Research Paper

**Hand-Held Optical Sensors for Optimizing Nitrogen Application and Improving Nutrient Use Efficiency**

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**ABSTRACT**

The traditional use of fertilizers as per the recommendations has some limitations as it does not consider the site-specific and timely application. In this practice, less emphasis was given to resource use efficiency which may leads to various problems related to non-judicious use of essential inputs and agricultural sustainability. In terms of fertilizer nitrogen application, there are various approaches available in resent day agriculture. Among them, site-specific nutrient management through variable rate application can be considered as an advanced method for optimization of nitrogen requirement in cereal crops. By using optical sensors like chlorophyll content meter and crop reflectance sensors, nitrogen can be optimized by application at right time in a right amount. These optical sensors work on the greenness of the leaf which is a directly related component of leaf nitrogen content. The threshold value given by these sensors called as chlorophyll Index value or Normalized Difference Vegetative Index (NDVI) can be considered to estimate the nitrogen deficiency or nitrogen sufficiency in plant tissue. The application of these sensors has a greater impact on resource conservation and precise application of nutrients. However, in developing countries like India, the economic viability and limitation of application of these sensors in small land holdings for fertilizer nitrogen management are still not adequately studied. The review article focuses on benefits of use of various hand-held optical sensors for optimizing N application and N use efficiency.

**HIGHLIGHTS**

- Hand-held optical sensors are important tools for precision nitrogen management in crops.
- Optical sensors-based nitrogen management improves nutrient use efficiency and agricultural sustainability.

**Keywords:** Cereals, Green seeker, SPAD, Crop Circle, NDVI, Chlorophyll content meter

In the present context of the intensification of agriculture, most of the farmers focus on high input farming practices to obtain the potential yield of crops. In developing countries like India, most of the farmers are of small land holders; however, they tend to apply nitrogenous fertilizer non-judiciously. Nitrogen (N), one of the important primary nutrients, has been considered as a major input in the modern agricultural practices (Kumar et al. 2022). Cereal crops are highly dependent on external fertilizer inputs with more concern to nitrogen application (Singh, 2018; Nduwimana et al. 2020; Shankar et al. 2020). Nitrogen has a significant role in crop growth, performance and productivity (Yadav et al. 2017). The new generation
high yielding varieties and hybrids of cereals are highly responsive to nitrogen application and the yields are affected by the amount and time of application (Wan et al. 2022). Based on the above fact, the crop growers aim to increase the yields by the application of more nitrogenous fertilizers in an unscientific manner that results in low nitrogen use efficiency (NUE) (Bage, 2008). Further, the most of the Indian farmers do not consider the NUE, soil health and ecological concern while applying excess quantity of N fertilizer (Sairam et al. 2023). The application of N fertilizer varies in developing countries as per the land holding size of the farmers (Ren et al. 2019). In India, the usage of N fertilizer by small (up to 2 ha), medium (2 to 10 ha) and large (above 10 ha) landholders is 148, 108.5 and 114.6 kg N/ha respectively (Agricultural census, 2016). In developing countries of the world, N fertilizer is managed by blanket application or standard recommended doses given by agriculturists by calibrating the crop response data with similar climate and lands collected for larger area (Ju et al. 2016). Such standard recommendations cannot consider the dynamic spatial variability of the soil resulting in under fertilization or over fertilization.

On the other hand, N fertilizer nitrogen management in cereals can be well optimized by observing the crop demand and supply during critical stages of the crop based on site-specific management (Ram et al. 2020; Siqueira et al. 2022). Site specific nitrogen management (SSNM) is an alternative approach for blanket recommendation of nitrogen, which can efficiently optimize N requirement by calculating the inherent soil fertility status and crop nitrogen requirement together (Bana et al. 2020). SSNM can recommend the variable rate application by considering the spatial variability of the field and manage N need of the crop throughout the growth stages.

To estimate the real time N requirement of the crop, it is essential to quantify the N concentration of the leaves by appropriate tools (Putra, 2020). The leaf N content is directly related to the chlorophyll content which is further responsible for the greenness of the plant (Zhang et al. 2022). In general, farmers consider the leaf greenness as a subjective indicator for N topdressing during mid-stage of the crop. These visual predictions may be influenced by various factors such as sunlight and may result in inaccurate decision. In this regard it can be informed that there are various optical sensors such as chlorophyll content meters, namely, Soil Plant Analysis Development (SPAD) 502 plus (Konika Minolta® Inc., Tokyo, Japan) and atLEAF (FT Green LLC®, Wilmington, DE, USA), and hand-held canopy reflectance sensors such as GreenSeeker (Trimble Inc., Sunnyvale, CA, USA) and Crop Circle (Holland Scientific® Inc., Lincoln, NE, USA) which have been developed during recent years (Singh and Ali, 2020). These optical sensors measure the visible and near infrared radiations, which are absorbed and reflected from crop canopies and expressed as Normalized Difference Vegetative Index (NDVI).

All these optical sensors work through principal of proximal sensing, when placed over the leaves or at a height of two meters from the canopy for prediction of vegetative index that guides to optimize the N application during mid-season (Singh et al. 2023). The present review emphasizes the usage of optical sensors and their application in major cereal crops for optimization of N requirement by adopting variable rate applications.

**Importance and role of nitrogen in plants**

Nitrogen plays an essential role in agriculture in enhancing the crop productivity and food supply (Singh et al. 2023). Many crops, including cereals, depend on nitrogen for growth, development and yield. For increasing plant growth, nitrogen is a vital nutrient that enhances plant biomass by stimulating cell division and elongation (Luo et al. 2020). Nitrogen is crucial component of chlorophyll, the pigment in charge of absorbing light energy during photosynthesis (Toth et al. 2002). Nitrogen is responsible for vegetative growth, improving the leaf area index, chlorophyll synthesis, and so on; thus, increasing photosynthesis and assimilate production in plants. N is deficient in most of the rice-growing areas, which requires a proper focus on nitrogen nutrition (Fageria and Baligar, 2013; Muhammad et al. 2021; Shankar et al. 2021). In cereals, nitrogen is essential component for protein synthesis (Wan et al. 2023). Nitrogen fertilizer affects the nitrogen metabolism enzyme and the key regulatory factors, which further regulate grain storage protein synthesis, and this induces the balance changes of grain storage substances and further regulates the grain quality (Wang et al. 2021).
When N content of soil rises, the aboveground crop biomass normally increases. On the other hand, if N supply in soil is insufficient to meet the crop demand, biomass may decrease due to N deficiency. N accumulated in crop biomass is divided into grain and stover. Under excess supply of N to cereals may lead to yield decrease because of improper conversion of source to sink with luxury N intake (Krupnik et al. 2004). During the reproductive stage of crops, an adequate N supply encourages the synthesis of grain storage proteins in reproductive parts that may result in larger and better-quality grains (Shen et al. 2022). N deficiency may hamper grain filling and finally, reduce crop yield in cereals (Lemaire and Gastal, 2009). The production and grain quality of crops can be significantly impacted by the nitrogen availability (Simic et al. 2020). The best nitrogen fertilization practice can greatly raise the crop productivity by promoting plant growth, photosynthetic rate and dry matter accumulation and proper partitioning of assimilates (Asraf et al. 2016). Additionally, nitrogen influences grain quality such protein concentration, starch composition, and nutritional value (Omar et al. 2022). Nitrogen shows a synergistic effect with most of the essential nutrients and its presence in optimum in soil as well as in plant tissue enhances the availability and uptake of other elements (Aulakh et al. 2005). By facilitating effective nutrient uptake and reducing nutrient imbalances or deficiencies, N improves plant growth and development. A balanced supply of nitrogen helps maintaining an ideal nutritional balance of the crop.

**Development of optical sensors for nitrogen management in cereals**

Use of optical sensors for nutrient optimization in cereal crops is a recent advancement (Singh et al. 2021). In the last few decades, various sensors have been developed through proximal sensing which works on absorption and reflection of light over crop canopy (Table 1). Chlorophyll meters can be used to evaluate the N status of a crop, however, there may be variance in the link between SPAD readings and leaf N content due to differences in the weight or thickness of individual leaves (Shen et al. 2022). Other variables that may influence on the SPAD reading of leaf N status includes crop growth stage, cultivars, environmental and stress factors because of either excess or deficit water conditions, a lack of nutrients (other than N), and pests and diseases (Padilla et al. 2018). Chlorophyll meter readings and leaf N status have often been found to be linearly related in most of the crops. Numerous studies have examined the use of chlorophyll meters with different crop species, mostly with cereals like maize and wheat, since they were developed for the purpose of monitoring the N status of rice in the early 1980s. The majority of studies used transmittance-based chlorophyll meters. The popularity of fluorescence-based chlorophyll meters was recently gained the popularity (Kalaji et al. 2018).

Generally, chlorophyll meter readings were substantially correlated with leaf and crop N contents, with better correlations being found when employed for individual cultivars in a specific region of study (Muhammad et al. 2021). Numerous studies were documented linear connections between crop or leaf nitrogen content and chlorophyll meter readings for measurements taken at specific times or growth stages. However, other investigations noted a plateau response, where the linear connection appears to “flatten out” at somewhat large nitrogen

**Table 1: Innovation of optical sensors for precision nitrogen management**

<table>
<thead>
<tr>
<th>Year</th>
<th>Optical sensors</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>SPAD chlorophyll meter (transmission of 650, 940 nm) for estimating crop nitrogen requirement by using threshold value</td>
<td>Turner and Jund, 1992</td>
</tr>
<tr>
<td>1996</td>
<td>Canopy reflectance sensor (reflectance of 671, 780 nm) for optimization of variability in plant nitrogen</td>
<td>Stone et al. 1996</td>
</tr>
<tr>
<td>2002</td>
<td>Green Seeker canopy reflectance sensor (reflectance of 650, 770 nm) for real time detection NDVI.</td>
<td>Raun et al. 2002</td>
</tr>
<tr>
<td>2004</td>
<td>Crop Circle canopy reflectance sensor (reflectance of 590, 880 nm or 670, 730, 780 nm)</td>
<td>Holland et al. 2004</td>
</tr>
<tr>
<td>2012</td>
<td>At LEAF chlorophyll content meter (transmission of 660, 940 nm)</td>
<td>Zhu et al. 2012</td>
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Concentrations. Similar plateau responses were observed at high leaf chlorophyll concentrations. There was persistent evidence that at high nitrogen and chlorophyll levels, chlorophyll meters can partially saturate (Huang et al. 2021). To the contrary, linear relationships between chlorophyll meter readings and leaf chlorophyll or leaf or plant nitrogen content were frequently found instead of the partial saturation response (Javaid et al. 2023). Wheat and maize were used in most studies. NDVI was one of the most popular vegetation indexes for crop nitrogen management (Hawkins et al. 2007). Proximal canopy reflectance sensors were widely used to apply variable rates of nitrogen fertilizer to cereal crops.

**Chlorophyll content meters**

Chlorophyll meters, which assume the relative chlorophyll concentration per unit of leaf surface area, are the first group of optical sensors to be researched to manage the topdressing of nitrogen to the crop (Monje et al. 1992). As most of the nitrogen in leaves is found in the enzymes and used in photosynthesis, chlorophyll is a nitrogen sensitive substance that is closely tied to the amount of nitrogen in leaves (Kim et al. 2006). Most of the chlorophyll meters are portable instruments that clip onto leaf or positioned near the leaf surface to obtain the greenness index (Kamarianakis and Panagiotakis, 2023). Chlorophyll meters quantify the amount of nitrogen that is closely related to the amount of chlorophyll present. Chlorophyll meters help farmers to assess and improve the management of nitrogen in plants and estimate the health of the plants by measuring the greenness of the leaves (Widjaja-putra and Soni, 2018). To determine the amount of chlorophyll present, these optical electrical instruments can measure the light that penetrates a leaf or the light that is reflected from its surface (Moya et al. 2004). Commercial chlorophyll meters, however, typically cost more amount, making them inaccessible to farmers, crop researchers, and communities lacking in resources, in general, as well as growers and common citizens interested in self-cultivation (Khan et al. 2020). Some of the commercially available transmittance-based chlorophyll metres are T SPAD-502 and N-tester, which are nearly identical, the more recent and affordable at LEAF+ sensor, or the MC-100 Chlorophyll Concentration Metre are a low-cost chlorophyll metre based on light-to-voltage measurements of the leftover light after two LED light emissions passed through a leaf is conceived, built, evaluated, and compared against the chlorophyll index (Padilla et al. 2018).

Further, it was proposed that SPAD meter readings might be utilized to estimate the fertilizer N requirements of cereal crops because they had a strong correlation with the rate of applied fertilizer N and leaf N concentration (Wan et al. 2022). SPAD meter accurately predicts the response of fertilizer N with lower error rate compared to N determination in leaf samples. There is a key SPAD value also called as threshold values for most of the cereal crops, that may be used to differentiate between responsive and non-responsive locations, and as a result, SPAD metres can be used to determine whether to apply or not to apply N fertiliser (Ali, 2020). There are two types of radiations used in chlorophyll meters such as red radiation which is absorbed by the chlorophyll and another one is near infrared (NIR) radiation, which is transmitted by the chlorophyll (Fox et al. 2008). Higher chlorophyll metre value results in increased red radiation absorption as chlorophyll concentration rises (Hu et al. 2011). The ratio of the chlorophyll fluorescence emission of red and far-red radiation is a different method of determining the relative leaf chlorophyll content (Yang et al. 2020). The ratio of red to far-red chlorophyll fluorescence is mostly dependent on the chlorophyll content; as chlorophyll content increases, this ratio falls due to red chlorophyll fluorescence being reabsorbed by the leaf (Buschmann, 2007). Fluorescence-based chlorophyll metres are the name given to the sensors that make use of this strategy. The Multiplex sensor such as Dualex is one such example with is having a potential use in crop nitrogen management fluorescence index (Tremblay et al. 2012). There are currently a number of commercially available chlorophyll metres, and they vary from each other in terms of different measuring principles that is transmittance versus fluorescence, the wavelengths used, the measurement units, and the calibration equations used to transform electrical signals into measurement units (Taskos et al. 2015). Comparisons between measurements taken with various chlorophyll metres are made more difficult by this diversity of methods. Numerous
investigations revealed that there were significant curvilinear connections between chlorophyll metre readings and the extractable chlorophyll concentration readings at high chlorophyll content (Uddling et al. 2007). The chlorophyll meter readings are unit less and exposed to large changes because of variables other than nitrogen status (Zhang et al. 2022). As a large portion of the nitrogen in leaves is found in chlorophyll metres such as the SPAD metre, have found useful in predicting the need for supplemental nitrogen in cereals like rice, maize, and wheat. There are differences with regard to the methods for assessing the N status of leaves using chlorophyll metres on which leaf to measure and which area of the particular leaf should be measured to estimate leaf N status from crop to crop. For example, in maize, during early vegetative stage, the readings are recorded from uppermost leaf (Ziadi et al. 2008). After the crop reached the tasselling stage in maize, readings with a SPAD metre were taken from the ear leaf (Hawkins et al. 2007). However, after silk emergence, chlorophyll N content in the first fully expanded maize leaf from the top was decreased. But the ear leaf’s chlorophyll concentration, either increased or remained constant in middle leaves (Singh et al. 2021). Additionally, SPAD measurements in maize and have been done at one-quarter, two-thirds, or halfway between the leaf tip and the stalk from the leaf tip towards the stem. Similarly in rice, it is standard practise to collect SPAD measurements on the topmost fully expanded leaf to determine the leaf’s N status. Additionally, it has been recorded that lower leaf SPAD values have a stronger correlation with the total N in the plant’s leaves (Singh et al. 2021). Therefore, the lower, biologically older leaves’ SPAD readings were more responsive to fertiliser N rates than the top, younger leaves.

**Crop reflectance sensors**

The use of proximate reflectance sensors such as green seeker has been subjected to extensive research over past two decades for crop nitrogen management (Diacono et al. 2013). The visible and NIR spectral reflectance from plant canopies is measured by canopy reflectance sensors, and the results are interpreted in terms of nitrogen stress (Daughtry et al. 2000). Between 70% and 90% of all incident light in the red wavelength bands is absorbed by the chlorophyll found in leaves, which controls the reflectance of visible light (Gitelson et al. 2003). The structure of mesophyll tissues controls the reflectance up to 60% of the incident NIR radiation (Xu and Ye et al. 2023). By monitoring wavelengths of radiation absorbed and reflected from foliage of the crop, reflectance sensors can provide information on the crop’s nitrogen status. Sensors are placed quite close to the crop in the proximal canopy reflectance i.e., 0.4–3.0 m from the crop canopy (Singh et al. 2021). When compared to N-sufficient crops to N-deficient crops, the N-deficient crops typically reflect more visible light and less NIR light. Wavelengths chosen for N assessment were picked because of their sensitivity in changing the biomass, leaf density, and chlorophyll status that come along with N deprivation (Kalaji et al. 2018). Based on their importance, these typically categorized into four distinct narrow bands and they are 675 nm (red absorption maxima), 905 nm (NIR reflection peak), 720 nm (mid-section of the red-edge), and 550 nm (green reflectance maxima) (Ulissi et al. 2011). The calculation of spectral vegetation indices, which include spectrum reflectance from 2-3 wavelengths, increases the sensitivity to a particular biophysical parameter and decreases variability (Zeng et al. 2022). Probably, the most popular is the Normalized Difference Vegetation Index (NDVI) (Huang et al. 2021). There are several indices that can differentiate between vegetation and soil, such as the Soil Adjusted Vegetation Index (SAVI), although the simple ratio indices and many normalized indices must be assessed directly on the crop canopy (Rhyma et al. 2020).

Depending on their own light source, reflectance sensors are of two types, namely, passive sensors and active sensors (Kipp et al. 2014). The majority of passive sensors have two sets of photodetectors, one measures incident radiation above the crop canopy and the other detects radiation reflected from the canopy (Loayza et al. 2023). The sensor uses the measurement of incident radiation to take various irradiance circumstances into account when in use. Modern active sensors have a light source that produces both NIR and visible light. Active sensors can be employed in all irradiance situations because they can discriminate between reflected radiation from their own light source and that obtained from ambient radiation by regulating the
light source (Akselrod et al. 2006). The active sensors include several Crop Circle and GreenSeeker sensors, as well as the N-Sensor ALS (Erdle et al. 2011). The Crop Circle and GreenSeeker sensors are available in a variety of models, with simpler, less expensive, and hand-held versions that are ideal for manual use with cereal crops (Samborski et al. 2009). The more costly types can typically be used for continuous data collection, for which they are frequently installed on tractors and connected to GPS systems for field mapping (Waqas et al. 2023). The application of mineral fertilizer at an automatic variable rate is the primary use for field installed crop canopy sensors.

**Fertilizer N management using chlorophyll content meters**

Chlorophyll meter is used to monitor status of nitrogen in the crop and increase nitrogen use efficiency (Yadav et al. 2017). The management of nitrogen fertilizer in crops can be done using at two different types of portable chlorophyll meters. The most popularly used is Soil Plant Analysis Development (SPAD) 502 Plus chlorophyll meter that measures chlorophyll concentration by measuring light transmittance through the leaf at 650 and 940 nm (Putra, 2020); while the SPAD meter utilizes a wavelength of 650 nm. The recently developed at LEAF chlorophyll meter uses 660 nm wavelength. Readings from an at LEAF chlorophyll meter are comparable to those from a SPAD meter, although the at LEAF chlorophyll meter is less expensive (Brown et al. 2022). Most of the research covered using of hand-held Minolta SPAD-502 chlorophyll meter, which continues to be the most used chlorophyll meter for nitrogen management in cereals (Bana, et al. 2020). N-Tester, is one of the modified SPAD-502 chlorophyll meter, mostly used in Europe to manage nitrogen fertilizer in field crops (Arregui et al. 2006). There are two main categories of research aimed to enhancing N use efficiency with chlorophyll meters: (i) establishing and evaluating the association between chlorophyll meter readings and the nitrogen content of leaves; and (ii) determining the relationship between chlorophyll meter readings and the fertilizer N dosages to be top dressed in field crops (Zhu et al. 2012).

**Fertilizer N management using crop canopy reflectance sensors**

For precise N management, estimation of nitrogen status in crops is essential. There are various crop reflectance sensors available to estimate the greenness index of the crop. GreenSeeker is one of the mostly used crop reflectance sensor to estimate the relative greenness of the leaf which was given as NDVI. The Crop growth status reflects soil nitrogen availability and crop nitrogen demand (Li et al. 2010). Therefore, the nitrogen need of the crop is frequently determined using estimates of the projected yield. Based on the anticipated yield and crop N status, active canopy reflectance sensors can aid in determining the nitrogen rate for fertilizer during the growing season (Siqueira et al. 2022). For an algorithm to easily understand sensor measures in terms of the crop’s need for fertilizer N at the sensed growth stage, relationships between sensor measurements and crop N status as well as projected yield of the crop must be created. For non-invasive ways to optimize nitrogen fertilization and to lower the environmental concerns related to improper use of fertilizer N, the precise prediction of N uptake is crucial (Xiong et al. 2019).

**Use of Absolute Sufficiency Values for Crop N Management**

Utilising the absolute sufficiency values of optical sensor measurements is an alternate method to get over the drawback of reference plots in the absence of saturation (Pacifici et al. 2008). Absolute sufficiency values for sensor measurements make a distinction between deficiency (below the value), sufficiency (around the value), and excess (above the value) (De Souza et al. 2019). Absolute sufficiency values can be connected to the cumulative thermal time and phenological phases to offer flexibility regarding planting dates, cropping cycles, and location (Padilla et al. 2015). The use of optical sensors is facilitated by sufficiency values for phenological stages since measurements may be linked to clearly distinguishable crop development stages (Liebisch et al. 2015). The drawback of using chronological age is that it ignores variations in crop development brought on by various
growing environments during each crop cycle. The uncomplicated management of crop N may be made easier using absolute sufficiency values (Ransom et al. 2019). Adjustments to N fertiliser management should be performed as soon as optical readings depart from absolute sufficiency levels to account for suboptimal crop N status. This can be accomplished using a semi-quantitative method by making modifications (adding more or less N) to an earlier schedule of N fertiliser applications (Vaccaro, 2023). This scenario serves as an illustration of prescriptive-corrective N management. The cultivar and growing circumstances may have an impact on how absolute sufficiency measurements are used for crop N management with optical sensors (Solie et al. 2012). To validate sufficiency values with various cultivars and growing conditions, additional research is need to be carried out with crop and climate specific conditions for better precision of nitrogen application.

Limitations on application of smart tools in Indian agriculture

There are still several restrictions that need to be considered when using smart precision nutrition tools in India, even though smart tools and technology have the potential to revolutionize many things in agriculture (Bhat and Huang, 2021). A fundamental obstacle to the widespread use of smart tools in agriculture is the lack of straightforward solutions. Smart tools have a high initial investment. Small-scale farmers, especially those in developing nations like India, may find it difficult to invest in the costly machinery or technologies needed for smart farming (Mizik, 2023). Many farmers may find the cost of sensors and other smart equipment to be expensive, which hinders their adoption for best performance. Further, a smart equipment frequently needs a dependable internet connection (Qu et al. 2022). However, in rural locations, poor connectivity may obstruct real-time data transfer, which is necessary for smart instruments to function effectively. In the developing countries, most of the farmers do not have digital expertise to independently work with smart tools. Farmers lack technical understanding and are ignorant of such technology, especially those in rural areas. The latest farming technologies in agriculture may flourish as knowledge grows and technologies are more readily available to the common farmer with smart tools driving the change (Javaid et al. 2023). Farmers must possess a particular level of technical knowledge and proficiency to successfully deploy smart instruments in crop production (Srivetbodee and Igel, 2021). For farmers who are unfamiliar with the technology or do not have access to training programmes, that can be a barrier to technology transfer (Kuhl, 2020).

CONCLUSION

Over use of fertilizers like nitrogen can result in various problem associated to soil degradation, contamination of water bodies through nitrate accumulation and volatilization of ammonia in to atmosphere. Optimization of fertilizer nitrogen can be easily achieved by site-specific approach. Variable rate application by using optical sensors can be an alternative for blanket application in which the required amount of nitrogen can be applied in more splits as per the crop requirement. Application of optimized amount of nitrogen in more splits can be more productive in terms of crop growth and productivity than compared with excess application of nitrogen. The hand-held optical sensors can provide the real time plant nitrogen status in an instant manner which can help crop growers to apply the nitrogen in a précised manner at the critical time of crop requirement.

REFERENCES


Sairam et al.


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