International Journal of Bioresource Science
Citation: IJBS: **12**(01): 135-146, June 2025
DOI: 10.30954/2347-9655.01.2025.15

ASSOCIATION FOR AGRICULTURE ENVIRONMENT AND BIOTECHNOLOGY

REVIEW PAPER

Optical Sensing and Site-Specific Nutrient Management for Sustainable Precision Agriculture

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Received: 23-02-2025 **Revised:** 08-05-2025 **Accepted:** 22-05-2025

ABSTRACT

Precision agriculture integrates artificial intelligence (AI) with other modern technologies such as site-specific nutrient management and optical sensing to optimize the yield and efficiency of resources. The technologies efficiently apply fertilizers, where the instances of proper adjustment of fertilization occur in response to real-time information about crop and soil health, hence enhancing sustainability while reducing negative environmental effects and endorsing the global approach to the resolution of food security and climate change issues. Through optical sensing, farmers can make data-driven decisions delivering actionable insights on parameters such as soil moisture or nutrient levels from real-time data. The application of nutrient inputs in particular ways concerning the actual conditions in specific field zones is site-specific nutrient management (SSNM). While promoting good resource management and environmental stewardship, the combination of strategies ensures that global Sustainable Development Goals (SDG) such as Zero Hunger and Climate Action are pursued. Technological difficulties, high initial cost, and limited access for smallholder farmers must be solved for widespread acceptance of these technologies in large scale. Possible solutions to these problems are reviewed within the assessment, including advances in AI, internet of things (IoT) applications, and legislative support for enhancing the accessibility of these technologies. This amalgamation delivers solutions to prominent issues such as food security and climate change, which may assist in establishing sustainable agriculture. Future research should focus on removing adoption hurdles and improving the scalability of these systems.

HIGHLIGHTS

- Enhancement of nutrient use efficiency ensures higher crop productivity.
- Precision nutrient management tools can optimize nutrient needs of crops for yield enhancement.

Keywords: Optical sensors, nutrient use efficiency, climate-smart agriculture, crop productivity enhancement, SDG

Increasing urbanization, shrinking land availability, and the depletion of natural resources have posed an incredible challenge to agricultural activity; thus, it becomes more and more difficult to feed the growing population in the backdrop of climate alterations change (Das *et al*. 2021; Gaikwad *et al*. 2022; Sairam *et al*. 2023 a,b; Santosh *et al*. 2024; Ray

How to cite this article: Ray, S., Hemasree, K.R., Maheswari, N., Maity, B., Sairam, M., Santosh, D.T., Sagar, L., Gitari, H.I. and Maitra, S. (2025). Optical Sensing and Site-Specific Nutrient Management for Sustainable Precision Agriculture. *Int. J. Bioresource Sci.,* **12**(01): 135-146.

Source of Support: IUCEA; **Conflict of Interest:** None

et al. 2024; Pattnayak *et al*. 2025a,b; Maitra 2025a). Agricultural sustainability in such a bleak scenario needs climate-smart crop production systems, better agronomic management, and the growing of environmentally strong crops (Santosh *et al*. 2023; Mukesh *et al*. 2024; Maitra,2018; Maitra *et al*. 2023a; Ray *et al*. 2024; Sairam *et al*. 2024; Hemasree *et al*. 2025). One of the commonly followed cropping systems in Indian agriculture involves growing grains and legumes, and the system can contribute sustainably to solving the difficult problem of providing subsistence to the rapidly growing population (Hossain *et al*. 2021; Maitra *et al*. 2023a,b; Priya *et al*. 2023; Maitra *et al*. 2019; Maitra *et al*. 2021; Maitra and Ray,2019). This problem has to be addressed by using the scientific knowledge and technological developments that have been accumulated over time. These developments include precision farming techniques incorporating tools such as optical sensors and site-specific nutrient management (SSNM) for better resource utilization (Maitra *et al*. 2024; Sairam *et al*. 2023c). Optical sensing and SSNM are precise methodologies to increase nutrient use efficiency, crop yields and agricultural sustainability (Chivenge *et al*. 2022).

Optical sensing technologies are a set of devices and techniques that facilitate the measurement of the crop health system along with various environmental parameters through light. These sensors have become increasingly popular as they provide farmers with real-time data regarding soil moisture, soil nutrient status, and plant health so a more purposeful decision regarding crop management could be taken (Zhang *et al*. 2020). The farmers use these data to tailor fertilizer applications to the crops' specific needs given optical sensing and SSNM, thereby, optimizing input use and reducing the environmental impact (Raj *et al*. 2024). Hence, the integration not only gives sustenance to increased agricultural production but also supports global efforts toward achieving certain United Nations Sustainable Development Goals (SDGs), including Goal-2: Zero Hunger, Goal-12: Responsible Consumption and Production, and Goal-13: Climate Action (Maitra *et al*. 2025b). Sustainable agricultural practices are widely recognized to be the foundation for food security along with reducing unfavourable environmental effects. Traditional nutrient management systems mostly involve blanket fertilizer applications of nitrogen, which often lead to nitrogen imbalances, soil degradation, and runoff contaminating water (Sairam *et al*. 2025a; Ray *et al*. 2025a; Bora, 2022).

In contrast, SSNM focuses a bit more on a careful application of nutrient inputs and a thorough evaluation of the soil and crop requirements, thus improving efficiency in the use of nutrients, maintaining the long-term sustainability of soil health by reducing the use of chemical fertilizers, and enhancing agricultural sustainability (Santosh *et al*. 2024). Furthermore, the stimulus of adding the optical sensing apparatus to SSNM, the farmer will derive in-depth knowledge of the dynamic interactions between crops, soil, and nutrients; this knowledge can be used to develop better and more effective management approaches (Maggioni *et al*. 2019). The amalgamation of optical sensing with SSNM holds much promise for addressing concerns posed by climate change (Pramanick *et al*. 2024). Climatic unpredictability is impacting the agricultural production system, hence making it all others important for crop health and fertilizer requirements to be recorded in real time (Swathy *et al*. 2024). Optical sensors will provide vital data about crop stress arising from environmental variables such as drought, nutrient deficit, or insect pressure, enabling farmers to respond from an informed position while adjusting their management planning (Ray and Masina 2024; Zhou *et al*. 2019; Priya *et al*. 2025). With these technologies, farmers will not only mitigate the negative impacts of climate change but facilitate sustainable and climate-smart agriculture.

Despite the clear benefits of integrating optical sensing and SSNM, there are many barriers to implementation across all scales (Santosh *et al*. 2022). There are technical barriers, as sensor technologies and data management systems are technical and can be a challenge to farmers applying them independently (Ndufa *et al*. 2021). There are also economic barriers, meaning that farms that need the technology the most may not have access to the technology. This is particularly salient for smallholder farmers. Researchers, policymakers, and industry stakeholders need to collaboratively find solutions to increase the use of these technologies that support precision agriculture and benefit all agricultural producers, regardless of scale (Sairam *et al*. 2023c, Javaid *et al*. 2022). This review explores the simultaneous dynamic of optical sensing about SSNM, examining the current state of technology, successful applications, and future opportunities for exploration and implementation (Sairam *et al*. 2025). This review also addresses the potential for utilizing both approaches to create sustainable agricultural practices that increase production while enhancing environmental stewardship and social equity. The goal of this paper is to provide a comprehensive review of the barriers and opportunities related to the integration of these two approaches and to contribute to the broader discussion of sustainable agriculture as a response to global issues.

Optical Sensing Technologies

Optical sensing technologies consist of equipment and techniques that utilize the electromagnetic spectrum to gather information on different crop and soil parameters. Optical sensing technologies are experiencing rapid developments which have provided farmers with new levels of visibility of their land (Kganyago *et al*. 2024). Different types of optical sensors serve very different purposes in agriculture, which may potentially help farmers to make appropriate decisions. Optical sensors are a broad set of technologies associated with precision agriculture; each being used to leverage insights related to crop health and management in some unique way (Rajak *et al*. 2023). Reflectance sensors can provide some critical information on indicators such as chlorophyll content and leaf area index; all of which can help verify plant types, vigour and or stress due to nutritional deficits, insect damage, or disease (e.g. green seeker (Fig. 1), SPAD meter (Fig. 2) by using sensors that capture reflected light at specific wavelengths (Zhang *et al*. 2020). Fluorescence sensors measure lights emitted by plants when they absorb sunlight, and they are useful for detecting the kind of stress reactions and nutritional deficits that can't be seen by the human eye. For example, changes in chlorophyll fluorescences may indicate water stress before crop loss from the drought becomes so severe that it leads to irreversible damage. (Wang *et al*. 2018).

Advanced technologies such as multispectral and hyperspectral imaging systems make it easier to perform complete plant health assessments. Multispectral sensors measure distinct wavelengths while hyperspectral sensors measure continuous spectral channels over a larger spectrum that can detect small differences in plant conditions (Lu *et al*. 2020). This technology has become more scalable because of the access to drones and satellites that allow for the use of these sensors to collect spatial information about crop conditions at a whole field level (Liu *et al*. 2020). There are many advantages to using these optical sensing systems. For example, instant and accurate monitoring of crop conditions allows producers to respond quickly to ameliorate

Fig. 1: Green Seeker

Fig. 2: SPAD meter

a potential loss. Several studies have shown the ability to increase yield (Table 1) while decreasing input costs through enhanced nutrient application through optical sensing. Mulla (2016) showed that farmers use of optical sensing technology, increased their average productivity by 10-15% compared to farmers that relied on conventional management practices. These sensors can also help facilitate environmental sustainability through the elimination of excess fertilizer and pesticide use. Timely crop health data enables farmers to only use inputs when they are realistic, eliminating the chance to risk excess applications, which can cause runoff and water contamination.

This targeted strategy will not only enhance fertilizer use efficiency but also broader environmental aims such as soil and water conservation (Zhang *et al*. 2020: Ray *et al*. 2021b). In addition to optical sensing technologies, decision support systems can also revolutionize agricultural practices. These systems can interpret and analyze information acquired from optical sensors, providing relevant data so that farmers can make even better decisions (Padhiary *et al*. 2024). Farmers can design tailored irrigation (Ray *et al*. 2024) and fertilization plans to meet crop needs by synthesizing sensor data with weather trends and historical crop yields, ultimately leading towards more sustainable and productive agricultural systems.

Site-Specific Nutrient Management (SSNM)

Site-specific nutrient management (SSNM) is a holistic approach to nutrient management that acknowledges the inherent spatial variability of agricultural fields (Chappa *et al*. 2023). SSNM considers the specific needs of varying areas, while conventional methods apply a standard fertilizer application across the whole field. This makes use of inputs that are tailored to the differing requirements of each area improving efficiency while ensuring sustainability (Srivastava *et al*. 2014). Some of these include leaf colour charts (Fig. 3.), STCR etc. SSNM strategies derive from the understanding that soil fertility and crop nutrient requirements can be heterogeneous even within a single location as soil texture, concentration of organic matter and past usage of the land can markedly impact nutrient availability and crop yield (Gudla *et al*. 2023 b: Santosh *et al*. 2021: Srivastava *et al*. 2014). The use of SSNM strategies allows farmers to use fertilizers efficiently taking into account specific characteristics of their fields and leads to greater yields whilst reducing waste and limiting environmental effects (Fageria *et al*. 2016). SSNM strategies mostly require several key components, including soil testing, crop monitoring and qualified data analysis (Koley *et al*. 2024). Soil testing is an important part of understanding nutrient levels and overall soil health. Recent advancements in technology have

Table 1: Effect of optical sensor on crop yield

Sl. No.	Optical sensor	Crop	Result	Reference
1	Leaf colour chart (SI-based nitrogen management)	Rice	SI-based nitrogen (N) management, along with recommended amounts of phosphorus and potassium, recorded the highest grain yield (5335 kg ha^{-1}) compared to control (2715 kg ha^{-1})	Sagar *et al*. (2023)
2	Green seeker	Rice	SSNM consisting of 20 kg N ha^{-1} as basal along with application of 20 kg N ha^{-1} as per Green seeker value (> 1.25 Response index) combined with phosphorus and potassium based on soil test recommendation, produced the maximum grain yield (5.74 t ha^{-1}).	Sahoo *et al*. (2022)
3	NDVI and chlorophyll meter	Rice	Basal application of 30 kg N ha^{-1} and topdressing of 20 kg N ha^{-1} guided by NDVI threshold value of 0.8 was superior in grain yield (4438.6 kg ha^{-1}). N [basal and SPAD threshold level of 37.5] has recorded the grain yield (4143.8 kg ha^{-1})	Saishree *et al*. (2023)
4	SPAD	Rice	SPAD guided N application with 25 kg N ha^{-1} as basal recorded the grain yield (5.61 $Mgha^{-1}$)	Baral *et al*. (2021)
5	SPAD based N management	Maize	Enhances maize yield and saves 30-45 kg N ha^{-1}. Improves the chlorophyll content of soybean	Edalat *et al*. (2019)

permitted real-time soil analysis to allow the farmer to make informed, data-driven fertilizer application decisions. This data-driven approach is important in increasing fertilizer efficiency and lowering costs while minimizing environmental impacts.

Fig. 3: Leaf color chart

An important benefit of SSNM is its ability to improve crop yields (Table 2). Ndufa *et al.* (2021) indicated that SSNM farmers demonstrated up to 20% increased yields relative to farmers using generalized blanket rates of fertilizer to determine their rates of application. This astounding increase can be attributed to the precise determination of fertilizer rates based on crop needs, which ensures that plants receive necessary nutrients at the appropriate growth stage. Besides enhancing crop yields, SSNM enhances environmental sustainability, through decreased fertilizer runoff and levels of soil degradation (Pampolino *et al.* 2006). Traditional agriculture is plagued by too much fertilizer application, resulting in water quality and soil health issues. Implementing SSNM can help farmers reduce the amount of excess fertilizer input, thus reducing pollution issues while creating a healthier soil ecosystem (Manasa *et al.* 2021; Maggioni *et al.* 2019). Sagar *et al.* (2023) showed that while using crop nitrogen management

Table 2: Effect of SSNM on crop yield

Sl. No.	Site specific nutrient management	Crop	Result	Reference
1	Leaf colour chart	Maize	Nitrogen application (200%) along with optimum phosphorous and potassium (100% each) has recorded the highest grain yield two years 2021-22 (7850 kg ha $^{-1}$), 2022-23 (7900 kg ha $^{-1}$) compared to control of maize.	Sairam *et al.* (2023c)
2	Site specific nutrient management (225:60:80 kg/ha of N-P_2O_5-K_2O) over state recommendation and STCR	Maize	The grain and straw yields of maize were the highest with the application of SSNM which was 19.3 % higher over state recommendation and 12.0 % over STCR practice, respectively.	Singh (2016)
3	Integrated nutrient management	Rice	The crop fertilized with the combination of NPK @ 60:30:30 + ZnSO4 @ 25 kg ha^{-1} recorded the highest seed yield of 3.96 t ha^{-1} followed by dose of NPK @ 80:40:40 kg ha^{-1} (3.71 t ha^{-1}).	Mondal *et al.* (2019)
4	Primary nutrients on nutrient use efficiency	Maize	The incorporation of rice straw at the rate of 2 t ha^{-1} with 100 % RDF has recorded the highest grain yield (6354 kg ha^{-1}) compared to the control (2408 kg ha^{-1})	Raghava *et al.* (2024)
5	Site specific nutrient management	Maize	NE-based nutrient management for a target productivity for 10 t ha^{-1} has recorded the highest grain yield (7065 kg ha^{-1})	Krishna *et al.* (2024)
6	Point placement of N fertilizer	Wheat	Increased grain yield of wheat 10%-12% compared to surface application	Nayak *et al.* (2022)
7	Precision nitrogen management STCR	Maize	Based on STCR based NPK management for target of 11 t ha^{-1} recorded the grain yield (110.46 q ha^{-1})	Prakash *et al.* (2020)
8	Sensor-based irrigation and depletion of available soil moisture (DASM)- based irrigation schedule	Sugarcane	Sensor-based drip irrigation at 125% ETC along with 100% water soluble fertilizer enhanced cane yield. Irrigation at 75% field capacity improved photosynthetic performance and energetics of soybean	Anjaly *et al.* (2024)

techniques based on site-specific information, with a total of 150 kg of nitrogen per hectare split into four application splits (the basal, 28 days after transplanting, 42 days after transplant, 63 days after transplant) while using average values of phosphorus and potassium, that yield a grain yield increase of 16.68% and a biological yield increase of 13.17% in rice.

Additionally, by lowering input costs, SSNM promotes economic sustainability. Smallholders can profit financially from farmers' ability to apply fertilizer just where necessary, maintain or boost yields, and lower unit costs (Pampolino *et al*. 2006). For instance, a case study from Kenya revealed that farmers who used SSNM techniques increased yields while saving an average of 30% on fertilizer (Ndufa *et al*. 2021). By using resources more effectively, SSNM increases production and the agriculture system's long-term viability.

Synergy of Optical Sensing and SSNM

Combining optical sensing technologies with site-specific nutrient management (SSNM) forms a strong basis for precision agriculture, offering many major advantages that contribute to agricultural efficiency and sustainability (Pramanick *et al*. 2022; Gorai *et al*. 2021). The most impactful advantage relates to data-driven (real-time) decision-making because the information gained from optical sensors is vital to making nutrient management decisions (Sairam *et al*. 2023c) for example, reflectance sensors allow a user to retrieve. This capability also supports targeted fertilizer application because field data from optical sensors allow farmers to target their fertilizer applications based upon the needs of various field zones; For example, if the data indicate that some parts of the field are still nutrient-deficient and others are nutrient-sufficient, farmers can vary their application rates to match crop nutrient requirements, minimizing overapplication, improving nutrient use efficiency while lessening the potential for fertilizer run-off, thereby reducing any immediate environmental risks (Papadopoulos *et al*. 2024; Ray *et al*. 2021a). In addition, if optical sensing and SSNM approach are used, farmers can save money when lowering the total amount of Fertilizer applied compared to just using SSNM and will provide better nutrient management while ensuring the same or higher crop yield. The application of SSNM would again improve environmental sustainability at a larger scale in agriculture by providing farmers with accurate real-time agricultural input data on crop nutrient needs of specific crops, targeted applications for specific crops, reducing avoidable nutrient loss and minimizing (or improving) soil health and soil ecosystems, which is critical in managing the urgent environmental issues of soil degradation and water pollution that threaten the future of agriculture (Al-Shammary *et al*. 2024). data on chlorophyll level determines crop nitrogen status. When it is paired with SSNM, it allows farmers to apply nutrients when and where they are needed, resulting in a more efficient use of resources (Swathy *et al*. 2024). These technologies also allow producers to continuously monitor their crops for crop health throughout the growing season, catching early stages of stressors like nutrient deficiencies or disease outbreaks and providing timely alterations to reduce yield loss.

Additionally, the combination of optical sensing and SSNM provides farmers with the ability to respond to climate change effects on agriculture including changes in precipitation patterns and higher pest and disease incidence for instance, optical sensors can observe crop responses to drought, allowing farmers to adjust nutrient management to account for drought and ultimately improve the resilience and stability of agricultural systems in climate change variability. (Grigorieva *et al*. 2023; Mohamed *et al*. 2021). Several case studies have highlighted the effectiveness of agricultural systems like this based on optical sensing. For instance, chlorophyll content meter sufficiency index (SI)-based nitrogen management labelled at SI 90-95% produced significantly substantially higher grain (7.74 t/ha), stover (12.40 t/ha), biological yield (20.12 t/ha), agronomic nutrient use efficiency and higher agronomic nutrient use efficiency (Sairam *et al*. 2023a, 2025b). Indicators such as these propose that maize can utilize chlorophyll content meter sufficiency index (SI)-based nitrogen management at SI 90-95% to improve its growth, productivity, and nutrient use efficiency (Sairam *et al*. 2023 a, b).

However, there are multiple hurdles to overcome before wide-scale integration of optical sensing and SSNM becomes common practice. Technical challenges arise as both technologies involve advancements in sensor technology and data-management systems that can be daunting to farmers with little technical background therefore, efforts must focus on removing these complexities, and providing training and support will be vital to increasing adoption (Alahmad *et al*. 2023). Economic barriers are also a limitation, as accessing new optical sensing technologies can be a major barrier for all dimensions of smallholder farmers, such as the cost of the technology. Consequently, policymakers and agricultural organizations must work together to create financial frameworks that support accessibility to these technologies, for instance, through subsidies or access to credit (Pedersen *et al*. 2024b). Furthermore, effective use of the data produced by optical sensors requires some level of technical capability; thus, there is a need to develop user-friendly decision support systems which allow farmers to make management decisions based on reliable information (Kumar *et al*. 2024). Integration of optical sensing and SSNM into established agricultural drills may also require significant adaptations to established preconceptions that practitioners have around production, underscoring the importance of involving farmers in the development of such integrated systems to ensure that they are aligned with local practices and knowledge (Ali *et al*. 2024). Ultimately, continued research and development are necessary to advance optical sensing technology's capabilities and clarify its applications in a range of cropping systems, and this will require partnership among researchers, agricultural extension services, and farmers to help innovatively solve the evolving challenges of precision agriculture. (Abbasi *et al*. 2022).

Technical Considerations

The successful integration of optical sensing technologies with SSNM heavily relies on many technical aspects that ensure the successful implementation of these astounding technologies (Sairam *et al*. 2023d). Optical sensing technologies like multispectral and hyperspectral sensors collect data at different wavelengths to determine plant health and nutrients of crops however, the accuracy and reliability of this data must be ensured (Gorji *et al*. 2024). The sensors need to be calibrated to ensure they measure reliable readings under different condition categories. Air interference, soil reflectance, and plant structure (canopy level) can potentially affect sensor readings therefore calibration and validation against ground truth measurements are essential to ensure accurate readings out of the sensors. The correct wavelengths must also be selected to maximize the potential of optical sensing technologies. Specific crops and stress conditions have unique spectral signatures, thus understanding these specific traits allows farmers to then adjust nutrient management practices more effectively (Gorji *et al*. 2024). For example, some wavelengths are more sensitive to chlorophyll content which allows farmers to accurately evaluate the nitrogen level of their crops. An additional technological aspect would be the formation of algorithms that transform raw spectral data into actionable data. These algorithms must be able to process big data adequately to generate the right recommendations to provide farmers with real-time recommendations for fertilization practices. Integration also relates to the process of aggregating information from a range of different sources such as satellite data, drone-based sensor data, and on-field observations, into a unified whole. This data fusing helps enhance the spatial accuracy of nutrient assessments, enabling farmers to better understand variability in their fields (Ahmad *et al*. 2022). In addition, farmers also need technical training, which helps to develop the skills required to operate that technology and analyze information effectively. Solving these technological issues will finally integrate optical sensing and SSNM, enhancing the overall effectiveness of precision agriculture approaches (Papadopoulos *et al*. 2024).

Environmental Impact

The introduction of optical sensing technologies with SSNM results in significant environmental impacts because both optical sensing technologies and SSNM lower the environmental footprint of agricultural practices (Balasundram *et al*. 2023). Agricultural practices often result in the over-application of fertilizers that cause nutrients to run off, which eventually ends in streams and can destroy habitat and soil health. While nutrient runoff contributes to eutrophication that can destroy aquatic habitats and lead to water quality problems, optical sensing technologies can mitigate the risks of excess fertilizer application by providing accurate nutrient applications via real-time information (Sarkar and Maji, 2024; Monteiro-Silva *et al*. 2019). Rather, the appropriate applications of fertilizers and nutrients allow for fertilizer application just where nutrients are needed while optimizing fertilizer application ensures that the nutrients have limited opportunities for leaching in either groundwater or surface water. This process not only protects water quality but also benefits the soil ecosystem by limiting overfertilization damage. Healthy soils ultimately contribute to improved carbon sequestration which, in turn, improves the sustainability of agricultural practices overall (Gudla *et al*. 2023 a; Eddy and Yang, 2022; Ray *et al*. 2025b). In similar ways, the attachment of optical sensing with SSNM increases resource efficiency amidst growing concerns for environmental outcomes. That is, farmers can minimize their resource use by utilizing optical sensing technologies to improve their water and fertilizer applications (Li *et al*. 2009) which not only improves efficient resource use but is also relevant for water-challenged countries where water use is critical for supporting agricultural output.

FUTURE PERSPECTIVE

The future of integrating optical sensing technologies with SSNM looks positive, with many new trends and opportunities that may increase agricultural sustainability and production (Koley *et al*. 2024). New technologies will solve current challenges by enabling farmers to better farming practices with increased efficiency. The use of artificial intelligence (AI) and machine learning (ML) algorithms from the optical sensing space is becoming popular (Karunathilake *et al*. 2023). AI and ML algorithms can greatly reduce datasets created by optical sensors and make more accurate predictions about crop health and nutrient needs. For instance, AI decision support systems can help farmers optimise nutrient management recommendations in real-time to handle system complexity by using current information about the weather, field conditions, the last time that the crop received nutrients, as well as past data, to predict when a given crop will need more nutrients (Talaviya *et al*. 2020) and thus improve nutrient timing and placement information. Likewise, the integration of IoT with optical sensors is another emerging trend. Transparent IoT-enabled sensors can provide continuous crop health monitoring and environmental conditions while sending data to the stakeholders through cloud-based or mobile application interfaces in real-time (Sharma and Shivandu, 2024). This connectivity will allow farmers to respond to changing conditions in the field promptly and make timely decisions, enhancing the efficiency of resources and the sustainability of agricultural practices. The integration of optical sensing and SSNM is a complex process that requires collaboration between farmers, researchers, agronomists, and technology developers. Promoting knowledge-share initiatives and collaborations, the engagement of knowledge exchanges, and the transfer of best practices and innovations around data-driven decision support systems between stakeholders can help build a collaborative landscape to solve sustainable agricultural challenges (Papadopoulos *et al*. 2024). In addition, the role of government policies and regulations around precision agriculture will also shape the future of precision agriculture as some policies can create incentives for the adoption of sustainable practices. For instance, providing financial offsetting around the adoption of new technologies, by providing sustained tax rebates to farmers in the lodging of new technologies or awareness in the field or simply promoting RD in precision agriculture, could potentially promote the adoption of more optical sensing and SSNMs. Aspects of Ehlers *et al*. (2021) referenced that governments could be a positive disrupter in this area. Similarly, where we are learning new technologies, public-private partnerships can help establish new technologies for smallholder farmers who may have difficulty identifying and accessing new technologies where the partnerships between governmental organizations, NGOs and private companies would help ensure that innovative solutions reach those who may need them most.

CONCLUSION

The interaction of optical sensing technologies and site-specific nutrient management is a major opportunity for sustainable agriculture because each technique provides farmers with improved monitoring of crop health and nutrient needs and, therefore, better efficiency while reducing environmental consequences. This amalgamation operates on multiple fronts to elevate agricultural productivity, while contributing to systems that help support global food security and sustainable development as defined by the UN SDGs. Nevertheless, many challenges must be addressed before the full realization of the transparent pipeline of optical sensing and SSNM such as technical, economic and environmental constraints that can make adoption slow and inhibit the advantages optical sensing and SSNM offer. Additionally, collaborative growth to take place to support the enabling conditions of sustainable agriculture, and cooperation amongst farmers, academics, government, and technologies will be paramount. Along with advances in AI, IoT, and climate-smart agricultural practices creating increased potential for sustainability and productivity, the prospect of precision agriculture is bright. Furthermore, unleashing these innovative solutions through funding and supporting farmers to implement them, have the opportunity to produce a climate-resilient and sustainable agriculture system that can feed the growing population, while conserving our natural resources for future generations.

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