



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(4): 224-233
Received: 17-01-2026
Accepted: 19-02-2026

Shilpa Kaushal
University Institute of Agricultural
Sciences, Chandigarh University,
Mohali, Punjab, India

Dev Kumar
University Institute of Agricultural
Sciences, Chandigarh University,
Mohali, Punjab, India

Md Tanvir Hossain Shishir
University Institute of Agricultural
Sciences, Chandigarh University,
Mohali, Punjab, India

A review on Ai – Driven Soil health monitoring and prediction

Shilpa Kaushal, Dev Kumar and Md Tanvir Hossain Shishir

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i4Sc.5402>

Abstract

Soil is considered as the foundation in agricultural activities as the comparison. Soil management is always lacking in the agriculture sector. The Precision soil management is one such approach that can assist us in the precise treatment of the soil, as well as in determining the different factors that contribute to the health of the soil and its nutritional content. It's a site-specific treatment that will involve various digital process in managing soil structure, composition and the macro and micro level of nutrient management. Advanced technologies such as GIS, GPS, Remote sensing, Internet of Things (IOT), Artificial intelligence (AI) and spatial data analysis make precision management of the soil possible. The tool will assist in keeping track of the soil levels that form part of the soil parameters, such as temperature, pH, and organic carbon content would be assisting in making site-based decision as opposed to adhering to ground report. Digitalization can assist in breaking down big field data into smaller form with a precise and actionable sight. (Variable rate technology) are also assisted in their use in irrigation, fertilizers, amendment of soils on crop which assists in the reduction of inputs and economical way. The decision support system also assists the farmers to receive real procedures to be applied on the ground based on predictive simulation performed on the system. The accuracy soil management assists in conservation of soil and alleviation of nutrient leaching and enhancing nutrient cycling in order to ensure healthy growth of crops. On overall basis precision soil management with a combination of digital agriculture practice has not only simplified but boosted agriculture practice. It has also led to sustainable development, climate smart approach and a resource efficient farming.

Keywords: Artificial intelligence (AI), GIS, GPS, Internet of Things (IOT), Precision soil management, Remote sensing, Spatial data analysis, VRT (variable rate technology).

Introduction

Soil is one of the most important natural resources that make the world food producing, ecosystem, and food secure. However, increased human activity, agricultural practices and pressure of climatic change has been a huge challenge to conventional soil management practices. Conventional models tend to use homogenous application of inputs, and as such, it does not take into account natural spatial heterogeneity of soil properties on agricultural lands^[1, 2].

Even at a micro-level, the soil systems are highly heterogeneous and there exists a difference in the texture, nutrient availability, moisture content and organic matter. These variations make it inefficient to use resources, they decrease crop yield, and cause environmental problems like soil erosion and nutrient drain^[3, 4]. All these restrictions emphasize the fact that the application of more specific and dynamic soil management methods is necessary.

Precision soil management has evolved to be a data-based solution that enables the evaluation and management of the soil resources in a site-specific fashion. It integrates the novel technologies of Geographic Information Systems (GIS), Global Positioning Systems (GPS), remote sensing, Internet of Things (IoT), and artificial intelligence (AI) to monitor the condition of the soil and make reasonable decisions^[5, 6]. Thanks to these tools, the key parameters of the soil can be studied in real-time and specific interventions are made in the field and sub-field level. The soil contains different layers which we should be aware of and explore with different technology-based methods.

Another benefit of the Digital Agriculture is the high quality of soil management since it can be

Corresponding Author:
Dev Kumar
University Institute of Agricultural
Sciences, Chandigarh University,
Mohali, Punjab, India

used to gather, process, and analyze the massive quantity of data. Some technologies that can turn the complex field data to actionable insights are sensors networks, machine learning algorithms, and cloud-based platforms, just to name a few. This allows maximization of inputs through application of technologies such as variable rate technology that leads to high efficiency with minimal effect to the environment ^[7]. The real time sensors or soil monitoring system help to measure field moisture level with direct measurement of temperature, along with soil nutrient level in continuity.

In addition, it is observed that the sustainable and climate-smart agricultural systems can be achieved as a result of precision soil management, in terms of efficient nutrient cycling, conservation of soil resources and reduction of greenhouse gases. It aligns with the global efforts related to strengthening the resilience of agriculture and delivering long-term productivity under the condition of the changing climatic conditions ^[8, 9]. This soil management method entails optimized irrigation practice consideration under the consideration of minimizing water wastage and it contribute to ameliorating water retention ability. The field is divided into different clusters and they are treated according to their nutrient requirement. Farmers are provided with betterment that they can analyze situation and give better approaches with these.

Despite the strengths; implementation of the precision soil management is constrained by the fact that it involves high initial expenses, technical problems and is not easily accessible in the developing world. These are the issues that need to be resolved to enable widespread use and to provide as much benefits as possible in digital agriculture. This adaptation of precision soil management system will require building that will assist in overcoming the issues with a collaborative approach. The government organization and private sector have to collectively develop a cost-effective approach with technology driven and will be easily adapted by farmers. The capacity building approach made different farmer training programs' extension service and different awareness programs. as well as with a voyage furthermore promoting the open accesses data-platforms and ensure data transparency enhance the trust and wider adaptability.

This chapter gives a summary of precision soil management in the context of digital agriculture with the concepts, technological advancements, application, and contribution to sustainable farming systems. The integrated workflow of precision soil management within digital agriculture is illustrated in Figure 1.

Figure 1. Integrated framework of precision soil management in digital agriculture showing data acquisition (sensors, GIS, remote sensing), data processing (AI and analytics), decision support systems, and site-specific implementation for sustainable outcomes.

2. Concept of Precision Soil Management

Precision soil management refers to a data intensive and site-specific approach to soil management to achieve an optimal environment to achieve high yields of agricultural products and profitability. As opposed to conventional uniform methods of soil management it recognizes natural spatial and temporal heterogeneity of the soil properties and permits specialized treatment based on the real-time information and requirements of the field^[1]. To optimize field level intervention, the weather performance and crop analysis will be conducted to make it easy to obtain real time soil management and analysis. The predictive analysis capability assists in obtaining proactive management approaches uttering to modify the nutrient application prior to the shortage of nutrient composition in soil. The expected crop yield of these farmers can reduce the risk and predictability of crop production.

2.1 Principles of Precision Soil Management

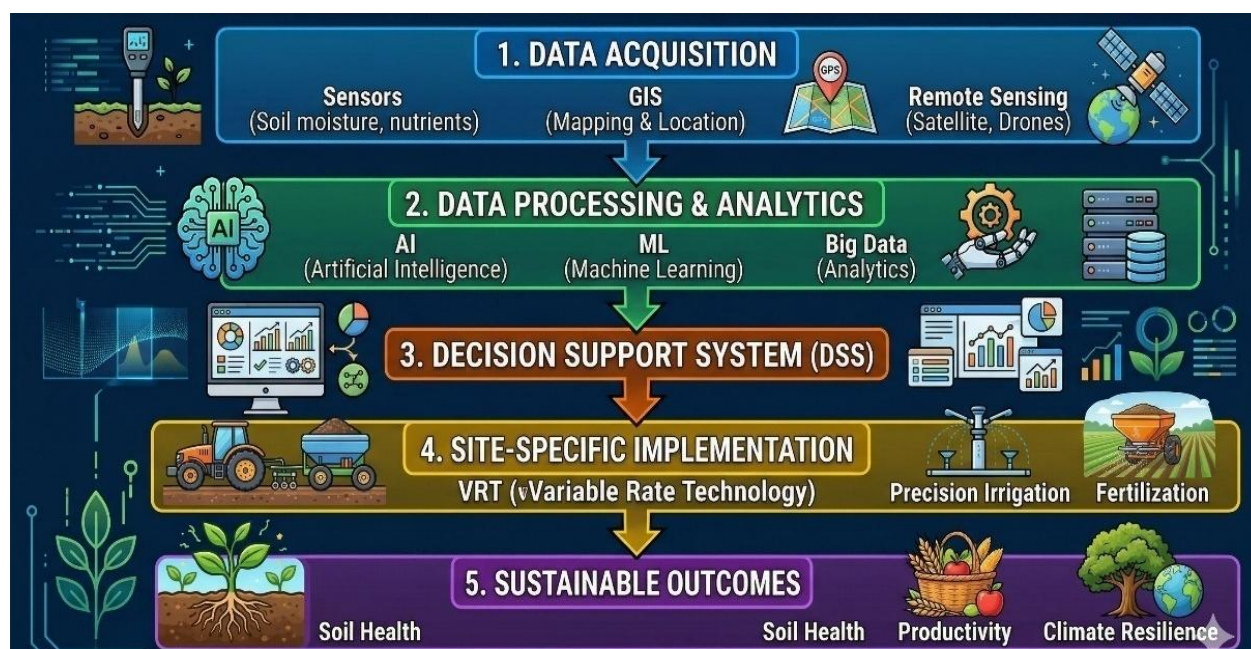
There are fundamental tenets that underlie precision soil management that is contrary to conventional procedures. Central to this is spatial variability that recognizes the heterogeneity in the properties of the soil and helps in site-specific input application to maximize nutrient utilization and to reduce the leaching and runoff^[1].

The other principle is the data-driven decision-making that integrates sensor data, satellite images, and history to come up with actionable information. Prediction, monitoring, and interventions at the right time during irrigation and fertilization are also improved by machine learning and decision support systems ^[6].

The concept of resource optimization also focuses on the reduction of input wastage without reducing the productivity or even enhancing it. Precision soil management also provides economic and environmental sustainability by matching the application of inputs and the real needs of soil.

2.2 Soil Variability and Its Significance

Soil variability is the key to precise soil management, as it depends on topography, parent material, and management



history and introduces the variation in the texture, nutrients, moisture, and organic matter influencing the growth and yield of crops^[9].

Crop performance is not even because of spatial and time changes, which include variations in water-holding capacity between sandy and clay soils. This heterogeneity is disregarded leading to poor use of inputs and degradation of the environment. To overcome this, accuracy soil management embraces location-specific zoning, which is supported with geospatial instruments, soil sensors, and data-driven systems. The combination of high-resolution datasets and geo-statistics and AI allows targeted intervention, optimization of inputs, increased productivity and sustainability of the environment.

2.3 Components of Precision Soil Management

Precision soil management can be broken down into various components, which are interrelated and all able to facilitate proper monitoring and management of the soil.

- **Data Acquisition:** Data on the soil in form of sensors, remote sensing and field sampling. Real time or periodic monitoring of parameters like soil moisture, pH, temperature and nutrient level occurs. The use of georeferenced sampling would be enabling the precise mapping in field variability. Use of cloud-based storage facility will be having a continuous data access and analysis. The automated sensor network will help out to reduce the manual labor and have a reduced human error.
- **Data Processing/Analysis:** Data are collected and interpreted with advanced analytical tools, such as geographic information system (GIS) and machine learning algorithms to find their variability patterns. The integration for the multi – layered data sets will have a holistic interpretation in field condition. Also, the creation of management of delineation maps will be based on the clustering and variability indices^[5].
- **Decision-Making Systems:** Decision support systems (DSS) offer suggestions that are made using the analyzed information to assist the farmers in identifying the best management practices. The platform will be subjected to provide real -time alerts with predictive analysis on field. It basically emphasis's more on data – drive agriculture practice. Therefore, precision soil management incorporation with digital agriculture and tools supported with them is giving return of analysis at the expected level.
- **Site-Specific Implementation:** These technologies include the variable rate application systems that provide precise input applications depending on spatial differences in the field. The application of variable rate technology (VRT) helps farmers regulate the application of resources in the right quantities. This ensures that the right number of resources is applied at the right place in the fields. Therefore, overuse and underuse of resources are reduced to the minimum, and this helps in increasing crop productivity and efficiency. In addition, it helps in the reduction of environmental risks such as nutrient runoff, groundwater contamination, and soil degradation. Site-specific management helps in the efficient use of resources since it targets the areas that need the

resources. In this regard, it helps in conserving the resources and energy.

These elements are used to work together in enhancing the efficiency of soil management and that the interventions are timely and location-specific.

2.4 Role in Digital Agriculture

The greater leap of digital agriculture is precision soil management. It is a critical point of contact between soil science and highly developed digital technologies, using which it is possible to transform raw information into useful knowledge. The IoT and cloud computing solutions along with the artificial intelligence sphere allow supervising the soil conditions at all times and studying them in advance. The most important part of digital agriculture is that, the real time data collection and monitoring of field in accurate level. With the help of this continuous data driven approach will make the farmer understand the continuous changing of` soil condition and respond to the appropriate intervention. The decision support system and the data analytics also play an important role. This digital platform makes the analysis of` large input data of a particular area this reduces the time of` management and create a output that is much more reliable as compared to traditional method of` analysis^[6].

Such digital integration makes decision-making more precise and enables automatization of agriculture. One such application would be the real-time data on the soil is used to turn on the automatic irrigation system or even to automatically apply the fertilizer, when necessary, as opposed to having people manually apply the fertilizer, which is less efficient. Furthermore, proper soil management is also a consideration that can contribute to constructing smart farming systems as it enables responsive and adaptive farming.

3. Digital Technologies in Soil Management

The innovation of digital technologies has drastically changed the mode of practice in handling soil management since it allows making decisions that are accurate and based on data. The technologies are implemented to facilitate the sustained monitoring, space analysis and predictive modelling of the soil conditions, which sustain efficient and sustainable agricultural systems. Geospatial technologies, sensor networks and smart algorithms can be combined to result in the appropriate assessment of soil variability and interventions in management in real-time. The sophisticated technologies would become a sub-component of the high-resolution acquisition and interpretation of the cropping pattern with a more accurate land distribution through a natural development. However the incorporation of` IOT – internet of things will make things more easy in understanding and especially the pH of` soil^[10, 11].

Digital soil management is built on the basis of gathering big data sets developed as a result of various sources, such as satellites, in-field sensors, and historic data. These data are then processed with more sophisticated computational tools to provide actionable information in order to maximize soil health, nutrient management, and water use efficiency. In the following subsections, key digital technologies that aid the modern precision soil management are outlined.

3.1 Geographic Information Systems (GIS) and Global Positioning Systems (GPS)

The spatial analysis is founded on Geographic Information Systems (GIS) and Global Positioning Systems (GPS). GIS also permits integration, displaying as well as analyzing spatial data

and may be employed to develop comprehensive soil maps and administration areas. Achievement of proper field positioning will be achieved using the GPS technology, making it easy to collect data and input the data to the specific site. Both of these combined makes the field operation and mapping far easier to agronomist and farmers that utilize this information very valuable- variable rate technology VRT is part of this precision soil management. In addition to this the data obtained from `satellite imaging will make the work easier. SDSA - spatial decision support system with a GIS framework can assist the long-term approach also analyze trend and future scenario based on the climate and soil data. Reduces the overlapping and skipped in operation of seeding, irrigation and the application of pesticides. Making of the synergy between GIS and GPS technology will be facilitating a data driven approach to farmers farming leading to higher productivity, cost effectiveness and environmental sustainability with a support to approach of` precision management. In addition to this the data obtained from `satellite imaging will make the work easier. SDSA - spatial decision support system with a GIS framework can assist the long-term approach also analyze trend and future scenario based on the climate and soil data. Reduces the overlapping and skipped in operation of seeding, irrigation and the application of pesticides. Making of the synergy between GIS and GPS technology will be facilitating a data driven approach to farmers farming leading to higher productivity , cost effectiveness and environmental sustainability with a support to approach of` precision management^[12].

The tools assist in establishing spatial variability of such soil properties as the distribution of nutrients, pH levels, and moisture content. Mapping of these variations is useful in that farmers are able to apply specific management habits which enhance efficiency and minimize wastage of resources. Long-term monitoring of soil and land-use planning are also enabled with the use of GIS-based decision-making. With these tools' combination the conservation practices of 'contour farming, organic amendments will be keen to save the soil health.

With the advent of remote sensing technologies, this has simplified the identification of hidden resources and the presence of other related components within the system.

3.2 Remote Sensing Technologies

Remote sensing is important in the surveillance of the soil and crop conditions in large regions. The aerial and ground level based (satellite and unmanned aerial vehicle (UAV)) can deliver high-resolution and clear comparison of the data on soil

moisture, surface temperature, vegetation indices with assimilation of organic matter content. These technologies would be helping to make it possible to check the conditions in the fields without invasiveness, quickly, and cheaply ^[13].

Remote sensing platforms are utilized to measure the soil degradation, salinity and nutrient shortages based on spectral line of analysis. This data is useful to assist in an early intervention with the optimize the use of inputs. Also, remote sensing time-series data have a trace that can be used to transformations in soil conditions for better strategies to manage the soil in the long-term platform.

3.3 Internet of Things (IoT) and Sensor-Based Monitoring

The internet of things would be helping to monitor the soil and will allow to accesses the real time collection of big data on ground basis. This is achieved via a network of sensors and artificial non imaging network system. soil sensors can be included in the moisture content, temperature, the electrical conductivity, and the nutrient levels, which can give the information about the soil conditions continuously ^[14].

These sensory devices will be sending the information to the cloud computing services, where they are processed and analyzed to the decision-making platform. Systems built using IoT can be automated, as a part of example we can say that irrigation may be activated when the soil moisture level drops below a set point level of moisture content.

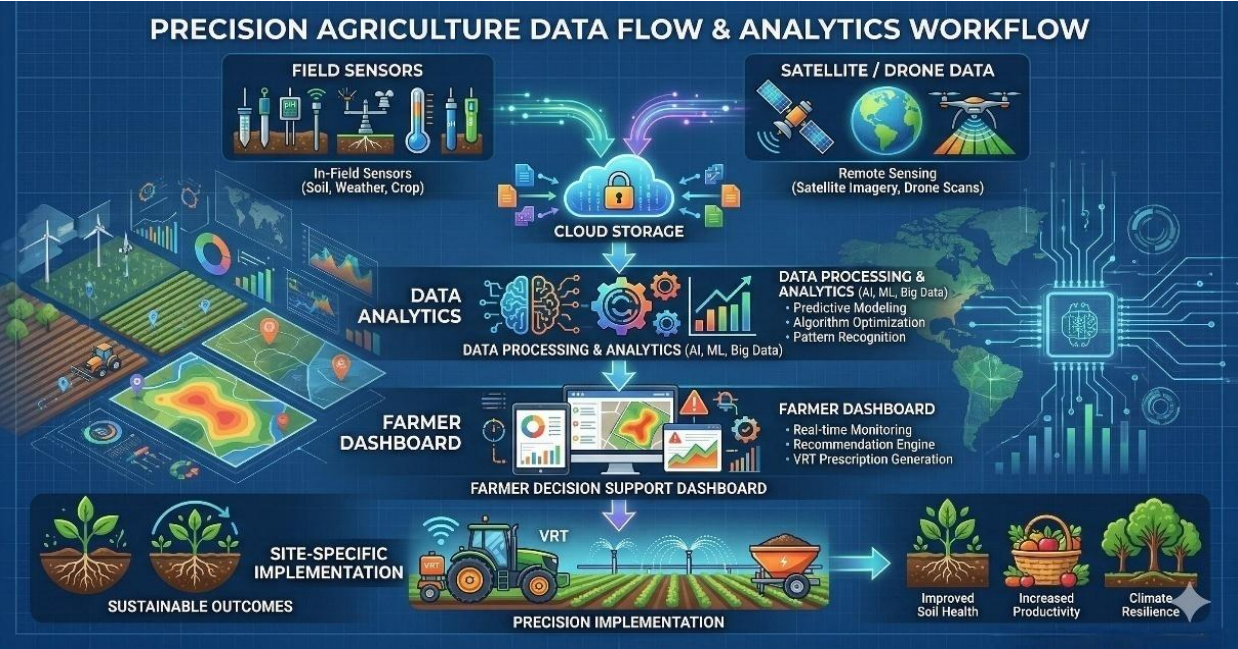
3.4 Artificial Intelligence and Machine Learning

As artificial intelligence (AI) and machine learning (ML) accelerate, such an approach would be even more commonly used to analyze complex agricultural data and generate predictive data. Technology will be capable of seeing the patterns and relationships that are present in large volumes of soil and environmental data and in this manner, they can be able to predict the correct behavior of the soil and crop reaction. These models are not only predictive, but also prescriptive analytics. Speaking of which, advanced algorithms such as neural networks and deep learning can make predictions that can be refined over time, as they learn using new data. This enables inter-reactive responses to climatic changes. Moreover, farmers can also use AI-powered models to identify the early indicators of soil degradation, nutrient deficiency, and pests and diseases. These models can identify anomalies which are otherwise impossible. This aids in effective management of resources and minimization of wastage^[15].

3.5 Cloud Computing and Big Data Analytics

The cloud computing helps us to analyze and offer platform for the stire processing and a grip hold analysis with the big data available in agriculture sector. These technologies allow a stable combination of the information of various sources, such as sensors, satellites, and farm machine. Cloud computing also makes data management more effective since it eliminates the need for high-end infrastructure in local environments. Such tools also make data-driven decision-making more effective since they allow farmers to respond quickly to any emerging issues in their farms. Furthermore, the integration of cloud computing with big data also creates an interface that fosters innovation in agriculture since it enables data sharing and cooperation among stakeholders in creating more effective, efficient, sustainable, and climate-resilient agricultural

Remote Sensing	Non-invasive acquisition satellites/UAVs	data via	Mo ter
IoT Sensors	Real-time in-field collection	data	Co ter



systems^[11].The major digital technologies and their role in soil monitoring and decision-making are presented in **Figure 2**.

Figure 2. Digital technologies supporting precision soil management, including data acquisition, processing, analytics, and decision support systems for real-time soil monitoring and management.

Cloud-based platforms can also be used to share and collaborate data with the stakeholders, which increases the scalability and accessibility of digital soil management systems. The major digital technologies enabling precision soil management and their applications are summarized in **Table 1**.

Table 1: Major Digital Technologies Supporting Precision Soil Management

Technology	Core Function	
GIS & GPS	Spatial mapping and geolocation	Artificial Intelligence (AI) & Machine Learning (ML) Predictive analytics and pattern recognition Cloud Computing & Big Data Data storage, integration, and processing

4. Soil Health Monitoring and Data Analytics

To be on a note that one of the central themes in the area of precision soil management will be giving a set of monitor soil health, thereafter soil physical, chemical and biological properties are monitored constantly to enable informed decision making. The system will be contrasted to the old systems of periodic soil testing, rely on real-time and high-resolution data acquisition systems, capturing dynamic changes of soil conditions. This enables the possibility of intervening in time and increasing the accuracy of the soil management practices ^[16, 17].

4.1 Key Soil Health Indicators

Definition of management zones, soil variability mapping, site-specific input application
Effective surveillance of the soil has necessitated selection of relevant indicators used to ascertain the operation and performance of the soil. These parameters are often classified as three, physical, chemical and biological parameters.^[18]

When these indicators are combined, the full image of the soil condition is formed and maybe used in management decisions at

the site. Key soil health indicators and their functional roles in precision agriculture systems are presented in **Table2**.

Table 2: Soil Health Indicators and Their Functional Significance in Precision Agriculture

Indicator Type	Parameters	Functional Significance
Physical	Texture, bulk density, porosity, moisture	Texture, bulk density, porosity, and moisture influence water retention, aeration, and root growth in the soil.
Chemical	pH, EC, N, P, K, organic carbon	Spatial representation of soil variability through visualization, tissue like digital soil maps and dashboards, can be easily interpreted and implemented. The real time information and predictive analytics will improve decision and operations effectiveness.
Biological	Microbial biomass, enzyme activity, soil respiration	Reflects soil biological activity and nutrient cycling capacity.
Integrated Indicators	Soil organic matter, C:N ratio	Precision agriculture relies on soil health monitoring and data analytics to provide continuous feedback and adaptive management. During real-time monitoring, optimization of field activities can be realized in terms of dynamic adaptations to the needs of the real soil, where the inputs are implemented according to the real needs of the soil and not based on a generalization of the requirements ^[1] . Overall soil health, sustainability, and carbon sequestration potential. The methodology reduces the efficiency of resource use, increases crop yield, and reduces environmental effects, including nutrient leaching, and soil erosion. Additionally, the data-based management of soil promotes the long-term sustainability of soils by ensuring their sustainability and their balance with other elements.

4.2 Sensor-Based Soil Monitoring

sensor technologies will provide the opportunity to continuously examine the parameters in the soil on-site. Sensors will be providing real-time measurements of soil moisture, temperatures, salinity, and nutrient contents include capacitance probes, tensiometers, and ion-selective electrodes. Sensors mounted on ground system correction would be giving us the precise and continuous monitoring of the condition of the soil. farmers would be having a timely and informed decisions regarding the irrigation and fertilization for crops. The real-time data collected by the sensors helps in the early detection of moisture stress, nutrient deficiencies, and salinity in the soil. This helps in avoiding crop loss. Application of resources such as water and fertilizers are possible with the help of these sensors. This helps in making the decisions regarding the management of the farm more responsive. The data collected by the sensors over time helps in creating the profile of the soil. This is extremely important in the context of precision agriculture. The approach of the sensor-based monitoring of the soil helps in improving the perseverance and efficiency of the resources. In addition to this, it also helps in the sustainable management of the soil.^[1].

4.3 Data Integration and Analytics

Soil health practice monitoring is based on the utilization and processing of bulk data generated by different sources. Tools such as GIS, cloud-based applications combine sensors, satellite images and field observations. The soil data are observed in the way of using advanced tools with analytical technique with a integration of statistical tools with machine learning and with a tool developed with predictive analysis with respect to crop response.Data segmentation platforms help in integration of the temporal and spatial data will be able to generate maps that show the fertility levels of the soils and the moisture levels. Machine algorithms such as regression models, decision trees, and neural networks would be able to improve the accuracy of the prediction. Machine learning

algorithms learn continuously from the new data that is constantly being inputted..^[19].

4.4 Decision Support and Visualization

The decision support systems (DSS) help in converting complex soil data into measures that can be taken. These systems combine the results of the analytical processes with the easy-to-use interfaces to allow farmers and other stakeholders to make informed decisions on scheduling irrigation, applying the right amount of fertilizers and amending the soil. Spatial representation of soil variability through visualization, tissue like digital soil maps and dashboards, can be easily interpreted and implemented. The real time information and predictive analytics will improve decision and operations effectiveness.

4.5 Role in Precision Agriculture

Precision agriculture relies on soil health monitoring and data analytics to provide continuous feedback and adaptive management. During real-time monitoring, optimization of field activities can be realized in terms of dynamic adaptations to the needs of the real soil, where the inputs are implemented according to the real needs of the soil and not based on a generalization of the requirements^[1]. Overall soil health, sustainability, and carbon sequestration potential. The methodology reduces the efficiency of resource use, increases crop yield, and reduces environmental effects, including nutrient leaching, and soil erosion. Additionally, the data-based management of soil promotes the long-term sustainability of soils by ensuring their sustainability and their balance with other elements.

5. Applications in Nutrient and Water Management

Precision soil management facilitates the effective management of nutrient and water through the alignment of input application with soil variability in space and time. This is a focused method that is more efficient in the use of inputs, more effective in crop production, and less damaging to the environment than the traditional homogenous applications^[20].

5.1 Precision Nutrient Management

Precision nutrient management is concerned with optimization of fertilizer application, taking into account the site-specific soil nutrient status and crop demands. Spatial variability of nutrient availability is solved using soil mapping, sensor data, and yield history analysis. This allows marking the management zones and aids in applying different amounts of fertilizer ^[20].

A variable rate technology (VRT) is at the heart of it, adjusting the application level of fertilizers in real-time as per field conditions. This prevents excess use and under-use, enhance nutrient utilization and limit nutrient loss by leaching and volatilization ^[21].

There are also decision support tools and prediction models that help to establish the best timing and dosage of fertilizer. These systems combine soil measurements with weather forecasts and crop development stages and give advice on how to optimize nutrient uptake and reduce environmental effects.

5.2 Water Management and Precision Irrigation

Good water management will help keep the soil healthy and produce crops in a sustainable manner. Precision irrigation employs the environment to apply water to fields at the precise timing and amount required instead of relying on pre-established routines ^[22].

Irrigation practices can be adjusted in real-time, using technologies like automated irrigation systems and IoT-based

monitoring platforms. This will help in water wastage reduction, over-irrigation, reduction of soil salinity and nutrient leaching. Another way of enhancing water productivity is site-specific irrigation management that guarantees that water is released where and when it is required. This is especially essential in water-limited areas where effective water consumption is essential to support agriculture.

5.3 Integrated Nutrient–Water Management

Nutrient and water management are also integrated to improve the effectiveness of the entire system in identifying the interdependency between moisture content in the soil and the nutrient content in soil. The water content of soil affects the mobility of nutrients, their uptake and transformation.

Precision management systems are irrigation scheduling and nutrient application strategies used to maintain the right soil conditions to grow plants. Fertigation systems are also an example: they enable nutrients to be applied at the same time as water, enhancing nutrient availability and minimizing losses [23]. The combined practice contributes to a synchronized input application, which results in better crop performances and lower environmental risks.

5.4 Environmental and Economic Implications

Exact nutrient and water control can greatly improve environmental impacts in farming. It reduces the risk of contamination of groundwater, eutrophication, and greenhouse gas emissions by reducing the amount of excess fertilizer and water used [7].

Economically, maximized use of inputs decreases the costs of production and increases profitability. Farmers enjoy increased efficiency in input, more stable yield and less wastage of resources. The benefits of precise soil management render it a feasible approach towards sustainable agricultural intensification. The application of variable rate technology (VRT) for site-specific nutrient and water management is illustrated in **Figure 3**.

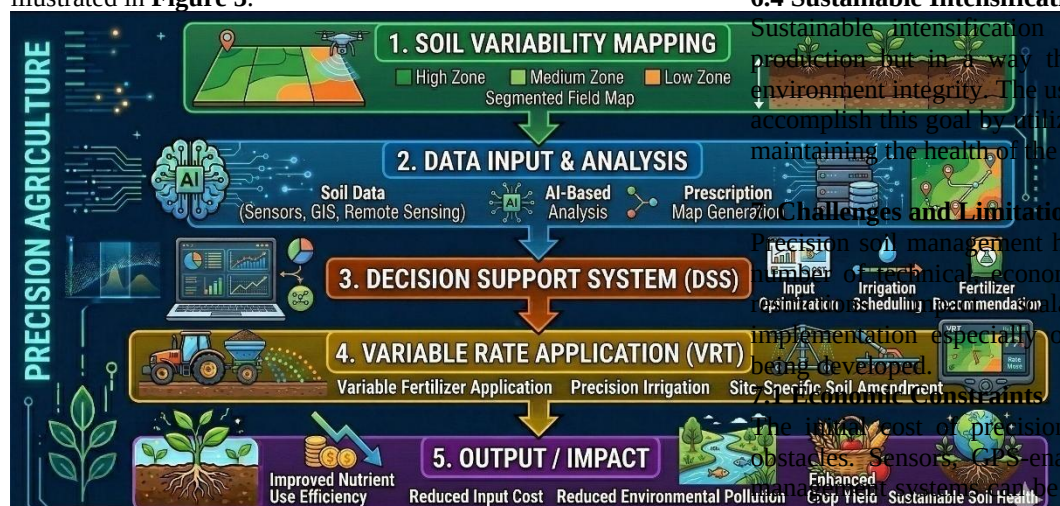


Figure 3. Site-specific nutrient and water management using variable rate technology (VRT), illustrating soil variability mapping, data-driven decision-making, and optimized input application for improved efficiency, productivity, and sustainability.

6. Sustainability and Climate-Smart Agriculture

Proper soil management is a major component of sustainable and climate sensitive agricultural systems development in addition to maximization of resource-use efficiency, health of soil and the reduction of environmental impacts. It is ecologically balanced and prolific as it adjusts the agricultural

inputs according to site-specifics of the soil.

6.1 Resource-Use Efficiency and Soil Conservation

Sustainable agriculture entails the use of inputs such as fertilizers, water and energy. Precision soil management eliminates unnecessary inputs because it puts resources in areas of need, thereby enhancing the efficiency of the nutrient use and minimizing losses [24].

Another significant number is better soil protection. The application of controlled inputs, reduced tillage, and certain soil additions are those methods that would help maintain the soil structure, prevent soil erosion, and enhance the soil organic matter. These activities enhance the future soil fertility and strength.

6.2 Climate Change Mitigation

Farmers are a significant source of green-house gases particularly nitrous oxide because of the overuse of fertilisers. Precise management of soil diminishes these emissions by maximizing the utilization of nitrogen and minimizing its losses because of the leaching and volatilization [25].

In addition, enhanced soil management will enhance the carbon sequestration through increased carbon content of the soil organic matter. Accurate technology like grime control and effectiveness in nutrient application procedures, assists in the storage of carbon and reduces the overall carbon footprint of agricultural frameworks.

6.3 Climate Adaptation and Resilience

Proper management of soil is more efficient in enhancing the adaptability of agricultural systems to climate change. The real time monitoring of soil moisture and soil temperature is carried out to initiate timely interventions to curb drought and weather extremes.

An analytics tool and a decision-support tool, which are predictive in nature and adjusted with adaptive management strategies, enable the farmers to change with the changing climatic situation. This increases stability in the crop, reduces risks in production particularly in the risky regions [26].

6.4 Sustainable Intensification

Sustainable intensification tries to increase the agricultural production but in a way that avoids compromising with the environment integrity. The use of precision soil management can accomplish this goal by utilizing inputs to the maximum and yet maintaining the health of the soil and ecosystem services [27].

Challenges and Limitations

Precision soil management has the potential but is limited by a number of technical, economic, and institutional factors. Such as input optimization, irrigation scheduling, fertilizer recommendation, and site specific soil amendment.

The high cost of precision technologies is one of the main obstacles. Sensors, GPS-enabled machinery, drones, and data management system can be quite expensive to invest in, which can be challenging with small and medium-scale farmers. Recurring costs, such as maintenance, software update, and data service, also add to the financial burden, not to mention capital costs [28].

The payback period can also be difficult to predict because of the size of the farm, type of crop, and environmental factors which can deter use in resource constrained environments.

7.2 Technical and Infrastructure Limitations

High-tech technologies and online infrastructure are essential to precision soil management. Digital tools are not used effectively in many regions due to the unavailability of reliable internet

connection, power, and support.

There are also challenges with the accuracy of data and reliability of sensors. Data quality can be impacted by calibration problems, environmental interference, and sensor performance variability, all of which can result in erroneous decision-making. Secondly, the interoperability of various technologies and platforms is also a problem as most systems are used within closed systems^[29].

7.3 Data Management and Complexity

The huge amount of data produced by sensors, remote sensing platforms and field observations, needs to be stored, processed and interpreted efficiently. Such data might be challenging to handle, especially when the managing farmers have little technical knowledge.

Integration of data and data sources does not always go hand in hand and the absence of standardization of data formats only complicates further analysis. In addition, raw data may have to be converted into actionable insights using sophisticated analytical tools and human expertise, which are not necessarily readily available^[30].

7.4 Knowledge and Skill Gaps

Precision soil management implementation demands technical expertise and skills among the operators to make the process effective. Not every farmer has been trained to read and interpret data and apply digital tools and use site-specific management practices^[31].

This is the problem that extension services and training programs are not enough to address in the developing regions. This limits the usefulness of precision technologies and their potential application.

7.5 Socio-Institutional and Adoption Barriers

Socio- institutional factors that determine adoption of precision soil management include policy support, availability of credit and awareness. Lack of awareness of the benefits of precision technologies, government incentives, and extension support are limiting their widespread adoption.

Also, there are issues of data ownership, privacy, and security, which might deter farmers to join the digital platforms. Another aspect of adoption is trust in technology, and perceived risk.

8. Future Perspectives

The future of precision soil management is a broad term that can't be explained in a couple of sentences. accurate management of soil have helped in getting out the best possible outcome that make the input cost cut up to 50% of the expenditure. The integration of artificial intelligence and digitalization in analysis of soil and their branches have kept the farming more in smooth process. Digitalization have helped farmers to easily identify nutrient availability, GPS integration have gained site specific management leading to time reduction and reduces input cost. Therefore, the future of precision management of soil and agricultural practices along with its allied sectors will be having a positive approach and response to the 'on field management' using a digitalized way of Agri practices.

8.1 Integration of Advanced Technologies

The convergence of artificial intelligence, robotics, and advanced sensing technologies is expected to further improve soil management practices. Autonomous systems equipped with real-time sensors can enable continuous soil monitoring and automated field operations. These systems will enhance precision while reducing labor dependency and operational costs^[32].

Advancements in Hyperspectral imaging and proximal sensing are also likely to improve the detection of soil properties at higher resolutions, enabling more accurate assessment of soil variability^[33].

8.2 Big Data and Predictive Analytics

The increasing availability of large-scale agricultural data driven with the maximize strength of predictive capabilities in soil management. Machine learning and data-driven models would be enabling us in forecasting of soil moisture dynamics, nutrient availability, and crop responses under varying environmental fluctuation^[34].

8.3 Digital Platforms and Decision Support Systems

Future in the due course of developing with the cloud specific platform and integrated with cloud-based platforms with the integration of mobile application. The accessibility and usability of precision soil management tools will increase the User-friendly interfaces and real-time analytics that will be allowing us to make the farmers and an informed decisions without requiring advanced technical expertise as compared on field^[35].

8.4 Scalability and Inclusive Adoption

We have to put down the effort will be reducing cost and the accessibility would be scaling up the precise soil management level. Particularly in smallholder farmers. The development of low-cost sensors, open-source platforms, and government-supported initiatives can facilitate wider adoption.

Collaborative approaches involving researchers, policymakers, and industry stakeholders will play a key aspect in bridging the gap between tech developments with the integration of field-level implementation.

8.5 Towards Sustainable Digital Agriculture

Future precision soil management systems will increasingly focus on sustainability by integrating environmental monitoring with production goals. This includes optimizing resource use, reducing emissions, and enhancing soil resilience under climate stress^[13].

The transition toward fully integrated digital agriculture systems will enable real-time, adaptive management of soil resources, contributing to long-term agricultural sustainability and food security.

CONCLUSION

Precision soil management help us in providing a significant advancement in 21st modern day agriculture by enabling land and method based site-specific, data-driven management of soil resources. Through the introduction of digital technologies such as GIS, remote sensing, IoT, and artificial intelligence, it helps us to gain accurate monitoring, analysis, and optimization of soil conditions. This method provides us with the limitations of age 'old practices having a uniform management practice, accounting for spatial and temporal variability inside the agricultural systems.

The application of precision techniques in nutrient and water management help to enhance the input-use efficiency, reduces environmental losses, and increase crop productivity. In addition, the continuous soil health monitoring and data analytics support have been given and informed decision-making, enabling timely and targeted interventions. These approaches and capacity will contribute to maintaining soil fertility, improving resource conservation, and ensuring long-term agricultural sustainability. Precision soil management is some or the other way interlinked to climate resilient agriculture system enhancing the productivity of climate smart agriculture system. This approach makes the farmer analyze in a very short duration of time about their productivity and future management aspect of field. This also

helps` in` reduction of greenhouse gas emission followed by carbon sequestration, and improved resilience of climate. Though we know `the maximum benefits we can get from this` management practices `but `there is a hindrance created due to the data` manipulation and` handling, economic instability, technical complexity and limited accesses to widespread adaptation.

Future of this resulting in movement towards digitalization making things easier to understand and manipulate with the use of Machine learning, cloud-based automation system and DSS Decision support system. This helps in increasing the scalability and the effectiveness of precision soil management. We can address the barriers present in through policy support, capacity building and cost effectiveness solutions approaches will be essential for broader implantation.

CONSENT FOR PUBLICATON

None Declare

CONFLICT OF INTEREST

None Declare

ACKNOWLEDGEMENT

None Declare

References

- Gebbers R, Adamchuk VI. Precision agriculture and food security. *Science*. 2010;327:825-828.
- Zhao L, Bao Y, Zhang Y, et al. Recognition of abnormal chest compression depth using one-dimensional convolutional neural networks. *Sensors*. 2021;21:1-16.
- Lal R. Soil health and carbon management. *Food Energy Secur*. 2020;9(2):200.
- Tilman D, Cassman KG, Matson PA, et al. Agricultural sustainability and intensive production practices. *Nature*. 2002;418:671-677.
- Liakos KG, Busato P, Moshou D, et al. Machine learning in agriculture: a review. *Sensors*. 2018;18:2674. <https://doi.org/10.3390/s18082674>
- Wolfert S, Ge L, Verdouw C, et al. Big data in smart farming: a review. *Agric Syst*. 2017;153:69-80.
- Zhang C, Kovacs JM. The application of small unmanned aerial systems for precision agriculture: a review. *Precis Agric*. 2012;13:693-712.
- FAO. The state of the world's land and water resources for food and agriculture – systems at breaking point (SOLAW 2021). Rome: Food and Agriculture Organization; 2021. <https://doi.org/10.4060/cb7654en>
- Lal R. Soil organic matter and water retention. *Agron J*. 2020;112:3265-3277.
- Khanal S, Fulton J, Shearer S. An overview of current and potential applications of thermal remote sensing in precision agriculture. *Comput Electron Agric*. 2017;139:22-32.
- Kudama G, Dangia M, Wana H, et al. Will digital solutions transform Sub-Saharan African agriculture? *Artif Intell Agric*. 2021;5:292-300.
- Sishodia RP, Ray RL, Singh SK. Applications of remote sensing in precision agriculture: a review. *Remote Sens*. 2020;12:1-31.
- Xie C, Yang C. A review on plant high-throughput phenotyping traits using UAV-based sensors. *Comput Electron Agric*. 2020;178:105731. <https://doi.org/10.1016/j.compag.2020.105731>
- Jawad HM, Nordin R, Gharghan SK, et al. Energy-efficient wireless sensor networks for precision agriculture: a review. *Sensors*. 2017;17:1781. <https://doi.org/10.3390/s17081781>
- Kamilaris A, Prenafeta-Boldú FX. Deep learning in agriculture: a survey. *Comput Electron Agric*. 2018;147:70-90.
- Basso B, Fiorentino C, Cammarano D, et al. Variable rate nitrogen fertilizer response in wheat using remote sensing. *Precis Agric*. 2016;17:168-182.
- Martín MÁ, Reyes M, Taguas FJ. Estimating soil bulk density with information metrics of soil texture. *Geoderma*. 2017;287:66-70.
- Doran JW, Sarrantonio M, Liebig MA. Soil health and sustainability. *Adv Agron*. 1996;56:1-54.
- McBratney A, Whelan B, Ancev T, et al. Future directions of precision agriculture. *Precis Agric*. 2005;6:7-23.
- Kaur T, Sharma PK, Brar AS, et al. Precision irrigation and fertilization strategies for sustainable cotton-wheat systems in water-scarce regions. *Agric Water Manag*. 2025;317:109669. <https://doi.org/10.1016/j.agwat.2025.109669>
- Robertson MJ, Llewellyn RS, Mandel R, et al. Adoption of variable rate fertiliser application in the Australian grains industry: status, issues and prospects. *Precis Agric*. 2012;13:181-199.
- Evans RG, Sadler EJ. Methods and technologies to improve efficiency of water use. *Water Resour Res*. 2008;44. <https://doi.org/10.1029/2007WR006200>
- Hagin J, Lowengart A. Fertigation for minimizing environmental pollution by fertilizers. *Fertil Environ*. 1996;23-25.
- Foley JA, Ramankutty N, Brauman KA, et al. Solutions for a cultivated planet. *Nature*. 2011;478:337-342.
- Paustian K, Lehmann J, Ogle S, et al. Climate-smart soils. *Nature*. 2016;532:49-57.
- Lipper L, Thornton P, Campbell BM, et al. Climate-smart agriculture for food security. *Nat Clim Change*. 2014;4:1068-1072.
- Grieco R, Cervelli E, Bovo M, et al. The role of geospatial technologies for sustainable livestock manure management: a systematic review. *Sci Total Environ*. 2024;954:176687. <https://doi.org/10.1016/j.scitotenv.2024.176687>
- Lowenberg-DeBoer J, Erickson B. Setting the record straight on precision agriculture adoption. *Agron J*. 2019;111:1552-1569.
- Kernecker M, Knierim A, Wurbs A, et al. Experience versus expectation: farmers' perceptions of smart farming technologies for cropping systems across Europe. *Precis Agric*. 2020;21:34-50.
- Meesala H, Brunori G. Dynamics of using digital technologies in agroecological settings: a case study approach. *Agriculture*. 2025;15:151636. <https://doi.org/10.3390/agriculture15151636>
- Yusoff SF, Haron FF, Asib N, et al. Development of Vernonia amygdalina leaf extract emulsion formulations in controlling gray mold disease on tomato (*Lycopersicon esculentum* Mill.). *Agronomy*. 2021;11:373. <https://doi.org/10.3390/agronomy11020373>
- Shamshiri RR, Weltzien C, Hameed IA, et al. Research and development in agricultural robotics: a perspective of digital farming. *Int J Agric Biol Eng*. 2018;11:1-11.
- Akinleye AO. Analyzing the effectiveness of wireless sensor networks in smart agriculture with OPNET. *MAS J Appl Sci*. 2025;10:740-748.
- Willett W, Rockström J, Loken B, et al. Food in the Anthropocene: the EAT-Lancet Commission on healthy

- diets from sustainable food systems. *Lancet*. 2019;393:447-492.
35. Lawal Y, Adebisi O. AI and IoT-based smart irrigation: a review of challenges and future trends. *Int Congr Turkish Sci Technol Publ*. 2025:770-776.