

Review

Site-Specific Nitrogen Fertilizer Management Using Canopy Reflectance Sensors, Chlorophyll Meters and Leaf Color Charts: A Review

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Abstract: The efficient management of nitrogen (N) on a site-specific basis is critical for the improvement of crop yield and the reduction of environmental impacts. This review examines the application of three primary technologies—canopy reflectance sensors, chlorophyll meters, and leaf color charts—in the context of site-specific N fertilizer management. It delves into the development and effectiveness of these tools in assessing and managing crop N status. Reflectance sensors, which measure the reflection of light at specific wavelengths, provide valuable data on plant N stress and variability. The advent of innovative sensor technology, exemplified by the GreenSeeker, Crop Circle sensors, and Yara N-Sensor, has facilitated real-time monitoring and precise adjustments in fertilizer N application. Chlorophyll meters, including the SPAD meter and the atLeaf meter, quantify chlorophyll content and thereby estimate leaf N levels. This indirect yet effective method of managing N fertilization is based on the principle that the concentration of chlorophyll in leaves is proportional to the N content. These meters have become an indispensable component of precision agriculture due to their accuracy and ease of use. Leaf color charts, while less sophisticated, offer a cost-effective and straightforward approach to visual N assessment, particularly in developing regions. This review synthesizes research on the implementation of these technologies, emphasizing their benefits, constraints, and practical implications. Additionally, it explores integration strategies for combining these tools to enhance N use efficiency and sustainability in agriculture. The review culminates with recommendations for future research and development to further refine the precision and efficacy of N management practices.

Keywords: site-specific nitrogen management; canopy reflectance sensors; chlorophyll meters; leaf color charts



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1. Introduction

Nitrogen (N) is a key macronutrient necessary for plant growth and development, playing a crucial role in enhancing agricultural productivity. However, natural soil N levels frequently fall short of crop requirements, necessitating the application of synthetic fertilizers to fulfill plant N needs. The pervasive use of N fertilizers has resulted in a profound transformation in modern agriculture, markedly enhancing crop yields and facilitating the sustenance of an expanding global population [1]. As illustrated in Figure 1, in 2021, N fertilizers constituted 56% of the total global consumption, while phosphate and potash fertilizers accounted for 24% and 20%, respectively [2]. This significant usage underscores the reliance of modern agriculture on N fertilizers to meet the growing food demands of the global population. Despite their critical role in boosting food production, the optimization

of N fertilizer use remains a significant challenge due to substantial losses of N to the environment through leaching, volatilization, and denitrification [3].

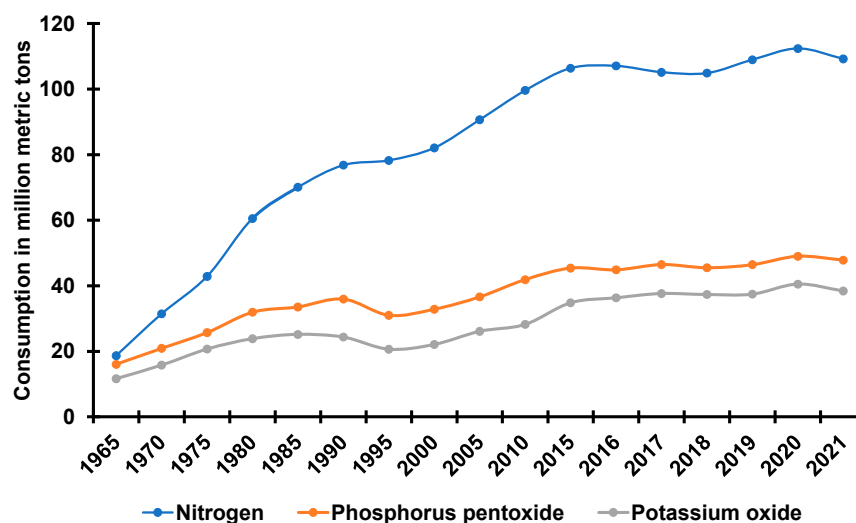


Figure 1. Global consumption of agricultural fertilizer from 1965 to 2021, disaggregated by nutrient. Data source: <https://www.statista.com> (accessed 26 July 2024).

The environmental impact of excessive N fertilizer use has prompted considerable concern. Nitrogen leaching into water bodies can lead to pollution and the degradation of aquatic ecosystems, creating issues such as eutrophication and hypoxia [4–6]. These processes deplete oxygen levels in water, causing dead zones where aquatic life cannot survive, thus severely disrupting marine and freshwater ecosystems. Furthermore, N fertilizers contribute to greenhouse gas emissions, particularly N_2O , which exacerbates climate change [7–9]. N_2O is a potent greenhouse gas with a global warming potential approximately 300 times that of CO_2 , making its release from agricultural activities a significant contributor to global warming. The economic aspect is also critical, as the rising cost of N fertilizers significantly increases production expenses for farmers [10–12]. This financial burden can be particularly challenging for small-scale farmers in developing countries, where access to affordable agricultural inputs is already limited. High fertilizer costs can reduce profit margins, potentially making farming less sustainable and economically viable. Additionally, over-reliance on synthetic N fertilizers can degrade soil health over time, diminishing its fertility and productivity, and necessitating even greater fertilizer inputs in a vicious cycle of dependency. Consequently, there is an urgent need to develop sustainable agricultural techniques that optimize N fertilizer utilization, enhancing crop yields while mitigating negative environmental impacts.

Site-specific N management (SSNM) represents a pivotal approach in modern agricultural practices aimed at achieving these goals. SSNM involves tailoring N applications to the specific needs of each field, taking into account soil characteristics, crop requirements, and environmental conditions [13–16]. This precision approach allows farmers to maximize N use efficiency, reduce input costs, and protect natural resources. By applying the right amount of N at the optimal time, farmers can improve crop yield and quality while minimizing N losses to the environment. This is particularly important in regions with intensive farming practices or sensitive water sources, where N pollution poses a significant threat. SSNM helps mitigate these risks by reducing N run-off, leaching, N_2O emissions, and NH_3 volatilization, thereby protecting water quality and ecosystem health [17–19].

Implementing SSNM involves various tools that estimate crop N needs through measurements of canopies or plant leaves. Among these tools are canopy reflectance sensors, chlorophyll meters, and leaf color charts (LCCs). These technologies are invaluable for both researchers and growers. Canopy reflectance sensors are increasingly used in agriculture for N management, as they measure the light reflected by plants to provide

insights into plant health, N status, and growth patterns [20–23]. Chlorophyll meters, another essential tool, quantify the chlorophyll content in plant leaves, offering crucial data on plant health and photosynthetic activity [24–27]. LCCs, which are cost-effective and user-friendly, provide a visual representation of leaf color to estimate N supply to plants [28–30].

The objective of this review is to critically assess the use of canopy reflectance sensors, chlorophyll meters, and LCCs in the context of SSNM for agricultural crop production. This review examines the practicality and efficiency of these technologies in optimizing N fertilizer application, along with their potential benefits and limitations. Additionally, the review evaluates the precision and reliability of these techniques in assessing crop N levels across different crops, growth stages, and environmental conditions. The integration of these technologies into precision agriculture systems to enhance crop yield and improve N use efficiency while minimizing environmental impacts is also explored. Finally, a comparative analysis of the three technologies is provided, along with future prospects and recommendations for farmers, agronomists, and policymakers in implementing SSNM.

2. Site-Specific N Management

Site-specific N management involves the dynamic management of N fertilizer throughout a cropping season to synchronize the supply of N with the crop's demand, thereby minimizing losses that occur when these are not aligned. Unlike general recommendations, SSNM tailors fertilizer application to the specific conditions of each field, ensuring that N is applied at optimal rates and times to meet crop needs precisely. Whether implemented in small fields in developing regions or through advanced variable rate adjustments in large fields with spatial and temporal variations, SSNM aims to enhance efficiency and sustainability. This approach integrates tools like GPS, sensors, drones, and data analytics to collect comprehensive data on soil conditions, weather patterns, and crop health [31–34]. By analyzing this information, farmers can make informed decisions on planting, irrigation, fertilization, and harvesting, ultimately optimizing yields, reducing resource usage, and minimizing environmental impact. SSNM plays a critical role in this precision agriculture framework by addressing the diverse needs within a field, ensuring that crops receive the necessary nutrients at the right time, thereby boosting productivity and resource efficiency [35,36].

SSNM plays a pivotal role in environmental conservation by reducing N losses from leaching and runoff [17,36–38]. By adapting the N application to the particular requirements of different regions within a field, farmers can mitigate the risk of water contamination and eutrophication in proximate water bodies. This proactive strategy not only safeguards water quality but also enhances the overall health of the ecosystem, ensuring the sustainability of agricultural production and the conservation of resources for future generations.

The implementation of SSNM has the potential to significantly reduce the emission of greenhouse gases from agricultural activities [39,40]. Excessive N in the soil can be transformed into nitrous oxide, a potent greenhouse gas. Through the efficient application of N in specific areas where it is required, farmers can actively contribute to reducing the environmental impact of agriculture and participate in efforts to mitigate climate change.

An additional crucial aspect of SSNM is its capacity to enhance soil health and bolster crop productivity over an extended period. By avoiding over-fertilization and nutrient imbalances, farmers can maintain optimal soil nutrient levels and promote favorable microbial activity [41–44]. Consequently, this can result in an improved soil composition, greater water retention, and enhanced nutrient circulation, which ultimately leads to increased yields and the promotion of sustainable agricultural methods.

Moreover, the practice of SSNM can assist farmers in adhering to regulations and certification programs on nutrient management and environmental conservation [45–48]. By demonstrating a commitment to sustainable practices and the responsible utilization of resources, farmers can enhance their reputation and gain access to markets that prioritize

sustainability and environmental consciousness. This, in turn, can lead to an improved reputation and increased opportunities for market access.

An additional advantage of SSNM is the potential for cost reduction for farmers [49–51]. Applying N fertilizer with greater precision and efficiency allows farmers to reduce costs while maintaining or even increasing crop yields. This is of particular significance in the contemporary competitive agricultural sector, where farmers persistently endeavor to optimize their production methods and enhance their financial outcomes. SSNM serves as a tool to assist farmers in achieving these objectives by maximizing the returns on their investments in nitrogen fertilizers.

While there are numerous benefits associated with SSNM based on soil and climate data, there are also various challenges that must be overcome for its successful execution. The composition of soil, the characteristics of weather patterns, the diversity of crops cultivated, and the techniques employed in farming all contribute to the complex dynamics of N in agricultural fields. This complexity makes it challenging to accurately predict the N requirements of crops [51,52]. Consequently, farmers must possess a comprehensive understanding of these factors and demonstrate the ability to adapt their N management strategies to align with the specific conditions of each field or zone within a field.

The customization of N fertilizer management for specific sites can be achieved through the use of plant-based tools, including canopy reflectance sensors, chlorophyll meters, and leaf color charts [20,22,30,53–55]. These innovative tools facilitate the precise estimation of N requirements for crops through the analysis of multiple indicators, including plant reflectance, chlorophyll content, and leaf color. The integration of these tools into farming practices allows for the optimization of N application rates based on real-time data, which in turn leads to increased crop yields and a reduction in environmental impact. This is of particular importance as plants reflect the overall variability observed in the field, including factors such as soil composition, weather conditions, and agricultural techniques. Table 1 provides an overview of the key innovations in three primary categories of leaf sensing technologies: canopy reflectance sensors, chlorophyll meters, and leaf color charts. These technologies offer a range of methods for evaluating leaf chlorophyll content and overall plant vigor, enabling more precise and efficient fertilizer management.

Table 1. Important innovations in proximal leaf sensing for guiding N fertilizer management.

Year	Innovation Description	References
1987, 1996	The implementation of leaf color charts (LCC) in Asia represents a significant advancement in the field of precision agriculture, offering a cost-effective means of assessing leaf N content.	[28,56]
1992	The SPAD chlorophyll meter, which measures transmission at 650 and 940 nm, was developed to identify N deficiencies and assess N fertilizer requirements in maize.	[57,58]
1995	The introduction of N sufficiency indices is based on a comparison of SPAD meter readings from the test plot with those from a well-fertilized or N-rich reference plot.	[59]
1996	Development of a canopy reflectance sensor (measuring reflectance at 671 and 780 nm) to detect variations in plant nitrogen stress.	[60]
2002	The launch of the GreenSeeker canopy reflectance sensor, which measures reflectance at 650 and 770 nm, is announced to monitor N levels.	[61]; NTech Industries
2004	The introduction of the Crop Circle canopy reflectance sensor, which is capable of measuring reflectance at 590 and 880 nm, or 670, 730, and 780 nm.	[62]; Holland Scientific
2009	The Yara N-Sensor is employed for the management of N in crops, to provide real-time N management through the measurement of canopy reflectance and the dynamic calculation of N requirements.	[63]; Yara International
2012	The release of the atLeaf chlorophyll meter, which measures transmission at 660 and 940 nm, is announced as a new tool for assessing leaf N content.	[64]; FT Green LLC

3. Canopy Reflectance Sensors

Canopy reflectance sensors quantify the degree to which light is reflected off of plants, thereby providing insight into their physiological status (Figure 2). The evolution of optical sensors for N fertilizer management is closely tied to the broader advancement of remote sensing technologies in agriculture, which commenced in the mid-20th century. In the beginning, these technologies were principally utilized for the mapping of extensive agricultural regions and the observation of crop well-being from aerial and satellite imagery [65]. The initial notable applications of optical sensors in N management emerged in the 1980s with the advent of handheld devices capable of measuring reflectance in specific wavelengths associated with plant N content [66]. These initial sensors established the foundation for more sophisticated and integrated systems capable of providing real-time data on crop N status. In the 1990s and early 2000s, advancements in optical sensor technology and the integration of GPS systems markedly enhanced the precision and utility of these devices in N management. Researchers developed more sensitive and accurate sensors that could measure specific wavelengths of light reflected by crops, correlating these measurements with N content [67].

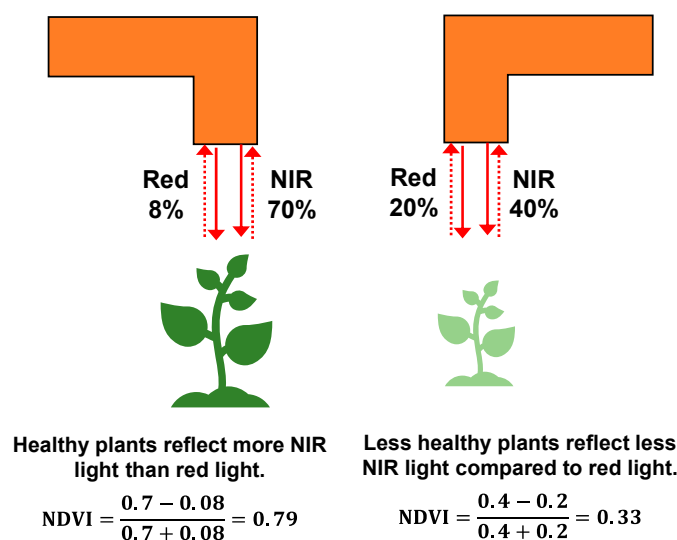


Figure 2. Illustrative example of normalized difference vegetation index (NDVI) measurement and analysis using a hand-held optical sensor.

Canopy reflectance sensors are employed to quantify the visible and near-infrared (NIR) spectral reflectance from plant canopies, which can then be subjected to analysis to evaluate N stress [68,69]. The absorption of light in the red wavelength bands by chlorophyll in leaves accounts for between 70% and 90% of all incident light, thereby influencing visible light reflectance. Conversely, the reflectance of up to 60% of incident NIR radiation is determined by the structure of mesophyll tissues [70]. Early research demonstrated a robust correlation between spectral measurements of crop canopies and plant biomass [71,72] as well as plant N content [73–75]. In the mid-1990s, Stone et al. [60] developed a canopy reflectance sensor that was capable of measuring spectral reflectance from wheat canopies in the red (671 nm) and NIR (780 nm) bands. This resulted in the creation of the plant N spectral index (PNSI), which was inversely correlated with the normalized difference vegetation index (NDVI) and demonstrated a strong correlation with estimates of wheat forage N uptake. Solie et al. [76] employed an algorithmic approach to correlate wheat N uptake with PNSI values, thereby enabling the adjustment of N fertilizer rates based on sensor readings. This technological advancement ultimately resulted in the commercialization of the GreenSeeker active sensor in 2001 [77]. The NDVI, calculated from the reflectance of red and NIR radiation, provides valuable information on photosynthetic efficiency, pro-

ductivity potential, and potential yield [20,78–81] and has also been demonstrated to be responsive to leaf area index, green biomass, and photosynthetic efficiency [82].

In a study conducted by Raun et al. [61,78], NDVI measurements of wheat at different growth stages were used to develop the concept of the response index. This is defined as the ratio of NDVI values within the crop to those in a well-fertilized reference strip, considering the potential yield. By integrating the potential yield and response index, Raun et al. [61] developed an N fertilizer algorithm for determining the requisite amount of N fertilizer for wheat production. The algorithm considered not only the spatial variability of N supply within a field but also the temporal variability in crop performance across different seasons. This was achieved by introducing the concept of in-season estimated yield (INSEY). As a consequence of their research, many algorithms have been developed for estimating potential crop yield and N uptake for a range of crops and regions across the globe [77]. These algorithms are valuable tools for optimizing fertilizer application and enhancing crop productivity while also taking into account the environmental impact of excessive fertilizer use.

Holland et al. [62] developed a crop sensor called Crop Circle. It uses green and NIR bands to evaluate N stress and N fertilizer requirements. The NDVI derived from green light reflectance is more sensitive to changes in chlorophyll concentration and potential crop yield than the red NDVI obtained from the GreenSeeker optical sensor. This innovation fixed the GreenSeeker sensor's problems during the later stages of crop growth. The GreenSeeker and Crop Circle sensors can be mounted on a tractor or pole to measure crop reflectance. This helps farmers make decisions about N fertilizer management. In recent years, handheld versions have been introduced. These handheld sensors are user-friendly, lightweight, and cost-effective. They are suitable for manual applications, especially in small farms. In these handheld models, the user simply positions the sensor over the plant canopy, triggers it while walking at a slow pace, and the sensor promptly calculates the vegetation index.

Canopy reflectance sensors are unable to directly determine the quantity of N fertilizer required to address crop N stress. Therefore, an algorithm is necessary to convert sensor readings into the requisite N fertilizer level. The creation of reference strips that receive sufficient N fertilizer, as demonstrated by Raun et al. [61], Sripada et al. [82], Kitchen et al. [83], and Ali [84] has been a pivotal step in the development of N response functions. These functions constitute an indispensable element of the algorithm utilized to convert sensor readings into the requisite amount of N fertilizer for the crop based on the anticipated yield, as elucidated by Scharf et al. [85]. The reference strips serve a dual purpose: they facilitate the development of N response functions and provide local calibration. Strategically positioned in fields, they account for spatial variability in yield response to N fertilizer, as Mamo et al. [86] have emphasized. This strategic placement is necessary to ensure that sensor readings accurately reflect the N fertilizer requirement of the crop, taking into account yield response variations across different areas of the field.

It is important to assess the N levels of crops at regular intervals throughout the growing season to ensure accurate N management. The growth stage of crops is indicative of both the N requirements of the crop and the N levels present in the soil [20,84,87]. It is a common practice to adjust the application rates of N fertilizer based on the crop's N needs, estimated yield, and growth stage [88]. Active optical canopy sensors are used to provide real-time recommendations for N fertilizer application, considering the crop's anticipated yield and N status. A correlation has been established between data collected from optical sensors and factors related to fertilizer management, particularly the N status of the crop and the projected yield of different cereal crops, to determine the essential parameters for an N fertilization optimization algorithm (NFOA). This development permits the deployment of sensors for the administration of N fertilizer across diverse crops, thereby ensuring that the application is tailored to the specific requirements of each crop. By integrating technology and data-driven methodologies, farmers can optimize N management practices, which in turn leads to enhanced crop yields and a reduction in environmental impact.

The GreenSeeker optical sensor employs the NFOA, which was initially developed by Raun et al. [61] and subsequently updated by Raun et al. [89]. This approach is based on the N-rich strip methodology. This method involves a “mass balance” calculation to determine the optimal nitrogen rate required to achieve the anticipated yield, which is then compared to the potential yield estimated from the nitrogen-rich strip, as elucidated by Colaço et al. [90]. The NFOA involves estimating the anticipated yield in the absence of supplementary N application through the utilization of optical sensor readings and calibration equations derived from experiments that correlate INSEY with grain yield. Conversely, the yield increase due to additional N (the N-rich strip) is calculated by multiplying the predicted yield in a specific field area by the “response index” (RI). The RI is determined by comparing NDVI values from the N-rich strip to those from other parts of the field. This approach has had a significant impact on various research groups and is now widely recognized as one of the most commonly used methods for utilizing crop reflectance sensors in N fertilizer management for cereals. Moreover, a comparable approach described by Holland and Schepers [91] has become one of the recommended algorithms for the Crop Circle sensor, further emphasizing the extensive adoption and impact of this methodology in precision agriculture. The Yara N-Sensor, an electromagnetic sensor utilized in the commercial evaluation of the N condition of field crops, is commonly employed in real-time correction of reflected signals within the wavelength range of 450 to 900 nanometers. This sensor, which is mounted on a tractor and equipped with two spectrometers—one for scanning the crop and the other for measuring ambient light—is widely recognized for its effectiveness in calculating NDVI and other vegetation indices of interest [92–94].

3.1. Canopy Reflectance Sensor-Based N Fertilizer Management in Rice

The application of N fertilizer in irrigated transplanted rice is typically made at the transplanting, active tillering stage, and the panicle initiation stage. However, due to the interference of water on the soil surface with the measurement of NDVI using optical sensors, it is recommended that a sensor-guided N fertilizer dose be applied only at the panicle initiation stage when the crop canopy is not affected by water in the field [95–97]. The studies conducted in the Indo-Gangetic Plain of South Asia by Ali et al. [98] and Bijay-Singh et al. [97] have demonstrated a significant correlation between NDVI measurements at the panicle initiation stage and rice yield at maturity. These studies have also demonstrated the feasibility of accurately predicting the potential crop yield using the GreenSeeker optical sensor. Similarly, research in China by Yao et al. [99] and Xue et al. [96] has confirmed the relationships between NDVI measurements and rice yield at both the tillering and panicle initiation stages. This highlights the importance of utilizing sensor technology to optimize N fertilizer application in rice cultivation for improved crop productivity.

The study conducted by Bijay-Singh et al. [97] suggests that for optimal rice production, the application of 30 kg N ha^{−1} during transplanting, followed by 45 kg N ha^{−1} during the active tillering stage, is advisable. This should be followed by the utilization of a GreenSeeker-guided dose at the panicle initiation stage. This approach, based on the GreenSeeker technology, yielded rice grain yields comparable to conventional recommendations or farmers’ practices, but with the advantage of lower N rates and increased N fertilizer use efficiency. Ali et al. [100] observed a significant enhancement of over 12% in N use efficiency for direct-seeded rice in northwestern India when N fertilizer management was guided by the GreenSeeker system. Xue et al. [96] further developed this concept by creating a GreenSeeker-based N-model in conjunction with traditional target yield and split fertilization methods. Yao et al. [99] discovered that crop sensors could accurately estimate rice yield potential without the need for additional topdressing N application at specific growth stages. The regional optimal N rate for precision N management using GreenSeeker technology was determined to be between 90 and 110 kg N ha^{−1} initially, with 45% and 20% allocated for basal and tillering N application, respectively. Cao et al. [101] demonstrated the effectiveness of the GreenSeeker active canopy sensor in predicting rice

yield potential and responsiveness to topdressing N application during the stem elongation stage. However, the sensor exhibited less reliability during the heading stage. In contrast, the Crop Circle ACS 470 sensor demonstrated consistent performance across all growth stages, underscoring its reliability in precision agriculture practices.

3.2. Canopy Reflectance Sensor-Based N Fertilizer Management in Wheat

In a study conducted in the northwestern region of India by Bijay-Singh et al. [102], it was demonstrated that the implementation of GreenSeeker-guided N fertilizer applications during the second irrigation stage of wheat led to enhanced yield levels and optimized N use efficiency. This was achieved by the application of 90 kg N ha⁻¹, either at sowing or in two equal doses at the sowing and crown root initiation stage before the sensor-guided N dose. In a subsequent study, Bijay-Singh et al. [103] further refined the management of N fertilizer applications before the sensor-guided, field-specific N dose for wheat. The study indicated that the most suitable N management approach before the GreenSeeker-guided dose at the maximum tillering stage was the application of 30 kg N ha⁻¹ at sowing and 45 kg N ha⁻¹ at the crown root initiation stage of wheat. The grain yield obtained through the optical sensor-based SSNM was comparable to that achieved with the standard recommendation of 120 kg N ha⁻¹, yet with enhanced N fertilizer use efficiency. Similarly, Sulochna et al. [104] reported comparable findings. Thus, the application of a moderate quantity of N fertilizer at the time of wheat sowing, in conjunction with sufficient N to meet the crop's elevated demand between the crown root initiation and maximum tillering stages, preceded by the sensor-guided N dose at the maximum tillering stage, resulted in not only increased yields but also enhanced N fertilizer use efficiency in irrigated wheat. In a winter wheat-summer maize rotation system in the North China Plain, Cao et al. [105] observed that the GreenSeeker optical sensor-based precision N management strategy consistently demonstrated superior performance compared to both farmer's practice and regional optimum N management for both crops. Ali [84] concluded that the application of 40 and 60 kg N ha⁻¹ at 10 and 30 days after sowing of wheat, in conjunction with a sensor-guided dose of N estimated by using the algorithm developed in his study, resulted in yields that were comparable to those obtained by following the general recommendation.

3.3. Canopy Reflectance Sensor-Based N Fertilizer Management in Maize

It has been demonstrated that the application of N guided by sensors can markedly enhance the efficiency with which N is utilized, resulting in enhanced crop performance and a reduction in environmental impact. For example, research conducted by Solari et al. [106] demonstrated that maize fields managed with canopy reflectance sensors exhibited a 30% higher N use efficiency compared to fields utilizing traditional N application methods. This increase in efficiency translates to a more effective use of fertilizers, which in turn reduces the amount of N lost to leaching and volatilization, and thus ultimately leads to higher maize yields. In the United States, field trials conducted in the Midwest demonstrated that maize farmers utilizing canopy reflectance sensors could achieve higher yields and enhanced N efficiency in comparison to those employing conventional methods [67]. Similarly, in Europe, sensor-based N management has been adopted in countries like Germany and France, where it has led to improved maize production and environmental stewardship [77].

In a study conducted in northeast China, Wang et al. [107] demonstrated that the integration of plant height data with NDVI markedly enhanced the precision of yield projection, obviating the necessity for supplementary N fertilizer and RI when compared to the utilization of NDVI in isolation. The enhanced NFOA (INFOA) method, which involved the use of NDVI in conjunction with relative plant height, was demonstrated to be a more effective means of optimizing N application rates than the traditional NFOA method. The implementation of precision N management strategies based on INFOA has the potential to generate higher marginal returns, particularly in black and aeolian sandy soils. Conversely, research conducted in Egypt by Ali et al. [108] indicated that the V9

growth stage is the optimal time for applying a corrective N fertilizer dose, as guided by the GreenSeeker optical sensor in calcareous soil. The application of a prescriptive dose of 150 kg N ha⁻¹ in two equal split applications at 14 and 30 days after maize sowing, in conjunction with a corrective dose guided by the optical sensor, resulted in maize grain yield that was similar to that achieved through general recommendations. This approach led to a reduction in total N fertilizer application and an increase in N fertilizer use efficiency, thereby demonstrating the potential for more sustainable and efficient N management practices in agricultural settings.

3.4. Comparative Analysis of Canopy Reflectance Sensors in N Fertilizer Management

Tools such as the GreenSeeker, Crop Circle, and Yara N-Sensor provide diverse approaches to N management based on real-time crop health data. The GreenSeeker, known for its cost-effectiveness and simplicity, functions by measuring light reflectance in specific wavelengths to estimate the crop N status of the crop. This tool is distinguished by its ease of integration into existing farm practices and its capacity to offer actionable insights with minimal setup [61]. Its practical applications have demonstrated significant enhancements in N use efficiency, particularly in contexts where budgetary constraints are a concern.

The Crop Circle offers a more advanced approach to crop monitoring by measuring multiple vegetation indices, including NDVI, NDRE, and REVI. These indices are vital indicators of plant health, enabling a comprehensive assessment of growth parameters and N requirements. The ability of the Crop Circle to capture NDVI, NDRE, and REVI at various growth stages provides a more refined approach to nitrogen management, enhancing the precision of fertilizer application throughout the crop cycle [76]. However, despite its superior accuracy compared to the GreenSeeker, the Crop Circle's higher cost and complexity may pose challenges for smaller operations or those with limited resources.

The Yara N-Sensor is distinguished by its pioneering technology and comprehensive data integration capabilities. By employing real-time reflectance measurements and sophisticated algorithms, this tool is capable of accurately calculating the precise N requirements of crops. Its capacity to adapt to diverse field conditions and crop types renders it highly versatile [94]. Furthermore, the incorporation of the Yara N-Sensor with decision support systems augments its utility by furnishing comprehensive recommendations that can be readily adjusted in response to evolving field conditions. Despite its exceptional accuracy and adaptability, the cost and technical intricacy associated with the Yara N-Sensor may impede its extensive adoption, particularly in resource-constrained settings.

A comparative analysis of the three SSNM tools, as illustrated in Table 2, shows that each one exhibits distinctive strengths and limitations. The GreenSeeker is distinguished by its affordability and ease of use, rendering it a viable option for numerous farmers who seek to adopt precision N management without a considerable financial commitment. The Crop Circle offers sophisticated NDVI measurement, enabling a higher level of precision that can be vital for optimizing N application in crops with varying growth stages or environmental conditions. On the other hand, the Yara N-Sensor provides the most comprehensive data and highest accuracy but requires a significant investment and technical expertise, limiting its use to larger operations or those with access to advanced support systems.

Table 2. A comparative analysis of canopy reflectance sensors for the management of N fertilizers.

Tool	Methodology	Performance	Advantages	Limitations
GreenSeeker	-Data Collection: Uses NDVI to assess crop health. -Calibration: Establish calibration models with plant tissue samples. -Application: Real-time data collection and variable rate application integration.	-Accuracy: High accuracy in predicting crop N status. -Efficiency: Effective in optimizing N application rates, leading to higher yields and reduced waste.	-Simple and user-friendly. -Effective real-time data collection. -High adaptability to various crops and conditions.	-Can be influenced by soil moisture, residue cover, and sunlight intensity. -Requires site-specific calibration adjustments.

Table 2. Cont.

Tool	Methodology	Performance	Advantages	Limitations
Crop Circle	-Data Collection: Measures multiple vegetation indices (NDVI, NDRE, REVI). -Calibration: Similar calibration process with tissue sampling. -Application: Used for real-time assessments and variable rate technology.	-Accuracy: Comparable to GreenSeeker with additional indices providing more detailed insights. -Efficiency: Enhances N use efficiency and improves yield predictions.	-Measures multiple indices for detailed insights. -Useful in fields with high variability. -Provides comprehensive assessment of plant health.	-More complex data interpretation. -Requires advanced training and understanding.
Yara N-Sensor	-Data Collection: Measures canopy reflectance across various wavelengths. -Calibration: Uses pre-calibrated models specific to crop types. -Application: Mounted on tractors for real-time application.	-Accuracy: High precision in variable N application. -Efficiency: Reduces N use and improves crop performance under varying conditions.	-High precision and detailed analysis. -Real-time, on-the-go assessments. -Integrates seamlessly with tractor-mounted systems.	-Higher cost and complexity. -May be less accessible for smaller operations.

4. Chlorophyll Meters

Figure 3 illustrates the operational principles underlying the functioning of chlorophyll meters. Schepers et al. [58] were the first to transition from remote sensing to proximal sensing by employing a SPAD (Soil Plant Analysis Development) meter to quantify leaf greenness or relative chlorophyll content in maize crops at the silking stage across a range of applied N fertilizer rates. They demonstrated a robust correlation between SPAD meter readings, the rate of applied N fertilizer, and leaf N concentration. It suggests that SPAD meter readings could serve as an effective means of estimating N stress in maize. Building on this foundation, Fox et al. [109] discovered that the SPAD meter accurately predicted the response of wheat to N fertilizer with a lower error rate compared to traditional leaf sampling methods. Piekielek and Fox [110] successfully identified a critical SPAD value for maize that could differentiate between responsive and non-responsive sites, thereby facilitating more informed decisions regarding the application of additional N. The use of chlorophyll meters for binary decisions on N application, particularly in cases involving manure N as part of the N supply, is highly beneficial. This approach remains prevalent in developing countries, where chlorophyll meters are still utilized in fields with minimal or no manure application [14].

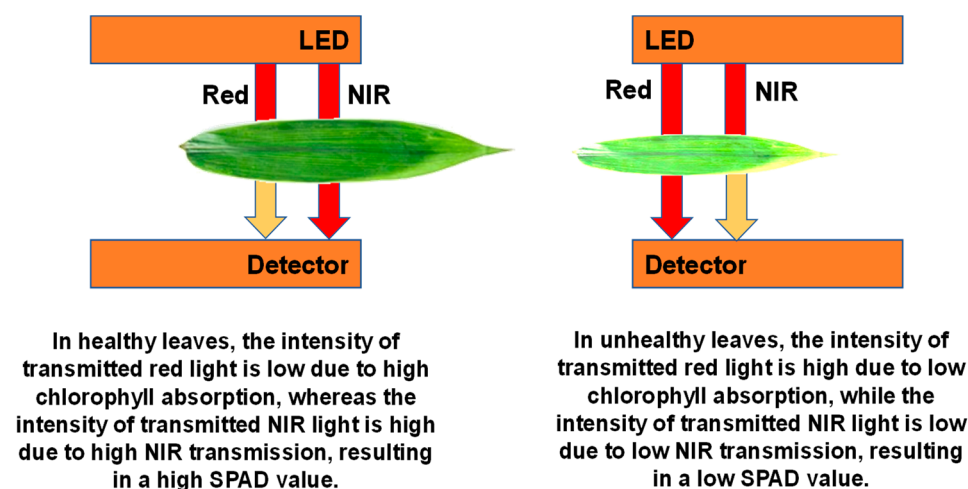


Figure 3. Example of chlorophyll index measurement and analysis using a SPAD meter.

It should be noted that the displayed value of the chlorophyll meter is unitless and can vary widely due to factors other than N status. To address this issue, Schepers et al. [58]

proposed the creation of a reference strip in each field that is adequately fertilized with N. This is based on research indicating that chlorophyll content and maximum yield tend to plateau at similar N rates. The chlorophyll meter reading of the reference strip serves as an indicator of the potential for maximum greenness. Blackmer and Schepers [59] introduced the concept of an N sufficiency index, defined as the ratio of SPAD meter readings from crops in the test field compared to those from a well-fertilized reference strip. An N sufficiency index value below 0.95 was employed as a criterion for determining the necessity of additional N fertilizer. Varvel et al. [111] employed the N sufficiency index, based on SPAD meter readings, for in-season correction of N deficiency in maize. Chlorophyll meters, such as the SPAD meter, were originally designed to measure the concentration of chlorophyll in leaves. Nevertheless, given that a considerable proportion of leaf N is present in enzymes associated with chlorophyll, these meters have become a widely utilized tool for predicting the necessity for additional N in cereal crops such as rice [57,112], and maize [110,113,114].

The use of chlorophyll meters for the estimation of leaf N status is a technique that is subject to a degree of variation in practice, concerning the specific leaf and the precise location on the leaf that is selected for measurement. The results of various studies have demonstrated that the preferred approach varies depending on the specific growth stage of the crop in question. Argenta et al. [115], Rashid et al. [116], Zhang et al. [117], and Ziadi et al. [118] measured chlorophyll content in the topmost leaves during the earlier vegetative stages of maize. In contrast, after the tasseling stage, Fox et al. [119] and Hawkins et al. [120] focused on the ear leaf for SPAD meter measurements. Zhang et al. [121] observed that after silk emergence, chlorophyll content in the topmost fully expanded leaf decreased, while it increased or remained the same in the ear leaf, highlighting the dynamic changes in leaf N status.

The literature reveals a multitude of protocols for SPAD readings in maize, underscoring the necessity for consistency in methodology. Some studies have employed a distance measurement of one-quarter of the distance from the leaf tip toward the stem [119], while others have utilized a distance measurement of two-thirds [115] or midway between the leaf tip and the stalk [117,118]. In rice, the greenness or chlorophyll content of the first fully opened leaf from the top, as measured with a SPAD meter, has been identified as the most reliable indicator of N demand [122]. This methodology has been employed to direct the application of fertilizers at various growth stages. In South Asia, the center portion of the fully opened leaf from the top is utilized to guide N applications in rice, wheat, and maize, based on SPAD measurements [14].

Although the conventional approach involves measuring SPAD readings from the uppermost fully expanded leaf to assess plant N status in rice, research findings suggest that lower leaves may offer more accurate differentiation of N levels when total N content is employed as an indicator [123]. The SPAD readings of lower leaves demonstrate a superior correlation with total N in whole leaves and the entire plant in comparison to upper leaves [124]. Jinwen et al. [125] concluded that SPAD readings from physiologically older lower leaves were more sensitive to N rates than those from younger upper leaves. This finding suggests a potential advantage in monitoring lower leaves for more accurate N management.

Recent advancements in chlorophyll meter technology have significantly enhanced the accuracy and reliability of N status assessments. Modern chlorophyll meters now feature advanced sensors that provide more precise measurements of chlorophyll content, which directly correlates with plant N levels. Integration with other precision agriculture tools, such as remote sensing and machine learning algorithms, has further improved the interpretation of SPAD readings. For example, the use of remote sensing allows for large-scale monitoring of crop health, while machine learning models can analyze complex datasets to predict optimal N application rates based on historical and real-time data [126]. Additionally, new developments in sensor technology have led to the creation of handheld meters with greater sensitivity and faster response times, as well as the incorporation of

GPS for spatially targeted N applications. These technological innovations are crucial for optimizing N use efficiency, reducing input costs, and promoting sustainable agricultural practices across various crops and regions [127].

4.1. Application of Chlorophyll Meters for N Management

Chlorophyll meters are highly sensitive in detecting N levels within the deficient to adequate range in leaves and possess the advantage of being self-calibrating for different soils, seasons, and cultivars. Monitoring leaf greenness or chlorophyll content throughout the crop growing season helps in the early detection of minor N deficiencies, allowing for corrective actions to be taken before yield potential is negatively impacted. This enables timely interventions, thereby enhancing the efficiency of fertilizer use [120,122]. By managing N fertilizer based on crop needs as indicated by chlorophyll meter readings, farmers can optimize N applications, reducing waste and environmental impact [128].

Two principal methodologies have been utilized in the deployment of chlorophyll meters for the administration of N fertilizers in cereal crops. The first approach is the fixed threshold greenness method, which entails the application of a dose of N fertilizer whenever the chlorophyll meter reading falls below a predetermined threshold [13,115]. This method is straightforward to implement, rendering it suitable for small farms. The second approach is the dynamic threshold greenness method, which involves applying a dose of N fertilizer whenever a sufficiency index—calculated as the chlorophyll reading of the plot in question divided by that of a well-fertilized reference plot or strip—falls below a critical value [14,129].

The dynamic threshold approach offers greater reliability and precision than other methods, as it accounts for variations in environmental conditions and crop growth stages [30,117]. However, having a well-fertilized reference plot is a prerequisite, which may not be feasible for all farmers, especially those with limited resources. In contrast, the fixed threshold approach does not necessitate such a reference, thereby rendering it more practical and accessible for smallholder farmers [116]. Both methods have been demonstrated to enhance N use efficiency and crop yields; however, the selection between them is contingent upon the particular circumstances and capabilities of the farming operation [120].

4.1.1. Critical Threshold Value Approach

The chlorophyll meter reading at a critical N level below which the crop will suffer from N deficiency, resulting in yield loss, is defined as the threshold greenness or SPAD threshold value [130]. This threshold can be determined by establishing a relationship between SPAD readings and leaf area-based N concentration. Given that a plant produces only the requisite amount of chlorophyll, irrespective of the N concentration within the plant, the SPAD threshold value remains uninfluenced by an excess of N supply and N uptake by crop plants [131]. In the context of rice cultivation by smallholder farms in developing countries in Asia, Peng et al. [122] were among the first to establish a critical SPAD value that could be readily employed by farmers in the field.

A SPAD threshold of 35, which represents a leaf area-based N concentration of 1.4 g N m^{-2} of leaf area, was successfully employed to ascertain the necessity for N topdressing of the rice variety IR72 [122]. Applying N fertilizer was deemed essential when levels fell below this threshold to prevent yield loss. The fundamental premise of real-time SSNM via SPAD meter assessment is the maintenance of a threshold level of leaf greenness throughout the cropping season. The application of N fertilizer is initiated when the color of the first fully opened leaf from the top of the crop plants falls below the established threshold, ensuring optimal N levels [122,130].

The application of N fertilizer guided by chlorophyll meters has been demonstrated to result in an enhanced congruence between the supply of N and the demand by the crop, leading to elevated grain yields and high levels of N fertilizer use efficiency [14,122]. The efficacy of the fixed threshold leaf greenness approach in the management of N fertilizers

in rice and wheat has been demonstrated in research. This method provides a practical and efficient means for farmers to manage N fertilization, ensuring that crops receive adequate N throughout the growing season without excessive application [129].

On-farm adaptive research was conducted to tailor the SPAD meter-based fixed threshold leaf greenness technique for transplanted and wet-seeded rice. This research considered local cultivar groups, soil, crop, and environmental conditions in the Philippines and Indonesia, and yielded critical insights [130]. Specifically, the research demonstrated that a SPAD threshold value of 35 is an effective indicator for transplanted rice during the dry season. However, for wet-seeded rice in the dry season and all rice during the wet season, which is typified by cloudy weather and low radiation, the threshold must be reduced to 32 to achieve high rice yields alongside high N fertilizer use efficiency. Similarly, in northwestern India, a SPAD reading of 37.5 was identified as a critical threshold for rice cultivation [54].

Balasubramanian et al. [132] put forth the hypothesis that distinct rice varietal groups may necessitate disparate threshold SPAD readings. For example, a threshold SPAD reading of 37 or 37.5 has been deemed appropriate for rice cultivars grown in the Indo-Gangetic plain of India [54,133]. In contrast, the threshold SPAD reading for rice cultivars grown in South India was determined to be 35 [134]. Huang et al. [135] observed that the optimal SPAD threshold for determining the timing and rate of N application was two units higher in rice varieties with thicker leaves. In Pakistan, Hussain et al. [53] identified a threshold SPAD reading of 37.5 as an appropriate indicator for the application of N fertilizer topdressing in transplanted rice. In Bangladesh, Islam et al. [136] proposed a SPAD meter reading of 35 as the threshold for guiding SSNM in transplanted rice. Further research by Kyaw [137] indicated significantly higher yields of rice with 3–12% less fertilizer application than the standard recommendation. This was achieved by managing N fertilizer following a threshold greenness equivalent to a SPAD meter reading of 35. Additionally, Ali et al. [13] reported that a SPAD threshold of 37 for dry direct-seeded rice could result in high yield levels and high N fertilizer use efficiency.

The variability in SPAD threshold values across different regions and rice varieties underscores the significance of local adaptation in N management strategies. By employing the SPAD meter-based fixed threshold approach, which is tailored to specific conditions, farmers can achieve optimal yields and enhance the efficiency with which they use fertilizer. This approach highlights the necessity of precise, location-specific agricultural practices to meet the diverse needs of rice cultivation in varying environmental contexts [54,122].

In contrast to rice, where the application of N fertilizer can be made at any time up to the flowering stage of the crop, the application of N in wheat is closely linked with irrigation events. This makes the decision-making process regarding chlorophyll meter-guided N fertilizer applications more complex. The objective of crop demand-driven N management using a SPAD meter in wheat is twofold: firstly, to ascertain the optimal mid-season N fertilization stages based on leaf greenness, and secondly, to identify the threshold chlorophyll meter values corresponding to different growth stages of the crop that align with irrigation events. This approach has been previously validated by Hussain et al. [53] and Kyaw [137].

In wheat, N fertilizer is typically applied in two or three split doses. The first dose is applied at planting, while the second and third doses are applied along with the first and second irrigation events, which occur around 20–25 and 45–50 days after planting, respectively. These doses coincide with the crown root initiation and maximum tillering stages, respectively. For example, the application of a dose of 20 kg N ha⁻¹ following a SPAD threshold value of 44 at the maximum tillering stage has been demonstrated to enhance wheat yield in the lower Gangetic plains of Bangladesh [137]. Similarly, in Pakistan, a SPAD threshold of 42 has been identified as an effective criterion for guiding N fertilizer top dressing in wheat [53].

Moreover, research conducted by Maiti and Das [138] indicated that a SPAD threshold value of 37 could be employed to direct N fertilizer management in wheat in the eastern

Indo-Gangetic plain, where winters are relatively mild, and yields are comparatively lower than those observed in the western Indo-Gangetic plain. This variability in threshold values across different regions and environmental conditions underscores the necessity for region-specific SPAD meter calibration to optimize N management in wheat.

It is important to maintain optimal leaf chlorophyll content between 50 and 75 days after sowing wheat, as determined by a SPAD meter, to achieve high grain yields [139]. Bijay-Singh et al. [54,140] established criteria based on SPAD meter readings to guide N applications at the tillering stage, aiming to achieve high yield levels. The results demonstrated a statistically significant relationship between grain yield of wheat and leaf greenness at the maximum tillering stage, indicating that higher SPAD readings correspond to higher chlorophyll content and better crop health [140].

The application of 30 kg N ha⁻¹ to treatment plots exhibiting varying levels of leaf greenness at the maximum tillering stage revealed a significant negative linear relationship between wheat grain yield response and SPAD meter readings. This suggests that the extent of the wheat grain yield response to N application increased linearly with the reduction of SPAD meter readings at the maximum tillering stage. For example, the application of 30 kg N ha⁻¹ resulted in an increase of wheat yield by 1.0 or 0.5 t ha⁻¹ when the leaf greenness was equivalent to SPAD meter readings of 32.5 or 42.5, respectively [140].

4.1.2. Dynamic Sufficiency Index Approach

In instances where threshold leaf greenness exhibits variability among varietal groups, seasons, or regions, the utilization of dynamic threshold greenness, expressed as a percentage of the sufficiency index, is a viable approach for SPAD meter-based N management. Hussain et al. [129] monitored the sufficiency index in rice at 7- to 10-day intervals. If the SPAD reading of the field fell below the threshold of 90% of the reading of the N-rich strip, 30 kg N ha⁻¹ was applied. This method ensured that rice yields for different cultivars following SSNM based on the sufficiency index approach were comparable to those obtained with the local recommendation treatment but with the application of 30 kg less N ha⁻¹. Additionally, Bijay-Singh [141] demonstrated the effectiveness of this approach for rice cultivars in northwestern India.

In a study conducted in the West Delta region of Egypt, the atLeaf chlorophyll meter was employed to refine N management for wheat at the Feekes 6 growth stage [30]. The atLeaf-based strategy involved the initial application of 40 kg N ha⁻¹ 10 days after seeding and a second application of 60 kg N ha⁻¹ 30 days after seeding, with a subsequent adjustable dose administered at the Feekes 6 stage. The final dose was calculated by multiplying the difference between the atLeaf readings of the test plot and an N-sufficient plot by a factor of 42.25, as determined by a functional model. This approach resulted in grain yields that were comparable to or exceeded those of standard treatments and enhanced N use efficiency, reducing the total fertilizer required by 57–60 kg N ha⁻¹ on average.

4.2. Comparative Analysis of Fixed Threshold vs. Sufficiency Index Methods for N Fertilizer Management with Chlorophyll Meters

The fixed threshold value approach for N fertilizer management involves using a predetermined chlorophyll meter reading as a benchmark for application decisions. This method relies on a static value established through prior research or empirical data, making it relatively straightforward to implement. By setting a clear cut-off point, this approach simplifies the decision-making process, as farmers can easily determine when to apply N based on whether their readings meet or fall short of the threshold. However, this approach's rigidity may limit its effectiveness in dynamic agricultural environments where crop growth and environmental conditions fluctuate (Table 2).

The dynamic sufficiency index approach offers a more flexible and responsive method for the management of N fertilizer. This approach calculates a sufficiency index by comparing current chlorophyll meter readings with those from a well-fertilized reference plot, thereby enabling adjustments to be made based on the crop's specific needs and envi-

ronmental factors. Consequently, it offers a more detailed perspective on N sufficiency, which can facilitate more accurate and efficient N management. Despite its benefits, this approach necessitates regular measurements and more intricate data interpretation, which can increase the labor and time required for effective implementation.

Both fixed threshold and sufficiency index approaches have advantages and disadvantages (Table 3). The fixed threshold method is advantageous for its simplicity and ease of use, particularly in stable conditions where the variability in crop growth and environmental factors is minimal. However, this approach may not fully account for the inherent variability in crop and environmental conditions, which could potentially result in suboptimal N management strategies. Conversely, the dynamic sufficiency index method is more appropriate for precision agriculture, where frequent adjustments are necessary to accommodate changing conditions. Although it offers a more adaptable and potentially more accurate approach to N management, it necessitates a more intensive data collection and analysis effort. Ultimately, the decision between these methods will depend on the specific agricultural context and the resources available for monitoring and decision-making.

Table 3. A comparative analysis of the fixed threshold value and dynamic sufficiency index approaches in the context of chlorophyll meter-based N fertilizer management.

Aspect	Critical Threshold Value Approach	Dynamic Sufficiency Index Approach
Definition	Uses a predetermined chlorophyll meter reading as a threshold for N application.	Uses a calculated sufficiency index, comparing the chlorophyll reading to a reference value, to guide N application.
Threshold	Fixed value, often based on previous research or empirical data.	Dynamic value, is often based on crop-specific and environmental factors.
Flexibility	Less flexible, as it does not adjust for varying crop and environmental conditions.	More flexible, and adjusts based on current crop and environmental conditions.
Application Frequency	May require fewer measurements if the threshold is stable and well-defined.	Requires frequent measurements to assess the sufficiency index.
Data Interpretation	Straightforward, with a clear cut-off for application decisions.	Requires comparison to reference values and calculation of the sufficiency index.
Adaptability	Less adaptable to changes in crop growth or environmental conditions.	More adaptable to varying conditions, allowing for precise adjustments.
Example Use	Commonly used in general recommendations where conditions are stable.	Often used in precision agriculture where conditions and crop needs vary.
Advantages	Simple to implement and easy to understand.	Provides a more nuanced approach, potentially leading to better N management.
Disadvantages	May not account for variability in crop growth or environmental conditions.	Requires more frequent data collection and analysis.

5. Leaf Color Charts for N Fertilizer Management

The LCC is a standardized tool designed to provide users with a range of color references, from light green to dark green, for the objective assessment of leaf greenness through visual comparison. This is accomplished by comparing the light reflected from the leaf surface with the colors displayed on the LCC. The LCC is comprised of a plastic strip with a series of color panels representing varying degrees of leaf greenness, from minimal to excessive N supply (Figure 4). The concept of the LCC was initially introduced in Japan by Fuji Film Co. in the mid-1980s [28]. The original LCC comprised seven panels, ranging from light green (panel 1) to dark green (panel 7), enabling users to match leaf color with the panels and assign numerical values from 1 to 7. In 1996, the International Rice Research Institute (IRRI) introduced a six-color panel LCC, which rapidly became a widely utilized tool for guiding N fertilizer management in rice cultivation. The six panels, numbered 1 to 6, correspond to increasingly green shades. Subsequent enhancements by IRRI resulted

in the creation of a four-panel LCC, which refined the color panels to more accurately reflect the spectral reflectance of rice and maize leaves [142]. Similarly, researchers at Zhejiang Agriculture University (ZAU) in China developed an eight-color panel LCC for the management of N in various rice cultivars. The University of California, Davis (UCD) also developed an eight-color panel LCC for evaluating leaf greenness and N content [29]. The study by Yang et al. [29] found strong correlations among leaf greenness scores measured by the IRRI, ZAU, and UCD LCCs. In India, four, five, and six-panel LCCs are being used for different crops in various regions of the country [143].

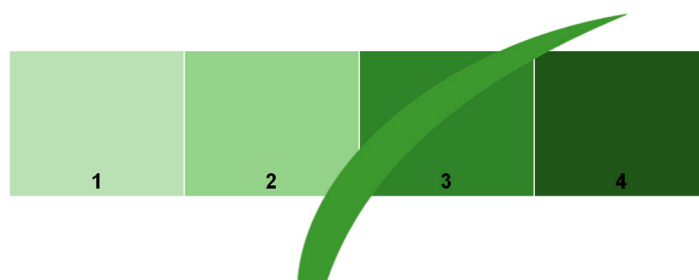


Figure 4. Illustration of an LCC showing a series of color panels representing varying levels of leaf greenness. The leaf in the example corresponds to panel number 3 on the LCC.

LCCs provide a range of flexible options for the targeted application of N fertilizers in field crops, employing three distinct methodologies. The initial approach, real-time N management utilizing LCC, entails the continuous monitoring of leaf greenness. Such an approach allows for immediate adjustments to the application of N based on the current readings of the LCCs, thereby optimizing efficiency and minimizing waste. The second approach, fixed-time adjustable dose N management with LCCs, entails the application of N at predetermined intervals. This method allows for the amount to be adjusted based on periodic LCC assessments. This approach combines the benefits of scheduled applications with dose adjustments according to the crop's needs. The third approach, the dynamic threshold greenness approach for N management using LCC, utilizes specific greenness thresholds from LCC readings to guide N application. This method allows for flexible timing and precise N management that adapts to the crop's changing requirements throughout its growth cycle. Each method capitalizes on the ability of LCC to quantify leaf greenness, providing tailored strategies to enhance N management and improve crop productivity.

5.1. Real-Time N Management Using LCC

In the case of crops such as irrigated transplanted rice, where the application of N fertilizer can be initiated at any point in the growth cycle, the LCC can be employed to ascertain both the optimal timing and the requisite quantity of N fertilizer required for optimal growth. The application timing of N fertilizer doses is adjusted based on the crop N demand throughout its growth cycle [122]. By employing the LCC, farmers monitor the color of the most recently fully expanded leaves of the crop at intervals of 7 to 10 days. Once the leaf color falls below the specified greenness threshold on the LCC, typically ranging from 20 to 45 kg N ha⁻¹, the recommended amount of N fertilizer is applied. The threshold LCC score is determined through initial experiments conducted on a specific varietal group within a particular region. Guidelines for real-time management of N fertilizer based on LCC are now available in various regions across South Asia [143]. This innovative approach allows farmers to optimize N fertilizer application, leading to improved crop yields and reduced environmental impact.

The findings of several studies conducted in northwestern India by Bijay-Singh et al. [54], Varinderpal-Singh et al. [144], Yadvinder-Singh et al. [145], and Thind et al. [146] indicate that maintaining the critical leaf greenness level equivalent to LCC shade 4 (LCC4) is essential for effective N management in irrigated rice. These studies have demonstrated

that the application of an N fertilizer dose of approximately 30 kg N ha^{-1} or less to rice when the color of the most recent fully expanded leaves drops below the LCC4 threshold results in optimal yield levels. In South Indian states where rice is cultivated in both the dry and wet seasons, Porpavai et al. [147] observed that the threshold leaf greenness for transplanted rice was LCC5 during the wet season and LCC4 during the dry season. In northwestern India, Bijay-Singh et al. [148] identified LCC3 as the threshold leaf greenness for direct wet-seeded rice, while Ali et al. [13] discovered that using LCC4 as the threshold could result in increased yields and improved N fertilizer use efficiency for direct dry-seeded rice. Numerous studies have underscored the importance of specific leaf greenness levels for the management of N fertilizer in diverse rice cultivars and growth conditions, including aerobic and basmati rice [149–152]. For hybrid rice, maintaining a greenness threshold equivalent to LCC5 has been demonstrated to enhance yield and N use efficiency [152,153].

In some fields, the implementation of LCC-based N management can result in the utilization of elevated N fertilizer levels, thereby facilitating increased yields in comparison to conventional farming techniques. For example, Shukla et al. [152] demonstrated that the application of the recommended 150 kg N ha^{-1} dose resulted in a grain yield of 6.9 t ha^{-1} for the rice hybrid PHB-71. However, the implementation of real-time N management based on LCC scores of 4 and 5 resulted in an increased yield of 7.6 and 8.1 t ha^{-1} , respectively, with N application rates of 135 and 165 kg N ha^{-1} . Similarly, Suresh et al. [154] demonstrated that the application of real-time N management based on a threshold LCC4.5 greenness score resulted in a grain yield of 5.88 t ha^{-1} with an application rate of 180 kg N ha^{-1} . In contrast, the recommended 120 kg N ha^{-1} dose led to a significantly lower yield of 5.13 t ha^{-1} . In Nepal, Marahatta [155] reported that the average N fertilizer dose of 53 kg N ha^{-1} under traditional farming practices yielded 4.62 t ha^{-1} of rice grain. In contrast, LCC4-based SSNM resulted in a yield of 6.67 t ha^{-1} with 100 kg N ha^{-1} application.

5.2. Fixed-Time Adjustable Dose N Management with LCC

To effectively manage N fertilizer, it is essential to calculate an estimated dose based on expected yield improvements and targeted N use efficiency. This approach allows for the achievement of desired yields or adherence to regional recommendations. This approach entails the division of the total N fertilizer into multiple applications that are synchronized with pivotal growth stages, the duration of the cropping season, the specific crop variety, and the method of establishment. The LCC is employed to modify these pre-established N doses at pivotal growth stages, except for the planting or early growth phases, when plants are still relatively small. Adjustments are made by comparing the color of the most recent fully expanded leaf with the thresholds established by the LCC [156], thereby allowing for dynamic modifications of split N doses that reflect the crop's growth and N needs at each stage. This allows for the total amount of fertilizer applied to be tailored to specific field conditions and seasonal requirements.

The fixed-time adjustable dose method, which is based on LCC, is particularly advantageous for farmers who are unable to regularly visit their fields, in contrast to real-time management, which necessitates frequent monitoring and adjustments. In this method, the evaluation of leaf color is conducted at crucial growth stages, such as active tillering, panicle initiation, or near flowering. Based on the observed leaf color, the N fertilizer dose is adjusted, indicating the crop's relative N requirement. Variants of this approach, which adjust fertilizer application based on specific LCC values at critical growth stages, have been demonstrated to outperform general recommendations in terms of efficiency and effectiveness [156–158].

A number of studies conducted in South Asia have demonstrated the efficacy of adjusting N fertilizer applications based on leaf color in order to optimize rice yields. In a study conducted by Bijay-Singh et al. [159] on puddled transplanted rice, it was determined that achieving high yields necessitated the application of a basal N dose of 30 kg ha^{-1} . During critical growth stages, such as maximum tillering and panicle initiation,

the application of N was recommended at a rate of 45, 30, or 0 kg ha⁻¹, based on the level of leaf greenness observed. If the leaf greenness was less than LCC4, between LCC4 and LCC5, or more than LCC5, respectively, the specific N doses ensured optimal yields while reducing the total amount of fertilizer used compared to the regional general recommendations. Moreover, a pre-flowering application of 30 kg ha⁻¹ was observed to be advantageous when leaf greenness was below LCC4. In years with favorable climatic conditions, this tailored approach resulted in higher yields than general recommendations and achieved agronomic efficiencies greater than 25 kg of grain per kg of N fertilizer.

In a study on direct-seeded dry rice, Ali et al. [13] found that applying 20 kg N ha⁻¹ at 14 days after sowing and 30 kg N ha⁻¹ at 28 days after sowing, followed by additional applications of 30, 40, or 50 kg N ha⁻¹ at 49 and 70 days after sowing based on leaf greenness relative to LCC4, LCC3.5, or above LCC4, resulted in a more effective strategy for achieving optimal yield and high N use efficiency compared to general recommendations. In another study conducted by Ali et al. [30] in Egypt, a field-specific N management strategy for wheat at the jointing stage (Feekes 6 growth stage) was developed using the LCC. The study demonstrated that the most efficacious LCC-based approach for N application was as follows: 150 kg N ha⁻¹ for LCC ≤ 4, 100 kg N ha⁻¹ for LCC between 4 and 5, and 0 kg N ha⁻¹ for LCC ≥ 5. This method not only resulted in higher grain yields but also exhibited enhanced N use efficiency compared to traditional treatments.

5.3. Dynamic Threshold Greenness Approach for N Management Using LCC

The degree of greenness observed in the leaves of crops can vary considerably as a result of a number of factors, including the cultivar, the growth stage, and environmental conditions such as temperature, moisture stress, and sunlight. For instance, prolonged periods of overcast weather can result in diminished leaf greenness in crops such as rice, attributable to a reduction in sunlight exposure. To manage these fluctuations, Bijay-Singh et al. [160] introduced the concept of dynamic threshold LCC greenness. This approach is tailored to the specific conditions of each field, including soil type, crop variety, and the prevailing environment. This approach entails maintaining a reference strip in the field with excessive fertilization and utilizing its LCC readings as a baseline to ascertain the optimal threshold leaf greenness for the crop's growth stage and season. In the case of rice, the dynamic threshold is set at a level of 0.5 units below the LCC reading of the reference strip that has been over-fertilized [160]. By employing this approach, farmers can make more precise adjustments to their fertilizer applications to achieve optimal yields and improve N use efficiency.

In wheat cultivation, the management of N fertilizer is typically aligned with critical growth stages and irrigation events. However, it should be noted that not all farmers consistently adhere to this practice. Research has explored the efficacy of employing LCC for real-time SSNM with a particular focus on the timing and quantity of fertilizer application. In a study conducted by Shukla et al. [152], the efficacy of various LCC thresholds (LCC3, LCC4, and LCC5) was tested for different sowing times. The results indicated that LCC4 was the most suitable for real-time management. However, in eastern India, where temperatures are higher during the wheat season compared to northwestern India, Maiti and Das [138] found that LCC5 was a more effective indicator.

5.4. Comparative Evaluation of N Fertilizer Management Approaches Using LCC

The real-time N management approach using LCC provides a highly responsive and adaptive strategy for optimizing N applications. This method entails the continuous monitoring of LCC readings throughout the growing season, thereby enabling farmers to make prompt adjustments to N applications based on the prevailing crop conditions. By dynamically aligning N applications with the actual needs of the crop, this approach maximizes N efficiency and minimizes potential waste. However, the necessity for frequent monitoring and real-time data collection renders this method more complex and resource-intensive, necessitating sophisticated equipment and consistent attention from farmers.

In contrast, the fixed-time adjustable dose N management method with LCC involves the application of N at pre-determined times during the crop's growth cycle, with adjustments made based on LCC readings taken at these fixed intervals. This approach strikes a balance between ease of use and efficiency, simplifying the scheduling of applications and reducing the need for constant monitoring. Those who employ this method enjoy the benefits of a structured application schedule while retaining the flexibility to modify doses in response to periodic LCC readings. However, this approach may not effectively capture immediate changes in crop N needs as much as the real-time method, potentially resulting in less precise management of N resources.

The dynamic threshold greenness approach using LCC offers a flexible and precise method of adjusting N applications based on specific greenness thresholds identified from LCC readings. This method enables the precise management of N by allowing for the tailoring of applications to align with the specific needs of the crop as it progresses through different growth stages. While this approach offers the potential for enhanced crop health and yield, it necessitates a comprehensive grasp of the applicable greenness thresholds and unwavering monitoring to guarantee precise adjustments. This can render the method intricate and challenging, particularly for farmers lacking sophisticated monitoring instruments or expertise in interpreting LCC data.

Each of these methods possesses distinctive advantages and limitations, rendering them appropriate for diverse agricultural settings (Table 4). Real-time N management is optimal for circumstances where prompt adjustments are required, and farmers have access to sophisticated monitoring instruments. The fixed-time adjustable dose approach is well-suited to those who prefer a more structured and less demanding scheduling system. Meanwhile, the dynamic threshold approach offers high precision for farmers who can adapt to changing conditions and have the resources to monitor and interpret LCC readings effectively. Ultimately, the choice of method will depend on the specific needs of the crop, the available resources, and the farmer's ability to implement and manage the chosen strategy.

Table 4. Comparison of N management approaches using LCCs: Real-time monitoring, fixed-time application, and dynamic threshold methods.

Aspect	Real-Time N Management Using LCC	Fixed-Time Adjustable Dose N Management with LCC	Dynamic Threshold Greenness Approach for N Management Using LCC
Definition	Adjusts N application in real-time based on current LCC readings.	Applies N at fixed times with adjustable doses based on LCC readings.	Adjusts N application dynamically using specific threshold greenness levels from LCC readings.
Timing of application	Continuous monitoring and application as needed.	Pre-determined fixed times during the growing season.	Flexible timing based on greenness thresholds, not fixed.
Adjustment flexibility	High, as it responds to real-time changes in crop conditions.	Moderate, adjusts doses at set times based on LCC readings.	High, allows for dynamic adjustments based on changing greenness levels.
Complexity	Higher due to the need for continuous monitoring.	Moderate, requires scheduling and dose adjustments.	Higher, requires determining and monitoring appropriate greenness thresholds.
Resource requirement	Needs frequent monitoring for real-time data collection.	Needs periodic LCC readings and planning for dose adjustments.	Needs a detailed understanding of threshold levels and good monitoring tools.
Farmer suitability	Best for farmers with real-time monitoring tools.	Good for farmers who follow a set schedule.	Ideal for farmers who can adjust to changing conditions.

6. Comparative Analysis of SSNM Tools

A comparative evaluation of canopy reflectance sensors, chlorophyll meters, and leaf color charts highlights the unique advantages and disadvantages of each tool for SSNM (Table 5). Canopy reflectance sensors, which measure light reflectance to assess plant health and N levels, provide high accuracy and can detect subtle variations in plant health over large areas. These sensors can be integrated with advanced technologies such as drones, GPS, GIS, the Internet of Things (IoT), and artificial intelligence (AI), making them ideal for large-scale precision agriculture. However, their high initial cost and requirement for technical expertise may limit their adoption, especially among smallholder farmers.

Table 5. Comparative analysis of tools for SSNM.

Feature/Tool	Canopy Reflectance Sensors	Chlorophyll Meters	Leaf Color Charts
Principle of Operation	Measures light reflectance properties to assess plant health and N status.	Measures leaf greenness (chlorophyll content) to determine N levels.	Visual comparison of leaf color to a standard chart indicating N status.
Accuracy	High accuracy with the ability to detect subtle differences in plant health.	High accuracy, particularly effective in identifying N deficiency.	Moderate accuracy, dependent on human visual assessment.
Ease of Use	Requires training and calibration, and can be integrated with UAVs and other systems.	Simple to use with portable devices like SPAD meters.	Very easy to use, and no special equipment or training is required.
Cost	The high initial cost for equipment and integration.	Moderate cost for handheld devices.	Low cost, highly affordable for smallholder farmers.
Data Collection	Provides real-time, continuous data collection over large areas.	Provides immediate readings at specific points, requiring multiple samples for large areas.	Provides immediate visual assessment, requiring manual sampling.
Integration with Technology	Easily integrated with GPS, GIS, IoT, and AI for advanced precision farming.	Can be integrated with data logging devices and software for data analysis.	Limited integration, primarily manual use.
Environmental Impact	Low impact due to non-destructive and precise application of N.	Low impact with efficient N application, reducing environmental contamination.	Low impact, though less precise, and may result in over/under-application.
Applicability in Various Conditions	Effective in a variety of crops and environmental conditions.	Effective across different crops and growth stages, especially in vegetative stages.	Effective in various crops but may be less reliable in low-light conditions.
Suitability for Small Farms	Less suitable due to cost and complexity	Suitable due to the balance of cost and accuracy	Highly suitable due to simplicity and low cost
Limitations	High initial cost and need for technical expertise.	Requires periodic calibration and multiple readings for accuracy.	Subjective interpretation and limited precision.
Examples of Use	Used in advanced precision agriculture setups, often combined with drones for large-scale monitoring.	Commonly used in both research and practical farming for site-specific management.	Widely used in developing countries due to low cost and ease of use.

Chlorophyll meters, such as the popular SPAD meter, assess N levels by measuring leaf greenness. They provide immediate and accurate readings, making them effective for detecting N deficiencies. Chlorophyll meters are easier to use and less expensive than canopy reflectance sensors, making them accessible to a wider range of farmers. They are particularly useful for both research and practical site-specific management. However, they require regular calibration and multiple readings to maintain accuracy, which can be time-consuming.

LCCs provide an inexpensive and user-friendly method for assessing N status in crops. By comparing leaf color to a standard chart, these charts indicate N levels. While they are affordable and do not require special equipment or training, their accuracy is moderate and

relies on subjective human judgment. This subjectivity can lead to less accurate N management, potentially resulting in inappropriate fertilizer application. Despite these limitations, LCCs are widely used in developing countries due to their low cost and simplicity.

Incorporating these SSNM tools into N management strategies can significantly improve crop productivity while reducing environmental impacts. Canopy reflectance sensors provide real-time, continuous data collection, making them ideal for large-scale monitoring and precise N application. Chlorophyll meters provide a practical balance between accuracy and cost, making them suitable for both research and field use. Although less accurate, LCCs are critical in low-resource settings and provide a straightforward approach to nitrogen management. The choice of tool for SSNM depends on factors such as farm size, available resources, and desired precision. Canopy reflectance sensors are best suited for advanced precision agriculture, while chlorophyll meters offer a versatile and cost-effective solution for different farming contexts. LCCs remain valuable in resource-limited environments to help growers make informed N application decisions.

7. Conclusions

The application of canopy reflectance sensors, chlorophyll meters, and LCCs holds significant promise for enhancing SSNM in both developed and developing countries. This review explored various strategies to utilize these tools effectively within SSNM, emphasizing their role in optimizing N application, improving crop yields, and reducing environmental impacts. In developing countries, where resources may be limited, the accessibility and practicality of tools like LCCs offer a valuable means for farmers to enhance N use efficiency. Meanwhile, in developed regions, advanced sensor technologies enable more sophisticated, data-driven approaches to SSNM. By translating the data from these tools into actionable N management strategies, farmers can ensure that N is applied precisely when and where it is needed, fostering sustainable agricultural practices and contributing to global food security.

However, there are several limitations and considerations highlighted by recent studies. For instance, differences between cultivars within a species can affect optical sensor measurements and their relationships with crop N status [161]. This variability can impact the consistency of recommendations and the accuracy of N application, emphasizing the need for standardized and adaptable calibration protocols that can be used across different crop types and environmental conditions.

Another significant aspect is the necessity for enhanced precision and uniformity in the interpretation of sensor data. The use of traditional LCCs for assessing leaf N status relies on subjective visual assessments, leading to inconsistencies. Future research should focus on developing digital or electronic versions of LCCs that employ sensors or imaging technology for objective and accurate measurements, along with comprehensive validation studies to establish standards tailored to different crop varieties and growth stages. Additionally, integrating these digital tools with mobile applications could streamline real-time data collection and analysis, enhancing accessibility and user-friendliness for growers.

Despite advances in N management technologies using these tools, there are still significant limitations that hinder their full effectiveness and widespread adoption for SSNM in different crops. One of the critical gaps is the lack of universally standardized calibration protocols. Calibration methods for these tools often vary widely and are customized for specific conditions or crop types. This variability can lead to inconsistent recommendations and inaccuracies in N application, ultimately impacting crop yields and environmental outcomes. It is essential to develop standardized and adaptable calibration protocols that can be used across different crop types, growth stages, and environmental conditions. This research would ensure that these technologies provide reliable and accurate data, thereby increasing their effectiveness in optimizing N management practices. For example, research on muskmelon and sweet pepper demonstrated that while NDVI is less affected by cultivar differences, SPAD and N Balance Index (NBI-R) values showed

significant variability between cultivars [161]. This highlights the importance of choosing the appropriate sensor and calibration method for specific crops and conditions.

Another pressing issue is the incorporation of advanced data analytics and machine learning into these technologies. While canopy reflectance sensors and chlorophyll meters provide valuable data, there is significant untapped potential in integrating and analyzing these input variables along with crop models, environmental data, and management practices using sophisticated algorithms. Research should focus on leveraging machine learning to effectively handle these diverse data sets, producing output variables such as optimal N application rates, predicted crop performance, and environmental impact assessments. Current methods often fail to account for the complexities of real-time data integration, resulting in suboptimal decision-making. Developing robust analytical models that can process these inputs and generate accurate, actionable insights through user-friendly decision support systems will greatly enhance N management accuracy and promote more sustainable agricultural practices. This integration is crucial, as evidenced by the potential for machine learning to improve the interpretation and application of data from various sensors, thus enhancing the precision of N management decisions.

The potential for scalability and practical application of such technologies, particularly for smallholder farmers with limited resources, is a significant challenge. While advanced solutions are promising, their high cost and complexity may hinder their adoption by agricultural producers. Efforts should focus on improving the accessibility and affordability of these technologies by reducing the cost of sensors, streamlining their functionality, and establishing comprehensive training initiatives to enable farmers to use these tools efficiently. Overcoming these barriers will promote the broader integration of N management technologies and expand their positive impact across diverse agricultural landscapes. For instance, the practicality and lower cost of LCCs make them particularly suitable for resource-limited settings, offering an accessible means to enhance N use efficiency.

The opportunity for critical research lies in the development of integrated systems that combine multiple technologies. Rather than focusing on individual tools, current solutions should aim to create integrated platforms that provide a comprehensive view of crop N status. Research should explore the seamless integration of data from canopy reflectance sensors, chlorophyll meters, and LCCs into a unified system that provides real-time, actionable insights. These integrated systems have the potential to improve decision-making by increasing understanding of N needs and optimizing application strategies under different conditions. The integration of various sensor data into a cohesive platform would address the challenge of isolated measurements, offering a more holistic approach to N management.

Further extensive research conducted in real-world conditions is necessary to verify the efficacy of these technologies. A substantial proportion of the extant research is conducted in controlled or restricted environments, which may not accurately reflect the complexities of actual farming settings. Field trials should evaluate the performance of these tools across diverse crops, soil types, and climatic conditions, identifying practical challenges and constraints. Additionally, more research is needed specifically on vegetable crops, as they often exhibit unique nutritional requirements and sensitivities that may not be fully addressed in existing studies. This approach will provide invaluable insights for enhancing the design and implementation of these technologies to better address the varied needs of farmers, ensuring their practicality and effectiveness in real-world applications. For instance, studies have shown that various monitoring approaches, including soil monitoring, destructive methods, and non-destructive crop-based methods, are crucial for optimal N management in vegetable production [162,163].

In conclusion, while the application of canopy reflectance sensors, chlorophyll meters, and LCCs holds significant promise for SSNM, there remain challenges that need addressing to maximize their effectiveness. Standardized calibration protocols, advanced data analytics, practical integration of multiple technologies, and extensive field research are critical to overcoming these challenges. By addressing these limitations, these technologies can

significantly enhance N management, improve crop yields, and reduce environmental impacts, ultimately contributing to sustainable agricultural practices and global food security.

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