

Overview on Recent Progress in Optical Sensing for Soil NPK Nutrient Assessment – A Conceptual Analysis

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Received: 08.07.2025 | Accepted: 06.08.2025 | Published: 12.12.2025

Abstract

The accurate and timely assessment of soil Nitrogen (N), Phosphorus (P), and Potassium (K) is crucial for optimizing fertilizer use in precision agriculture, addressing limitations of traditional time-consuming laboratory methods. Optical sensing offers a promising non-destructive alternative for rapid, in-situ analysis. The optical sensor technologies for soil NPK detection covers principles and progress in Visible-Near-Infrared (Vis-NIR), Mid-Infrared (MIR), and Raman spectroscopy, as well as modernized colorimetry and optical imaging techniques. The review highlights the integration of these sensors with microcontrollers, IoT, and AI/ML for enhanced performance. The Significant progress includes the development of portable spectroscopic and colorimetric sensors, often leveraging MEMS technology for miniaturization and increased sensitivity. AI/ML algorithms are increasingly vital for data processing, calibration, and mitigating environmental interference. Remote sensing platforms provide valuable spatial variability data. Despite advancements, challenges remain, including the impact of soil heterogeneity and environmental factors, calibration complexity, and achieving consistent accuracy across diverse conditions. Extensive innovation is seen in optical soil NPK sensing, driven by hardware miniaturization and sophisticated data analytics. Future research focuses on multi-sensor integration, robust calibration transfer, and seamless integration into precision agriculture decision support systems to enable sustainable nutrient management.

Keywords: Optical Sensors, Soil Nitrogen (N), Phosphorus (P) & Potassium(K), Spectroscopy, Colorimetry, Precision Agriculture.

Introduction

The recent advancements, shows the availability of essential soil nutrients, particularly nitrogen (N), phosphorus (P), and potassium (K), is fundamental for vigorous plant growth and achieving the high crop yields required to feed a growing global population. As per Potdar et al. 2021 effective management of these macronutrients is a cornerstone of modern agricultural practices. Precise and timely knowledge of soil NPK levels is paramount for optimizing fertilizer application, thereby avoiding both insufficient fertilization, which reduces yields, and

excessive application, which can lead to significant environmental damage like nutrient runoff and eutrophication. As Conventional soil nutrient analysis methods, typically performed in laboratories using wet chemistry, are accurate but often suffer from drawbacks such as being time-consuming, labour-intensive, requiring specialized equipment, and involving complex sample preparation and these limitations hinder their practicality for the real-time, in-situ monitoring necessary for implementing precision agriculture techniques (Potdar et al., 2021). The inability to quickly assess nutrient status directly in the field impedes dynamic decision-making regarding fertilization strategies. Optical sensing technologies have emerged as a promising alternative to these traditional approaches as Studies by (Liu et al., 2023). These techniques offer the potential for rapid, non-destructive, and potentially portable analysis of soil nutrients, facilitating the acquisition of real-time data directly in the field.

The availability of such real-time nutrient data is a key enabler for implementing site-specific nutrient management strategies and developing effective decision support systems aimed at sustainable agriculture. This document provides a comprehensive overview of recent advancements in optical sensor technologies specifically applied to the detection of NPK nutrients in soil. Focusing on literature published between 2020 and 2025, it delves into the underlying principles of these methods, highlights key technological developments and their applications, examines the inherent challenges faced by researchers, and outlines future perspectives in this rapidly evolving field.

Literature Review

The last five years have witnessed considerable advancements in the use of optical sensing technologies for the assessment of soil macronutrients—nitrogen (N), phosphorus (P), and potassium (K)—driven by the growing need for real-time, non-destructive, and in-field nutrient diagnostics in precision agriculture. Traditional laboratory-based methods, although accurate, are constrained by high costs, time-intensive sample preparation, and lack of portability, making them less suitable for dynamic on-field nutrient management. Some research studies (Potdar et al., 2021; Masrie et al., 2018) have highlighted the potential of Visible and Near-Infrared (Vis-NIR) spectroscopy for rapid NPK detection. This technique capitalizes on the distinct absorption features associated with nutrient-related compounds in the 700–2500 nm range. However, its reliability varies, with nitrogen estimation proving more robust than phosphorus and potassium, due to indirect correlations and weaker spectral signatures for the latter. Research by (Reza et al., 2025) optimized specific wavelengths (e.g., 850 nm for N) and introduced ML-enhanced calibration models to improve accuracy across soil types. Mid-Infrared (MIR) spectroscopy is gaining traction for its higher specificity and stronger molecular signals.

The research study conducted by (Liu et al., 2023) have emphasized its utility for nitrate-N detection, although challenges with carbonate and moisture interference persist. Meanwhile, Raman spectroscopy, particularly Surface Enhanced Raman Spectroscopy (SERS), has emerged as a niche but promising technique for water-soluble nitrogen and phosphorus detection. Advances in portable Raman devices and signal enhancement algorithms (e.g., wavelet packets) have increased field applicability (Reza et al., 2025). Colorimetric techniques, historically used in laboratory settings, are now being transformed into automated systems using MEMS, microfluidics, and Arduino-based microcontrollers. The use of LED-based photometric detection, as reported by (Potdar et al., 2021), enables high-sensitivity detection

of nutrient concentrations down to ppm levels. These innovations enable real-time, user-friendly, and cost-effective soil testing suitable for smallholder farming contexts.

Optical imaging and remote sensing, including hyperspectral imaging and UAV-based platforms, offer an indirect yet valuable approach to spatially map nutrient distributions. By leveraging vegetation indices and soil reflectance models, researchers have successfully predicted nutrient deficiencies and soil fertility trends across large areas (Reza et al., 2025). While these systems often require extensive ground-truthing, they contribute to site-specific fertilizer recommendations and integrated nutrient management.

The integration of Artificial Intelligence (AI) and Machine Learning (ML) is a critical trend across all optical sensing modalities. Algorithms like SVM, PCA, and neural networks are being utilized to denoise spectral data, calibrate models across varying soil types, and enhance prediction robustness. IoT-enabled systems further allow remote monitoring and real-time data transmission, facilitating decision-making frameworks for farmers. Despite the technological progress, challenges remain in achieving universal calibration models, addressing environmental interferences, and improving detection accuracy for P and K. Future research is anticipated to focus on sensor fusion, robust model transferability, and full integration with precision agriculture decision support systems. Collectively, the reviewed literature underscores the transformative potential of optical sensing, especially when integrated with digital technologies, to revolutionize soil nutrient management for sustainable agriculture.

Need & Relevance

Effective management of soil nutrients—Nitrogen (N), Phosphorus (P), and Potassium (K)—is critical for enhancing crop productivity and promoting sustainable agriculture (Shukla & Tripathi, 2020). Traditional laboratory-based soil testing methods, though accurate, are often time-consuming, costly, and impractical for real-time, on-field decision-making. This creates a pressing need for rapid, non-destructive, and field-deployable alternatives to support precision agriculture practices. Optical sensing technologies have emerged as a powerful solution to this challenge.

The recent innovations in Visible-Near Infrared (Vis-NIR), Mid-Infrared (MIR), Raman spectroscopy, and advanced colorimetric methods, combined with microcontroller integration, IoT connectivity, and AI/ML-driven data analytics, have significantly enhanced the accuracy, portability, and usability of nutrient detection systems. However, the existing literature is fragmented, and a consolidated review of recent developments, challenges, and future prospects is lacking. This paper addresses that gap by offering a comprehensive literature overview (2020-2025) of advancements in optical sensing for soil NPK assessment. It evaluates sensor principles, field applications, integration trends, and limitations such as calibration complexity and environmental interference. The insights provided are highly relevant for researchers, technologists, and policymakers aiming to develop scalable, smart sensing solutions that enable site-specific nutrient management, reduce fertilizer misuse, and support sustainable farming practices globally.

Objective

To review and conceptually analyze the recent advancements in optical sensing technologies for accurate and real-time assessment of soil NPK nutrients in support of precision agriculture

Method of Study

The entire study is based on the secondary data sources and adopted descriptive research design for explaining the observations based on the conceptual overview.

Optical Sensing for Soil NPK

Optical sensing approaches for analysing soil nutrients are based on how light, a form of electromagnetic radiation, interacts with the various components within the soil matrix. These interactions can include the absorption, reflection, and scattering of light at specific wavelengths. Different soil constituents, including nutrient ions or compounds linked to them, possess distinct spectral signatures. These signatures indicate how they absorb or reflect light across particular regions of the electromagnetic spectrum, notably the visible (Vis), near-infrared (NIR), and mid-infrared (MIR) ranges. By analysing these interactions, the presence and concentration of specific nutrients can be deduced. Several optical techniques such as spectroscopy, colorimetry, and optical imaging are employed for NPK detection and discussed below:

Spectroscopy

This technique measures the intensity of light absorbed or reflected by a soil sample as a function of wavelength. The resulting spectrum serves as a unique identifier of the soil's composition. By analysing the patterns within this spectrum, researchers can identify and quantify the presence of specific nutrients or properties correlated (Potdar et al., 2021). Reflectance spectroscopy, which measures the energy reflected from the soil surface, is a widely used method. Another technique, Raman spectroscopy, examines the inelastic scattering of light, providing structural information about the molecules present in the sample.

Colorimetry

This method involves chemical reactions within a soil extract that produce a colour change. The intensity of this colour change is directly proportional to the concentration of the target nutrient. This colour intensity is then measured optically (Potdar et al., 2021). While traditionally relying on visual comparison with calibrated charts, recent progress focuses on automating the optical detection of these colour changes using electronic sensors.

Optical Imaging

This approach captures spatial information about soil or plants using cameras, which can be multispectral or hyperspectral. Also, by analysing the spectral data associated with each pixel in the image, it is possible to infer the nutrient status of the soil or identify signs of nutrient deficiencies in plants (Potdar et al., 2021). This technique is particularly valuable for mapping nutrient variability across larger areas. These optical principles form the basis for developing

sensors capable of offering faster, more convenient alternatives to conventional soil testing methods.

Observation & Discussion

The period between 2020 and 2025 has witnessed significant progress in the application and refinement of optical sensing technologies for detecting soil NPK. Research continues to explore the potential of various spectral ranges and sensing modalities, often integrating them with modern computational and electronic platforms.

Visible-Near-Infrared (Vis-NIR) & Mid-Infrared (MIR) Spectroscopy: Vis-NIR spectroscopy remains a key area of focus due to its non-destructive nature and suitability for developing portable devices. The studies conducted by Potdar et al. 2021 have concentrated on developing portable instruments and optimizing the selection of wavelengths to enhance detection accuracy for specific nutrients. Studies have identified particular wavelengths, such as 850 nm for nitrogen, 620-630 nm for phosphorus, and 460-470 nm for potassium, as especially relevant for portable sensor designs by (Aitkenhead et al. 2017). NIR spectroscopy is recognized for its effectiveness in detecting soil organic matter, nitrogen, and moisture levels. Concurrently, MIR spectroscopy is gaining increased attention. This spectral region offers features that are often more intense and numerous than those in the Vis-NIR range, providing richer information about soil constituents. Also, the Nitrate Nitrogen, in particular, exhibits more distinct spectral features in the MIR region compared to the NIR range (Masrie et al., 2018). This characteristic suggests that MIR spectroscopy holds greater potential for improving the accuracy of nitrogen detection. The parallel research efforts in both Vis-NIR and MIR spectroscopy reflect a strategic approach to leverage the unique strengths of different spectral ranges. Vis-NIR is pursued for its established techniques and potential for portability, while MIR is explored for potentially improved specificity for certain nutrients like nitrate. This dual focus indicates that no single spectral range is currently considered universally optimal for accurately detecting all NPK nutrients, prompting research into both optimizing single-range systems for specific applications and exploring multi-spectral approaches that could combine information from different ranges for more comprehensive and accurate analysis.

Raman Spectroscopy: While perhaps less widespread than Vis-NIR, Raman spectroscopy is demonstrating specific utility in soil nutrient sensing. Recent advancements include the development of portable Raman sensors specifically for detecting phosphorus in soil as studies by (Potdar et al., 2021). The use of Surface Enhanced Raman Spectroscopy (SERS) has been investigated for detecting water-soluble forms of nitrogen. Researchers are also employing advanced signal processing techniques, such as wavelet packets, to extract useful signals from complex Raman spectra for phosphorus concentration analysis (Potdar et al., 2021). The increasing availability of miniaturized and field-tested Raman spectroscopy equipment further supports its potential for practical application (Masrie et al., 2018). The focus on portable devices and sophisticated signal processing methods indicates a concerted effort to make Raman spectroscopy a viable field-deployable technique, particularly for specific nutrient forms or elements where it may offer advantages over other optical methods.

Colorimetry: The traditional colorimetric method is undergoing significant modernization through integration with contemporary electronics and micro-technologies. Recent work

moves beyond subjective visual interpretation towards automated, sensor-based systems. Combinations of colour-detecting sensors, microcontrollers (such as Arduino platforms), LEDs, and optical fibers are being utilized to construct portable, independent soil sensors capable of objective measurement (Potdar et al., 2021). A notable trend is the integration of miniature microfluidic channels and Micro-Electro-Mechanical Systems (MEMS) technology to create colorimetric sensors with enhanced sensitivity, capable of detecting nutrients at parts per million (ppm) levels. Furthermore, compact UV-Vis spectroscopy systems coupled with optical fibers are being investigated for analysing NPK in aqueous soil extracts, employing artificial intelligence (AI) algorithms to manage spectral interference issues. This revitalization of colorimetry through integration with modern engineering aims to improve its accuracy, portability, and automation, transforming it from a simple, semi-quantitative method into a more precise, real-time sensing technology, with MEMS integration pointing towards significant miniaturization potential.

Optical Imaging & Remote Sensing: Optical imaging techniques, particularly hyperspectral and multispectral imaging systems, are increasingly deployed on aerial platforms like Unmanned Aerial Vehicles (UAVs) for large-scale mapping of soil properties. The study conducted by (Liu et al., 2023) provided indirect estimations of nutrient levels based on correlations or indicators like soil colour or organic matter, this approach offers crucial spatial information. The vegetation indices, mathematical combinations of spectral bands, are being adapted from plant monitoring to estimate soil properties and nutrient distribution, helping to minimize the influence of varying soil backgrounds. The analysis conducted by Potdar et al. 2021 indicated the images of plant leaves is also being explored as an indirect method to predict nutrient deficiencies in the soil. This shift from point-based measurements to spatial mapping provides essential information on nutrient variability across fields, which is fundamental for implementing site-specific management strategies in precision agriculture. Moreover, Aitkenhead et al. 2017 established PHYLIS: Portable Hyperspectral Low-Cost Imaging System which uses Microsoft visual studio 2010 software for sensing NPK.

Integration with Microcontrollers, IoT, AI and ML: A critical aspect of recent advancements is the integration of optical sensors with sophisticated computational and connectivity platforms (Pužin, 2020). Microcontrollers, such as Arduino, are fundamental components in the design of portable sensors, managing data acquisition, processing, and communication. Integration with the Internet of Things (IoT) enables real-time data transmission from the field and remote monitoring capabilities (Liu et al., 2023). Crucially, Machine Learning (ML) and Artificial Intelligence (AI) algorithms are becoming indispensable for processing the complex data generated by optical sensors, calibrating models across diverse soil types, mitigating the impact of environmental interference, and significantly improving prediction accuracy (Potdar et al., 2021).

Various algorithms, including neural networks, Principal Component Analysis (PCA), genetic algorithms, Random Forest, Support Vector Machines (SVM), and Naive Bayes classification, are being employed for tasks such as data analysis, noise reduction, and classification. AI is specifically noted for its ability to address interference problems encountered in UV-Vis spectroscopy. The integration of microcontrollers, IoT, and AI/ML is transforming raw optical signals into actionable, site-specific nutrient information. This addresses major challenges like calibration complexity and environmental variability, demonstrating that the effectiveness of recent optical sensor advancements relies heavily on sophisticated data processing and

connectivity, not just hardware development. In furtherance, to provide a clear overview of the technological aspects mentioned in the aforesaid observations and discussions in accordance with optical sensing methods, principles, key advancements, and limitations are compared and represented in Table 1.

Table 1: Comparison of Key Optical Sensing Methods for Soil NPK

Method	Principle of Operation	Suitability/Application for NPK	Key Advancements (2020-2025)	Major Limitations	Potential for Portability/Field Use
Vis-NIR Spectroscopy	Absorption and reflection of light (700-2500 nm) based on molecular vibrations.	Promising for N; challenging for P & K (indirect correlation needed). Effective for Organic Matter & Moisture. (Potdar et al., 2021)	Portable devices, optimized wavelength selection (e.g., 850nm N, 620-630nm P, 460-470nm K), advanced calibration methods, ML/AI integration. (Potdar et al., 2021)	Affected by soil type, moisture, environmental factors. Calibration transfer issues. Poor direct prediction for P & K. Bulky/expensive lab units. (Potdar et al., 2021)	High (portable devices developed)
MIR Spectroscopy	Absorption based on fundamental molecular vibrations (2500-25000 nm).	Stronger, more specific signals for some nutrients like nitrate N. (Liu et al., 2023)	Increased focus on potential for N detection accuracy, denoising models for water/carbonate interference, data fusion. (Liu et al., 2023)	Carbonate interference. Less explored for field use compared to Vis-NIR. (Liu et al., 2023)	Moderate (developing)
Raman Spectroscopy	Analyses inelastic scattering of light to provide structural information.	Applied to P detection (portable sensors) and water-soluble N (SERS). (Potdar et al., 2021)	Portable sensors invented, SERS for soluble N, signal processing (wavelet	Affected by environmental factors. Interference from cuvette/base materials.	High (portable devices available)

			packets), miniaturized equipment available. (Potdar et al., 2021)	(Potdar et al., 2021)	
Colorimetry	Measures colour change intensity after chemical reaction in soil extract.	Used for NPK; traditionally semi-quantitative. (Potdar et al., 2021)	Automated sensor-based systems (colour sensors, microcontrollers, LEDs), MEMS/microfluidics for high sensitivity, UV-Vis spectroscopy with AI for interference. (Potdar et al., 2021)	Traditionally subjective (visual). Requires soil extraction/sample preparation. Interference from competing ions. (Potdar et al., 2021)	High (portable devices developed)
Optical Imaging / Remote Sensing	Captures spatial spectral data (multispectral/hyperspectral) from soil/plants.	Indirect estimation of NPK based on correlations or plant health. (Potdar et al., 2021)	UAV deployment, adaptation of vegetation indices for soil properties, analysis of plant images, portable hyperspectral systems (PHYLIS). (Potdar et al., 2021)	Often indirect measurement. Requires ground truth for calibration. Underdeveloped for direct soil NPK sensing. Need for appropriate libraries. (Potdar et al., 2021)	High (platform-based)

Suggestions

Despite remarkable progress in the field of optical sensing for soil nutrient analysis, several challenges continue to limit the widespread adoption, accuracy, and reliability of these technologies. These limitations stem mainly from the inherent complexity and heterogeneity of soil environments, coupled with the intricate interactions between light and soil constituents.

Influence of Soil Properties & Environmental Conditions: One of the most significant obstacles is the influence of diverse soil characteristics on optical measurements. Parameters such as soil texture, type, colour, organic matter content, and moisture level can substantially affect the way light is absorbed, scattered, or reflected by the soil. These variations introduce noise into the spectral data, making it difficult to isolate the specific signals associated with individual nutrients like nitrogen, phosphorus, and potassium. This variability complicates the creation of universal calibration models that function accurately across multiple regions and soil types. Moreover, external environmental conditions—including ambient light, humidity, and temperature—can also distort sensor readings, further complicating real-time field application. Infrared spectroscopy, for example, often suffers from spectral interference caused by water and carbonate compounds, whose absorption characteristics overlap with those of the target nutrients. These complex and variable interactions represent a central technical challenge that must be addressed for effective field deployment.

Calibration Complexity & Transferability: Due to soil variability and environmental influences, optical sensing systems require site-specific calibration models to yield reliable nutrient estimations. A calibration model that performs well in one soil environment may fail in another, especially if soil composition and field conditions differ significantly. This “calibration transferability” issue is a major barrier to the development of truly portable and user-friendly nutrient sensing devices. Additionally, models developed using one spectroscopic instrument are often not compatible with data collected from a different device, even when measuring the same soil type. Overcoming these inconsistencies demands the use of advanced data science techniques and robust calibration methodologies capable of adapting across instruments, locations, and soil types.

Accuracy & Sensitivity: Achieving consistently high accuracy and sensitivity across different soil conditions remains a significant hurdle. While Vis-NIR spectroscopy has shown considerable promise in estimating nitrogen content, it tends to be less effective for phosphorus and potassium. This is primarily because these nutrients lack strong, direct absorption features in the Vis-NIR range, making their detection dependent on indirect correlations with other soil parameters. At low nutrient concentrations, prediction accuracy tends to decrease further. In the case of traditional colorimetric methods, while cost-effective and simple, they often provide only semi-quantitative assessments, as they rely heavily on subjective interpretation of colour intensity, limiting their utility in precision nutrient management.

Cost & Robustness: Although research increasingly focuses on developing low-cost optical sensors, particularly for use in smallholder or resource-constrained farming contexts, many advanced spectroscopic and imaging systems remain expensive and physically bulky. Their deployment in challenging field environments introduces concerns regarding durability and operational reliability. Components such as Attenuated Total Reflectance (ATR) devices used in some MIR spectroscopic systems are often fragile and costly. Developing robust, low-cost, and easy-to-use sensors capable of withstanding harsh agricultural conditions is essential. Given the noisy and variable background in soil measurements, sophisticated data processing and calibration strategies are vital for improving sensor accuracy, reliability, and broader field applicability.

Future Outlook & Recommendations

The future of optical sensors for soil NPK detection is centered on overcoming current limitations and improving their usability, accuracy, and scalability for precision agriculture. Key research areas are expected to lead this advancement.

Miniaturization & Multi-Sensor Integration will remain a top priority, with efforts focused on creating compact, portable, and user-friendly devices, including handheld tools and sensors that can be mounted on agricultural machinery. Combining different sensing technologies—such as optical and electrochemical sensors—will help generate more accurate and comprehensive real-time nutrient data. MEMS technology offers promise for integrating multiple sensing and sample preparation functions onto a single chip, supporting miniaturization.

Advancements in Data Fusion and Machine Learning are crucial for addressing soil variability and calibration challenges. Integrating data from multiple sensor types, including moisture and pH sensors, will improve the accuracy of nutrient detection. Machine learning models will be essential for analysing complex datasets, reducing noise, and enabling model transfer across diverse soils and instruments.

Developing Cost-Effective and Durable Sensors is vital to ensure affordability, especially in developing regions. Enhancing physical robustness and exploring new materials will improve field reliability.

Finally, integration with decision support systems through IoT and AI will enable real-time, site-specific recommendations, supporting efficient fertilizer use and sustainable farming.

Development of More Robust & Cost-Effective Sensors: Reducing the cost of portable spectroscopic and imaging systems is essential to make these technologies accessible to a wider range of farmers, particularly in developing regions where cost is a significant factor. Simultaneously, improving the physical robustness and durability of sensors is crucial for their reliable operation in demanding field environments. Research will also continue to explore new materials and designs to enhance the response performance and sensitivity of existing optical sensing technologies.

Integration into Precision Agriculture Decision Support Systems: The ultimate goal is the seamless integration of real-time nutrient data from optical sensors with IoT platforms, cloud computing infrastructure, and AI-driven decision support systems. This integrated ecosystem will enable the translation of raw sensor data into actionable insights and recommendations for optimized, site-specific nutrient management. This data-driven approach will facilitate practices such as variable-rate fertilization, ensuring that fertilizers are applied precisely where and when needed, thereby minimizing waste, reducing environmental impact, and improving resource use efficiency. The future of optical soil NPK sensing lies in creating integrated, intelligent systems that combine miniaturized hardware with advanced software and connectivity to deliver actionable insights for precision agriculture.

Conclusion

The observation is that between the years 2020 till 2025, a significant progress has been made in optical sensing for soil NPK detection, driven by advances in Vis-NIR and MIR spectroscopy, modernized colorimetry with MEMS, and portable Raman systems. Integration with IoT, AI/ML, and microcontrollers has transformed raw data into actionable insights, enabling field-scale applications. However, challenges like soil heterogeneity, calibration transfer issues, and low-nutrient sensitivity persist. Future research will focus on miniaturized, robust, multi-sensor devices and advanced data processing to enhance accuracy. The ultimate aim is real-time, site-specific nutrient monitoring through intelligent, connected systems that support precision fertilization and sustainable agriculture.

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