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# The transformative potential of precision farming in India: A comprehensive review

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**Abstract**
Precision farming represents an innovative approach to modern agriculture, optimizing crop production through site-specific management of resources. With the use of cutting-edge technology like Geographic Information Systems (GIS), remote sensing, satellite images and artificial intelligence (AI), this system tracks crop conditions, soil health and climate trends constantly. Precision farming reduces resource waste and environmental effects by using these technologies to apply water, fertilizer and pesticides more efficiently. This strategy tackles important issues with food security and sustainable agriculture in light of India's varied agroclimatic zones and expanding population. However, financial and technological obstacles prevent widespread adoption, especially for small and marginal farmers who comprise a sizable share of the farming community. To overcome these obstacles, deliberate investments in technology availability, education and regulations that promote precision farming's growth are required. Emphasizing these elements is crucial for enhancing agricultural productivity, ensuring environmental sustainability and securing long-term food resilience in India.

**Keywords:** GIS, GPS, IoT, precision farming, remote sensing, sensors, sustainable, VRT

## Introduction
Despite being a leading global food producer, India's agricultural sector faces productivity challenges. This is partly due to the country's diverse rainfall patterns, which contribute to its overall climatic variability (Vijay *et al.* 2021) [1]. While India holds a prominent position in global food production, its agricultural sector grapples with productivity gaps compared to nations sharing similar agro-climatic conditions. This discrepancy can be attributed to the impacts of climate change and the country's diverse agricultural landscape (Das *et al.* 2021) [2]. Data from the Ministry of Statistics and Programme Implementation reveals that approximately one-third of India experiences heavy rainfall. The west coast, particularly the Western Ghats and the Sub-Himalayan regions of Northeast India, including areas like the Meghalaya Hills, Assam and West Bengal, receive the highest precipitation levels, exceeding 200 centimeters (cm) annually. Moderate rainfall (100-200 cm) is observed in regions such as southern Gujarat, eastern Tamil Nadu, parts of the Western Ghats, eastern Maharashtra, Madhya Pradesh, Odisha and the middle Ganga Valley. Conversely, the upper Ganga valley, eastern Rajasthan, Punjab and the southern plateau regions of Karnataka, Andhra Pradesh and Tamil Nadu experience lower rainfall (50-100 cm). Scanty rainfall (less than 50 cm) is primarily found in northern Kashmir, western Rajasthan, Punjab and the Deccan Plateau. Notably, India's rainfall patterns exhibit two key trends: A westward decrease in precipitation in northern India and an eastward decrease in Peninsular India, except for Tamil Nadu.
India, currently home to the world's largest population of approximately 1.417 billion people, faces a looming challenge: ensuring food security for its rapidly growing populace. Projections suggest that by 2050, the population could surge to 1.668 billion, placing immense pressure on the nation's agricultural systems and resources (Mir *et al.* 2024) [3]. This projected population boom necessitates innovative and sustainable food production solutions to meet the escalating demand. The solution is Precision farming, it is a modern farming system, which means the precise application of agricultural inputs for optimum crop cultivation, taking into account

factors like edaphic conditions, weather and crop management practices. This farming method is driven by information and technology and inputs are applied and controlled according to site-specific needs, aiming for long-term sustainability and benefits It focuses on the 5 R's as shown in Figure 1.

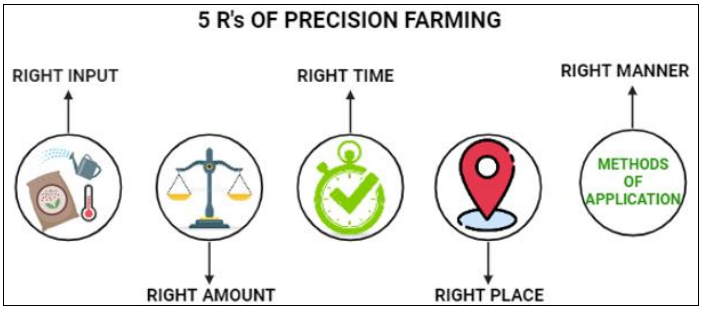


**Fig 1:**5 R's of Precision Farming

It offers a significant opportunity to revolutionize agricultural practices by integrating technology and data-driven decision-making, ultimately maximizing yields and promoting sustainability (Nabi *et al*. 2017) [4]. One crucial aspect where this approach proves particularly beneficial is in mitigating weather-related risks. Precision farming tackles this challenge by utilizing weather forecasts and real-time data to guide farming decisions. Farmers can leverage this information to avoid fertilization or irrigation before anticipated heavy rainfall, preventing nutrient loss and water contamination. Similarly, adjusting harvesting schedules based on weather predictions helps avoid soil compaction caused by heavy machinery on wet fields, preserving soil health (Agrawal *et al*. 2023) [5].

Despite the transformative potential of precision farming, its adoption has been primarily concentrated among large-scale farming operations due to the high initial investment required for the necessary technology (Finger *et al.* 2019) [6]. However, recent technological advancements, such as cloud computing, mobile applications and affordable sensors, have made precision farming increasingly accessible to small and medium-sized farms (Onyango *et al.* 2021) [7]. In countries like India, where the count of marginal farmers is high, precision farming holds immense potential to address food security challenges and enhance productivity. While India has made significant strides in agricultural production, challenges such as yield stagnation, resource depletion and climate vulnerability persist (Bhakta *et al.* 2019) [8]. Precision farming offers a solution by empowering farmers with data-driven insights to conserve resources, enhance yields and build resilience against climate uncertainties. To fully realize the potential of precision farming in India significant investments in education, training and infrastructure development are crucial. Farmers need training on utilizing precision tools and technologies effectively. Establishing accessible support systems to provide affordable equipment and services is essential. Government policies and private sector investments play a crucial part in promoting precision farming and facilitating its benefits to reach all farmers, including smallholders, driving agricultural growth and sustainability.

## Components of Precision Farming

**Data Collection and Analytics:** A data-driven methodology is used in precision agriculture, combining data from several sources to maximize decision-making. In addition to thorough soil analysis, it tracks crop health markers including growth phases, nutritional needs and general well-being. To maximize production potential, soil characteristics such as temperature, salinity, nutrient content, depth and texture are taken into account (Bhargava *et al*. 2016) [9]. Furthermore, microclimate data is included, including wind, humidity, canopy temperature and other seasonal elements. Water resource management, irrigation and drainage are also included in effective farm design. Comprehensive datasets are gathered with the aid of sophisticated data-gathering techniques, such as the use of satellite imaging, weather stations and soil sensors. These are examined to produce practical recommendations for enhancing pest management, fertilizer, irrigation and planting, eventually increasing crop health and resource efficiency (Farooqui *et al*. 2024) [10].

**Advanced Technologies:** In precision agriculture (PA), advanced technology is essential in optimizing farming through innovative tools like computer-based software, Geographic Information Systems (GIS), Remote Sensing (RS), Global Positioning Systems (GPS), Global Navigation Satellite Systems (GNSS), spectral imagery, drones and variable-rate controllers (Gawande *et al*. 2023) [11]. GIS and GPS enable precise field mapping, allowing farmers to manage specific zones based on location-specific data. Spectral imagery from satellites or drones provides insights into crop health, moisture and nutrient levels. Drones offer real-time aerial views to detect crop stress, pest infestations and irrigation issues. Variable-rate technology adjusts inputs like water and fertilizers to ensure each field area gets exactly what it needs. These technologies enhance resource efficiency, reduce negative effects on the environment and improve yields (Rimpika *et al*. 2023) [12], forming the foundation for sustainable, data-driven farming.

**Decision Support System:** Precision agriculture relies heavily on Decision Support Systems (DSS), which convert unprocessed data into useful insights for improved farm management (Lindblom *et al*. 2017) [13]. In addition to gathering data, a DSS analyzes field variability and makes useful suggestions. Finding the biological and environmental elements that influence crop production is the first step in the process. Equipment and sensors are selected to collect pertinent data, which is subsequently processed, stored and examined to glean insights. Farmers may make well-informed decisions about pest management, fertilizer and irrigation by using the DSS's simple presentation of this information. DSS helps maximize agricultural growth and profitability by offering customized advice on crop selection, planting schedules and input management. Productivity is increased by these insights, which are based on historical trends and current data and allow for more accurate, sustainable agricultural methods (Gallardo *et al*. 2020) [14].

## Tools of Precision Farming

**Global Navigation Satellite Systems (GNSS):** Satellite networks that offer exact worldwide navigation and positioning are known as GNSS and they include systems like GPS, GLONASS, Galileo and BeiDou. Through trilateration, these satellites send signals with orbital and temporal information that ground receivers utilize to determine location with an accuracy of 10-15 meters. In agriculture, GNSS supports farm mapping and optimizes water, fertilizer and pesticide use (Perez-Ruiz *et al*. 2021) [15]. Integrating GNSS with software allows farmers to monitor crops, allocate resources efficiently and boost productivity. To provide real-time global positioning, GNSS infrastructure includes three segments:the space segment (satellites), control segment (stations) and user segment

(receivers), working together for real-time global positioning.

**Geographic Information Systems (GIS):** GIS is vital in precision agriculture, serving as a platform for managing and analyzing spatial data to optimize farming practices. It integrates data layers like soil, topography, weather and crop health, helping farmers make data-driven decisions tailored to field conditions (Sood *et al*. 2015) [16]. This data-driven approach enhances resource allocation, reduces environmental impact and boosts productivity using five components: hardware, software, data, people and methods.

**Remote Sensing (RS):** Remote sensing is crucial in precision agriculture, offering information about the Earth's surface without having direct contact. Using aerial or satellite sensors, it detects variations in spectral signatures, highlighting soil types, crop stages and field boundaries (Sishodia *et al*. 2020) [17]. Remote sensing relies on the interaction between incident radiation and the target of interest, typically involving seven key elements shown in Figure 2.

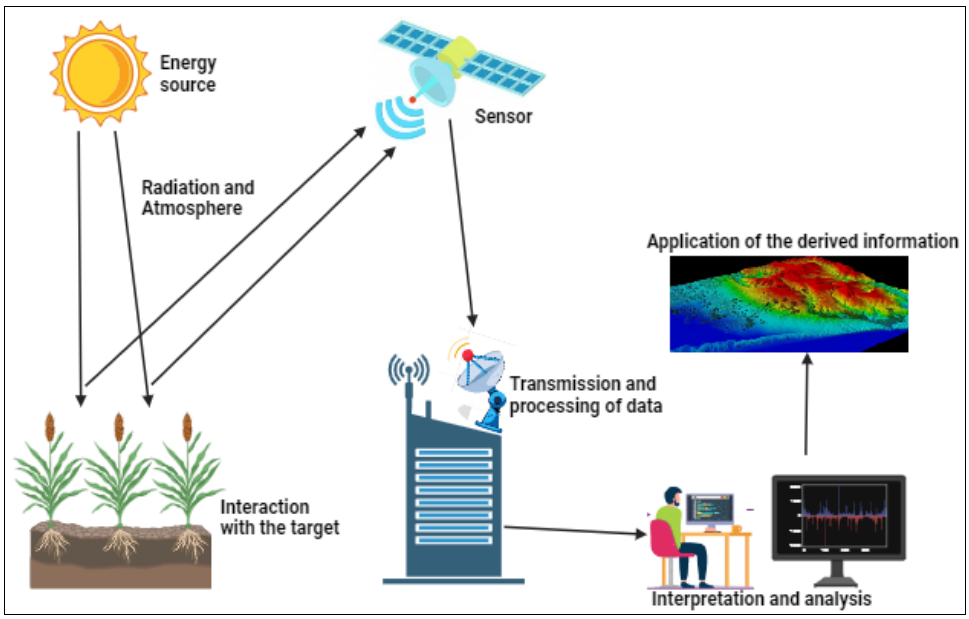


**Fig 2:** Elements of Remote Sensing

**Grid Sampling (GS):** In precision agriculture, grid sampling (GS) separates fields into grids (0.5-5 hectares) to analyze the soil. To provide exact fertilizer recommendations, soil samples from every grid are mixed and examined in a laboratory. The number of samples per grid, sampling strategies and grid size are still being studied. Grid cells are typically 100-400 feet in size and sampling are done every 5 years to check for non-mobile nutrients like potassium, phosphorus and soil pH, particularly in locations that fluctuate (Singh, 2021) [18]. Nutrient distribution maps are produced using mapping methods such as kriging, inverse distance weighting and splines. Site-specific management, fertilizer optimization, production enhancement and waste reduction are all supported by GS.

**Variable-Rate Technologies (VRT):** Variable Rate Technology (VRT) is an automated system in modern farming that optimizes the application of inputs like seeds, fertilizers, pesticides and herbicides. Using GIS-mapped soil data, VRT adjusts input delivery rates to ensure precise application, making it a key technology in precision farming (Masi *et al*. 2023) [19]. VRT systems include a control computer, locator and actuator. The control computer accesses field data to manage operations, while the locator provides equipment location, allowing the actuator to apply inputs based on specific conditions. Precision farming relies on grid sampling data, often gathered by sensors, to adjust inputs instantly according to field needs. Positioning systems ensure accurate machinery location. Since the mid-1990s, VRT has been essential in enhancing crop production efficiency, particularly in the US and Europe.

**Diagnosis and Recommendation Integrated System (DRIS):** The DRIS system, created by Beaufils in 1973, interprets plant or leaf analysis to maximize agricultural yields and fertilizer recommendations. DRIS employs nutrient ratios (e.g., N/P, N/K, Ca/Mg) to discover imbalances in plant nutrition, finding both excesses and shortages, in contrast to standard approaches that evaluate individual nutrient levels. It emphasizes nutritional balance by calculating "Nutrient Index" values, where positive values denote excesses and negative values indicate deficiencies (Villamil-Carvajal *et al*. 2021) [20]. DRIS determines key yield-influencing parameters and establishes calibrated criteria for specific crops to ensure precise nutrient management. It maintains consistent nutrient ratios, considering concentration changes as plants mature, promoting balanced plant nutrition. This approach helps farmers optimize fertilizer use and boost yields.

**Site-Specific Nutrient Management (SSNM):** Site-Specific Nutrient Management (SSNM) is a crop-based approach that optimizes the application of nitrogen, phosphorus and potassium for rice crops and other crops by altering nutrient management to specific field conditions. By ensuring that crops receive the appropriate nutrients at the appropriate time, it improves productivity, profitability and yields (Rodriguez 2020) [21]. SSNM gives farmers the skills to modify nutrient treatments according to soil conditions, management techniques and climatic fluctuations since soil alone frequently lacks enough nutrients for good yields. This focused approach promotes sustained crop performance across several fields and seasons and improves fertilizer usage efficiency.

**Crop Metrics:** In digital agriculture, various statistical metrics are essential for evaluating and measuring crop health, characteristics and properties. Among these metrics, Vegetation Indices (VIs) play a significant role. VIs are calculated using spectral imaging transformations and combine different spectral bands from the electromagnetic spectrum. This process highlights vegetation-related features, enabling precise monitoring of photosynthetic activity, canopy structure and other plant traits (Ghazal *et al*. 2024) [22]. These indices are extensively used in precision agriculture to compare crop health both spatially and temporally. A comprehensive overview of frequently utilized VIs and their applications can be found in the precision farming literature, providing valuable insights for improving crop management, as detailed in Table 1.

**Table 1:** Vegetation Indices and their Use in Agriculture (Ghazal *et al*. 2024) [22]

| **Normalized Difference Vegetation Index (NDVI)** | |
|---|---|
| Spectral Bands (in nm) | Applications in Agriculture |
| R (655-665) & NIR (835-865) | Vegetation land cover mapping |
| R (670) & NIR (800) | Yield prediction |
| R (575-675) & NIR (810-890) | Vegetation density prediction |
| R (615-685) & NIR (755-805) | Nitrogen & water stress detection |
| R (640-680) & NIR (770-810) | Biotic stress detection |
| **Soil Adjusted Vegetation Index (SAVI)** | |
| Spectral Bands (in nm) | Applications in Agriculture |
| R (670) & NIR (800) | Yield prediction |
| R (575-675) & NIR (810-890) | Vegetation density prediction |
| R (660) & NIR (790) | Nitrogen & water stress detection |
| R (630-690) & NIR (760-900) | Biotic stress detection |
| **Enhanced Vegetation Index (EVI)** | |
| Spectral Bands (in nm) | Applications in Agriculture |
| R (670), NIR (800) & B (490) | Yield prediction |
| R (670), NIR (800) & B (450) | Biotic stress detection |
| **Normalized Difference Water Index (NDWI)** | |
| Spectral Bands (in nm) | Applications in Agriculture |
| NIR (750-1300) & SWIR (1300-2500) | Biotic stress detection |
| **Crop Water Stress Index (CWSI)** | |
| Spectral Bands (in nm) | Applications in Agriculture |
| – | Water stress detection |
| **Leaf Area Index (LAI)** | |
| Spectral Bands (in nm) | Applications in Agriculture |
| – | Yield prediction |
| – | Biotic stress detection |
| **Disease Sensitivity Index (DSI)** | |
| Spectral Bands (in nm) | Applications in Agriculture |
| – | Disease injury & severity diagnosis |

*nm - nanometers, R- Red, NIR- Near Infrared Radiation, B- Blue

**Artificial Intelligence:** Precision farming is changing as a result of artificial intelligence (AI) and machine learning (ML), which improve reliability and effectiveness through sophisticated data analysis. Massive volumes of agricultural data are collected and processed by AI-powered drones, robots and IoT devices (Raj *et al.* 2022) [23]. This allows for automated activities like precise water distribution and fertilizer application optimization. These technologies can spot trends in insect infestations, crop development and Edaphic factors that are challenging for people to recognize. AI and ML minimize the need for human labour by automating processes like weed identification and spraying, opening the door to more intelligent and sustainable agricultural methods. In addition to AI, Machine Learning and IoT, precision farming also incorporates a variety of other advanced technologies.

- Autonomous vehicles are used for tasks like sowing, transplanting, harvesting and soil maintenance, reducing the need for manual intervention.
- Drone and satellite imaging provide real-time aerial views of crops, offering valuable insights into plant health, irrigation needs and potential problem areas.
- Mobile applications help farmers track and manage operations more efficiently.
- Sensor technology (e.g., WNS) monitors soil moisture, nutrient levels and environmental conditions (Nabi *et al.* 2022) [24].
- Yield and crop monitoring systems further enhance decision-making by delivering precise data on crop performance, enabling farmers to maximize productivity and sustainability.

**Why Precision Farming is crucial for India's Agriculture?**

**Changing and Diversified Climate:** India's diverse climate, ranging from arid deserts to tropical rainforests and temperate mountains to coastal plains, creates regional variations in crop production, soil types, water availability and pest pressures. These distinctions are frequently difficult for traditional agricultural practices to handle, which results in variable yields and wasteful resource consumption. By using technology like remote sensing, GPS mapping and data analytics to tailor agricultural methods according to area circumstances, precision agriculture provides an efficient solution (Roy and George 2020) [25]. In addition to optimizing the use of water, fertilizer and pesticides, this site-specific strategy promotes sustainable practices, increases yield and adapts to climate difficulties. In India's diverse terrain, these systems are essential for controlling the effects of climate change and guaranteeing food security (Pande and Moharir 2023) [26].

**Limitations of Traditional Conventional Farming Practices:** Conventional farming often employs a "one-size-fits-all" strategy, implementing general tactics for common circumstances without taking into consideration variances within a farm (Maindi *et al*. 2024) [27]. Even within one field, there can be substantial differences in soil type, microclimate and insect populations, which can result in ineffective methods and less-than-ideal yields. Monocropping, extensive tillage and overuse of agrochemicals are among practices that further lower production and damage the environment (John *et al.* 2023) [28]. Changing to more accurate, flexible management techniques is necessary to achieve agricultural sustainability and food security.

**Population Growth:** Presently, India holds the title of the world's most populous country, boasting a population of approximately 1.417 billion (141.72 crores). The projected figure for 2050 is approximately 1.668 billion (166.8 crores) (WHO 2023) [29]. Urbanization and industrialization, along with rapid population growth, are contributing significantly to the degradation of cultivable land, presenting a major challenge to the agricultural sector. As the population increases, so does the demand for food, placing immense pressure on agriculture to produce more while resources like land, water and soil fertility become increasingly scarce (Pandey *et al.* 2021) [30]. Meeting rising food needs in a stressed environment is made more difficult by the depletion of natural resources and the shrinking amount of arable land. Due to their limited capacity to boost production per unit area, traditional agricultural practices are unable to meet the expanding food needs of a growing

population.

**Majority of Small and Marginal Farmers:** In India, approximately 82% of farmers are classified as small and marginal, cultivating less than 2 hectares of land. Small and marginal farmers often have limited financial resources, struggle to access modern inputs and are highly vulnerable to weather and market fluctuations. Traditional high-input methods, relying on fertilizers, pesticides and labour, can be costly and inefficient, further straining their resources. Precision farming offers a solution by optimizing the use of inputs based on real-time data and site-specific conditions (Mizik 2023) [31]. This strategy minimizes waste, cuts expenses and increases yields by only using water and agrochemicals wherever and whenever necessary (Erickson and Fausti 2021) [32]. It increases production and advances the sustainability of Indian agriculture by allowing small farmers to make well-informed decisions.

**Indian Farmers Face High Risk:** Precision farming techniques are essential for managing risks associated with crop production. By closely monitoring crop health and identifying early indicators of stress or disease, farmers can take targeted actions to mitigate the effects of adverse weather, pests and diseases. This proactive strategy helps minimize crop losses and reduces financial uncertainty. In India, where a significant number of farmers live in poverty, the risks of crop failure, unpredictable weather and fluctuating market prices are particularly acute (Birthal *et al.* 2021) [33]. Many farmers rely on traditional methods that leave them vulnerable to these financial challenges due to a lack of effective risk management tools. Precision farming provides a solution by delivering data-driven insights that support informed decision-making (Liu *et al.* 2017) [34]. For example, access to real-time weather information, soil moisture levels and crop status enables farmers to act swiftly to safeguard their crops and enhance their overall productivity.

**Challenges in Resource Management:** Indian farmers often struggle with efficient resource management due to limited access to modern technology, leading to overuse of water, fertilizers and pesticides. It damages the environment in addition to raising expenses. By maximizing input application and making sure resources like water and fertilizers are only utilized when and where they are needed, precision farming solves these problems while lowering costs and fostering sustainability. Precision farming gives small and marginal farmers with limited resources comprehensive data on crop status, moisture and soil fertility, allowing them to make well-informed decisions and maximize input efficiency while reducing waste (Gulaiya *et al.* 2024) [35].

**Lack of Data-Driven Decision-Making:** Most Indian farmers still rely on traditional knowledge and intuition rather than scientific data to make farming decisions. This limits their ability to maximize yields and efficiently manage resources. Precision farming introduces a new way of farming by incorporating advanced technologies such as remote sensing, GPS and data analytics to provide actionable insights. By using precise data on soil health, crop conditions and weather patterns, farmers can make smarter, more efficient decisions, leading to better productivity and higher profits (Kar *et al.* 2020) [36].

**Technological Barriers in Indian Agriculture:** India's agricultural sector faces technological challenges, particularly in precision farming, as many small and marginal farmers have limited access to modern technologies, leading to higher input costs and lower productivity (Kumari *et al*. 2018) [37]. Resource optimization and production enhancement are hindered by conventional agricultural practices and the underutilization of data-driven alternatives. connection to cutting-edge tools is further restricted by a lack of funding for R&D, inadequate infrastructure (such as internet connection and storage) and budgetary limitations. The adoption of contemporary methods is further hampered by cultural aversion to change. To fully use precision farming, increase output and guarantee sustainability in Indian agriculture, these obstacles must be removed (Khaspuria *et al*. 2024) [38].

## Applications of Precision Farming

**Yield Monitoring:** GPS, sensors and data analytics are some of the technologies used in precision farming to track crop conditions, soil and weather parameters in real time. This lowers waste and boosts productivity by enabling farmers to precisely control insecticides, fertilizers and water. Crop yields rise as a consequence, while expenses fall. Additionally, the method facilitates improved planting and harvesting decision-making, which raises output and profitability. According to studies, precision agriculture may reduce the use of pesticides and fertilizers by 10-20% while increasing yields by up to 20% for wheat, 15% for maize and 5% for soybeans. With efficiency levels of 92-95%, this sustainable approach shows promise for transforming contemporary agriculture (Sishodia *et al*. 2020) [17].

**Crop Health Monitoring:** Precision farming tracks crop health and soil conditions at various development phases using cutting-edge technologies including sensors, drones and artificial intelligence. Farmers can safeguard crops from harsh weather conditions thanks to these technologies, which offer real-time data on soil moisture, nutrient levels and meteorological variables like temperature, wind speed and humidity. Wireless sensors installed in the field help monitor fields and improve insect control, fertilization and irrigation. Precision farming has been shown to enhance efficiency by 20-25%, decrease investments by 25-30% and increase crop yields by 15-20% (Monteiro *et al*. 2021) [39]. Farmers may use focused interventions to maximize production and encourage sustainable practices by identifying problems early on, such as insect infestations or nutrient deficits.

**Nutrient Management:** Precision farming improves fertilizer management by using technology to determine crop requirements and soil health. This method uses data analytics, satellite images and soil samples to pinpoint nutrient deficits and maximize application rates. Through accurate field mapping and selective fertilizer application, farmers may increase crop yields and minimize waste. To guarantee that plants receive the proper nutrients at the appropriate time, real-time monitoring allows for prompt modifications to fertilizer delivery. By reducing environmental effects and optimizing efficiency, this focused approach promotes sustainable farming methods and more robust ecosystems (Gorai *et al*. 2021) [40]. According to research, precision farming has a lot of potential to reduce fertilizer consumption. It shows the potential to save around 18.5-27.3% in urea to produce the same level of yield (Gupta *et al*. 2021) [41].

**Soil Management:** By providing thorough information on soil conditions, precision farming improves soil management and allows farmers to make well-informed decisions. Real-time information on the elements influencing crops, including soil

composition, is available through methods including GPS mapping, soil sampling, remote sensing and drones. To enhance farm management and detect soil variability within fields, this data may be used to generate yield maps that interface with other precision technologies (Sona *et al*. 2016) [42]. Additionally, by optimizing soil usage and minimizing bunds and channels, precision farming may increase arable area by 3-6% and increase crop yields by 10-60%. This strategy promotes food stability in addition to maintaining soil quality (Gupta *et al*. 2021) [41].

**Irrigation Management:** Precision farming improves irrigation management by using advanced tools like soil moisture sensors, GPS and satellite imagery to monitor and manage water use efficiently. It ensures water is applied at the right time, in the right amount and only where needed, reducing waste. The components include remote sensing to access crop water needs, drip or sprinkler irrigation systems for targeted application and data analytics to optimize irrigation schedules. This approach minimizes water consumption, increases crop yields and reduces environmental impact, making farming more sustainable and cost-effective (Jiménez *et al*. 2022) [43]. The Tamil Nadu Precision Farming Project (TNPFP) demonstrated notable yield increases, ranging from 30% to 200%, for various crops, primarily horticultural, when employing precision farming techniques in comparison to traditional methods. This improvement was largely attributed to the use of irrigation and fertigation systems. Research has shown that orchard crops and vegetables benefited significantly from precision techniques like micro-irrigation, with yields increasing by 10% to 60% over conventional practices. Additionally, a survey-based study reported a 42.4% rise in fruit crop productivity and a 52.7% increase in vegetable yields using micro-irrigation systems (Gupta *et al*. 2021) [41].

**Pest and Disease Management:** Evaluating crop conditions, edaphic and weather factors through precision farming improves pest and disease management using sensors and drones for real-time data collection allowing for early detection of pest outbreaks and disease symptoms. By using pesticides and treatments only where required, this focused approach minimizes the impact on the environment and lowers chemical consumption. Crop yields and agricultural sustainability are eventually improved by methods like soil mapping and crop rotation, which create healthier ecosystems that are more resistant to pests and diseases (Kanwal *et al*. 2022) [44]. Compared to conventional techniques, precision farming significantly reduces insect and disease infestations, according to research. For example, European farms have reduced their usage of pesticides by 30% by tracking insect activity using pheromone traps and sensor-based monitoring. In contrast to conventional farming's wider use of pesticides, this focused strategy preserves crop yields while safeguarding beneficial insects (Papadopoulos *et al*. 2024) [45].

**Weed Management:**Precision farming helps in weed management by utilizing technologies such as GPS, sensors and drones to monitor crops and detect weeds with high accuracy. Precision farming technologies showed effective results by precisely managing weeds, crop yields improved, leading to higher profitability. According to a study, field tests for sugar beet (2014) and soybean (2013-14) assessed the effects of automatic steering technologies for inter-row weed hoeing, utilizing cameras or RTK-GNSS on crop growth and production and efficient weed control. The most common weed species were *Chenopodium album*, *Polygonum convolvulus*, *Polygonum avicularia*, *Matricaria chamomilla* and *Lamium purpureum*, with weed densities ranging from 15-154 plants per $m^2$. In soybean and sugar beet, automatic steering decreased weed densities by 89% and 87%, respectively, while traditional approaches were only 85% effective (Parasca *et al*. 2024) [46].

**Economic Aspects:** Precision farming enhances economic benefits by optimizing the use of resources through advanced technologies by which farmers can accurately monitor and manage soil conditions, crop health and environmental factors leading to increased crop yields and improved quality while reducing input costs and minimizing waste. The ability to apply resources only where needed helps cut down on excessive usage, leading to savings in labour, fuel and raw materials. Additionally, precision farming enables better decision-making, improving efficiency and reducing the risk of crop failure. This results in more stable income for farmers and contributes to overall agricultural productivity. As a result, precision farming supports rural economies by increasing profitability, promoting sustainability and fostering innovation in agriculture (Lowenberg-DeBoer 2018) [47]. According to the Tamil Nadu Precision Farming Project (TNPFP) study precision farming increased cost of cultivation by 30-100%, depending on the crops. However, the yield boosted to 33-200% more than the conventional systems, boosting the net income for farmers (Balaganesh *et al.* 2016) [48].

**Environmental Sustainability:** Precision farming enhances environmental sustainability by sustaining agricultural practices. Farmers may drastically cut waste and chemical runoff by applying water, fertilizers and pesticides more effectively by regularly monitoring crop conditions, soil health and moisture levels. Thus, reducing emissions of greenhouse gases, conserving natural resources, biodiversity promotion and have the least negative effect on nearby ecosystems (Getahun *et al*. 2024) [49]. According to data, precision farming reduced the use of pesticides and herbicides upto 9% and the use of fossil fuels by 6%. A thorough analysis of the economic and environmental advantages of digital agricultural technologies (DATs) in crop production focuses on five main areas:

- Farm Management Information Systems (FMIS)
- Robotic Systems or Smart Machines (RSSM)
- Variable Rate Technologies (VRT)
- Guidance and Controlled Traffic Farming (CTF)
- Recording and Mapping Technologies (RMT).

Important results indicate that CTF and RMT can save fertilizer use by as much as 80%. VRT boosts output by 62% while reducing fertilizer and pesticide consumption by 60% and 80%, respectively. While FMIS increases production by 10-15% and reduces labour and input expenses, RSSM may save labour by 97% and diesel usage by 50%. Along with large reductions in greenhouse gas emissions, VRT also saves 20-50% of water in pear orchards and vineyards. These findings demonstrate the significant advantages of DATs in raising environmental sustainability and production (Gupta *et al*. 2021) [41] and (Padhiary *et al*. 2024) [50].

## Challenges in Precision Farming

**High Upfront Investment Cost:** One of the biggest obstacles to precision farming is the high upfront costs, which include investments in cutting-edge technologies like sensors, drones,

GPS-guided equipment and data analytics software. The high cost of these instruments prevents many people from using them as shown in table 3 (Abioye *et al.* 2020) [51].

**Table 3:** High-Cost Technologies Used in Precision Farming

| Tools | Investment Cost |
|---|---|
| Global Positing System | Rs. 1.7 lakhs per year |
| Geographic Information System | Rs. 0.4-1.7 lakhs per year |
| Soil Sensors | Rs. 0.8-2.5 lakhs per unit |
| Drones and Aerial Imaging | Rs. 1.2-4.2 lakhs |
| Variable Rate Technology | Rs. 12.6-21 lakhs |
| Automated Machinery | Rs. 8.4-42 lakhs |

**Secure Data Storage and Management:** As a component of the "digital agricultural revolution," smart farming increases sustainability and production by utilizing technology such as cloud computing, big data, precision agriculture, mobile devices, cybersecurity, analytics, remote sensing, etc (Trendov *et al.* 2019) [52]. With unsolved problems including device compatibility, data processing and protection, security is still a major concern. For these technologies to be integrated effectively, certain security issues must be resolved.

**Internet Connectivity:** One of the biggest obstacles to precision agriculture in rural regions is inadequate internet connectivity. High-speed internet is necessary for technologies like remote sensing and IoT devices, however point out that connectivity in such regions is frequently restricted to 50-100 Kbps (Bhat and Huang 2021) [53]. This impairs decision-making and reduces the usefulness of precise instruments by slowing down real-time data delivery. Poor rural internet access is another major obstacle to making the most of smart agricultural systems (Jerhamre *et al.* 2022) [54]. Slow internet speeds prevent precision agriculture from being widely used, even with breakthroughs.

**Integration with Legacy Infrastructure:** Many nations worry that conventional agricultural methods and jobs may be disrupted by automation and technological improvements in agriculture. The strain on food production is growing as the global population is expected to touch 10 billion people by 2050 (Teklu *et al*. 2023) [55]. Increased use of fertilizers and pesticides by farmers is deteriorating the soil and lowering harvests. Approximately 40% of crops worldwide are destroyed by pests and current approaches are not keeping up with demand. When combining contemporary IoT devices with outdated machinery, farmers can encounter interoperability problems. This case study examines compatibility gaps and makes recommendations for investments and legislative frameworks to remove obstacles to the implementation of precision agriculture (Soori *et al.* 2023) [56].

**Access to Specialized Skills:** As precision farming depends on technology like AI, IoT and data tools, a significant obstacle is the lack of specialized expertise. Farmers require knowledge of digital tools and equipment, yet many lack digital literacy and training, particularly in developing nations. Without the right expertise, it can be difficult to analyze big data sets from gadgets like remote sensors, which restricts the useful application of insights (Bajaj *et al.* 2022) [57].

**Environmental Variability:** Environmental variability challenges precision agriculture by affecting crop health through factors like soil differences, weather changes and pest activity. Unpredictable weather increases uncertainty and variations in soil type, nutrient levels and moisture necessitating thorough mapping. It's also challenging to integrate different data sources since models frequently ignore local circumstances. Farmers may increase resilience and production through adaptive management that makes use of modern data analytics (Ukhurebor *et al.* 2022) [58].

## Future Prospectives in Precision Farming

**Adaptation of Technology:** Precision farming demands the adaptation of varied modern technologies like IoT, drones, UAVs, sensors, etc. for monitoring, processing and evaluating the different factors contributing to crop growth and development (Boursianis *et al.* 2022) [59]. Technologies such as IoT sensors help monitor soil parameters and crop quality, allowing farmers to make precise decisions on irrigation and nutrient application. Drones and aerial imaging facilitate precise crop surveillance and targeted pesticide application, reducing chemical use and environmental constraints. Automation and robotics streamline labour-intensive tasks like transplanting, weeding and harvesting. The mobile applications enhance farmers' access to critical information, fostering better decision-making and market access (Singh 2022) [60]. As these technologies become more accessible and affordable, their integration will drive a transformation in Indian agriculture, ensuring increased productivity, resource optimization and sustainable practices, ultimately contributing to food and nutritional security and the development of the farming community.

**Quick Data Analytics:** Leveraging data analytics to analyze large farming data into simpler forms, allowing farmers to make precise and correct decisions based on crop demand and performance, climatic patterns and market trends. Predictive modeling of agricultural yields, pest and disease outbreaks and fertilizer requirements is possible through advanced analytics and machine learning algorithms to recognize patterns and trends. This enables farmers to inoculate their inputs precisely, reducing post-production waste and enhancing productivity (Shaikh *et al.* 2022) [61]. As data analytics tools become more sophisticated and accessible, they will empower farmers to make analyzed choices that enhance crop performance, improve profitability and promote environmental sustainability, ultimately revolutionizing the agricultural landscape.

**Promotion of Sustainable Practices:** Promoting sustainable practices in precision farming is a transformative force in India's agricultural landscape. As the country faces challenges like climate change, soil degradation and water scarcity, precision farming techniques such as soil moisture sensors, drone technology and data analytics offer innovative solutions that enhance resource use efficiency and crop productivity (Karunathilake *et al.* 2023) [62]. Integrating sustainable practices such as crop rotation, crop and livestock integration, organic farming, etc. with precision agriculture supports biodiversity and improves soil health over time. By focusing on targeted interventions, farmers can optimize inputs, while yielding larger output (Sharma *et al.* 2019) [63]. As India aims to increase food security and enhance farmer incomes, adopting these advanced techniques, aligned with sustainable principles, will be crucial for fostering resilience in agriculture and encouraging longevity for farming communities.

**Rural Empowerment**

Precision farming enables smallholder farmers to make accurate decisions that optimize crop yields and resource use. The empowerment is accessed through training and knowledge-sharing platforms, which equip farmers with the skills necessary to adopt these innovative practices (Choruma *et al.* 2024) [64]. Additionally, by fostering cooperative models and local partnerships, rural communities can collectively invest in technology and infrastructure, reducing individual financial burdens. As precision farming promotes sustainable agricultural practices and increases productivity, it paves the way for improved economic stability, food security and social equity in rural areas (John *et al.* 2023) [65], ultimately driving a more inclusive rural and agricultural transformation across India.

**Conclusion**

Precision farming emerges as a transformative force in agriculture, merging cutting-edge technologies with data-driven insights to revolutionize farming practices. By harnessing the power of tools like GIS, GNSS, remote sensing and artificial intelligence, this approach empowers farmers to optimize resource allocation, enhance crop yields and champion sustainable agriculture. Studies, including initiatives like the Tamil Nadu Precision Farming Project, highlight the remarkable potential of precision farming to significantly boost yields, particularly in regions employing irrigation and fertigation systems. However, widespread adoption faces hurdles such as high initial investment costs and limited accessibility for small and marginal farmers. Addressing these challenges necessitates strategic investments in infrastructure, education and supportive government policies to foster the growth of precision farming across all scales of agricultural operations.

Looking toward the future, precision farming emerges as a critical solution for tackling global challenges like food security, resource scarcity and climate change. By equipping farmers with real-time data and tailored recommendations, precision farming can play a pivotal role in enhancing productivity, ensuring environmental sustainability and bolstering long-term agricultural resilience. As technology advances and accessibility improves, precision farming is poised to become a cornerstone of modern agriculture, driving efficiency and sustainability for generations to come.

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**Ethical Standards:**

This review article does not contain any studies with human or animal participants.

The authors declare that they have no conflict of interest

Informed consent is not required

**References**

1. Vijay A, Sivan SD, Mudbhatkal A, Mahesha A. Long-term Climate Variability and Drought Characteristics in Tropical Region of India. J Hydrol Eng. 2021;26(4):05021003.
2. Das U, Ansari MA, Ghosh S. Measures of Livelihoods and their Effect on Vulnerability of Farmers to Climate Change: Evidence from Coastal and Non-coastal Regions in India. Environ Dev Sustain. 2024;26(2):4801-4836.
3. Mir IA, Goreau TJ, Campe J, Jerden J. India's Biogeochemical Capacity to Attain Food Security and Remediate Climate. Environ Geochem Health. 2024;46(1):17.
4. Nabi A, Narayan S, Afroza B, Mushtaq F, Mufti S, Ummyiah HM *et al*. Precision Farming in Vegetables. J Pharmacogn Phytochem. 2017;6(6):370-375.
5. Agrawal AV, Magulur LP, Priya SG, Kaur A, Singh G, Boopathi S. Smart Precision Agriculture Using IoT and WSN. In: Handbook of Research on Data Science and Cybersecurity Innovations in Industry 4.0 Technologies. T Murugan, Nirmala E, editors. IGI Global, 2023, 524-541.
6. Finger R, Swinton SM, El Benni N, Walter A. Precision Farming at the Nexus of Agricultural Production and the Environment. Annu Rev Resour Econ. 2019;11(1):313-335.
7. Onyango CM, Nyaga JM, Wetterlind J, Söderström M, Piikki K. Precision Agriculture for Resource Use Efficiency in Smallholder Farming Systems in Sub-Saharan Africa:A Systematic Review. Sustainability. 2021;13(3):1158.
8. Bhakta I, Phadikar S, Majumder K. State-of-the-art Technologies in Precision Agriculture: A Systematic Review. J Sci Food Agric. 2019;99(11):4878-4888.
9. Bhargava K, Ivanov S, Donnelly W, Kulatunga C. Using Edge Analytics to Improve Data Collection in Precision Dairy Farming. In 2016 IEEE 41st Conference on Local Computer Networks Workshops (LCN Workshops). IEEE; c2016 .p. 137-144.
10. Farooqui NA, Haleem M, Khan W, Ishrat M. Precision Agriculture and Predictive Analytics: Enhancing Agricultural Efficiency and Yield. In: Intelligent Techniques for Predictive Data Analytics. N Singh, S Birla, MD Ansari, NK Shukla, editors. Wiley Online Library; c2024 .p. 171-188.
11. Gawande V, Saikanth DRK, Sumithra BS, Aravind SA, Swamy GN, Chowdhury M, *et al*. Potential of Precision Farming Technologies for Eco-friendly Agriculture. Int J Plant Soil Sci. 2023;35(19):101-112.
12. Rimpika, Anushi, Manasa S, Anusha KN, Sharma S, Thakur A, *et al*. An Overview of Precision Farming. Int J Environ Clim Change. 2023;13(12):441-456.
13. Lindblom J, Lundström C, Ljung M, Jonsson A. Promoting Sustainable Intensification in Precision Agriculture: Review of Decision Support Systems Development and Strategies. Precis Agric. 2017;18:309-331.
14. Gallardo M, Elia A, Thompson RB. Decision Support Systems and Models for Aiding Irrigation and Nutrient Management of Vegetable Crops. Agric Water Manage. 2020;240:106209.
15. Perez-Ruiz M, Martínez-Guanter J, Upadhyaya SK. High-precision GNSS for Agricultural Operations. In: GPS and GNSS Technology in Geosciences. GP Petropoulos, PK Srivastava, editors. Elsevier; c2021 .p. 299-335.
16. Sood K, Singh S, Rana RS, Rana A, Kalia V, Kaushal A. Application of GIS in Precision Agriculture. In: Paper Presented as Lead Lecture in National Seminar on Precision Farming Technologies for High Himalayas; c2015 .p. 04-05.
17. Sishodia RP, Ray RL, Singh SK. Applications of Remote Sensing in Precision Agriculture: A Review. Remote Sens. 2020;12(19):3136.
18. Singh A. Nutrient Mapping of Balod District of Chattisgarh with Machine Learning Technology using Soil Health Card Data. Master's Thesis. Indira Gandhi Krishi Vishwavidyalaya, Raipur; c2021.

19. Masi M, Di Pasquale J, Vecchio Y, Capitanio F. Precision Farming: Barriers of Variable Rate Technology Adoption in Italy. Land. 2023;12(5):1084.
20. Villamil-Carvajal JE, Pineda-Álvarez EO, Cabezas-Gutiérrez M. Diagnosis and Recommendation Integrated System, its Application and Use in Agriculture. A Review. Ciencia Y Agricultura. 2021;18(3):29-45.
21. Rodriguez DGP. An Assessment of the Site-Specific Nutrient Management (SSNM) Strategy for Irrigated Rice in Asia. Agriculture. 2020;10(11):559.
22. Ghazal S, Munir A, Qureshi WS. Computer Vision in Smart Agriculture and Precision Farming: Techniques and Applications. Artif Intell Agric. 2024;13:64-83.
23. Raj EFI, Appadurai M, Athiappan K. Precision Farming in Modern Agriculture. In: Smart Agriculture Automation Using Advanced Technologies: Data Analytics and Machine Learning, Cloud Architecture, Automation and IoT. A Choudhury, A Biswas, TP Singh, SK Ghosh, editors. Springer, Singapore; c2022 .p. 61-87.
24. Nabi F, Jamwal S, Padmanbh K. Wireless Sensor Network in Precision Farming for Forecasting and Monitoring of Apple Disease: A Survey. Int J Inf Technol. 2022;14(2):769-780.
25. Roy T, George KJ. Precision Farming: A Step Towards Sustainable, Climate-Smart Agriculture. In: Global Climate Change: Resilient and Smart Agriculture. V Venkatramanan, S Shah, R Prasad, editors. Springer, Singapore; c2020 .p. 199-220.
26. Pande CB, Moharir KN. Application of Hyperspectral Remote Sensing Role in Precision Farming and Sustainable Agriculture Under Climate Change: A Review. In: Climate Change Impacts on Natural Resources, Ecosystems and Agricultural Systems. CB Pande, KN Moharir, SK Singh, QB Pham, A Elbeltagi, editors. Springer, Cham; c2023 .p. 503-520.
27. Maindi CN, Nyarindo WN, Ndirangu SN, Isaboke HN. Debunking the One-size-fits-all Approach: Synergistic and Trade-off Effects of Collective Action on Household Food Security Among the Smallholder Farmers in Central Kenya. J Glob Innov Agric Sci. 2024;12(3):815-830.
28. John D, Hussin N, Shahibi MS, Ahmad M, Hashim H, Ametefe DS. A Systematic Review on the Factors Governing Precision Agriculture Adoption among Small-scale Farmers. Outlook on Agriculture. 2023;52(4):469-485.
29. WHO. Health Data Overview for the Republic of India; c2023; Available: https://data.who.int/countries/356.
30. Pandey H, Singh D, Das R, Pandey D. Precision Farming and Its Application. Smart Agriculture Automation Using Advanced Technologies: Data Analytics and Machine Learning, Cloud Architecture, Automation and IoT. A Choudhury, A Biswas, TP Singh, SK Ghosh, editors. Springer, Singapore; c2021 .p. 17-33.
31. Mizik T. How Can Precision Farming Work on a Small Scale? A Systematic Literature Review. Precis Agric. 2023;24(1):384-406.
32. Erickson B, Fausti SW. The Role of Precision Agriculture in Food Security. Agronomy Journal. 2021;113(6):4455-4462.
33. Birthal PS, Hazrana J, Negi DS. Effectiveness of Farmers' Risk Management Strategies in Smallholder Agriculture: Evidence from India. Clim Change. 2021;169(3):30.
34. Liu Y, Langemeier MR, Small IM, Joseph L, Fry WE. Risk Management Strategies Using Precision Agriculture Technology to Manage Potato Late Blight. Agronomy Journal. 2017;109(2):562-575.
35. Gulaiya S, Sharma A, Singh S, Kumar R, Chaudhary D, Yadav K *et al*. Precision Agriculture: Transforming Farming Efficiency with Cutting-edge Smart Technologies: A Comprehensive Review. J Exp Agric Int. 2024;46(9):1126-1138.
36. Kar S, Nandan R, Raj R, Suradhaniwar S, Adinarayana J. Improving Data Management and Decision-Making in Precision Agriculture. In: Improving Data Management and Decision Support Systems in Agriculture. L Armstrong, editor. Burleigh Dodds Science Publishing; c2020 .p. 135-156.
37. Kumari S, Jeble S, Patil YB. Barriers to Technology Adoption in Agriculture-based Industry and Its Integration into Technology Acceptance Model. Int J Agric Resour Gov Ecol. 2018;14(4):338-351.
38. Khaspuria G, Khandelwal A, Agarwal M, Bafna M, Yadav R, Yadav A. Adoption of Precision Agriculture Technologies among Farmers: A Comprehensive Review. Journal of Scientific Research and Reports. 2024;30(7):671-686.
39. Monteiro A, Santos S, Gonçalves P. Precision Agriculture for Crop and Livestock Farming—Brief Review. Animals. 2021;11(8):2345.
40. Gorai T, Yadav PK, Choudhary GL, Kumar A. Site-specific Crop Nutrient Management for Precision Agriculture – A Review. Curr J Appl Sci Technol. 2021;40(10):37-52.
41. Gupta N, Pradhan S, Jain A, Patel N. Sustainable Agriculture in India 2021: What We Know and How to Scale Up. New Delhi: Council on Energy, Environment and Water; c2021.
42. Sona G, Passoni D, Pinto L, Pagliari D, Masseroni D, Ortuani B *et al*. UAV Multispectral Survey to Map Soil and Crop for Precision Farming Applications. Int Arch Photogramm Remote Sens Spatial Inf Sci. 2016;41:1023-1029.
43. Jiménez AF, Cárdenas PF, Jiménez F. Intelligent IoT-multiagent Precision Irrigation Approach for Improving Water Use Efficiency in Irrigation Systems at Farm and District Scales. Comput Electron Agric. 2022;192:106635.
44. Kanwal S, Khan MA, Saleem S, Tahir MN, Muntaha ST, Samreen T *et al*. Integration of Precision Agriculture Techniques for Pest Management. Environ Sci Proc. 2022;23(1):19.
45. Papadopoulos G, Arduini S, Uyar H, Psiroukis V, Kasimati A, Fountas S. Economic and Environmental Benefits of Digital Agricultural Technologies in Crop Production: A Review. Smart Agricultural Technology; c2024 .p. 100441.
46. Parasca SC, Spaeth M, Rusu T, Bogdan I. Mechanical Weed Control: Sensor-Based Inter-Row Hoeing in Sugar Beet (*Beta vulgaris* L.) in the Transylvanian Depression. Agronomy. 2024;14(1):176.
47. Lowenberg-DeBoer J. The Economics of Precision Agriculture. In: Precision Agriculture for Sustainability. J Stafford, editor. Burleigh Dodds Science Publishing; c2018 .p. 481-502.
48. Balaganesh G, Yash G, Mangalasseri A, Singh HP. Economics and Rate of Adoption of Precision Farming in Banana in Theni District, Tamil Nadu. Int J Agric Sci. 2016;8(52):2553-2556.
49. Getahun S, Kefale H, Gelaye Y. Application of Precision Agriculture Technologies for Sustainable Crop Production and Environmental Sustainability: A Systematic Review. Sci World J. 2024;2024(1):2126734.

50. Padhiary M, Saha D, Kumar R, Sethi LN, Kumar A. Enhancing Precision Agriculture: A Comprehensive Review of Machine Learning and AI Vision Applications in All-Terrain Vehicle for Farm Automation. Smart Agricultural Technology. 2024;8:100483.
51. Abioye EA, Abidin MSZ, Mahmud MSA, Buyamin S, Ishak MHI, Rahman MKIA *et al*. A Review on Monitoring and Advanced Control Strategies for Precision Irrigation. Comput Electron Agric. 2020;173:105441.
52. Trendov NM, Varas S, Zeng M. Digital Technologies in Agriculture and Rural Areas - Status Report. FAO, Rome; c2019.
53. Bhat SA, Huang NF. Big Data and AI Revolution in Precision Agriculture: Survey and Challenges. IEEE Access. 2021;9:110209-110222.
54. Jerhamre E, Carlberg CJC, Zoest VV. Exploring the Susceptibility of Smart Farming: Identified Opportunities and Challenges. Smart Agricultural Technology. 2022;2:100026.
55. Teklu A, Simane B, Bezabih M. Multiple Adoption of Climate-smart Agriculture Innovation for Agricultural Sustainability: Empirical Evidence from the Upper Blue Nile Highlands of Ethiopia. Clim. Risk Manag. 2023;39:100477.
56. Soori M, Arezoo B, Dastres R. Internet of Things for Smart Factories in Industry 4.0, A Review. Internet Things Cyber Phys. Syst. 2023;3:192-204.
57. Bajaj K, Sharma B, Singh R. Implementation Analysis of IoT-based Offloading Frameworks on Cloud/edge Computing for Sensor Generated Big Data. Complex and Intell Syst. 2022;8(5):3641-3658.
58. Ukhurebor KE, Adetunji CO, Olugbemi OT, Nwankwo W, Olayinka AS, Umezuruike C *et al*. Precision Agriculture: Weather Forecasting for Future Farming. In:AI, Edge and IoT-based Smart Agriculture. A Abraham, S Dash, JJPC Rodrigues, B Acharya, SK Pani, editors. Academic Press; c2022 .p. 101-121.
59. Boursianis AD, Papadopoulou MS, Diamantoulakis P, Liopa-Tsakalidi A, Barouchas P, Salahas G *et al*. Internet of Things (IoT) and Agricultural Unmanned Aerial Vehicles (UAVs) in Smart Farming: A Comprehensive Review. Internet of Things. 2022;18:100187.
60. Singh AK. Precision Agriculture in India – Opportunities and Challenges. Indian Journal of Fertilisers. 2022;18(4):308-331.
61. Shaikh TA, Rasool T, Lone FR. Towards Leveraging the Role of Machine Learning and Artificial Intelligence in Precision Agriculture and Smart Farming. Comput Electron Agric. 2022;198:107119.
62. Karunathilake EMBM, Le AT, Heo S, Chung YS, Mansoor S. The Path to Smart Farming: Innovations and Opportunities in Precision Agriculture. Agriculture. 2023;13(8):1593.
63. Sharma R, Aravind T, Sharma R. Sustainable agriculture: Trends and opportunities for 21st Century. J Appl Nat Sci. 2019;11(3):666-672.
64. Choruma DJ, Dirwai TL, Mutenje M, Mustafa M, Chimonyo VGP, Jacobs-Mata I *et al*. Digitalisation in Agriculture: A Scoping Review of Technologies in Practice, Challenges, and Opportunities for Smallholder Farmers in Sub-Saharan Africa. J Agric Food Res. 2024;18:101286.
65. John D, Hussin N, Shahibi MS, Ahmad M, Hashim H, Ametefe DS. A Systematic Review on the Factors Governing Precision Agriculture Adoption Among Small-scale Farmers. Outlook on Agriculture. 2023;52(4):469-485.