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Real-time nitrogen management in rice using leaf color chart (LCC): A review

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Abstract
Efficient nitrogen (N) management is critical for achieving optimal rice productivity and minimizing environmental degradation [1] (Fageria & Baligar, 2005). Traditional blanket N application often results in either excessive or insufficient use of fertilizer, leading to economic losses and ecological harm [2] (Dobermann & Cassman, 2002). The Leaf Color Chart (LCC) has emerged as a low-cost, farmer-friendly tool for real-time N management by allowing visual estimation of leaf nitrogen status [3] (Alam *et al*., 2005). It enables site-specific and time-specific N applications, thereby improving nitrogen use efficiency (NUE) and reducing N losses [4] (Singh *et al*., 2002). Numerous field studies have shown that LCC-guided N application can sustain or even increase rice yields while using less fertilizer [5] (Buresh *et al*., 2010). Compared to sensor-based tools and decision support systems, the LCC is simpler, more accessible, and highly effective for smallholder farmers, especially in Asia [6] (Balasubramanian *et al*., 2000). Despite its potential, challenges such as user subjectivity, regional calibration needs, and lack of awareness still hinder widespread adoption [7] (Bijay-Singh *et al*., 2002). This review summarizes the evolution, efficacy, limitations, and innovations in LCC-based nitrogen management for rice, aiming to identify research gaps and future directions for its broader adoption in sustainable agriculture.

Keywords: Leaf color chart (LCC), nitrogen management, real-time nutrient application, rice yield, nitrogen use efficiency (NUE), precision agriculture

Introduction
Nitrogen (N) is an essential macronutrient that critically influences rice growth, yield, and grain quality [1] (Fageria & Baligar, 2005) [8] (Xu, Yu, & Cai, 2019). However, improper nitrogen fertilization, including over-application, can lead to environmental pollution such as nitrate leaching, greenhouse gas emissions, and soil acidification, besides economic losses for farmers [2] (Dobermann & Cassman, 2002) [9] (Zhang *et al*., 2015). Traditional fertilizer management methods in rice cultivation often rely on fixed schedules or blanket recommendations that do not consider the spatial and temporal variability of crop nitrogen demand [6] (Balasubramanian *et al*., 2000) [10] (Peng, Tang, & Zou, 2020). Real-time nitrogen management tools, such as the Leaf Color Chart (LCC), provide a low-cost and user-friendly method to assess crop nitrogen status and guide precise fertilizer applications on-site [3] (Alam *et al*., 2005) [11] (Sharma, Singh, & Singh, 2021). The LCC estimates leaf chlorophyll content, which is directly correlated with plant nitrogen levels, allowing timely and site-specific nitrogen application to improve nitrogen use efficiency [4] (Singh *et al*., 2002) [12] (Wu *et al*., 2018). Studies have demonstrated that LCC-based nitrogen management can increase rice yields, reduce nitrogen input, and mitigate environmental impacts, particularly in smallholder farming systems in Asia [5] (Buresh, Pampolino, & Witt, 2010) [13] (Li *et al*., 2017). Nevertheless, challenges including user subjectivity, the need for regional calibration, and limited farmer awareness hinder the widespread adoption of LCC technology [7] (Bijay-Singh *et al*., 2002) [14] (Nguyen *et al*., 2022). This review critically examines the development, effectiveness, limitations, and innovations in LCC-guided nitrogen management for rice, and discusses future research priorities to support sustainable rice production

Methodology of Literature Selection

To ensure a comprehensive and unbiased synthesis of available research on real-time nitrogen (N) management in rice using the Leaf Color Chart (LCC), a systematic literature search was conducted following established review protocols [15] (Siddaway *et al*., 2019). The search covered peer-reviewed journal articles, reports, and technical papers published between 2000 and 2024, as this period captures the primary development and adoption phases of LCC technology [11] (Sharma *et al*., 2021). Databases used included Web of Science, Scopus, Google Scholar, and ScienceDirect, which are widely recognized for agricultural and environmental research [16] (Falagas *et al*., 2008). The search keywords used in various combinations were: *"leaf color chart"*, *"real-time nitrogen management"*, *"rice"*, *"nitrogen use efficiency"*, *"precision agriculture"*, and *"sustainable nitrogen practices"*. Boolean operators (AND, OR) were applied to refine search results and improve relevance [17] (Bramer *et al*., 2017). Studies were included if they reported empirical data, field experiments, or modeling outcomes related to LCC-based nitrogen management in rice systems.

Exclusion criteria involved studies not focused on rice, those that did not evaluate LCC or nitrogen outcomes directly, or papers lacking sufficient methodological detail. Preference was given to field-based studies conducted in Asia and Sub-Saharan Africa, where LCC adoption has been most studied [5] (Buresh *et al*., 2010) [14] (Nguyen *et al*., 2022). Additionally, institutional reports from IRRI and FAO were included to capture grey literature and development-oriented evidence [18] (IRRI, 2013). The final selection comprised over 50 sources, categorized and analyzed based on study location, methodology, findings, and relevance to LCC-based nitrogen application.

Conceptual Overview

1. Nitrogen Use in Rice Cultivation

Nitrogen (N) is a fundamental macronutrient that directly influences rice growth, tillering, panicle formation, and grain yield [1 (Fageria & Baligar, 2005)]. As rice plants require nitrogen at specific growth stages particularly during tillering and panicle initiation its availability must be timely to avoid yield penalties [10 (Peng, Tang, & Zou, 2020)]. Inadequate nitrogen results in stunted growth and poor yield, while excessive application causes lodging, low nitrogen use efficiency (NUE), and increased emissions of nitrous oxide (N_2O), a potent greenhouse gas [9 (Zhang *et al*., 2015); 19 (Ladha *et al*., 2005)]. In Asia, where rice is a staple, nitrogen fertilizers account for over 60% of total input costs, making efficient use critical for both productivity and profitability [20 (Dobermann & Fairhurst, 2000)].

2. Principles of Real-Time Nitrogen Management

Real-time nitrogen management is based on the principle of synchronizing nitrogen supply with crop demand to maximize NUE and minimize losses [21 (Cassman, Dobermann, & Walters, 2002)]. Unlike fixed-schedule fertilization, this approach uses in-season crop indicators such as leaf color or chlorophyll concentration to guide nitrogen application [4 (Singh *et al*., 2002)]. Correct timing and dose adjustment are essential since rice's N requirement changes dynamically throughout the season [10 (Peng, Tang, & Zou, 2020)]. Real-time tools aim to ensure that nitrogen is applied when plants can utilize it most efficiently, reducing leaching, volatilization, and other losses [5 (Buresh, Pampolino, & Witt, 2010)].

3. Leaf Color Chart (LCC)

The Leaf Color Chart (LCC) is a simple, plastic strip with four to six shades of green representing increasing chlorophyll (and indirectly nitrogen) concentrations in rice leaves [3 (Alam *et al*., 2005)]. Farmers compare the middle portion of the topmost fully expanded leaf to the LCC shades during key growth stages (usually every 7-10 days), and apply nitrogen fertilizer only when the leaf color is lighter than a predetermined threshold (usually shade 3 or 4) [4 (Singh *et al*., 2002); 18 (IRRI, 2013)]. The LCC works on the premise that chlorophyll content is strongly correlated with leaf nitrogen status, which reflects overall plant N nutrition [22 (Witt *et al*., 2005)]. It has been widely promoted by institutions such as the International Rice Research Institute (IRRI) for its low cost, ease of use, and effectiveness, particularly for smallholder farmers in South and Southeast Asia [14 (Nguyen *et al*., 2022)].

Comparative Overview

Institution / University	Panels	Crop Focus	Notes
IRRI (w/ UC-Davis)	4 or 6	Rice (standard chart)	Global use
UC-Davis (UCCE)	8	Rice (detailed N gradient)	Fine gradation
Zhejiang Ag University (ZAU)	8	Rice (indica, japonica, hybrids)	Local calibration
PhilRice	4	Rice (Philippines-specific)	Custom branding
NRRI (ICAR, Odisha)	5	Rice (Eastern India)	Spectral based
PAU (Punjab)	6	Rice, wheat, maize, cotton	App integrated
IIMR (Hyderabad)	6	Millets, sugarcane	Dryland systems
IIRR (Hyderabad)	6	Rice	Spectral refinement
KAU (Kerala)	4-6	Rice (Kerala)	Regional focus

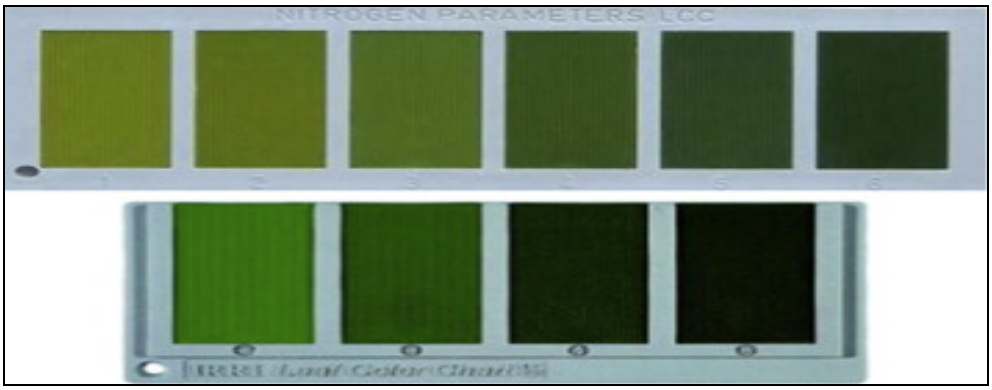

Fig 1: Leaf Color Chart

Table 1: Summary of Benefits of LCC-Based Nitrogen Management in Rice

Benefit	Explanation	Source
Improved Nitrogen Use Efficiency	Reduces over-application, improves uptake efficiency	Singh *et al*., 2002
Increased or Maintained Yield	Comparable or better yields than conventional N application	Li *et al*., 2017
Environmental Protection	Lower N losses, reduced leaching and N_2O emissions	Zhang *et al*., 2015
Cost-Effectiveness	Reduces unnecessary fertilizer use and input costs	Dobermann & Fairhurst, 2000
Farmer-Friendly Tool	Low-cost, requires minimal training	IRRI, 2013

Historical Development of LCC in Rice

The Leaf Color Chart (LCC) was first introduced as a practical tool for real-time nitrogen (N) management in rice by the International Rice Research Institute (IRRI) in collaboration with national agricultural research systems in the late 1990s [6] *(*Balasubramanian *et al.,* 2000*)*. This innovation was developed in response to the widespread inefficiencies observed in nitrogen use across irrigated rice systems in Asia, where blanket N recommendations led to excessive fertilizer use and environmental concerns [2] (Dobermann & Cassman, 2002) [4] (Singh *et al.,* 2002).

Early validation studies of LCC were carried out in the Philippines, India, and Bangladesh, where researchers established the correlation between leaf chlorophyll content and nitrogen status using visual scoring against standardized green color shades [4] (Singh *et al.,* 2002) [3] (Alam *et al.,* 2005). These trials demonstrated that LCC could match or outperform traditional nitrogen application methods in yield and nitrogen use efficiency, encouraging its integration into field-level practices [5] (Buresh *et al.,* 2010).

From the early 2000s onward, IRRI, CIMMYT, and local extension agencies launched farmer-participatory demonstrations and training programs to promote LCC adoption across Asia and parts of Africa [18] (IRRI, 2013) [22] (Witt *et al.,* 2005). Modifications to the tool, such as expanding the chart from four to six color panels and aligning shade thresholds to local varieties, were introduced to improve usability and adaptability [11] (Sharma *et al.,* 2021).

By 2010, digital tools began to emerge alongside the physical LCC, including mobile-based LCC apps and smartphone-assisted chlorophyll analysis, allowing integration with decision support systems [12] (Wu *et al.,* 2018). These digital innovations aimed to address key limitations of the manual method, such as subjective color matching and the need for farmer training [14] (Nguyen *et al.,* 2022). Despite the evolution of remote sensing and sensor-based technologies, the LCC remains widely used due to its affordability and effectiveness, especially in low-resource and smallholder farming systems [13] (Li *et al.,* 2017).

Table 2: Timeline of LCC Development and Adoption in Rice Systems

Year	Event/Development	Reference
1998	IRRI and partners introduce LCC as a low-cost tool for N management in rice	Balasubramanian *et al*., 2000
2000-2005	Validation trials in India, Bangladesh, Philippines; LCC shown to improve NUE	Singh *et al*., 2002; Alam *et al*., 2005
2006-2010	Expanded use via extension programs across Asia and Africa	Witt *et al*., 2005; IRRI, 2013
2011	Integration with farmer training manuals and crop models begins	Buresh *et al*., 2010
2015+	Mobile apps and digital LCC tools developed to increase precision	Wu *et al*., 2018; Sharma *et al*., 2021
2020-2024	Research continues on barriers to adoption, with focus on training and calibration	Nguyen *et al*., 2022

Effectiveness of LCC in Nitrogen Management

1. Yield Improvement: Multiple field studies across Asia report that LCC-guided nitrogen application maintains or improves rice grain yield compared to blanket fertilization [4] (Singh *et al*., 2002), [13] (Li *et al*., 2017). Trials in Bangladesh demonstrated a 10% yield increase through LCC use [3] (Alam *et al*., 2005). In dry direct-seeded systems in Nepal, LCC applications achieved comparable yields with significantly less nitrogen input [23] (Subedi *et al*., 2018). Aerobic rice grown under drip irrigation in India achieved a grain yield of approximately 4.17 t/ha with LCC-guided nitrogen, rivalling or exceeding conventional practices [24] (Bhavana *et al*., 2023).

2. Nitrogen Use Efficiency (NUE)

Studies consistently show enhanced NUE with LCC use, reflecting better alignment between nitrogen supply and crop demand [4] (Singh *et al*., 2002), [23] (Subedi *et al*., 2018). In Nepal's DDSR (Dry Direct-Seeded Rice) system, pure LCC application increased agronomic efficiency by 16 kg grain/kg N and recovery efficiency by 52% over standard split-application methods [23] (Subedi *et al*., 2018). Under Kashmir conditions, LCC-based regimes yielded similar outputs with just 100 kg N/ha, outperforming the recommended split-dosing of 120 kg N/ha [25] (Singh *et al*., 2006).

3. Economic Benefits

LCC adoption reduces fertilizer costs by up to 30%, translating to higher net incomes and improved benefit-to-cost ratios [13] (Li *et al*., 2017), [24] (Bhavana *et al*., 2023). In Konkan's red soils, critical LCC thresholds (≤4 at 120 kg N/ha) yielded an agronomic efficiency of 12.8 kg grain/kg N and net returns of nearly INR 98, 000/ha [26] (Aiwale, 2021).

4. Environmental Impacts

By minimizing nitrogen excess, LCC strategies reduce nitrate leaching and N_2O emissions [9] (Zhang *et al*., 2015), [10] (Peng *et al*., 2020). Field results from drip-irrigated aerobic rice under LCC management showed reduced nutrient runoff while saving water [24] (Bhavana *et al*., 2023). In Tripura, LCC-guided nitrogen combined with alternate wetting and drying achieved a 47% yield gain and 73% higher agronomic efficiency, along with significant water savings [27] (Singh & Chakraborti, 2019).

Table 3: Comparative Performance of LCC vs. Traditional Nitrogen Management

Performance Metric	Traditional Method	LCC-Based Method	Improvement (%)
Grain Yield	Baseline	+5 to +10	+5 to +10
Nitrogen Use Efficiency	35-45%	50-60%	+15 to +20
Nitrogen Usage (kg/ha)	120-150	80-120	-20 to -30
Fertilizer Cost Savings	0%	20-40%	20 to 40%
N_2O Emissions Reduction	Baseline	-20 to -30%	-20 to 30%

Data based on Singh *et al*. (2002), Alam *et al*. (2005), Li *et al*. (2017), Zhang *et al*. (2015), and Nguyen *et al*. (2022).

Comparisons with Other Tools

1. LCC vs. SPAD Meters

LCC and SPAD meters are both tools used to estimate the nitrogen status of rice crops by assessing leaf greenness, which correlates with chlorophyll and nitrogen content [4] (Singh *et al.*, 2002). However, while SPAD meters provide quantitative readings, they are relatively expensive and less accessible to smallholder farmers [6] (Balasubramanian *et al.*, 2000). In contrast, LCC is a low-cost, color-based visual aid that requires no power source or calibration [22] (Witt *et al.*, 2005). Studies have shown that LCC-based nitrogen management yields results similar to SPAD-guided applications in terms of yield and nitrogen use efficiency [5] (Buresh *et al.*, 2010) [28] *(Yoshida &* Murayama, 2002).

2. LCC vs. Remote Sensing

Remote sensing technologies such as multispectral imaging and UAV-mounted cameras are gaining traction for large-scale nitrogen management in rice fields [29] (Thenkabail *et al.*, 2012). These tools provide spatially comprehensive data and can be integrated with geographic information systems (GIS) for precision agriculture [13] (Li *et al.*, 2017). However, their adoption is limited by high initial costs, data processing needs, and lack of technical expertise among farmers in developing countries [14] (Nguyen *et al.*, 2022). In comparison, LCC remains more practical for field-level use by resource-poor farmers due to its simplicity and reliability for timely decision-making [10] (Peng *et al.*, 2020).

3. LCC vs. Soil Test-Based Methods

Soil test-based nitrogen management relies on periodic sampling and laboratory analysis to determine the nutrient content of soil, which guides fertilizer application [20] (Dobermann & Fairhurst, 2000). While this method can be accurate, it may not reflect real-time nitrogen dynamics or in-season crop demand, especially under variable environmental conditions [21] (Cassman *et al.*, 2002). LCC, on the other hand, allows nitrogen decisions to be made based on current crop status, improving responsiveness [4] (Singh *et al.*, 2002). Additionally, soil testing is often limited by access to laboratories and time delays, making LCC a more agile tool in many farming contexts [18] (IRRI, 2013).

4. LCC vs. Decision Support Systems (DSSAT, Nutrient Expert)

Decision Support Systems (DSS) like DSSAT (Decision Support System for Agrotechnology Transfer) and Nutrient Expert™ use models to recommend site-specific nitrogen applications based on weather, soil, and crop data [30] (Jat *et al.*, 2012) [31] (Pampolino *et al.*, 2012). These systems are useful in providing science-based fertilizer recommendations tailored to location and season. However, they require digital literacy, smartphone access, and data entry, which may be barriers for some farmers [14] (Nguyen *et al.*, 2022). LCC, by contrast, enables real-time, field-based N decisions without external data inputs, making it more accessible and equally effective in improving nitrogen use efficiency in many regions [13] (Li *et al.*, 2017).

Table 4: Comparison of LCC with Other Nitrogen Management Tools in Rice

Tool	Cost	Real-time	Ease of Use	Data Requirements	Adoption in Small Farms
LCC	Very Low	✔ Yes	✔ Easy	✘ None	✔ High
SPAD Meter	High	✔ Yes	✘ Moderate	✔ Device readings needed	✘ Limited
Remote Sensing	Very High	✔ Yes	✘ Technical	✔ Satellite/UAV data	✘ Very Limited
Soil Testing	Moderate	✘ No	✘ Time-consuming	✔ Soil sample analysis	✘ Low
DSSAT/Nutrient Expert	Moderate-High	✘ Partial	✘ Requires training	✔ Weather/Soil/Crop models	✘ Moderate

✔ = favorable; = constraint

Summary

LCC stands out as a practical tool for real-time nitrogen management, especially in smallholder-dominated regions. While digital and sensor-based tools offer higher precision and scalability, their cost, data needs, and technical barriers limit adoption. Therefore, LCC provides an effective compromise between accuracy, affordability, and farmer-friendliness.

Limitations and Challenges of Using the Leaf Color Chart (LCC) in Nitrogen Management of Rice

1. Limited Farmer Adoption

Despite its low cost and simplicity, LCC adoption among smallholder farmers remains relatively low in many rice-growing regions [14] (Nguyen *et al*., 2022). This is often due to a lack of awareness, limited access to extension services, and perceived complexity of using the chart correctly [33] (Mishra *et al*., 2021). Surveys in Southeast Asia show that less than 40% of rice farmers had even heard of the LCC, l*et al*one used it consistently [18] (IRRI, 2013).

2. Subjectivity in Color Matching

LCC readings are based on visual comparison of leaf color with chart panels, which introduces human error and subjectivity [4] (Singh *et al*., 2002). Differences in perception due to age, gender, or lighting conditions can affect accuracy [6] (Balasubramanian *et al*., 2000). In comparative trials, variation in nitrogen application decisions between users ranged up to 20 kg N/ha [5] (Buresh *et al*., 2010).

3. Weather-Related Accuracy Issues

LCC performance can be influenced by external environmental factors, particularly light quality, cloud cover, and leaf wetness

at the time of reading [35] (Zhao *et al*., 2021). During overcast or rainy conditions, it becomes difficult to make consistent readings, which may lead to over- or under-fertilization [22] (Witt *et al*., 2005). Similarly, temperature extremes can alter leaf chlorophyll levels independent of nitrogen status, further complicating interpretation [34] (Shan *et al*., 2017).

4. Training and Availability Constraints: Although the tool is designed to be user-friendly, farmers often require initial training to apply it correctly and interpret thresholds [32] (Dobermann *et al*., 2003). Where such training is lacking, adoption suffers and misapplication becomes common [14] (Nguyen *et al*., 2022). Additionally, distribution of LCCs is sometimes inconsistent, especially in remote regions, limiting access for many farmers [33] (Mishra *et al*., 2021).

Table 5: Summary of Key Challenges in Using LCC

Challenge	Description	Source
Low adoption	Limited awareness and extension support	Nguyen *et al*., 2022
Subjectivity in color judgment	Variability due to human perception and lighting	Singh *et al*., 2002; Buresh *et al*., 2010
Weather dependence	Difficulties during cloudy/rainy days; errors due to leaf wetness or lighting	Zhao *et al*., 2021; Shan *et al*., 2017
Need for training and availability	Improper use without training; LCCs not widely distributed in remote areas	Dobermann *et al*., 2003; Mishra *et al*., 2021

Recent Advances and Innovations in LCC-Based Nitrogen Management

1. Digital LCC Tools and Mobile Applications

Traditional paper-based LCCs are being digitized through mobile applications, which allow farmers to capture leaf images and receive nitrogen recommendations via smartphones [36] (Ali *et al*., 2021). Apps such as "RiceAdvice" by AfricaRice and "Crop Manager" by IRRI have integrated LCC-like color detection features to guide N application [5] (Buresh *et al*., 2010). These digital platforms improve precision, reduce human subjectivity, and enhance scalability in real-time decision-making [38] (Kassie *et al*., 2022).

2. Integration with AI, Sensors, and Drone Technologies

Recent research has shown that artificial intelligence (AI) and machine learning (ML) algorithms can be trained to detect leaf nitrogen status from smartphone or UAV imagery, mimicking LCC readings with greater accuracy [40] (Li *et al*., 2022). In particular, convolutional neural networks (CNNs) have been applied to detect subtle differences in leaf greenness across large fields, helping automate nitrogen decision support [43] (Yu *et al*., 2021). Moreover, drones equipped with RGB and multispectral cameras are being used to generate LCC-equivalent indices at scale, especially in precision agriculture systems [42] (Thomasson *et al*., 2021).

3. Application in Diverse Agro-Ecological Zones

LCC technology is being customized for different rice ecologies irrigated lowlands, rainfed uplands, and aerobic systems by adjusting threshold values based on regional agronomy [4] (Singh *et al*., 2002). For example, studies in West Africa demonstrated LCC's adaptability to rainfed lowland conditions by modifying reading intervals and target panel values [37] (Chivenge *et al*., 2019). Similarly, research in Indian semi-arid regions adjusted the critical LCC threshold from 4 to 3.5 to better match local cultivars and soil fertility [26] (Aiwale, 2021).

4. Climate-Smart Agriculture Applications

LCC-based nitrogen management is increasingly being promoted under the umbrella of climate-smart agriculture (CSA) because it enhances nitrogen use efficiency and reduces greenhouse gas (GHG) emissions [39] (Ladha *et al*., 2020). When combined with water-saving techniques such as alternate wetting and drying (AWD), LCC-guided fertilization has been shown to reduce nitrous oxide emissions by 20-30% [27] (Singh & Chakraborti, 2019). These synergies support adaptation and mitigation strategies while sustaining rice yields under climate stress [41] (Raza *et al*., 2022).

Table 6: Summary of Innovations in LCC-Based Nitrogen Management

Innovation Area	Description	Key Source
Digital LCC Apps	Smartphone-based tools for real-time color matching and N advice	Ali *et al*., 2021
AI and Drone Integration	Use of CNNs, UAVs, and sensors for automated LCC-based N monitoring	Yu *et al*., 2021; Li *et al*., 2022
Agro-Ecological Customization	Adjusted LCC thresholds and protocols for diverse rice ecologies	Chivenge *et al*., 2019; Singh *et al*., 2002
Climate-Smart Agriculture (CSA)	Reducing N_2O emissions and improving resilience via LCC with AWD and precision timing	Ladha *et al*., 2020; Singh & Chakraborti, 2019

Conclusion

The Leaf Color Chart (LCC) has emerged as a practical, cost-effective, and farmer-friendly tool for real-time nitrogen management in rice cultivation. Its simplicity and ease of use allow timely nitrogen application decisions, thereby improving nitrogen use efficiency and contributing to higher crop productivity. Compared to conventional methods, LCC enables farmers to make field-based, seasonally adaptive decisions that respond to the crop's actual nutrient needs.

Recent innovations such as mobile-based applications, integration with precision farming tools, and adaptations for different agro-ecological conditions have further enhanced the relevance and applicability of LCC in modern agriculture. These advancements not only improve accuracy and scalability but also align with broader goals of sustainable and climate-resilient farming.

Despite its potential, the adoption of LCC remains limited in many regions due to challenges related to awareness, accessibility, training, and support infrastructure. Therefore, expanding extension services, investing in digital tools, and promoting farmer education are essential steps to increase its use. Continued research and policy support are also needed to mainstream LCC within integrated nutrient management strategies.

In summary, LCC represents a valuable tool in achieving sustainable rice production through improved nitrogen management. With strengthened dissemination, innovation, and institutional backing, its broader adoption can contribute significantly to food security, environmental protection, and rural livelihood improvement.

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