

Precision Nutrient Application Techniques to Improve Soil Fertility and Crop Yield: A Review with Future Prospect

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Abstract

Precision nutrient application techniques have gained significant attention in modern agriculture as a means to enhance soil fertility management and optimize crop yield. This review provides a comprehensive exploration of various precision nutrient application techniques and their potential to address the challenges of food security and sustainability. The review highlights key technologies, methodologies, and practices that contribute to precise nutrient management, including real-time monitoring, variable rate application, GIS-GPS integration, drone-based data collection, and data analysis tools. The importance of accurate data, challenges related to field variability, and the need for skilled personnel is discussed. Furthermore, the review delves into the potential of advancements such as machine learning and AI-driven solutions in overcoming challenges and advancing precision nutrient application. These technologies offer predictive models, adaptive management strategies, and real-time decision support systems. By emphasizing the benefits of precision nutrient application, including improved nutrient uptake by plants, reduced nutrient runoff, and enhanced plant health, this review underscores its potential to revolutionize modern agriculture. Ultimately, precision nutrient application techniques hold promise in enhancing soil fertility, optimizing crop yield, and promoting sustainable agricultural practices, making a significant contribution to global food security and environmental sustainability.

Key words: GIS, GPS, precision agriculture, soil fertility, nutrient status, crop yield

1. Introduction

Precision agriculture (PA) is an advanced farming approach that utilizes modern technologies and data-driven techniques to optimize various aspects of crop production. The goal of precision agriculture is to enhance productivity, efficiency, and sustainability in agricultural practices by tailoring interventions to specific areas of a field based on variability in soil, climate, and crop conditions. This approach contrasts with traditional uniform application methods, where inputs like water, fertilizers, and pesticides are evenly spread across a field, often leading to inefficiencies and waste. Precision agriculture integrates tools such as Geographic Information Systems (GIS), Global Positioning System (GPS), remote sensing, sensor technologies, data analytics, and machine learning. These technologies allow farmers to create detailed maps of their fields' characteristics, monitor crop health and growth, and apply inputs precisely where they are needed most [1].

Nutrient management is a critical aspect of modern agriculture due to its profound impact on crop growth, soil fertility, and overall sustainable food production. Proper management of nutrients, such as nitrogen, phosphorus, and potassium, is essential to ensure optimal plant health, high crop yields, and environmental stewardship. Nutrient imbalances or deficiencies can lead to reduced crop productivity, increased susceptibility to diseases, and negative environmental consequences, such as water pollution from nutrient runoff. Nutrients are crucial for plant processes such as photosynthesis, growth, and reproduction. Proper management ensures the right proportion of elements leading to healthy plants and high yields. Imbalances can cause nutrient deficiencies or toxicities, leading to stunted growth, reduced yields, and lower quality. Efficient management can prevent these issues and minimize nutrient losses and pollution. Effective nutrient management maximizes fertilizer use, reduces production costs, and contributes to sustainable agriculture and climate change mitigation [2].

The objective of this review is to comprehensively explore precision nutrient application techniques used in modern agriculture and their impact on soil fertility and crop yield. The study aims to provide insights into how these techniques contribute to optimized nutrient management, leading to improved agricultural productivity and sustainability. Several studies have investigated the effects of precision nutrient application on soil fertility and crop yield. For instance, Smith et al. [3] found that Variable Rate Technology (VRT) led to more uniform nutrient distribution in fields, resulting in enhanced nutrient uptake by crops and improved yield outcomes. Similarly, Jones and Brown [4] examined the integration of sensor-based techniques and found that real-time monitoring of soil conditions facilitated timely adjustments in nutrient application rates, resulting

in better nutrient utilization efficiency and increased crop yields. Furthermore, Nguyen et al. [5] showed that GIS and GPS integration in precision agriculture allowed for targeted nutrient application, leading to improved soil fertility and reduced environmental impact.

2. Precision Nutrient Application Techniques

Precision nutrient application techniques are advanced strategies and technologies used in agriculture to apply fertilizers and other essential nutrients precisely and efficiently to crops. These techniques are designed to optimize nutrient delivery based on real-time data, field variability, and specific crop needs. The goal is to enhance crop productivity, minimize nutrient wastage, and promote sustainable farming practices. Some common precision nutrient application techniques include:

2.1. Variable Rate Technology (VRT):

Variable Rate Technology (VRT) is a key component of precision agriculture that involves adjusting the application rates of inputs such as fertilizers, pesticides, and seeds based on the variability of factors within a field. The goal of VRT is to optimize resource usage by tailoring the application of these inputs to the specific needs of different areas within the field. This approach contrasts with traditional uniform application methods, where inputs are applied evenly across the entire field, often leading to inefficiencies and overuse in some areas and underuse in others. VRT relies on the integration of various technologies, including Geographic Information Systems (GIS), Global Positioning System (GPS), sensor technologies, data analytics, and sometimes machine learning algorithms. These technologies enable farmers to create detailed maps of their fields, which highlight variations in soil characteristics, nutrient levels, moisture content, topography, and other factors. By analyzing these maps and real-time data collected from sensors, VRT systems can make informed decisions about adjusting input application rates on the fly. Variable Rate Technology (VRT) offers many benefits in modern agriculture, including reduced nutrient waste and cost savings, optimized crop growth, and environmental sustainability. By utilizing data on soil nutrient levels, historical crop performance, and other factors, VRT systems can adjust application rates in real-time, allowing farmers to apply fertilizers and other nutrients precisely where they are needed most. This precision minimizes the over-application of nutrients in areas where they are already abundant, reducing the risk of nutrient runoff and leaching into water bodies, protecting water quality and preventing environmental degradation. Tailoring input application rates to specific field conditions optimizes crop growth and yield potential. VRT also plays a crucial role in promoting

sustainable agricultural practices, preserving soil health, minimizing pollution, and contributing to long-term agricultural viability [6].

2.2. Sensor-based Techniques

Sensor-based techniques in agriculture involve the deployment of various types of sensors to collect real-time data on factors such as soil conditions, weather parameters, crop health, and more. These sensors provide valuable information that farmers can use to make informed decisions about resource allocation, input management, and overall crop management strategies. Sensor-based techniques are a cornerstone of precision agriculture, enabling farmers to monitor and respond to dynamic conditions in their fields. Soil sensors measure moisture, temperature, and nutrient levels. Farmers use this data to optimize irrigation schedules and nutrient application rates for better crop growth. Weather sensors collect data on temperature, humidity, wind speed, and solar radiation to understand environmental conditions that affect crops. Crop health sensors assess plant health by analyzing spectral characteristics to detect early signs of stress, diseases, and nutrient deficiencies. Nutrient sensors measure nutrient concentrations to optimize fertilizer application rates and avoid nutrient imbalances. Remote sensing captures imagery of fields using satellites or drones to provide insights into crop health, growth patterns, and stressors, which can be processed to create maps for targeted interventions [7]. The use of sensors to monitor soil nutrient levels, moisture content, and other relevant parameters is a key aspect of precision agriculture. These sensors provide real-time data that enable farmers to make informed decisions about nutrient management and irrigation strategies. Soil nutrient sensors are devices that measure the concentration of essential nutrients in the soil, such as nitrogen, phosphorus, and potassium. These sensors use various technologies, including ion-selective electrodes, optical spectroscopy, and electrical conductivity, to analyze the nutrient content of the soil. For instance, a study by Sadeghpour et al. [8] evaluated the use of ion-selective electrodes to measure soil nitrogen levels. The researchers found that these sensors provided accurate and real-time measurements of soil nitrate concentrations, allowing farmers to adjust nitrogen application rates accordingly.

2.3. GIS and GPS Integration

GIS (Geographic Information Systems) and GPS (Global Positioning System) integration is a fundamental aspect of precision agriculture that enables farmers to make data-driven decisions based on accurate spatial information. GIS is a technology that allows for the creation, management, analysis, and visualization of geospatial data. In precision agriculture, GIS is used to create detailed

maps of field variability, soil properties, topography, and more. These maps provide valuable insights for optimizing nutrient management strategies. A study by Gebbers and Adamchuk (2010) discussed the use of GIS in precision agriculture, emphasizing its role in creating site-specific management zones based on spatial variability. These management zones enable farmers to tailor nutrient application rates and other practices to specific areas within a field, resulting in improved resource utilization and crop yield [9]. GPS technology provides accurate and real-time positioning information, allowing farmers to precisely navigate agricultural equipment within fields. This integration with precision agriculture enables equipment to follow predetermined paths, ensuring consistent nutrient application and minimizing overlaps or gaps. A study by Rezaei et al. [10] explored the integration of GPS and GIS for precision nutrient application. The researchers demonstrated that combining GPS-guided equipment with GIS-generated prescription maps improved the accuracy of nutrient application and reduced input wastage. The combination of GIS and GPS technologies is a powerful tool in precision agriculture. GIS provides the spatial framework and data analysis capabilities, while GPS ensures accurate positioning for on-the-ground operations. A study by Kachanoski et al. [11] discussed the integration of GPS and GIS for site-specific nutrient management. The researchers highlighted how the precise positioning provided by GPS enhanced the efficiency of nutrient application equipment, resulting in improved yield and reduced environmental impact.

2.4. Drones and UAVs (Unmanned Aerial Vehicles)

Drones and Unmanned Aerial Vehicles (UAVs) have gained significant attention in precision agriculture due to their ability to collect high-resolution data over fields efficiently and cost-effectively. They offer a unique vantage point for monitoring crops, detecting stress conditions, and assessing nutrient deficiencies. Drones, also known as UAVs, are remote-controlled aircraft that can be equipped with various sensors and cameras. In precision agriculture, drones provide an aerial perspective that allows for the rapid collection of detailed data across large fields. This data can include multispectral and thermal imagery, which provide insights into crop health, nutrient distribution, and stress levels. A study by Torres-Sánchez et al. [12] investigated the use of drones for monitoring crop health. The researchers demonstrated that multispectral imagery collected by drones could effectively identify stress conditions in crops, enabling farmers to target nutrient applications to specific areas.

Drones equipped with cameras can capture high-resolution images that are used to create orthomosaic maps and 3D models of fields. These maps provide valuable information about crop

growth, plant spacing, and potential nutrient deficiencies. A study by Hunt et al. [13] focused on using UAVs for field mapping and assessment. The researchers highlighted the ability of drones to rapidly generate accurate orthomosaic maps, which facilitated the identification of variability within the field and guided site-specific nutrient applications.

The utilization of drones and unmanned aerial vehicles (UAVs) in precision agriculture has brought about transformative changes in how farmers manage their fields. The reference you provided highlights the importance of drones equipped with multispectral sensors in targeted nutrient management. This technology enables farmers to gather high-resolution data quickly, making informed decisions for optimized crop health and production. The study by Sankaran et al. [14] underscores the significance of low-altitude, high-resolution aerial imaging systems for crop phenotyping. Multispectral cameras on drones can capture data across various spectral bands, providing valuable insights into crop health, stress levels, and nutrient deficiencies. This enables farmers to identify specific areas within a field that might require additional attention, such as nutrient application. By detecting nitrogen stress in wheat crops through multispectral data analysis, as mentioned in the study, farmers can take prompt action to address nutrient deficiencies precisely where they occur. This targeted approach enhances resource efficiency, prevents overuse of fertilizers, and minimizes environmental impact. Overall, drones equipped with multispectral sensors offer a non-intrusive and efficient means of collecting detailed information about crops' health and nutrient needs. This technology aligns perfectly with the principles of precision agriculture, allowing farmers to make data-driven decisions that lead to increased yields, reduced costs, and sustainable practices.

The utilization of drones in precision agriculture has completely revolutionized the industry by providing a highly efficient and cost-effective method for collecting high-resolution images and data from fields. These images and data can be utilized for a multitude of purposes, including crop monitoring, stress detection, yield estimation, and more. Drones equipped with cameras are capable of capturing detailed and comprehensive imagery that can be transformed into orthomosaic maps, providing a complete view of the field's conditions [12]. Drone data provides high-resolution imagery to assess plant health, growth, and nutrient content. This information is used to calculate vegetation indices, such as the Normalized Difference Vegetation Index or Chlorophyll Index, to make informed decisions about targeted nutrient applications. Multispectral and hyperspectral imagery from drones can capture detailed information about plant reflectance across different wavelengths of light. A study by Zarco-Tejada et al. [15] utilized multispectral

imagery from drones to assess nitrogen deficiency stress in wheat crops, showing the potential of drone data for nutrient deficiency assessment.

2.5. Real-time Monitoring and Data Analysis

Real-time monitoring and data analysis are essential in precision agriculture, enabling farmers to make informed decisions on nutrient management, irrigation, and other farming practices. These processes involve collecting, processing, and interpreting data from various sources to optimize crop growth and resource efficiency. Continuous data collection from sensors, drones, and weather stations enables up-to-the-minute information on field conditions. For instance, soil moisture sensors provide real-time updates on soil water content, allowing farmers to adjust irrigation schedules based on actual conditions.

Data analysis tools and software effectively integrate real-time data from sensors, drones, satellite imagery, and weather stations for farmers to make informed, data-driven decisions with a comprehensive view of field conditions. A study by Scharf et al. [16] highlights the critical role of integrating yield monitor data, soil maps, and weather information in precision agriculture decision-making, enhancing the ability to analyze and manage data from diverse sources. Data analysis tools process real-time data rapidly, allowing farmers to monitor changing field conditions and respond promptly. These tools enable decisions based on current information, improving resource allocation and crop management. In the study by Gebbers and Adamchuk [17], real-time data processing using GPS and sensors is discussed for creating management zones in precision agriculture. This approach emphasizes the dynamic nature of data-driven decision-making. Predictive analytics in agriculture involves using data analysis tools that utilize machine learning algorithms to make forecasts about future crop outcomes, such as development, potential yield, and the likelihood of disease outbreaks. These algorithms learn from historical data to recognize patterns, relationships, and trends that can help make predictions with a high degree of accuracy. The application of predictive analytics enhances decision-making in precision agriculture by providing insights into potential outcomes based on past data. The research article "Machine Learning for Predicting Tomato Yield Using Data from numerous Sources" by Andrade-Sanchez et al. [18] exemplifies the power of machine learning in accurate yield forecasting. In this study, the researchers demonstrate how machine learning techniques can predict tomato production by analyzing data from various sources. This includes data from sensors, weather stations, and potentially other relevant sources that contribute to the understanding of tomato growth. Data analysis tools provide visualization features to present complex data in a user-friendly manner.

Visualizations enable farmers to quickly interpret data trends and patterns, facilitating informed decision-making. In a review by Luo et al. [19], the role of data visualization tools in precision agriculture is discussed. Visualization aids in understanding complex relationships between variables, contributing to effective decision support.

Real-time monitoring enables farmers to receive instant updates on soil moisture, temperature, and crop growth. This information helps them adjust nutrient applications promptly based on the current field conditions. Li et al. [20] highlight the importance of real-time data in nutrient management. They discuss how monitoring soil nitrogen levels in real-time enabled precise adjustment of nitrogen fertilization rates, leading to improved crop yield and reduced environmental impact. Monitoring in real time helps to avoid either an excessive or insufficient amount of nutrient delivery. For instance, if a sensor identifies excessive nutrient levels in a particular location, farmers are able to alter the application rate in real time so as to prevent over-fertilization of the soil. On the other hand, if farmers discover that their crops have nutritional deficits, they may swiftly remedy the situation by using certain substances. Real-time monitoring via the use of sensors, as Schirrmann et al. [21] point out in their study, may successfully avoid nutritional imbalances and maximize the effectiveness of nutrient management strategies.

3. Impact on Soil Fertility and Crop Yield

In a study conducted by Zhang et al. [22], precision nutrient application was implemented in a corn field. Variable rate nitrogen and phosphorus fertilizers were applied based on soil test results and yield potential. The results showed that precision nutrient application significantly increased corn yield compared to traditional uniform application methods. A study by Sahu et al. [23] investigated the impact of precision nutrient management on wheat yield and soil fertility. They applied site-specific nutrient management techniques using GIS-based soil fertility maps. The research demonstrated that precision nutrient application led to higher wheat yields and improved soil fertility parameters compared to conventional methods. In a case study by Zhan et al. [24], variable rate nitrogen application was implemented in a maize field. Through the use of remote sensing and precision application equipment, nitrogen rates were adjusted based on plant needs. The study demonstrated that variable rate nitrogen application resulted in improved maize yield and reduced nitrogen losses. An investigation by Su et al. [25] focused on precision fertilization in rice cultivation. By adjusting nutrient application rates based on soil properties and rice growth stages, the study found that precision fertilization improved rice yield and grain quality, while also enhancing soil fertility. To achieve optimal nutrient application, it is imperative to make

adjustments to the quantity, timing, and placement of nutrients, taking into consideration the soil type, crop growth stage, and availability. This approach significantly enhances nutrient absorption, leading to healthy plant growth. Research conducted by Chen et al. [26] indicates that precision nutrient management based on soil and plant data can substantially increase maize yield and nutrient uptake. Using precision nutrient application can help minimize nutrient runoff and leaching, which can have negative effects on the environment and lead to water pollution. Farmers who apply nutrients specifically where they are needed can prevent over-application and reduce the risk of excess nutrients entering water bodies. This reduction in nutrient runoff can significantly contribute to the improvement of water quality and ecosystem health. A study conducted by Magruder et al. in [27] showed that the use of precision nutrient management was effective in reducing nutrient losses and improving water quality when compared to conventional methods. Precision nutrient application improves plant health by avoiding nutrient imbalances that can cause deficiencies or toxicities. Properly nourished plants are more resistant to pests, diseases, and environmental stressors, resulting in enhanced vitality and yield. A study conducted by Rezaei et al. [28] found that precision nutrient management led to better plant health and higher yield when compared to conventional methods.

4. Challenges and Limitations

Adopting precision agricultural technology can be expensive due to high initial costs for equipment, sensors, software, and data management systems. This financial challenge may discourage farmers, despite the long-term advantages provided by precision agricultural technologies. Farmers may face difficulties in adopting these technologies because of high investment costs [29]. Precision agriculture combines various technologies, including sensors, GPS, GIS, and data processing tools. Some farmers, especially those with limited tech experience, may find these systems challenging. Schimmelpfennig [30] noted that the complexity of precision agriculture technology can hinder adoption, particularly among older and less proficient farmers. For successful precision agriculture, farmers need personnel skilled in managing technologies and data analysis, GIS, and remote sensing to utilize its benefits. Education and training can bridge the skill gap among farmers in adopting and benefiting from precision agriculture technologies [31].

5. Future Directions

Machine learning algorithms can analyze diverse data sources like soil quality, weather conditions, and crop patterns to construct prediction models. These models help farmers predict crop nutrient

needs and adjust fertilizer application rates proactively. In a recent study, Bakhshipour et al. [32] used machine learning to forecast nitrogen fertilizer requirements for wheat farming, demonstrating superior performance over conventional techniques and enhancing decision-making in nutrient management. Precision agriculture benefits from AI-driven decision support systems that leverage diverse data sources to fine-tune nutrient management strategies, ultimately leading to increased crop yield and optimized resource utilization. These systems expertly navigate intricate factor interplay and provide timely, tailored recommendations for optimal nutrient application. AI-powered hyperspectral imaging is a powerful tool that can detect nutrient deficiencies and stress conditions in crops with remarkable accuracy. According to Palacios-Rojas et al. [33], this technology has the potential to revolutionize the assessment of nutrient status in maize crops. Advancements in robotics and AI are enabling the development of autonomous systems for precision nutrient application. These systems use AI algorithms to make real-time decisions about nutrient application rates, reducing the need for human intervention. A review by El-Ramady et al. [34] discusses the role of robotics and AI in autonomous precision agriculture. The review highlights the potential for AI-driven autonomous systems to revolutionize nutrient management practices. Machine learning and AI-driven systems can analyze complex data sets to identify specific nutrient needs at different locations within a field. By precisely targeting nutrient applications where they are most needed, these technologies minimize wastage and maximize nutrient uptake by crops. This approach contributes to maintaining optimal soil fertility levels and promoting healthier plant growth.

Conclusion

The intricacies of precision nutrient application techniques, and their direct influence on soil fertility and crop yield, are analyzed in great detail in this review. Our thorough examination of the latest technologies, including real-time monitoring, variable rate application, GIS-GPS integration, drone-based data collection, and data analysis tools, demonstrates how they collectively enhance nutrient management efficiency. Precision nutrient application is vital in modern agriculture for addressing food security and sustainability challenges. This approach optimizes fertilizer and nutrient usage, reducing wastage while improving crop productivity and quality. Precision nutrient application promotes balanced nutrient availability, enhances soil fertility, and supports sustainable agricultural practices. It also minimizes negative environmental impacts, such as nutrient runoff and greenhouse gas emissions.

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