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Precision Nitrogen Management in Rice Using NDVI and SPAD: A Systematic Review of Current Applications and Research Gaps.

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ABSTRACT

The management of nitrogen is necessary to maximize the productivity of rice and enhance the nitrogen use efficiency. Vegetation Index and other remote sensing tools have been extensively employed to determine the nitrogen status of crops, but they can be affected by environmental fluctuation. The study aimed to evaluate the effectiveness of Vegetation Index in determining nitrogen status and predicting yield performance in rice systems. Scopus, ScienceDirect, and Web of Science were used to search the articles published between 2015 and 2025 by search query: (paddy OR rice) AND (NDVI OR Vegetation Index) AND (nitrogen). The methodology used was a four-step screening system, which left 13 applicable studies to be examined in detail. Results showed that Vegetation Index is highly correlated with nitrogen content and yield components, especially in late vegetative and reproductive periods. Diagnostic accuracy was further improved with SPAD chlorophyll meter and UAV-based images. Nevertheless, the diurnal variability of light, sensitivity to growth stages, and cultivar variability are a few of the challenges that decrease the uniformity of its implementation. Altogether, Vegetation Index is a useful non-destructive means of precision rice management if measurements are made under optimal conditions. Future research should focus on the integration of light quality and canopy structure parameters integration to enhance monitoring protocols and robust decision-making in sustainable rice production.

Keywords: Nitrogen, Paddy, NDVI, SPAD chlorophyll, Precision agriculture

INTRODUCTION

Rice is an essential staple crop in Malaysia and some cultivars like MR303 are crucial in the food security of the country. The unpredictable climate conditions, environmental pressures, and the need to be more productive due to the growing demand are major issues that the industry still has to face (Rajamoorthy et al., 2015). Hence, the urgency is to adopt the best management and monitoring strategies to sustain production of rice.

Sustainable nitrogen management in the production of rice has become important because of climate change and degradation of wetland habitats. Unproductive use of fertilizers not only leads to waste of nitrogen and pollution of water. Failure to manage nitrogen effectively leads to reduced rice growth and higher cost of production because of resource wastage. Proper management of nitrogen is sustainable since it helps to prevents loss of crop vigour over a growing period and reduces chances of environmental degradation. The sustainable nitrogen administration reduces the negative effects to the environment, but raises the agricultural yields, as well as conserving soil fertility. These practices are critical towards the stability and productivity of wetland rice systems when they are faced with changing environmental (Alam et al., 2023).

NDVI is one of the most widely adopted tools to determine the health of crops and even their nitrogen status. Unmanned aerial vehicles UAV-NDVI has already been used to study the initial development of rice, which provides a fast method of assessing the vitality of crops without harming the land (Rosle et al., 2019). Likewise, hyperspectral canopy sensing has also proven itself as a promising technique to estimate aboveground biomass at various stages of rice development, which supports utility of spectral data in predicting yield and managing crops (Gnyp et al., 2014). The technology of sensors has also enhanced the monitoring of nitrogen, and researchers have tested the use of single- sensor multispectral cameras as a relatively low-cost tool to estimate the nitrogen levels in leaves of paddy (Muliady et al., 2021). In more recent times, methodological models have been suggested to standardize spectral measurements and interpretation to improve the accuracy of nitrogen estimation of rice cropping systems (Ang et al., 2024). These methods are indicators of a significant shift in the notion of using remote sensing methods with the agronomic modelling to better support the decision-making process of fertilizer.

Though there have been developments in the use of vegetation indices to monitor crops, comparative analyses of the accuracy of these indices show that their usefulness depends on the types of sensors used, measurement scales, and the climatic conditions. This variability raises questions about the predictability of such indices due to predicting the yield and nitrogen status, which highlights a strong research deficit. The use of these indices in the present day is usually not based on standardized procedures to suit specific stages of growth, type of rice and agro-ecological conditions. This problem is also complicated by the research results that NDVI and SPAD threshold values are not always the same in various rice varieties and environments, which suggests that it is necessary to further calibrate these indices in rice production systems (Ge et al., 2022). Additionally, a study highlights the need for further research to validate SPAD measurements across different growth stages, as their study was limited to a single growth stage (80 DAT), which may not fully capture the variability across the entire rice crop lifecycle (Gholizadeh et al., 2009). Due to the few research works which consider these complexities, more studies are necessary to determine how the outcomes can be varied regarding factors like rice variety, growth stage and environmental conditions (Rehman et al., 2022).

Experiments in the local field to measure the rate of nitrogen application in Malaysian rice varieties indicate that NDVI can respond to the plants in question, yet, to convert the spectral results into practical fertilizer application recommendations, it is necessary to perform calibrations at the site (Shafiq et al., 2025). The research proves that nitrogen management instruments based on NDVI have to be adapted to local conditions. For instance, UAV-based NDVI has the potential to streamline the process of nitrogen fertilization, and depending on the agroecological area, calibration models must be adapted to provide valid recommendations (Yang et al., 2018). Therefore, even though NDVI shows potential routes to sustainable rice production based on precision nutrient management, additional study is required to standardize the approaches, test findings in different settings, and address uncertainty that restricts the applicability of this approach on the ground.

Despite the promising applications of Vegetation Index and SPAD in nitrogen management, there are still imbalance in its measurement protocols, calibration models and environmental flexibility. Varying results among rice varieties, climate zones and sensor types restrict the extrapolation of results. The systematic literature review is thus required to synthesize and assess past studies, determine methodological discrepancies, and develop standardized methods of accuracy nitrogen management in rice production. Systematic review will be used to consolidate the existing information, reduce the uncertainty, and inform the future studies concerning the implementation of Vegetation Index and SPAD to be more effective under different agroecological conditions.

MATERIALS AND METHODS

The review was also compiled following the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to make both the process clear, structured, and easy to reproduce (Page et al., 2021). PRISMA framework was selected as it provides a credible means of identifying, screening and selecting studies in a consistent and unbiased fashion. The PRISMA flow chart (Figure 1) illustrates the number of studies discovered, those filtered and ultimately included by each phase of the review. This graphic overview allows readers to see the way the selection was undertaken and view how thorough the search was. Through this strategy, the review minimizes the chances of overlooking significant studies and helps to include all pertinent research on the use of Vegetation Index to measure nitrogen status in rice and analyse them in an equal manner.

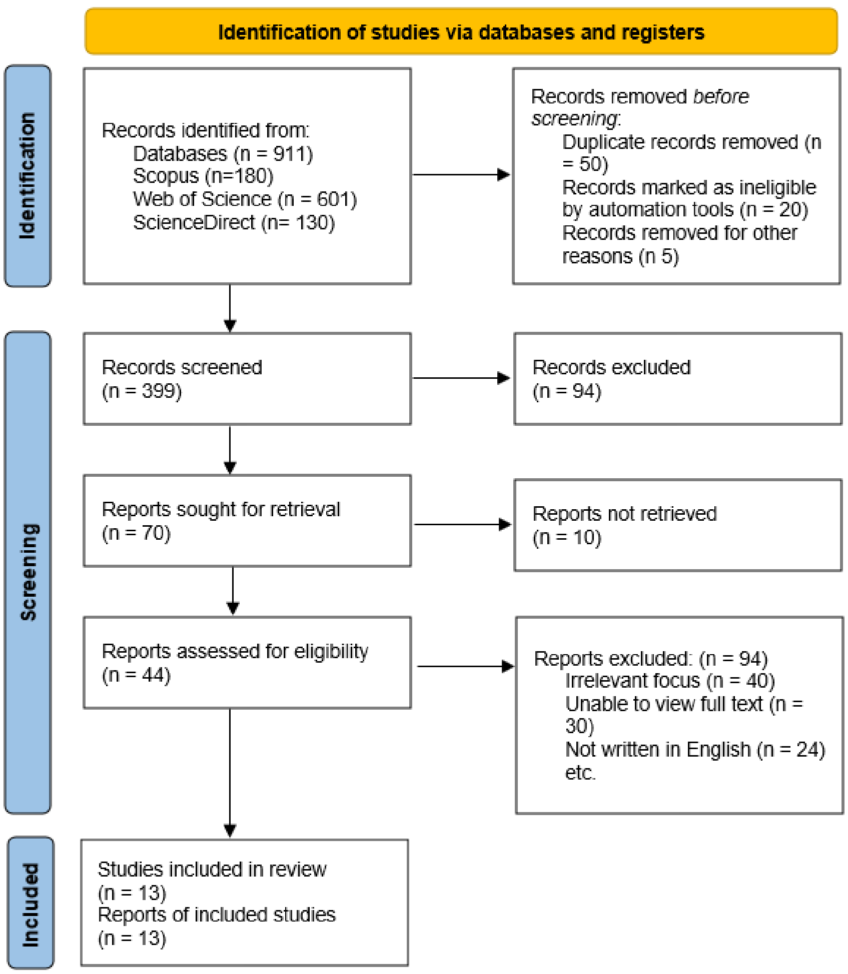

Figure 1. PRISMA 2020 flow diagram illustrating the systematic review process for identifying studies on NDVI applications in nitrogen management for rice systems. The diagram demonstrates how many records have been identified, screened, excluded and finally included at every step of the review process. (Page et al., 2021).

2.1 Prisma Framework and Methodology

The systematic literature review was implemented according to the recommendations of Preferred Reporting Items Systematic Review and Meta-Analysis (PRISMA) 2020 to ensure that the review is reproducible and transparent (Page et al., 2021). PRISMA framework has been selected due to its standardized methodology of identifying and selecting the relevant studies and reducing selection bias. The PRISMA flow diagram in figure 1 indicates how many records were identified and screened at each step and why certain records were excluded.

The major research question was as follows: How has NDVI been applied to the measurement of nitrogen status and the predictability of yield performance in paddy rice systems and what are the present and future applications and limitations of this technology? The objective of the review was to summarize the existing uses of NDVI in measuring nitrogen and determining the efficiency of the NDVI-based monitoring systems. It further analyzed the way NDVI can be used in conjunction with complementary instruments such as SPAD chlorophyll meters and the shortcomings and gaps in the research area.

Table 1. Overview of database search findings and study selection at each screening phase: Stage 1- Database initial retrieval; Stage 2- Title screening; Stage 3- Abstract and key word screening; Stage 4- Full-text evaluation and final selection.

No	Database sources	Query	All result	stage 1	stage 2	stage 3	stage 4
1.	Scopus	(paddy OR rice) AND (NDVI OR Vegetation Index) AND (nitrogen)	180	25	12	10	5
2.	ScienceDirect	(paddy OR rice) AND (NDVI OR Vegetation Index) AND (nitrogen)	601	280	50	14	4
3.	Web of science	(paddy OR rice) AND (NDVI OR Vegetation Index) AND (nitrogen)	130	94	32	20	4

2.2 Search Strategy and Selection Criteria

Systematic search of three key academic databases was done covering Scopus, Web of Science and ScienceDirect as show in table 1. The reason behind the selection of these databases is that they are comprehensive in terms of the coverage of agricultural and remote sensing studies. In January 2025, the search was conducted and covered the period between January 2015 and December 2025. This decade represents the new technological changes in remote sensing and accuracy farming methods. The Boolean query that was used to search all databases was: (paddy OR rice) AND (NDVI OR Vegetation Index) AND (nitrogen). Parentheses provide logical correctness of grouping similar words to each other. We reviewed only the first ten pages of results of each database because the preliminary testing revealed that the relevant studies are represented in the top results mostly.

Research was followed if it fulfilled certain criteria. They were required to be peer-reviewed original research publications in the English language and published between 2015 and 2025. The research had to be studies where experiments or observations of rice cultivations were carried out in the field. NDVI was to be accommodated as one of the variables of prime measurements and the study was to examine associations among NDVI and nitrogen application or nitrogen status or nitrogen use efficiency or yield performance. Research also had to give quantitative data or empirical findings. The studies that were not in the English language were excluded as well as those that were non-original and lacked empirical data like conference abstracts. We also discarded studies that were specifically dedicated to non-rice crops or failed to mention relations between NDVI and nitrogen. Researches whose methodology was not clear or that had no complete text were also eliminated.

2.3 Screening and Final Selection

A four-stage screening process was used in the review. Each stage was done by two reviewers, and any instance of disagreement was resolved by discussion. Stage 1 entailed implementation of search query in every database. This produced a total of 911 records of which 180 were obtained in Scopus, 601 in Web of Science and 130 in

ScienceDirect. The Stage 2 emphasized on eliminating duplicates and pre-screening records. At this point, we deleted 75 records and included 50 duplicates and 20 records that were indicated by automation tools as ineligible. The other 5 records were deleted on different grounds like retractions or a wrong match of keywords. This filtered off 399 distinct records to Stage 3. The two reviewers compared titles and abstracts with the criteria. Records were classified as include or exclude or uncertain. Cases of uncertainty were transferred to full text. At this point, we have filtered off 94 records which were evidently not meeting the criteria. This resulted in 70 reports being left to search full-text retrieval.

Stage 4 entailed the retrieval and evaluation of full-text articles. We accessed articles via institutional access. Out of 70 reports requested, we could not receive 10 reports because of access restrictions or non-availability. This left 60 complete texts to be analyzed. All the articles were read thoroughly and assessed to all standards. Following the full-text evaluation, 44 reports were eliminated. This was primarily caused by irrelevant focus in which 40 studies failed to substantially cover the NDVI-nitrogen relationships in rice. Furthermore, out of 30 reports, we could not access the full text even after multiple attempts. There were another 24 articles that were not English written. Other articles were omitted due to more than one reason which we only captured the major one. Having passed all the four filters, 13 studies were included in the final review after meeting all the inclusion criteria.

RESULTS AND DISCUSSION

Table 2. Summary of previous studies examining NDVI and SPAD applications for nitrogen status monitoring in rice systems from 2015 – 2025

Authors	Year	Crop / Experiment	Method / Tools	Key Findings	Limitations / Notes
Guan, S., et al.	2019	Rice	UAV (Parrot Sequoia multispectral) for high-resolution NDVI	Lots of correlation between NDVI and fertilizer levels and yield (R^2 about 0.601–0.809)	Spatial variability, need for calibration across fields
Shafiq, S., et al.	2025	Rice (Malaysian paddy)	NDVI and nitrogen rate experiments in Malaysian paddy fields	NDVI effectively detects nitrogen deficiency at different stages, with high correlation to rice yield performance. Spectral reflectance was used to determine optimal nitrogen rates for improved rice productivity.	Requires calibration for different rice varieties and field conditions.
Burns, B. W., et al.	2022	Maize (but comparative)	Remote sensing indices vs nitrogen deficiency assessments	NDVI and related indices effectively to detect nitrogen deficiency	Translational issues to rice systems; stage dependency of response
Yuan, Z., et al.	2016	Rice	SPAD chlorophyll meter (leaf position effects)	Most reliable readings from 2nd–4th fully expanded leaves; strong correlation with N uptake ($r = 0.88$)	Leaf position critical for accuracy
Carlos, G., et al.	2017	Brazilian crops (NDVI relevance to paddy)	UAV-based NDVI mapping	NDVI explained >70% variance in canopy vigor and N-related yield differences	Requires standardized monitoring frequency
Mohidem, N. A., et al.	2022	Rice (Paddy in Kedah, Malaysia)	Multispectral UAV for paddy growth monitoring	UAV-based NDVI mapping identified nitrogen deficiency in paddy fields, optimizing fertilizer application for improved crop yield predictions	Requires calibration for local field conditions

3.1 NDVI as an Indicator of Nitrogen Status

Vegetation Index has shown practical utility for nitrogen assessment in Malaysian paddy systems though its accuracy is limited by sensor type and environmental conditions. The superior performance of hyperspectral sensors is due to their broader wavelength range compared to Vegetation Index which relies on only two wavelengths (red and near-infrared). Recent Malaysian research has identified temporal instability in Vegetation Index measurements with values varying significantly by time of day due to changing solar angles and light

(Shafiq et al., 2025). Morning measurements produced different Vegetation Index values compared to midday readings from the same plots. This indicates that nitrogen status assessments could be inaccurate depending on when measurements are taken. The diurnal variation creates challenges for practical nitrogen management because farmers may take measurements at different times without following standard protocols. Dense canopies further complicate Vegetation Index measurements because leaf angles and shadowing effects change with sun position and reduce measurement reliability. Vegetation Index sensitivity also decreases in dense rice canopies particularly during active tillering stages in high-yielding varieties like MR303 that are widely grown in Malaysian paddy fields.

Malaysian paddy production requires integrated approaches rather than relying on Vegetation Index alone for nitrogen monitoring. Hyperspectral sensors capture more nitrogen-related information beyond the limited wavelengths used in Vegetation Index calculations. This integrated approach addresses both sensor limitations and temporal variability observed in Malaysian systems. Combining Vegetation Index with red-edge indices helps overcome saturation problems in dense canopies. Establishing standard measurement protocols with specific time windows such as 10:00-14:00 when solar angle is stable can reduce measurement errors (Shafiq et al., 2025). These integrated sensing methods are particularly useful in Malaysian paddy fields which typically consist of small, fragmented plots where traditional tissue sampling is labour-intensive. The year-round growing seasons in Malaysia also require multiple nitrogen applications making efficient monitoring essential. Future studies need to come up with Vegetation Index thresholds that are conditioned to the Malaysian varieties of rice and the local growing conditions. These thresholds ought to have correction factors of measurements time and growth stage and canopy density to enhance the accuracy of assessment of nitrogen and aid in the better determination of managing the use of fertilizers in Malaysia in the paddy production.

3.2 SPAD Measurements and Leaf Nitrogen Estimation

The use of chlorophyll meters SPAD offers a non-destructive technique of evaluating the nitrogen status of the leaves in rice. The studies indicate that the relationship between SPAD and Vegetation Index changes is significantly dependent on the growth stages. At the initial stages of vegetation, the relationship was relatively low with $r = 0.161$ and $r^2 = 2.6\%$ ($p = 0.066$) meaning that SPAD and Vegetation Index capture different features of nitrogen condition during fast canopy formations (Shafiq et al., 2025). At this stage, the individual leaf chlorophyll is not well correlated with the canopy level vegetation indices since the canopy cover is not complete and is interfered with by water background. Canopy structure stabilized and the relationship intensified to moderate values of $r = 0.713$ and $r^2 = 50.09\%$ ($p < 0.001$) (Shafiq et al., 2025). At the reproductive stages, the correlation $r = 0.739$ and $r^2 = 54.7\%$ ($p < 0.001$) indicated that the measurements of SPAD are closer to the values of Vegetation Index as rice matures. This gradual increase is achieved by the closure of the canopies and chlorophyll of the leaves becomes more reflective of the overall plant nitrogen conditions (Shafiq et al., 2025). Nonetheless the SPAD readings are highly influenced by both the environmental factors such as light condition and temperature. The studies indicate that the light-dependent chloroplast movement may lead to a reduction of SPAD values up to 13 percent at midday in low nitrogen conditions (Xiong et al., 2015).

The complementary relationship between SPAD and Vegetation Index indicates that combined methods are a better source of reliable nitrogen diagnostics compared to the two individual methods. The SPAD meters do a great job of identifying deficiencies in leaf levels at an early stage of growth when Vegetation Index is constrained by an unsaturated canopy cover. On the other hand, NDVI can be used in quick field-scale determination of object at the mid-to-late stages where the correlation is strong. It has been shown that at panicle initiation, Vegetation Index is strongly related to nitrogen uptake (r^2=2 0.66) and grain yield (r^2= 0.58) that makes this stage of growth highly important in the evaluation of nitrogen status (Rehman et al., 2019).

3.3 Camera-Based and Hyper Spectral Tools

Recent studies point at the effectiveness of camera-based technologies in tracking the availability of nitrogen. Unmanned aerial vehicles with low-resolution imaging can be used to monitor changes in the status of nitrogen and hence optimize the application of fertilizers. The results are supportive of the possibilities of sustainable rice production (Kim et al., 2019). Digital colour cameras that work under the natural lighting conditions can also estimate the chlorophyll content and nitrogen concentration with a reasonable measure of accuracy though with high consistency of light the measurements must be consistent (Wang et al., 2014). Spectral indices canopy height and phenological data collected using hyperspectral and UAV-based imaging have also been shown to be useful in forecasting rice aboveground biomass at various growth stages that have a relation between nitrogen availability and plant growth processes (Wang et al., 2022).

3.4 Malaysian Rice Production with Precision Agriculture Solutions.

The latest multispectral imaging study of Malaysian paddy fields has investigated the relationship between UAV-based Vegetation Index data and ground-based SPAD data, which is a valuable insight into the possibilities of precision agriculture solutions to optimize the use of nitrogen. In one study, a multispectral imagery with the UAV in a rice field in Jitra, in Kedah was conducted together with SPAD chlorophyll-meter measurements at 64 points. Nevertheless, the analysis revealed that Pearson correlation between UAV-derived Vegetation Index and SPAD values at the late vegetative state (47 days after planting) was very weak $r = 0.02$ ($p = 0.878$) indicating that there was no significance between UAV-Vegetation Index and SPAD relationship under the mentioned field conditions (Mohidem et al., 2022). This implies that at least in this instance of growth and in this paddy field setting UAV- Vegetation Index might not be a dependable measure of leaf chlorophyll or nitrogen condition.

Contrarily, another research used a single-sensor multispectral camera and has added machine learning tools to enhance the correlation between spectral indices and SPAD measurements. Their method showed a higher predictive accuracy, with R^2 values of about 0.85, 0.84 and 0.79 in training, validation and test sets respectively in predicting leaf nitrogen content by (Muliady et al., 2021). This implies that with the advanced modelling and a more controlled sensor configuration, multispectral imagery can also have a stronger correlation with SPAD readings. The different outcomes of both studies highlight that although UAV- Vegetation Index could be effective in paddy field monitoring, it may be necessary to further calibrate, adjust the sensors, and implement machine learning algorithms to provide high prediction accuracy of nitrogen status.

CONCLUSION

To sum up, this review indicates that Vegetation Index and SPAD chlorophyll meters are useful in enhancing the management of nitrogen in rice farming. Whilst Vegetation Index is useful in estimating the health of the canopy and its nitrogen level in large regions, SPAD offers accurate measurements of the chlorophyll content in the leaf, which helps in managing nitrogen application on a specific area. Nonetheless, there are still issues like sensor calibration, variability of the environment, and the necessity to have standardized protocols. Future studies in the area should be directed to the creation of calibration standards with various rice types, incorporation of other remote sensing technologies and application of machine learning to optimize the use of nitrogen. Finally, Vegetation Index and SPAD have the potential to enhance better and efficient ways of handling rice through its integration that can provide farmers with practical information on improved nitrogen management and improved crop yields under climate change.

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