply and plant uptake. For example, integrated nutrient management techniques such as the combined use of controlled-release fertilisers, stage-specific split applications and strategic crop establishment methods like planting densification and side-deep placement have shown substantial promise in enhancing N uptake and reducing environmental losses. Field trials indicated that these measures can reduce ammonia volatilisation by up to 60.8%, principally by lowering the concentration of ammonium-N in surface water and ensuring that N is available in the root zone during periods of high crop demand (Ma et al. 2025).

At the same time, these approaches have been shown to increase NUE by 90 – 160%, not only due to improved synchrony between N supply and crop demand but also because they promote robust root morphological development characterised by greater root length, volume, surface area and distribution density (Ma et al. 2025). Such morphological characteristics significantly boost the plant's ability to intercept and absorb N from the soil solution, particularly during important stages like tillering, panicle initiation and grain filling. A well developed root system promotes deeper and more efficient N acquisition, decreases leaching and volatilisation risks and extends the nutrient uptake window. Together, these data underline that adjusting both N fertiliser timing and root system architecture is critical for bridging the gap between N application and N absorption. Enhancing root characteristics in tandem with precision N supply is therefore an important method for obtaining high NUE, reducing environmental losses and assuring long-term sustainability in rice production systems.

An appropriate N management strategy is essential to increasing NUE and crop yields. Many studies have been conducted on the effect of N splitting on NUE and rice grain yield. In North Westen Ethiopia, Tadesse et al. (2017) found that the highest rice grain yield was contributed by split applications of N, which was also found to be optimal for NUE. Zhou et al. (2022) discovered that applying N in splits significantly boost rice grain production, N agronomic efficiency and N partial productivity in which they proposed specific N timing as a technique for improving grain production and NUE in Chinese double-cropping rice systems. A study was conducted by Kumar et al. (2017) to find out the effect of N management on yield attributes, yield and NUE in rice in the western plain zone of Uttar Pradesh, India. Uttar Pradesh is the second-largest rice-growing state after West Bengal, but its productivity is low. Thus, a sufficient method of N application and a suitable time of application may play an important role in minimising the present large gap between the potential and achievable yields of rice in these two locations. They found that yield (grain straw and biological) and NUE in basmati rice were improved by splitting N accordingly. Djaman et al. (2018) investigate hybrid rice responses to different N fertiliser levels and the timing of application in the Senegal River Delta. They found that hybrid rice genotypes and N timing improve rice production. The increase in rice grain yield was due to greater NUE. In Southwest Ethiopia, N timing produced the highest grain and biological yields and this treatment can be recommended to farmers in order to maximise grain and biological yields, N uptake efficiency, and agronomic NUE (Getachew & Nebiyu, 2018). Based on this previous research indicates that increasing NUE in rice production is critical for maximising grain output. Farmers may ensure that N is accessible when rice plants need it the most by carefully timing and changing N application rates based on crop growth stage and N requirements. This prevents both deficiencies and excesses, resulting in optimal development and yield. Splitting N applications into many doses throughout the growing season helps to synchronise N supply and crop needs. This method decreases N losses by leaching, volatilisation, or denitrification, enhancing efficiency and ensuring that the plants use more N.

Rice plants need certain nutrients and have unique physiological traits to grow and develop. Therefore, it is essential to comprehend the physiology and nutrient requirements of rice plants. Indeed, studies have demonstrated that maximising nutrient levels can have a big impact on the physiology and general growth of plants. Gorgy et al. (2009) found that splitting N applications were superior in dry matter, flag leaf area, leaf area index, N and potassium content in shoots, numbers of panicles, filled grain (%), 1000-grain weight, harvest index and rice grain yield because splitting N may delay leaf ageing and increase plant physiology performances (*Table 1*). Application of N splits at basal, mid-tillering, panicle initiation and flowering produced the highest 1000-grain weight, filled grain (%) and rice grain yield compared to two-splits and three-splits of nitrogen due to better plant physiology in terms of improving crop maturity, flowering and seed formation (Youseftabar et al. 2012). According to Jemberu et al. (2015) the highest number of panicles/m^2 and number of spikelets/panicle because of the right timing of N splittings that induce the plant to develop strong and active panicles, which helps to take the assimilates from the leaf or stem to panicle. In addition, Hirzel et al. (2011) reported that in Chile, the highest productivity of rice grain yield could be achieved due to N splits accordingly to rice growth stages that could promote N accumulation in the rice panicles. Elkhoby et al. (2013) conducted an experiment to determine the optimum development, morpho-physiological characteristics and grain yield of Egyptian hybrid rice. N splittings significantly improved high rice grain yields when hybrid rice was produced under broadcast-seeded rice in normal soil. Nitrogen application during late growth stages delayed leaf ageing and improved source and sink, which significantly boosted grain production. Based on these previous reports, N splitting improves rice plant physiology by promoting balanced growth, enhancing photosynthetic efficiency, stimulating root development and supporting reproductive growth. These physiological benefits contribute to overall crop health and rice grain productivity.

Nitrogen splitting by dividing the total N fertiliser dose into multiple applications during crop growth, rather than applying it all at once, is particularly beneficial for rice cultivation and can improve several yield components. According to Kamruzzaman et al. (2013) in Bangladesh, two key obstacles to producing larger yields of transplanted Aman rice are improper splits and dosages of nitrogenous fertiliser (*Table 1*). However, the split applications of N at the right time resulted in the maximum harvest index, panicle length, grains per panicle, total tillers/hill and effective tillers/hill, which could help Bangladeshi farmers gain more profit. Due to improved crop nutrition and decreased N losses, N applied in splits has a significant impact on the morpho-phenomenological characteristics of rice, including the number of tillers/hill, plant dry matter production and yield attributes (Bharti et al. 2022). In a study conducted in a non-granary area, Zaki et al. (2021) reported that the application of N fertiliser at three distinct growth phases resulted in a higher production of panicles, spikelet number/panicle and filled grain percentage of the MR 269 variety, thereby contributing to a greater yield among the treatments. On the other hand, NurulNahar et al. (2023) suggested that applying N at three different rice growth stages was an effective strategy for increasing rice grain yield due to the greater number of panicles per square meter and spikelets/m^2 based on two consecutive seasons of rice using the local variety of MARDI Siraj 297. In Meghalaya, the North Eastern Hilly Region, which is prone to N losses due to leaching and runoff caused by heavy rains, Bharti & Ram (2023) found that splitting N at the right time not only solved the problem but also had a significant impact on rice morpho-physiological features such as the number of tillers/hill, plant dry matter production, yield attributes and grain yield because of improved crop nutrition and reduced N losses. A similar finding was reported by Christian (2022) who noted that splitting N at the right growth stages produced the highest grain production and economic profitability in water-logged regions of Fogera and comparable agro-ecologies in Ethiopia. This method might also address one of Ethiopia's most difficult challenges, particularly in heavy rainfall and waterlogged areas, which are associated with N loss through ammonium volatilisation or fixation by clay minerals. Fertiliser N splitting, according to the previously cited studies, is the use of N fertiliser in several doses during the growing season as opposed to a single application. Utilising this technique frequently maximises the efficiency of N utilisation while guaranteeing crops receive sufficient nutrients during crucial growth phases. These factors collectively contribute to improved overall rice production and quality. However, this fertilisation is dependent on a number of variables, including crop type, soil properties and climate, which can affect when and how many N splits occur. But it is most likely contributed by the rice variety factor, such as the maturation period, that could have the biggest impact. *Table 1* summarises the different N splittings in which could contribute to the maximum rice grain yield. In summary, based on these various studies, split N application is a generally suggested approach to optimise NUE and boost rice grain production. The physiological rationale for dividing N consists of synchronising N availability with the crop's nutritional needs across its developmental stages. During the early vegetative phase, N is crucial for commencing tillering, a stage where the rice plant develops numerous shoots. Early applications, commonly at the three-leaf stage or active tillering, promote leaf area expansion and chlorophyll synthesis, which are important for high photosynthetic capability and the formation of productive tillers. For example, Malaysian recommendations (Zaki et al. 2021; NurulNahar et al. 2023) apply 20 – 30% of total N at the 3-leaf and tillering phases, correlating well with root development and N uptake capacity. The panicle initiation (PI) stage indicates the beginning of reproductive growth, when spikelet differentiation and panicle structure are established. Nitrogen supply at this stage has a major influence on sink capacity, affecting the number of spikelets/panicle and, consequently, final yield. Many studies in *Table 1* allocate 25 – 50% of total N at or shortly before PI and those that do, such as Gorgy et al. (2009), Abd El-Megeed & El-Habet (2020) and Sonboir et al. (2020), consistently report high yields (>10 t/ha), emphasising the ubiquitous importance of N at PI across agro-ecological zones, including tropical countries like Malaysia. Despite these differences, a common physiological consensus emerges across all environments and genotypes, PI is the most critical stage for N application. This stage coincides with the transition from vegetative to reproductive growth, during which the potential number of spikelets/panicle is determined. Late-stage applications, typically during booting, flowering, or milking, are less prevalent but strategically valuable, especially under high-yield systems or in nutrient-leaching soils. Late N enhances grain filling, raising grain weight and protein buildup. Studies adding N during flowering (e.g., Youseftabar et al. 2012; Elkhoby et al. 2013) indicated further yield improvements, suggesting that final treatments (up to 25%) can be justified under controlled water and loss-reduction methods. Across countries and climates, three- to four-way N splits appeared as the most consistently beneficial technique. Whether in Egypt (Gorgy et al. 2009), Bangladesh (Islam et al. 2009; Kamruzzaman et al. 2013), Ethiopia (Getachew & Nebiyu 2018), or Malaysia (Zaki et al. 2021; NurulNahar et al. 2023), high-performing systems typically shared a common structure: (i) moderate early N (20 – 30%), (ii) mid-stage boost at tillering or PI (30 – 50%) and (iii) optional late-stage top-up (20 – 25%). These studies revealed yields ranging from 5.1 t/ha to over 12 t/ha, illustrating the scalability of this method across locations. Variation in total N rates and their distribution patterns reflects site-specific management goals, soil fertility and environmental restrictions. For instance, low-rate systems (60 – 100 kg N/ha) with effective splits (e.g., Jemberu et al. 2015) nonetheless obtained respectable yields (5.09 t/ha), but high-input systems (>150 kg N/ha) were sometimes essential under intensive production with high yield targets (> 10 t/ha). Adjusting N rates based on soil residual N, water regime and varietal N uptake capacity enables personalising fertiliser use without sacrificing productivity or sustainability. In the Malaysian context, the rice check system currently favours early N use (up to 60% by active tillering). However, data from this table and regional studies imply a change toward reallocating part of this early N to PI or booting stages could boost NUE and better correlate with the crop's physiological requirement. This is particularly relevant under Malaysia's flooded paddy systems, where early N is prone to volatilisation and leaching losses.

Table 1. Recommended nitrogen management for high rice grain yield

Pre-planting	Rice growth stages			Total N (kg/ha)	Yield		Source
	Vegetative	Reproductive	Ripening		Best performance	Control	
33.3%	33.3 % mid tillering 33.3 % before panicle initiation	-	-	165	11.4 – 12.0 t/ha	10.53 – 11.29 t/ha	(Gorgy et al. 2009)
50%	25 % mid tillering	25 panicle initiation	-				(Gorgy et al. 2009)
-	33.3 % at 15 DAT	33.3 at 30 DAT	33.3 at 55 DAT	215	45.25 g/hill	30.61 g/hill	(Islam et al. 2009)
-	30% at 25 DAS	70% panicle initiation	-	69	3.5 t/ha	2.6 t/ha	(Tadesse et al. 2017)
25%	25% mid tillering	25% panicle initiation	25% flowering/anthesis	100 – 300	7818 kg/ha	7702 kg/ha	(Youseftabar et al. 2012)
50%	50% tillering	-	-	60	5.09 t/ha	4.02 t/ha	(Jemberu et al. 2015)
33.3%	33.3% tillering	33.3% panicle initiation	-	120 – 140	-	-	(Hirzel et al. 2011)
50%	-	50% panicle initiation	-	120 – 140	-	-	(Hirzel et al. 2011)
-	33.3 % at 15 DAT	33.3% at 30 DAT 33.3% at 45 DAT	-	120	5.77 t/ha	4.68 t/ha	(Kamruzzaman et al. 2013)
50%	25%	25 %	-	150	3.64 t/ha	3.48 t/ha	(Bharti et al. 2022)
-	25% at 15 DAS 25% at 35 DAS	40 %	10 %	150	225.75 g/pot	137.58 g/pot	(Bah et al. 2009)
-	40% at tillering	-	30% spikelet promoting 30% spikelet developing	120 – 150	-	-	(Zhou et al., 2022)
25%	25% at 45 DAT	25% at 60 DAT	25% at 75 DAT	150	3.89 t/ha	3.53 t/ha	(Bharti & Ram, 2023)
33%	67% tillering	-	-	136.5	3.55 t/ha	1.0 t/ha	(Christian 2022)
25%	25% tillering	25% panicle initiation	25% milking	120	52.40 q/ha	27.0 q/ha	(Kumar et al. 2017)
-	40% at DAT	30% panicle initiation 20% booting	10% flowering	150	31.4 g/hill	30.0 g/hill	(Djaman et al. 2018)
25%	50% active tillering	25% panicle initiation	-	64	1659 kg/ha	700 kg/ha	(Getachew & Nebiyu, 2018)
33.3% at 10 DAS	33.3 % active tillering	33.3% panicle initiation	-	120 – 150	4913 kg/ha	3848 kg/ha	(Sonboir et al. 2020)
25 %	25% mid tillering	25% panicle initiation	25% flowering	165	10.97 t/ha	10.02 t/ha	(Elkhoby et al. 2013)
26 %	26% mid tillering	26% panicle initiation	22% booting	165.6	10.95 t/ha	9.19 t/ha	(Abd El-Megeed & El-Habet, 2020)
39%		39% panicle initiation	22% booting	165.6	10.68 t/ha	9.19 t/ha	(Abd El-Megeed & El-Habet, 2020)
39%	39% mid tillering		39% booting	165.6	10.43 t/ha	9.19 t/ha	(Abd El-Megeed & El-Habet, 2020)
	20% at 3 leaf stages 30% active tillering	50% prior to panicle initiation	-	86 – 104	5.11 t/ha	4.29 t/ha	(Zaki et al. 2021)
-	20% at 3 leaf stages 30% active tillering	50% prior to panicle initiation	-	97 – 105	9.80 t/ha	7.81 t/ha	(Nurul Nahar et al. 2023)

Note: DAT = days after transplanting; DAS = days after sowing

Nitrogen fertiliser recommendations for rice cultivation in Malaysia

The development of rice varieties from 2010 to 2021 prioritised phenotypic traits such as plant height, early maturation and rice quality that satisfied local market preferences (Elixon et al. 2022). Among the introduced inbreed varieties are MR 253 (released in 2010), MR 263 (2010), MR 220-CL1 (2010), MR 220-CL2 (2010), MR 269 (2012), MARDI Siraj 297 (2016), MARDI Sempadan 303 (2018) and MARDI Sempadan 307 (2018). These varieties have maturities of 104 days, 109 days, 105 days, 97 days, 110 days, 106 days and 110 days after sowing (DAS), respectively. In addition, in 2021, the Malaysian Agricultural Research and Development Institute (MARDI) released MR 315 with a maturity of 109 DAS and the yield potentials of these varieties are 6.8 t/ha, 7.4 t/ha, 7.2 t/ha, 7.7 t/ha, 9.9 t/ha, 8.9 t/ha, 10.0 t/ha, 10.1 t/ha and 9.0 t/ha, respectively (Elixon et al. 2022).

In 2022, the Department of Agriculture, Malaysia (DOA) published a book 'Rice Check Padi' as guidelines for fertilisation management based on the maturity age of a variety. The fertiliser management is presented in *Table 2*. According to the DOA, (2022), for a variety with a maturity between 105 and 115 days, the first fertiliser application is recommended at 15 – 20 DAS, followed by 30 – 35 days, 45 – 55 days and 75 – 85 days, for a total of four splittings. In addition to the standard fertiliser (incentives), DOA also recommends applying monoammonium phosphate (MAP, 11% N) at a rate of 55 kg/ha at the first application. Based on the DOA recommendation, this will result in a total of N distributions of 27.7%, 33.3%, 31.3% and 7.7% across the four applications. As plants mature, their N needs increase in a fashion that often follows a sigmoid curve. Proper N uptake plays a critical role in improving plant biomass, as total growth is strongly tied to the balance between N absorption and loss (Ali & Akmal, 2021). This means that the rate of N absorption is relatively slow during the early stages (e.g. germination to early tillering), increases rapidly during the mid-growth stages (especially tillering and panicle initiation) and then slows down again as the plant enters the grain-filling and maturation stages. A significant amount of N fertiliser was lost and volatilised during the early stages of rice growth because the roots' ability to absorb nitrogen is limited and a substantial amount of N is retained in the soil and irrigation water (Zou et al. 2023). Additionally, under continuous flooding conditions, approximately 75% of N losses through leaching take place between the early vegetative phase and the booting stage, with the remaining 25% occurring from heading to maturity (Qi et al. 2020). Furthermore, too much N applied too early in the rice growth stage will decrease the period between leaf emergence, hasten the emergence of tillers and raise the quantity of defective tillers (Zou et al. 2023). This happens because N controls critical genes that determine how much N the plant absorbs and how many tillers it grows. One essential gene, OsGATA8, functions like a manager. It slows down N uptake by turning off a transporter gene (OsAMT3.2) and it also helps control tiller growth by turning on another gene (OsTCP19) that prohibits the plant from growing too many tillers. When there's too much N (75kg N/ha), OsTCP19 becomes more active, which tells the plant to develop fewer tillers (Wu et al. 2024). And since the plant also takes in less N, there isn't enough to support significant tiller growth. As a result, the plant ends up with fewer tillers and yield grain (Wu et al. 2024). Comparative studies from various rice producing regions indicate that high-yielding systems typically employ a strategy involving moderate early N applications (20 – 30%), succeeded by a significant mid-season application (30 – 50%) around the tillering or PI stages and a smaller yet strategic late application (10 – 25%) during flowering or grain filling. These application splits facilitate the synchronisation of N availability with the plant's actual physiological requirements, thereby enhancing NUE and yield outcomes (Abd El-Megeed & El-Habet, 2020; Gorgy et al. 2009; Sonboir et al. 2020). Although the Department of Agriculture's (DOA) current distribution of N, with 61% (67.4 kg/ha) applied before PI, generally aligns with the crop's uptake window, it appears somewhat front loaded. A slight reduction in early N applications (for instance, from 28% to approximately 20 – 25%) and a reallocation of that quantity towards PI and the grain-filling stage could more effectively match the nutrient needs of the rice plant and mitigate environmental losses. Hence, aligning N applications with the rice plant's sigmoid uptake pattern, which is characterised by slow-rapid-slow phases, can enhance synchrony between supply and demand, ultimately boosting both yield and sustainability in Malaysian rice production systems.

Table 2. Recommended nitrogen splits by growth stage and crop maturity

Fertiliser timing	Maturity period			Total Nitrogen (kg/ha)
	95 – 105	105 – 115	>115	
	Days after sowing			
3-leaf stage	15 – 20	15 – 20	15 – 20	23.8-24.5* + 6.1 (additional N through MAP)
Active tillering	25 – 30	30 – 35	35 – 40	36.8
Panicle initiation	35 – 45	45 – 55	55 – 60	34.5
Heading & flowering	70 – 80	75 – 85	85 – 90	8.5

DOA, (2022). * NPK compound fertiliser (17.5:15.510 for west coast; 17:20:10 for east coast)

Nitrogen management in rice cultivation: aligning growth stages with demand for optimal efficiency

Effective N management is crucial to obtaining high productivity and sustainability in rice agriculture. However, NUE in rice remains low due to inadequate alignment between fertiliser application and the crop's physiological N need across its three growth phases: vegetative, reproductive and ripening. This review integrates physiological and agronomic research to determine how N should be supplied at each stage to improve uptake, reduce losses and enhance output. The vegetative stage is from germination to the panicle primordia formation, while the reproductive stage occurs from panicle primordia initiation to heading and the ripening stage starts from heading to maturity (Yoshida 1981; Moldenhauer et al. 2013; Killenga et al. 2020). The life cycle of rice generally has the same length of the reproductive and ripening phases, but the length of the vegetative phase differs among varieties and for varieties that have a maturity age between 100 and 120 days, the vegetative phase is 35 – 55 days (Killenga et al. 2020). In addition, culm elongation, a decrease in tiller number, booting, flag leaf emergence, heading and flowering are the traits that define the reproductive phase and this phase typically lasts 30 days (Moldenhauer et al. 2013; Nawaz & Farooq, 2017). It is possible to conclude that the ripening phase also lasts for 30 days in general. As a result, the vegetative phase lasts for 60 days for rice varieties with a maturity age of 120 days, while the reproductive and mature phases last for 30 days each.

Vegetative phase: timing nitrogen with tiller formation

Tiller formation begins around the fifth leaf stage, typically at 30 – 35 DAS, with the first tiller emerging from the axillary bud of the second leaf (Moldenhauer et al. 2013; Badriyah et al. 2022). Nitrogen requirement during early vegetative growth is minimal due to immature root systems and limited canopy area, which constrain the plant's ability to absorb supplied nutrients. Hashim et al. (2015) demonstrated that NUE in MR 219 rice was merely 5% at 28 DAS and only 10% by 42 DAS, implying most of the fertiliser provided at this stage was lost by volatilisation, leaching and denitrification (Motasim et al. 2024; Swify et al. 2024). The Department of Agriculture (DOA) in Malaysia advises a total of 67.4 kg N/ha during the vegetative stage, split between 30.6 kg N/ha at the 3-leaf stage and 36.8 kg N/ha at active tillering. However, the 3-leaf stage coincides with a period of low NUE and high N losses. We recommend reducing this early application to 15 – 20 kg N/ha and reallocating the remaining 10 – 15 kg N/ha to the PI stage (60 – 70 DAS), where NUE reaches 50% and nitrogen is essential for panicle and spikelet formation (Hashim et al. 2015; NurulNahar et al. 2023; Coggins et al. 2025). This targeted redistribution enhances nutrient synchrony with physiological demand, increases yield potential and reduces environmental losses (Zhang et al. 2023). Recent studies indicate that fertilisation at this stage, whether conducted prior to or during early growth, presents both advantages and disadvantages contingent upon the type of fertiliser, timing and environmental conditions. Timely application delivers crucial NPK nutrients for root and shoot development, improving seedling establishment and tillering capacity (NurulNahar et al. 2023). This helps minimise early-stage losses while still promoting productive tiller development. This approach corresponds with the necessity to supply adequate nutrients during a pivotal growth period while minimising environmental losses. Timely application enables plants to absorb nutrients prior to their loss via leaching or volatilisation. Yet, excessive N fosters lush, dense canopies that attract pests and diseases such as leaf and panicle blast (Shrestha et al. 2022) and this issue is not unique to rice; similar patterns have been observed in crops like cabbage and cherry orchards where high N promotes susceptibility to pests and diseases (Rutkowski & Łysiak 2023; Gelaye 2024; Wu et al. 2024). Therefore, high fertiliser input during the vegetative stage may not be beneficial, as it is unlikely to be fully utilised by the rice plants and is prone to environmental loss.

Reproductive phase: aligning nitrogen with panicle formation and flag leaf function

The reproductive stage begins with panicle initiation, which occurs approximately 25 days before heading (Yoshida 1981) and a rice plant takes 10 – 14 days to complete heading because panicle extension varies among tillers of the same plant and between plants in the same area (Yoshida, 1981; Moldenhauer et al. 2013). In addition, the heading phase begins ±18 days after booting and the booting phase occurs ±28 days after the tillering phase (Badriyah et al. 2022). This is the period of peak N demand, as N is needed to support panicle structure, spikelet differentiation and reproductive organ formation. NUE also reaches its highest point at around 84 DAS (50%) before declining (Hashim et al. 2015). Given this heightened demand, applying N during PI has been shown to improve the number of panicles and grain weight, as reported by NurulNahar et al. (2023), who showed significant gains in yield components when N was applied to this stage. The third fertilisation proposed by the DOA is set immediately before PI to maximise the transition from vegetative to reproductive stages. This is scientifically justifiable, as it encourages reproductive organ growth and leads to flower and grain formation. Recent agronomic studies also affirm that reallocating surplus N from early stages to PI enhances yield while reducing nitrogen losses (Jose et al. 2024). The flag leaf, emerging 18 days before heading, plays a major role in photosynthesis and grain filling. Nitrogen supports its formation and function by enhancing rubisco content and canopy photosynthetic efficiency (Murchie et al. 2002; Tanaka et al. 2022; Kalaichelvi 2024). Ensuring N supply during this stage also helps maximise photosynthetic nitrogen use efficiency (PNUE), particularly in genotypes bred for higher NUE (Karthigaa et al. 2022).

Nitrogen uptake from soil decreases significantly throughout the ripening period, which lasts approximately 30 days from heading. Instead, the plant relies on N stored in its culm, leaves and panicles before anthesis (Hashim et al. 2015). Photosynthesis from the flag leaf accounts for at least 60% of the grain's total carbon content, with the remainder coming from stored carbohydrates in leaf sheaths and stems (Murchie et al. 2002). The fourth DOA recommended N application (8.5 kg N/ha; 7.7%), aligned with flag leaf emergence, also has scientific merit. Supporting flag leaf health is crucial for photosynthetic capacity and, ultimately, grain filling. However, as the plant transitions into ripening, N intake from the soil drops significantly and internal remobilisation becomes the predominant nitrogen source for grain filling. This lower absorption efficiency raises concerns regarding the usefulness of late-stage fertiliser applications. Recent studies indicate that N applied soon before or after heading may not be adequately absorbed due to reduced root activity and can be lost by volatilisation or leaching (Mohanty et al. 2023; Jose et al. 2024). Instead, reallocating this final N dose to the PI stage when N demand and physiological uptake are at their peak can significantly enhance spikelet development, panicle size and flag leaf strength (Coggins et al. 2025; Zhang et 2023). This strategic adjustment not only fits with the plant's developmental needs but also boosts NUE and yield responsiveness while minimising loss.

Ripening phase: supporting grain filling through remobilised and residual nitrogen

Following heading, flowering (anthesis) occurs about 10 days later, followed by the ripening stage, which is also 10 days after anthesis (Badriyah et al. 2022) and the time interval for flowering of an entire panicle is normally 4 - to 7 days (Moldenhauer et al. 2013; Nawaz & Farooq 2017). Hashim et al. (2015) argue that fertiliser administered during grain filling may have restricted direct uptake, making timing essential. Very late applications may not increase yield and may even contribute to plant N loss. As a result, the primary goal should be to provide enough N accumulation before the commencement of ripening.

Synthesis and practical implications for nitrogen management in Malaysia

Over application of N during the early vegetative phase not only results in nutrient wastage but also increases the crop's susceptibility to pests and diseases due to overly dense and humid canopies (Shrestha et al. 2022; Rutkowski & Łysiak, 2023). On the other hand, insufficient N application during the PI stage can hinder reproductive development, limiting panicle formation and reducing yield potential. To optimise NUE and maximise yield, it is recommended that approximately 22.1 kg N/ha (20%) at the 3-leaf stage, 33.1 kg N/ha at active tillering (30 – 35 DAS), 49.7 kg N/ha (45%) at PI (45 – 55 DAS) and 5.5 kg N/ha (5%) at heading. However, as discussed earlier, N uptake from the soil declines sharply as rice enters the ripening stage, prompting the plant to rely more on internal reserves accumulated before anthesis. Therefore, we propose reallocating the final 5.5 kg N/ha from the heading stage to the panicle initiation (PI) stage. This adjustment aligns with findings by Ju et al. (2021), who demonstrated that applying a greater portion of nitrogen around the PI stage significantly enhanced both grain yield and nitrogen use efficiency (NUE) across rice cultivars. The importance of nitrogen application at the panicle initiation (PI) stage has been strongly supported by Sun et al. (2023), who demonstrated that allocating a portion of N at PI significantly improved both grain yield and nitrogen use efficiency (NUE) in rice. Their study showed that applying 20% of the total N at PI resulted in a 5 – 26% increase in grain yield and a 4 – 27% improvement in agronomic NUE metrics, depending on the variety and environmental conditions. According to their study, these gains were attributed to the enhanced synchrony between crop nitrogen (N) demand and fertiliser availability during the PI stage, a period critical for spikelet differentiation and panicle formation. In contrast, treatments that did not include N application at the PI stage recorded noticeably lower yields, highlighting the importance of timely N supply to support reproductive development. The findings emphasise that shifting part of the N allocation to PI not only supports yield formation but also reduces environmental loss through more efficient uptake. By delivering the final 5.5 kg N/ha at PI, where uptake efficiency approaches 50% (Hashim et al. 2015), this approach simplifies the fertilisation process (reducing applications from four to three) while enhancing nutrient use, minimising environmental losses and maintaining or improving yield performance. This is especially true for Malaysian medium-maturity rice varieties like MR 315. In fact, this strategy aligns with the recommendations of NurulNahar et al. (2023) and Zaki et al. (2021) for local rice varieties. *Figure 1* illustrates the life cycle of the MR 315 rice variety (with a 109- day maturity period), adapted based on developmental stage timelines reported by Yoshida (1981), Moldenhauer et al. (2013) and Badriyah et al. (2022) and aligned with the N fertilisation schedule recommended by the Malaysian Department of Agriculture (DOA) for medium-maturity rice varieties.

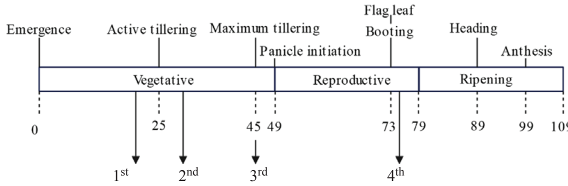

Figure 1. Life cycle of MR 315, a variety with 109 maturity period and recommended fertiliser schedule (schematic)

Future strategies: Enhanced-efficiency nitrogen fertiliser

Improving NUE in Malaysian rice cultivation is vital for assuring sustainable yields, minimising environmental consequences and cutting production costs. Notable types of enhanced-efficiency N fertilisers include controlled-release fertilisers (CRFs), slow-release fertilisers (SRFs), nitrification inhibitors, urease inhibitors, polymer-coated urea (PCU) and stabilised N fertilisers. Enhanced efficiency fertilisers (EEFs) have attracted prominence as a crucial technique yet, they represent just one aspect of a broader set of options. To enhance NUE more effectively, it is important to explore and implement additional approaches such as site-specific nitrogen management (SSNM) using precision agriculture tools (Dobermann, 2005; Peng et al. 2010), as well as the application of biostimulants and N-fixing microbes to improve soil nitrogen availability (Adesemoye et al. 2009). Climate-smart strategies like alternate wetting and drying (AWD) irrigation can also play a substantial role by boosting N retention while limiting environmental losses (Lampayan et al. 2015). A diverse and inclusive approach will enable a more balanced, practical and forward-looking plan for enhancing nitrogen management in Malaysian rice systems.

Controlled release fertilisers (CRFs) and slow release fertilisers (SRFs) improve N utilisation efficiency by matching N release with crop uptake patterns. CRFs include nutrients encapsulated in polymer, sulphur, or biodegradable coatings that regulate nutrient release dependent on environmental variables, including temperature and moisture. This precise control minimises N losses through leaching and volatilisation while ensuring a regular nutrient delivery to crops (Xiandong et al. 2018; Hongyu et al. 2022). SRFs, however less accurate, rely on chemical or microbial breakdown to slowly release nutrients, increasing their availability and lowering the need for multiple applications (Qingfei et al. 2023). Polymer-coated urea (PCU), a specific type of CRF, has been shown to dramatically raise NUE and grain yield in rice systems, with studies claiming NUE gains of up to 5.5% and yield increases of 11.6% (Fageria & Carvalho, 2014; Wang et al. 2015; Guang et al. 2018). included a blend with 70 % of N from 6 % (w/w.

Nitrification inhibitors further boost NUE by reducing the microbial conversion of ammonium to nitrate, thus maintaining N in a more stable state that is less prone to leaching and denitrification. This helps retain N in the root zone, especially under moist conditions. While some research revealed moderate or no improvement in yield (Quemada et al. 2013), others reported enhanced NUE and agricultural production (Abalos et al. 2014). Urease inhibitors, such as NBPT, function by temporarily blocking the urease enzyme that rapidly breaks down urea, considerably lowering N loss by ammonia volatilisation, particularly in dry, alkaline soils. This delay permits more N to be accessible for plant uptake (Kiss & Simihăian, 2002; Mira et al. 2017; Silva et al. 2017; Wang et al. 2020a). Stabilised fertilisers that combine both nitrification and urease inhibitors have proven even more effective, with reported rice yield gain of up to 16.3% and nitrogen agronomic efficiency improvements of up to 54.7%, outperforming single-inhibitor treatments (Zhang et al. 2013; Zhang et al. 2021). These advanced N management methods boost NUE by synchronising nutrient delivery with plant needs and decreasing N losses through environmental channels.

Site specific nutrient management is a precision agriculture strategy designed to enhance NUE by tailoring fertiliser inputs to the specific needs of crops and the spatial and temporal variability of soil nutrient availability (Meena et al. 2023; Koley et al. 2024). By aligning nutrient supply with crop demand throughout different growth stages, SSNM significantly reduces fertiliser waste, enhances nutrient uptake and mitigates environmental impacts such as leaching and emissions, while supporting sustainable soil health (Chivenge et al. 2021; Koley et al. 2024; Yousif et al. 2024). This approach addresses pressing agricultural challenges, including soil degradation, nutrient depletion and climate variability, thereby contributing to the development of resilient and sustainable farming systems. The effectiveness of SSNM is supported by advanced technologies, including soil and plant analysis, GIS, GPS, remote sensing and proximal sensing tools such as chlorophyll meters, which provide real-time assessments of crop nutrient status (Gorai et al. 2021; Ravikumar et al. 2024). Decision support systems (DSS), like Crop Doctor and Nutrient Expert (NE), use ongoing field data to generate dynamic, site-specific fertiliser recommendations, moving beyond traditional blanket applications (Gorai et al. 2021; Sapkota et al. 2021; Sarma et al. 2024). Variable rate application machinery further ensures precision in nutrient delivery, optimising both efficiency and crop performance (Gorai et al. 2021; Papadopoulos et al. 2024). In the Malaysian context, SSNM offers a strategic pathway to improving NUE, crop productivity and environmental sustainability across diverse agroecosystems. For effective implementation, efforts should begin in regions where the impact would be most immediate, particularly low yielding areas with poor or imbalanced fertiliser use, common among smallholder rice and upland farmers. By matching nutrient inputs to actual crop needs, SSNM can improve fertiliser efficiency and yield stability. To support adoption in these areas, Malaysia should promote farmer cooperatives to pool resources, establish demonstration projects to showcase agronomic and economic benefits, engage input suppliers to provide tailored fertilisers and tools, and strengthen agricultural extension services for farmer training and technical support. Additionally, collaboration between research institutions and government agencies on infrastructure investments. While SSNM offers considerable advantages, its implementation is not without challenges. Key barriers include limited access to reliable soil testing, high input costs, fragmented landholdings, climate variability, poor infrastructure and insufficient technical expertise (Sunny et al. 2018; Masso et al. 2024;

Prajapati & Patel, 2024; Vullaganti et al. 2025). Furthermore, inconsistent agricultural policies and a lack of local success stories reduce farmer confidence and hinder adoption. The recommended strategies include strengthening farmer cooperatives, launching targeted pilot projects, engaging input providers, expanding extension support and fostering collaboration between government and research institutions (Kalogiannidis et al. 2024; Pan et al. 2024; Prajapati & Patel, 2024). These actions can help build technical capacity, improve access to resources and establish supportive institutional frameworks. By integrating technology, local knowledge, and policy support, SSNM stands out as a cornerstone of precision agriculture and a viable path toward sustainable N management in Malaysia's farming systems.

Soil health is ecosystem vitality, but improper management has led to problems like erosion and nutrient pollution. Biostimulants either chemical, microbial, or material agents could offer a promising solution to improve soil health (Abiola et al. 2016). These agents do not directly feed plants but instead enhance nutrient efficiency, increase stress tolerance, and boost crop quality. By stimulating beneficial soil organisms, biostimulants improve soil structure, nutrient availability and its physical, chemical and biological properties and reduce soil degradation (Papnai et al. 2022). The continued advancements in biotechnology and formulation techniques are enhancing the effectiveness of these biostimulants, making them more accessible and practical for widespread use (Samantaray et al. 2024). Recent innovations in agricultural biotechnology have led to the discovery of several new biostimulants, inoculants, and biofertilisers, often utilising microorganisms such as bacteria, fungi and microalgae to stimulate crop growth. These compounds improve plant health by boosting nutrient uptake, regulating plant hormones and offering resilience to stress (Buisset et al. 2025). In another study, the impact of commercial biostimulants on soil microbial activity and N cycling was explored. The results showed that biostimulants promoted microbial activity even at low concentrations in the short term. However, they also inhibited some microbial processes while stimulating others. Over time, both biostimulants altered N cycling, particularly in alfalfa-amended soils, where they increased N mineralisation. These findings suggest that biostimulants can accelerate the breakdown of organic materials and enhance N availability, which could be beneficial for sustainable farming (Chen et al. 2002). To reduce the reliance on chemical fertilisers, studies have also focused on N-fixing species as an alternative method to improve plant growth and nutrient uptake. Bacteria and yeast strains have shown promise in reducing the need for N fertilisation and increasing nutrient utilisation efficiency. These microbes have been found to enhance plant growth and nutrient uptake, especially for N and phosphorus, making them potential candidates for use as biofertilisers (Abderrahim et al. 2024). Field studies have investigated the interaction between biostimulants and N rates to determine their impact on crop production and NUE. While increased N rates boosted crop output, they also decreased NUE efficiency. Combining biostimulants with reduced N rates positively impacted NUE, the potential for sustainable nitrogen management. This two year study reveals that the impact of biostimulants can vary depending on environmental factors, such as soil type and irrigation (Gajula et al. 2025). Despite their potential, microbial inoculants have demonstrated inconsistent results in the field. To improve their performance, greater collaboration between disciplines such as microbiology and agronomy is necessary. Advancements in microbial strain selection and the development of mixed inoculants are crucial for creating reliable products. Further field studies are needed to assess the effectiveness of these biostimulants under diverse farming conditions (O'Callaghan et al. 2022). The combination of plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi has shown promise in enhancing plant growth, nutrient uptake and resilience to environmental stresses such as drought and salinity. However, the success of these biostimulants depends on selecting the right strains and understanding their interactions with plants (Castiglione et al. 2021). Recent research has also demonstrated the effectiveness of biostimulants in improving soil microbial activity and agricultural yields. For example, a combination of N fertiliser, biofertilisers and humic substances significantly increased strawberry production by 95% compared to the control, which highlights the potential of biostimulants in improving both soil health and crop productivity (Makova et al. 2024). In rice cultivation, biostimulants, particularly endophytes, have shown significant benefits. In vitro tests revealed up to 38% increases in rice seedling vigour with endophyte inoculation. Field trials confirmed these benefits, with inoculated rice yielding up to 30% more than non-inoculated controls, especially when combined with reduced fertiliser doses. This approach offers a sustainable way to boost rice productivity while minimising chemical fertiliser use (Nantoume et al. 2023). A novel biostimulant, *Paecilomyces variotii* extract (ZNC), has also been shown to enhance N absorption in rice. Field trials revealed that combining ZNC with controlled-release urea (CRU) increased rice yield by 8.7 – 12.1%, NUE by 15 – 20%, and net returns by 10.9 – 15.4%. This combination offers an effective strategy to improve rice yield and returns while reducing the need for higher fertiliser doses (Wang et al. 2020b). In a three-season study, a methane-derived microbial biostimulant significantly increased rice yield by up to 39% under full fertiliser conditions. It also reduced methane (CH_4) emissions by 31 – 60% and nitrous oxide (N_2O) emissions by 34 – 50%. The biostimulant improved crop physiology and boosted yield, even under reduced N conditions, making it an environmentally sustainable solution for rice cultivation (Kumar et al. 2024). Therefore, biostimulants, whether microbial, chemical, or material, hold significant potential for improving soil health, enhancing crop yields and promoting sustainable farming practices. In the context of Malaysian rice cultivation, biostimulants could play a crucial role in addressing challenges such as soil degradation, nutrient management and the over-reliance on chemical fertilisers. The successful integration of biostimulants in Malaysia could lead to improved NUE, enhanced rice productivity and a reduction in environmental impact, particularly in terms of greenhouse gas emissions. However, challenges remain in terms of the consistency of biostimulant performance across different environmental conditions, soil types and rice varieties. In Malaysia, where rice cultivation spans diverse agro-ecosystems, the formulation and application of biostimulants must be tailored to local conditions to ensure optimal effectiveness. Additionally, the cost of biostimulant products and the need for proper training in their use could pose barriers to widespread adoption among farmers. Nonetheless, with continued research, particularly focusing on local microbial strains and field trials specific to Malaysian rice farming, biostimulants have the potential to transform rice cultivation into a more sustainable and resilient industry. Collaboration between researchers, agronomists and farmers will be essential to overcome these challenges and realise the full benefits of biostimulants for Malaysian agriculture.

Organic fertilisers, obtained from plants and animals, offer a wide range of benefits, including greater water retention, healthier soil and higher nutrient availability. Although they have lower nutrient concentrations compared to synthetic fertilisers, organic fertilisers are significantly less hazardous to the environment (Subedi & Poudel, 2021). A fundamental advantage of incorporating both organic and inorganic fertilisers is that it can maximise crop yields, boost soil structure and promote long-term sustainability. Educating farmers about organic fertilisers and Integrated Nutrient Management (INM) is vital for enhancing agricultural output and soil health while tackling pressing challenges like erosion and climate change (Wato et al. 2024). Organic fertilisers also enhance soil organic matter, microbial activity and nutrient uptake, enhancing crop growth and resilience to stress. When used alongside chemical fertilisers, they improve soil quality and productivity. However, additional research is needed across diverse climates and soil types to comprehend their full potential. Sustainable farming strategies, including crop rotation and precision farming, are also vital to lowering fertiliser dependency and limiting environmental effects (Nakachew et al. 2024). In regions like South Asia, factors including wealth, education and market access play a crucial role in farmers' decision between organic and inorganic fertilisers. While inorganic fertilisers are often associated with increased economic status, their abuse can lead to environmental damage. To encourage more sustainable practices, educational campaigns and labour-saving technology are needed to promote the use of organic fertilisers and preserve soil health (Aryal et al. 2021). Integrated Nutrient Management, which combines organic amendments, cover crops and crop rotations, enhances nutrient cycling and soil quality. Studies suggest that this strategy promotes soil organic carbon and microbial activity while lowering dependency on chemical fertilisers. A balanced use of both organic and inorganic fertilisers is crucial to ensuring sustainable agricultural production, with crop yields improving by as much as 66.5% (Paramesh et al. 2023). The combination of biofertilisers and organic fertilisers has been demonstrated to optimises nutrient uptake, accelerates photosynthesis and increases photosynthetic efficiency by roughly 74%, ultimately contributing to greater crop output and environmental sustainability (Mthiyane et al. 2024). In Malaysia, while chicken manure has demonstrated considerable potential to boost rice yields, farmers normally only receive 100 kg/ha of organic fertiliser (Dorairaj & Govender, 2023), which is considered insufficient. Applying 10 t/ha of chicken manure dramatically enhances soil nutrient availability, microbial activity and photosynthesis, resulting in grain yields reaching up to 8 t/ha. It also enhances the N content in both rice grains and straw, further boosting nutritional intake. However, for optimal outcomes, a balanced approach that incorporates both organic and inorganic fertilisers is necessary to maintain soil health and improve nutrient availability (Anisuzzaman et al. 2022). Overall, organic fertilisers in rice farming have tremendous potential to improve soil health, maximise nutrient cycling and encourage more sustainable farming practices. By mixing organic fertilisers with traditional chemical fertilisers through INM, farmers can enhance yields while ensuring environmental sustainability. However, the adoption of organic fertilisers confronts hurdles, including slower nutrient release rates, labour-intensive application and a lack of awareness and expertise about optimal management. Government support, including educational efforts and expanded access to organic fertilisers, is important for overcoming these barriers and building a more sustainable agricultural future.

Alternate wetting and drying (AWD) is a water efficient rice irrigation method where fields are allowed to dry between irrigations instead of being continuously flooded. This technique helps reduce water use by 14 – 28% without lowering rice yields, making it a valuable tool for sustainable rice farming, especially under climate change (Johnson et al. 2024). Alternate wetting and drying improves water productivity by up to 50% and lowers irrigation costs while also reducing environmental impacts. It supports healthy plant growth by maintaining enough soil moisture at critical stages and encouraging strong root and shoot development (Sridhar et al. 2022). Alternate wetting and drying can also improve nutrient uptake and NUE, especially when paired with good fertiliser practices that match crop needs. While overall NUE under AWD remained stable, poor fertiliser management limited potential gains, suggesting the need for site-specific strategies (Johnson et al. 2024). Alternate wetting and drying alters the soil environment by increasing oxygen levels, which promotes beneficial microbial activity and enzyme function, helping plants access nutrients more efficiently (Cao et al. 2022). It enhances soil health, increases phosphorus (P) availability in higher clay soils and supports better photosynthesis and antioxidant balance in plants, leading to stronger growth and improved grain yield (Hamoud et al. 2024). However, if drying is too severe or frequent, it can reduce P availability, hinder root development and cause oxidative stress in rice plants, ultimately lowering yields. Repeated drying can also lead to soil cracking and the loss of organic carbon and nitrogen over time, possibly affecting long-term soil productivity (Haque et al. 2021). Nonetheless, the addition of soil amendments like biochar can help offset some of these issues by improving water retention, nutrient availability and overall soil structure, though more research is needed to confirm cost-effectiveness and long-term impacts (Haque et al. 2021). Research also shows that AWD allows rice plants to compete successfully with microbes for organic N (like glycine), especially at higher fertiliser levels and increases N uptake from the soil. Alternate Wetting and Drying also promotes the growth of helpful bacteria and fungi in the root zone, creating a more balanced soil ecosystem (Cao et al. 2022) and maintaining consistent nitrogen uptake overall (Vitali et al. 2024). Given these findings, AWD offers promise for rice farming in Malaysia. With proper training, monitoring tools and support from agricultural agencies, Malaysian farmers could adopt AWD to improve productivity, lower costs and manage resources more sustainably.

Conclusion

This review underscores the critical importance of adopting split N application strategies in Malaysian rice cultivation to enhance NUE, improve yields and reduce environmental impacts. Evidence from multiple field trials and agronomic studies consistently shows that synchronising N application with rice plant growth stages, particularly during tillering, panicle initiation and grain filling, can substantially increase grain yield and NUE compared to single or front-loaded applications. While the Department of Agriculture's (DOA) fertilisation guidelines have made progress in recommending split applications, a re-evaluation is warranted to better align application timing with crop physiological demand, especially to avoid early-stage N losses.

Comparative analyses reveal that alternative, data-driven strategies such as Site-Specific Nutrient Management (SSNM) and 4R nutrient stewardship (Right Source, Right Rate, Right Time, Right Place) offer greater flexibility and efficiency than the current subsidy-driven DOA recommendations. These alternatives not only improve yield outcomes but also reduce nutrient losses that contribute to environmental degradation and fiscal burdens on government subsidies. The review also highlights the risks of excessive N use, including air and water pollution, greenhouse gas emissions and reduced soil health, which together threaten long-term agricultural sustainability and food security.

For Malaysian rice varieties, particularly those with a maturity period of around 105 – 115 days, such as MR 315, fertiliser recommendations should prioritise three main nitrogen applications: (1) 20 – 25% of total N at the early vegetative stage (3-leaf stage), (2) 30 – 35% at active tillering and (3) 40 – 45% at panicle initiation. Reallocating part of the nitrogen currently applied too early toward the panicle initiation stage would better match the plant's peak nutrient demand, minimise losses and support optimal yield formation.

To bridge the gap between agronomic efficacy and real-world implementation, future research should focus on customising N strategies to specific varieties, soil types and regional climates while integrating economic and policy frameworks that incentivise efficient practices. Enhanced-efficiency fertilisers, decision support tools and biostimulants represent promising innovations that can support these goals. Ultimately, aligning practical fertilisation approaches with scientific insights and policy reforms is essential for achieving sustainable intensification of rice production in Malaysia.

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