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Precision Agriculture: Transforming Farming Efficiency with Cutting-edge Smart Technologies: A Comprehensive Review

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ABSTRACT

Agriculture is the study, practice, and science of plant growth. Agriculture has a long history dating back thousands of years. Depending on the topography and climate, it started out separately in different places of the planet. Thanks to agriculture, the number of people on Earth has increased many times beyond what could be maintained by hunting and gathering. Precision farming has improved production in modern agriculture since the 20th century. Precision farming is a farming method that uses technology to measure, monitor, and analyze the demands of particular fields and crops. The primary goal of this farming style, in contrast to conventional farming, is to maximize crop yields and profitability by precisely using inputs. In today's world, artificial intelligence and the Internet of Things are indispensable. Modern agriculture uses AI and IoT technologies and their benefits. This improves the accuracy and profitability of contemporary agriculture. We go over a few of the modern uses of AI and IoT in intelligent precision farming. Furthermore, significant instruments and methods used in precision farming are also described. The crucial benefits and the real-time devices used in the precision farming are also discussed in detail.

Keywords: Modern agriculture; internet of things (IoT); artificial intelligence (AI); precision farming and sustainability.

1. INTRODUCTION

The agricultural production system is the product of the intricate interactions between crops, soil, water, and pesticides. Farmers must comprehend crop cultivation in a particular area, taking into account the resilience of the seeds to local disease and weather conditions, as well as the influence of the environment on the sowing of seeds, in order to achieve optimal development. For instance, planting near a river is best done using a seed that requires less fertilizer, which helps reduce fertilizer-related pollution. Fertilizing and maintaining crops after they have been sown is a labour-intensive operation that is greatly impacted by the weather. If heavy rain is forecast for the next day, farmers will opt against applying fertilizer because they believe it will be washed away [1]. Seventy percent of the freshwater used for agriculture globally will impact the freshwater supply and can be better controlled in terms of its utilization. The crop may be destroyed by the machinery in humid weather and muddy soil. Better judgments on which field workers should be sent ahead of time may be made with a clearer view of the weather and which fields will be affected in the coming days [2-4]. As soon as the crops are harvested, it is imperative to harvest and move them to supply centers. Therefore, the conventional method of doing agriculture involved planting and harvesting according to a set timetable. On the other side, by gathering real-time data on soil, crop maturity, weather, air quality, labour prices, and availability, predictive analytics will assist you in making better judgments [5-8]. This type of advanced agriculture is known as precision agriculture, or PA [9]. This kind of farm management uses artificial intelligence (AI) and information technology (IT) to make sure that crops and soil get the nutrients they need for the best possible yield and quality. Ensuring profitability, long-term viability, and environmental stewardship are its main objectives. The technique includes gathering ongoing data on the crop, soil, ambient air quality, and other crucial information like labour expenses, equipment availability, and hyper-local weather forecasts. Field sensors compute the temperature, relative humidity, and air quality [10-13]. Cultivators receive real-time photos of each plant they develop from robotic drones and satellites. When making immediate decisions, such when and where to grow a particular crop or which fields to irrigate, the data from the digital photos received may be retrieved, analyzed, and coupled with the data from the signals. At agricultural control centres, sensor and imaging data are merged with other data to help growers identify crops that require attention and choose which herbicides, water treatments, and fertilizers are most effective [14-17]. Larger businesses with the resources to invest in the IT infrastructure and other technical tools required to completely understand and reap the benefits of PA have historically been the only ones allowed to use it. Cloud computers, drones, sophisticated sensors, and mobile applications have made PA feasible for farming cooperatives and tiny family farms [18].

2. RELATED WORKS

The word "PA" is new to agricultural management and has several meanings. Two key definitions have been selected to provide context for the broader explanation of PA concepts. The first definition was introduced by the US House of Representatives in 1997. The statement reads as follows: "An integrated information and production-based farming system that is designed to mitigate unintended impacts on wildlife and the environment while improving long-term, site-specific, and whole farm production quality, productivity, and profitability." Crop management systems that are site-specific are the subject of the second definition. According to its definition, PA is "a type of precision agriculture in which agronomic practices and resource application are enhanced to better match soil and crop requirements as they differ in the field." The idea of PA as a dynamic management strategy is included in this phrase. Comprehensive discussions are held on the many facets of PA and its application in the twenty-first century [19], (Stafford 2000). In order to enhance crop performance and environmental quality, the concepts of managing spatial and temporal availability related to all facets of agricultural production are covered. Precision farming has become simpler in recent years thanks to technological innovations like the Internet of Things (IoT), artificial intelligence (AI), and satellite-based global positioning systems. The author describes the global evolution and present state of PA technologies in [1,20], (Baggio 2005); [21,9], (Robert 2005); [22,23]. There is a thorough explanation of the issues of variability management, the effect of PA, management zones, and the availability of natural resources. The phrase "Internet of Things" (IoT) describes the billions of physical objects that are globally connected to the internet and that are gathering and exchanging data. Modern agriculture is more lucrative and dependable when it integrates the Internet of Things. Authors García et al. [24], Keswani et al. [25], and Sanjeevi et al. (2020) described the different sensors used in precision farming. They spoke about the many protocols that have to be adhered to while using Internet of Things devices. We introduce an autonomous watering system powered by big data and facilitated by the Internet of Things. It will update contemporary agriculture in real time. Furthermore, the authors provide a brief overview of the use of wireless networks integrated with IoT for farming and PA. Applying WSN technology through the Internet of Things can help achieve appropriate control of water irrigation. In the field of AI, machine learning and deep learning are relatively new developments. The authors [26], (Wei et al. 2020) went into detail on how AI and IoT are being used in precision farming. They went into great depth about how remote sensing photos and plant-specific photographs may be used to automate crop monitoring. By using this, the cultivator may even keep an eye on each individual plant in the field from a distance. Additionally, farmers can make informed decisions about when to produce the ideal plants thanks to the knowledge provided by AI and remote sensing regarding weather forecasts and improved soil conditions. According to Lee et al. (2020), Talaviya et al. [27], and Costa et al. [28], precision farming also requires careful consideration of disease detection and crop yield analysis. The authors described in detail the yield mapping, AI and machine vision-based leaf stomata features, and the machine learning-based vegetation index for the PA that is driven by satellites. Another important technology that has recently developed is block chain technology. PA is more sustainable and lucrative when IoT and blockchain are integrated. In PA, land administration is one of the most important things to take into account. Block chain technology can be used as follows to enter data into the land information system: user data is collected and added to the chain; transactions are then replicated and verified; a block containing the transaction is created and added to the chain of all system participants [29]. A thorough discussion is held on the use of blockchain and information and communication technologies in the development of PA [30]. Numerous more such studies in the literature described how these contemporary technology were used to transform our traditional agriculture into modern PA. The next chapters of this article go into great length about the usage of AI and IoT in precision farming, the role of nanotechnology in precision farming, real-time modern equipment used in precision farming, and the advantages and disadvantages of precision farming.-

2.1 Technological Components of Precision Farming

The optimization of agricultural techniques through the integration of many technologies is a key component of precision farming. The main technology elements that support precision farming will be examined in this section:-

2.1.1 Global Positioning System (GPS) technology

Precision farming relies heavily on Global Positioning System (GPS) technology, which gives precise and up-to-date position data for agricultural machinery and operations. With GPS, farmers may develop personalized navigation routes, map fields precisely, and monitor the movement of machines. With the help of this technology, inputs like seeds, fertilizer, and pesticides can be placed precisely, maximizing resource efficiency and reducing environmental effect.

2.2 Applications of GPS in Precision Farming

- **Precision Navigation:** Agricultural equipment like harvesters and tractors can navigate more precisely thanks to GPS technology, which also minimizes waste and minimizes overlap during field activities.
- **Field Mapping and Surveying:** Farmers may make precise digital maps of their farms with GPS. Information about topography, soil types, and field borders may be included in this mapping, which can give decision-makers important information.
- **Automated Machinery Control:** Automated equipment control made possible by GPS-based technologies enables precise and reliable operations. This covers tasks where automated control systems travel preset routes inside the field, such as planting, spraying, and harvesting.
- **Boundary Mapping and Precision Planting:** To properly identify and maintain field borders, farmers can utilize GPS. GPS is also essential for precision planting, which makes sure that seeds are sown at the right depths and intervals to maximize production.
- **Spatial Data Analysis:** Farmers are better able to examine field variability thanks to the spatial data gathered by GPS. Implementing precision farming techniques, including variable rate technology, to meet particular demands in various fields requires this knowledge.

UAVs equipped with multispectral cameras can capture high-resolution imagery and data of farm fields. They're particularly useful for monitoring crop health, detecting pests and diseases, and spraying pesticides or fertilizers in a targeted manner. This section explores the role of drone technology in agriculture, emphasizing its applications in aerial imaging and mapping, crop scouting and monitoring, and the integration of artificial intelligence (AI) to enhance functionality.

Fig. 1. Unmanned Aerial Vehicles (UAVs) and drones in precision agriculture

- **Drone Technology in Agriculture**

1. **Overview of Drone Technology:** Drones are tiny, autonomous aircraft fitted with sensors and cameras that can record and process high-definition video and data. Drones have becoming increasingly popular in agriculture because they can gather data in real time and give farmers insightful information that helps them make decisions.
2. **Types of Agricultural Drones:** There are several different kinds of agricultural drones: quadcopters and hexacopters that provide more maneuverability in tight locations, and fixed-wing drones that cover broader regions. Every variety is appropriate for certain uses in precision farming.
3. **Cost-Effectiveness and Accessibility:** Compared to human aerial surveys or other traditional techniques, drone data collecting is more affordable. Because of its accessibility, farmers of all sizes may use this technology, democratizing the advantages of precision farming.

Satellite Remote Sensing in Precision Agriculture:

Precision agriculture has been completely international with the introduction of satellite remote sensing. Satellites are able to give continuous and detailed data on crop health, soil conditions, and weather patterns by taking pictures of the Earth's surface. Farmers who oversee vast areas can benefit greatly from this technology.

- **Comprehensive Field Coverage:** Farmers are able to monitor and analyze their whole field using a broad picture made possible by satellite imaging. It is essential to have such extensive coverage in order to detect geographical variations and comprehend the general health of crops.
- **Temporal Monitoring:** Temporal monitoring is made possible by the various time periods at which satellites take pictures. With the use of this capacity, farmers are able to monitor changes in agricultural conditions over time, spot trends, and react to changing conditions that affect crop development.

2.3 Grid Sampling for Targeted Farming

- One method for dividing fields into around 0.5–5 ha-sized pieces is grid sampling. The soil samples from those grids will be used to determine the appropriate rates at which crop inputs should be applied. After that, the Grid Samples are gathered, mixed, and brought to the lab for analysis.

Fig. 2. Drone technology in agriculture

- Utilizing grid sampling, soil samples from various fields may be gathered to comprehend the spatial variability of soil properties like pH, organic matter concentration, and nutrient content. Using this data, you may make well-informed judgments regarding irrigation, fertilization, and other related topics.

Variable Rate Technology (VRT): With the use of variable rate technology (VRT), inputs like water, herbicides, and fertilizers may be applied precisely to different parts of a field according to their individual needs. This technique creates prescription maps that direct machines to alter input rates dynamically using data from several sources, such as GPS and remote sensing. VRT guarantees optimal crop performance, minimizes waste, and improves the efficiency of resource utilization Banhazi et al. [31].

- **Fertilizers:** Depending on the crop requirements and soil nutrient levels in each location, variable rate technology (VRT) is used to apply fertilizers at varying rates throughout a field. This can increase crop yields and quality while saving farmers money on fertilizer Hostiou et al., [32].
- **Pesticides:** Depending on the frequency and distribution of illnesses and pests throughout the field, VRT is used to apply insecticides. This lowers the chance of environmental damage and aids farmers in managing the quantity of pesticides they use Berckmans et al., [33].
- **Seeding:** Depending on each area's unique crop requirements and soil qualities, VRT is utilized to plant seeds. This aids farmers in maximizing crop quality and yields Eastwood et al., [34].

Fig. 3. Variable Rate Technology (VRT)

2.4 Yield Monitors for Precision Agriculture

In precision agriculture, a yield monitor is a tool used to measure and log crop yields as they are harvested. A computer or other data recording device is usually used to record the yield data, while sensors detect the flow of grain or other crops as they travel through the combine harvester.

Fig. 4. Yield monitors for precision agriculture

Utilizing yield monitors, one may generate intricate maps of crop yields throughout a field, illustrating the geographic variability of yields and pinpointing regions with high or low performance.

Test weight and moisture content of harvested crops may be measured and recorded using yield monitors. By using this information, handling and storage procedures may be improved, and the crop's general quality can be raised.

- **Real-Time Yield Data Collection:** GPS tracks the operation of harvesting equipment as it travels over the field, making real-time yield monitoring easier. This information is essential for evaluating yield differences between various locations.
- **Data Analysis for Decision Making:** When yield monitoring data is evaluated, it can reveal important information about the variables affecting crop productivity. With this data, farmers can plan their overall farm strategy, future planting, and resource management with knowledge.
- **Identification of Yield Variability:** Finding fields with greater or lower yields is made easier with the use of GPS-enabled yield monitoring. This data can direct more research into the variables generating variability, allowing for more focused treatments aimed at improvement.

3. DATA MANAGEMENT SYSTEMS

Precision farming relies heavily on data management systems, which gather, store, and analyze massive volumes of data produced from many sources. These systems combine data from VRT, GPS, and remote sensing to provide farmers useful insights. Farmers are empowered to make educated decisions about crop planning, resource allocation, and general farm management by means of sophisticated analytics and decision support technologies.

3.1 Functions of Data Management Systems in Precision Farming

- Integration of data from multiple sources for comprehensive analysis.
- Generation of prescription maps for variable-rate applications.
- Monitoring and reporting on crop performance over time.
- Facilitation of data-driven decision-making for farm management.

3.2 Proximate Sensors for Precise Crop and Soil Data Capture

- Proximate sensors can be used to measure soil (N and pH) and crop properties as the tractor pass over the field.
- In precision agriculture, proximate sensors are used to measure the characteristics of crops or soil that are in close proximity to the sensor. After the soil sample has been collected and put up against an electrode, it is allowed to stabilize for ten to fifteen seconds before the reading is obtained. These sensors can be installed on cars or other agricultural equipment, or they can be held in the hand. With the help of proximate sensors, farmers may gather data in real-time or almost real-time, responding to changing conditions and making necessary modifications.

3.2.1 Proximate sensors can measure

- **Crop characteristics:** Crop attributes including biomass, leaf area index, and height are measured using proximate sensors. Crop yields can be increased by using this information to optimize crop management techniques Bharteey et al*.,* [35].
- **Soil characteristics:** Proximate sensors are used to monitor the pH, moisture content, nitrogen content, and nutrient content of soil. Enhancing resource management techniques such as irrigation and fertilization may be accomplished with the use of this data Hakkim et al*.,* [36].
- **Pests and diseases:** To maximize control methods and lower the danger of outbreaks, proximate sensors are used to track the incidence and spread of diseases and pests in a field Bhattacharyay et al.,2020.

3.2.2 Computer Hardware and Software

To evaluate the data collected by other precision agricultural technology components and make it available in formats like maps, graphs, charts, or reports, computer support is needed.

- **Data storage and management systems:** Systems for precision agriculture frequently produce vast volumes of data, which must be efficiently and systematically managed and stored. Numerous data management and storage technologies, including databases and cloud-based platforms like Cropin Cloud, can be used for this.
- **Data analysis and visualization tools:** Using specialist software tools to analyze and visualize data is frequently necessary for precision agricultural systems in order to extract insights and make well-informed decisions.

3.3 Technological Components of Precision Farming

The optimization of agricultural techniques through the integration of many technologies is a key component of precision farming. The main technology elements that support precision farming will be examined in this section:

In conclusion, precision farming's technical components complement one another to improve agricultural techniques' productivity, sustainability, and efficiency. Precision farming is positioned to be crucial in tackling the problems facing contemporary agriculture as these technologies develop further.

4. AUTO-GUIDANCE SYSTEMS FOR PRECISION AGRICULTURE

Precision agricultural technology known as auto-guidance systems employ GPS and other sensors to assist farmers in precisely navigating their cars and equipment around the fields.

A GPS receiver, a display unit, and occasionally other sensors (such cameras or lasers) that offer more details about the area and the vehicle's location within it make up these systems' standard components.

There are several applications for auto-guidance systems in precision agriculture.

- **Navigation:** Auto-guidance systems can lower the chance of mistake by assisting farmers in manoeuvring their vehicles and equipment across the fields with a high degree of accuracy.
- **Row Guidance:** Farmers may reduce overlap and skips by using auto-guidance systems to assist them maintain their equipment and vehicles on the right rows.
- **Equipment Guidance:** With the use of auto-guidance systems, farmers may more precisely manage and monitor the position and orientation of agricultural machinery, such as planters, sprayers, and harvesters, enhancing implement performance and lowering mistake rates.
- **Record keeping and Data Analysis:** For the purpose of preserving records and doing analysis, auto-guidance systems have the ability to capture information on the whereabouts and movements of equipment and vehicles.

4.1 Advantages of Precision Agriculture

- Instead of spreading inputs (such seeds, fertilizer, and pesticides) evenly throughout the field, farmers may target these regions with the most need by employing precision agriculture technology and methods Doruchowski et al*.,* [37].
- In addition to reducing input costs, farmers may improve crop quality and output with this focused strategy. Furthermore, farmers may monitor and manage their crops more efficiently with the use of

precision agriculture technologies, which enables them to react swiftly and effectively to possible issues (such pests or illnesses) Ojeda et al*.,* [38].

- Farmers can accurately apply fertilizers at the proper rate and place by using mapping tools and sensors. Precision agriculture technology may also assist farmers in optimizing their irrigation techniques, which can result in water and energy savings. Precision agriculture helps farmers in many ways since it allows for the tracing of specific regions within a single farm Njoroge et al*.,* 2002.

4.2 Discussed below are Some of its Key Advantages

- A refined set of cultivation practices and choice of crops based on the suitability of land
- Elimination of volatility and risk
- Waste management
- Reduced production costs
- Minimum environmental impact
- Optimized use of fertilizers
- Water management with optimized irrigation practices
- Improved soil health

5. ROLE OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN PRECISION AGRICULTURE

The governments of economies where agriculture is the primary industry invest in other cutting-edge technologies, such as artificial intelligence and machine learning (AI/ML), even while IoT is still in its infancy, in order to make more informed agricultural decisions. The application of IoT in agriculture has particular advantages and difficulties in nations like India.

First off, because they don't know how to use agritech in agriculture, farmers are afraid to upgrade to it. In addition, the sensors, robots, and drones are costly, need a lot of maintenance, and need workers with specialized training to operate. Additionally, the collected data must be examined in a laboratory or on the farm with specialist equipment. Additionally, a range of sensors are needed to gather data on various aspects, each of which needs to be evaluated independently, raising operational expenses. Because farms vary in size, the digital farming solution needs to be both highly scalable and reasonably priced.

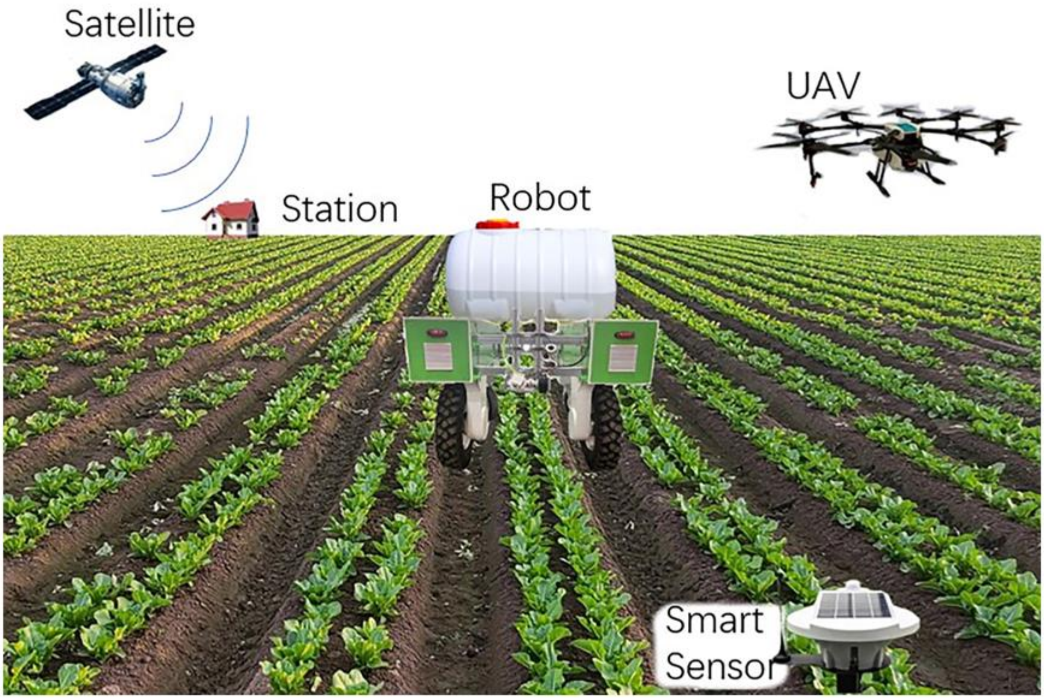

Fig. 5. Role of artificial intelligence and machine learning in precision agriculture

6. PRECISION AGRICULTURE'S DRAWBACKS AND DIFFICULTIES

The difficulties and restrictions associated with precision agriculture include the high initial cost and ongoing maintenance required because of the hardware, software, and infrastructure required. Another problem is the availability and quality of data, which varies according on the crop, season, and place. Optical sensors are used to measure soil characteristics, crop biomass, and/or leaf greenness in precision farming techniques such as LCC and SPAD meters. Climate, organic matter, and insufficient or excessive soil moisture all affect measurements and can influence the decision-making process when it comes to fertilizer management. P and K deficits can occasionally interfere with leaf greenness and have an impact on SPAD meter/LCC readings. Certain cultivars may have different spectral characteristics in their leaves. In these situations, distinct thresholds must be set for each cultivars. The incidence of insect pests also affects the plants' NDVI and degree of green colour. It is best to stay away from these plants when gathering data. These are the some constraints given below to adopt precision agriculture by the farmers in India because most of farmers are belongs to marginal and small categories of land holding:

High Costs: Putting precise agricultural technologies into practice can be costly. Drones, sensors, and GPS systems can be very expensive, especially for small-scale farmers.

Complexity: There may be complexity in the data management and technology involved. To use and understand precision agriculture instrument data successfully, farmers must possess or develop technical expertise.

Data Overload: Gathering a tonne of information sometimes be too much to handle. Without appropriate tools for analysis and decision-making, the data may end up being more of a liability than an asset.

Infrastructure Requirements: Reliable power sources and strong internet access are generally necessary for precision agriculture, however these amenities may not be available in all remote places.

Maintenance and Calibration: To guarantee accuracy and functioning, precision agriculture equipment needs to undergo routine maintenance and calibration. This raises the continuous expense and complexity.

Variable Returns on Investment: Depending on the crop variety, soil conditions, and management techniques, precision agriculture can offer different benefits. Sometimes the expenses may not be justified by the return on investment.

Problems with Integration: It might be difficult to integrate new precision agricultural technologies with current farm management procedures and systems. Data security and privacy are issues that are brought up by the gathering and storage of vast volumes of data. Farmers should exercise caution while sharing and managing their data.

Adaptation to Local Conditions: Customization and changes may be necessary because precision agricultural technologies are not always ideal for the local environment or particular farming methods.

Impacts on the Environment and Society: Although precision agriculture tries to be more sustainable, the increased use of technology and inputs can occasionally have unanticipated effects on the environment or society. For example, extensive data collecting and input utilization may have unexpected effects on nearby ecosystems.

Precision agriculture still has a lot of potential, but these drawbacks make it even more important to embrace these technologies with thoughtful planning and deliberation.

Future Line of Work: A number of new developments in technology and emerging trends are expected to have a significant impact on precision agriculture in the future by expanding its potential applications. The following crucial areas will probably determine how precision agriculture develops in the future: Supplying farmers with the knowledge and training they need to use the digital platform, as well as popularizing and raising awareness of digital technology. Creation of cost-effective smart farming technology for small and marginal farms. Despite the technological challenge, better agronomic decision-making at the same spatial scale can be achieved through precision agriculture by making more judgments in a given amount of time. This can be accomplished by providing suitable DSS tools and farmer training to enhance crop monitoring. To prove the benefits of need-based precision management techniques, research must be done. GPS, GIS, and remote sensing technologies should be used in research projects as well for a more accurate assessment of fluctuations within a field over the course of the growing season. Expanding the breadth of funding for precision agriculture-related new technologies is necessary. Precision agriculture's future course will be determined by research and the community's capacity to carry out studies for more productive use of resources and the newest technologies. Policies to make expensive farm equipment available for hire on a customized basis at the block level

7. CONCLUSION

Precision agriculture (PA) is a site-specific crop management concept that combines positioning system technology, variable rate technology, remote sensing, yield mapping, and other techniques to maximize profitability and sustainability while minimizing environmental impact. Soft precision agricultural technology has existed on Indian farms for ages. However, the limitations of a free and globalized market, as well as an ever-increasing population with high food grain demand, limit the scope for the implementation of hard precision agricultural technology in Indian fields. As a result, it is vital to learn about new agricultural technology created in industrialized countries, as well as to modify and apply it appropriately for home conditions. The use of inputs (such as chemical pesticides and fertilizers) in the appropriate amount, timing, and location. The term "Site-Specific Management" refers to this type of management. It allows for more exact application of pesticides, fertilizers, and water, reducing waste and the environmental effect of farming operations. Despite these shortcomings, precision agriculture has the potential to alter farming systems. Precision farming is thus an attractive idea, and its principles naturally raise the hope that farming inputs may be used more efficiently, enhancing profitability while producing less that affects the environment.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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