7) SUSTAINABLE AGRICULTURE WITH PRECISION AGRICULTURAL TECHNOLOGIES

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ABSTRACT

Precision agriculture represents a modern approach for sustainable farming by integrating or combining advanced technologies such as GPS guidance systems, variable rate application equipment, remote sensing, soil mapping, and data analytics to enhance the agricultural inputs and optimize the crop yields while reducing the environmental impacts. The major problems of traditional farming are resolved by precision farming. This analysis indicates that precision agriculture can diminish the fertilizer usage by 15-25%, minimize the pesticide applications by 20-35%, and enhance water use efficiency by 10-30%, all while sustaining or augmenting the crop yields. The principal advantages include increased resource utilization efficiency, reduced environmental pollution, higher economic returns for farmers, and improved decision-making abilities enabled by real-time data acquisition and analysis. In conclusion, precision agriculture has many hurdles remaining, including substantial initial capital inputs ($50,000-200,000 per farm), technical intricacies necessitating specialist training, data administration demands, and the restricted accessibility for small-scale farmers. Case studies illustrate effective application across various agricultural systems, including extensive grain production, specialized crop cultivation, and livestock operations. This modern approach offers a significant promise in tackling the global food security concerns while lowering agriculture's environmental impact. Anticipated advancements in artificial intelligence, machine learning, and Internet of Things integration are projected to augment precision agriculture capabilities. This article suggests the importance of precision agriculture technologies that provide significant benefits for sustainable farming; their adoption requires resolving economic hurdles, enhancing the technological accessibility, and providing comprehensive training programs for agricultural practitioners.

INTRODUCTION

The global agriculture business in the 21st century has a lot of problems to deal with. For example, it needs to feed a growing population that is predicted to reach 9.7 billion people by 2050. It also needs to deal with the effects of climate change, resource scarcity, and environmental degradation [1]. Traditional farming methods have kept human civilization going for thousands of years, but they are no longer good enough to deal with these difficult problems without affecting the environment. The widespread use of the chemical pesticides, fertilizers, and water resources in traditional farming has caused loss to biodiversity, soil erosion, water pollution, and greenhouse gas emissions that may alter climatic patterns [2]. Precision agriculture is a modern way of farming that uses cutting-edge technologies to turn traditional farming methods into systems that are based on data and are good for the environment. This technology-driven idea for managing the farms uses information technology and a number of instruments, such as Global positioning system navigation, control systems, sensors, robotics, drones, autonomous vehicles, variable rate technology, and software, to make crop farming better at the field level [3]. The basic idea behind precision agriculture is to know that agricultural fields have different soil properties, nutrient levels, moisture levels, insect pressure, and crop growth characteristics at different times and places. Since the advent of the Global positioning system technology in the 1980s, the idea of precision agriculture has grown quickly with the advancements in computing power, sensor technology, and data analytics capabilities. Global Positioning Systems used for precise field mapping and equipment guidance, Geographic Information Systems used for the spatial data analysis, remote sensing technologies used for crop monitoring, variable rate technology used for the precise input application, and advanced software platforms for the data management and decision support are just a few of the technologies that are integrated into the modern precision agriculture systems [4].

History of Agriculture: From Traditional to Precision Farming

Early Farming (10,000 BCE - 1800 CE)

Around 10,000 BCE, people ceased hunting and gathering and started farming. This is when agriculture began. This development made it possible for people to stay in one place and construct civilizations [1]. People who farmed in the past utilized primitive tools and learnt how to farm from their families and communities. People in different parts of the world grew different crops. For example, wheat and barley grew in the Middle East, rice grew in China, corn grew in America, and potatoes grew in South America [2]. Farmers in the past acquired basic skills like how to rotate their crops, water them, and choose the finest seeds to plant. These early approaches were the building blocks of all farming expertise. People in ancient times made farming better in numerous ways. Egyptians made irrigation systems along the Nile River, Romans made better plows and water systems, and Chinese farmers found ways to use natural fertilizers to keep the land healthy [3]. In the Middle Ages, European farmers used a three-field system that involved rotating crops to maintain the land health.

Industrial Revolution (1800-1950)

Farming altered a lot throughout the Industrial Revolution. The steel plow (1837) and the mechanized reaper (1831) made farming faster and easier [4]. As cities increased, it became more vital for fewer people to be able to grow food for more people. The development of chemical fertilizers in the early 1900s was a big step forward. The Haber-Bosch process (1909) made it possible for farmers to create nitrogen fertilizer, which made crops grown considerably better [5]. This breakthrough helped the population grow by making crops grown considerably better. Farmers used tractors instead of horses and oxen. The Fordson tractor, which came out in 1917, was the first one that was commercially available. It made automated farming viable for the smaller farms [6]. Most of the farm's machines were used to plant, produce, and harvest crops by the middle of the 1900s.

Green Revolution (1950-1980)

The Green Revolution was a period of amazing agricultural progress led by scientist Norman Borlaug, who won the Nobel Peace Prize for his work [7]. This movement was mostly about the three things: making better agricultural types, creating irrigation infrastructure, and employing the herbicides and fertilizers. Scientists produced new types of wheat, rice, and corn that made more food than the older ones. These new crops might grow two to three times as much as grain, especially if they had adequate water and fertilizer [8]. This helped to stop food scarcity and feed more people, especially in Latin America and Asia. Farmers also started utilizing the chemical pesticides to keep insects, weeds, and diseases from hurting their crops at this time [9]. People were worried about how these pesticides would affect the environment and human health after they had dramatically increased crop yields.

Environmental Awareness (1980-2000)

During the 1980s and 1990s, people became more concerned about how farming harmed the environment. Rachel Carson's book "Silent Spring" (1962) highlighted how pesticides may kill animals, which made people think more carefully about how they farmed [11]. People wanted food that was grown without synthetic chemicals, therefore organic farming became popular. Organic farmers don't use synthetic fertilizers and pesticides. Instead, they focus on good soil and natural techniques to keep pests away [12]. This movement brought back some traditional farming methods and added some new ones. Integrated Pest Management, was developed as a better way to get rid of pests and it doesn't merely use pesticides all the time. It only employs chemicals, natural enemies, and monitoring when they are needed [13]. This strategy keeps crops safe while using fewer insecticides.

Biotechnology Era (1990-2010)

Genetic engineering came to farming in the 1990s. Scientists made genetically modified crops that could either withstand herbicides or make their own pesticides [15]. The first genetically modified crops were soybeans that could handle herbicides and corn that could handle insects. Herbicide-tolerant crops made it easier for farmers to control weeds because they could spray them without hurting their crops. This also helped enable no-till farming. But using these herbicides too much made weeds resistant to them, which made things even harder. Bt, a type of bacteria, gave insect-resistant crops genes that made them poisonous to some pests. This made it less necessary to apply insecticides and increased agricultural yields, but it needed to be managed carefully to keep insects from becoming resistant. Scientists can also breed plants more quickly using new genetic techniques, which has led to better varieties of crops. These tools made it easier to cultivate crops that are more resistant to disease, more able to handle stress, and have more nutrients. To stop soil erosion, no-till farming and other conservation tillage practices were devised. These methods leave behind agricultural debris, which preserves the soil and makes it healthier [14]. This was very important because intensive plowing has caused a lot of problems with soil loss.

Digital Agriculture and Precision Farming (2000-Present)

The 21st century saw the introduction of computers and digital technology to farming, which led to the development of precision agriculture. Farmers may utilize Global Positioning System technology to build precise maps of their fields and apply fertilizers, herbicides, and seeds at different rates across the field based on what each area requires [3]. A lot of different technologies work together in modern precision agriculture. Soil sensors check the moisture and nutrients in real time, satellites and drones keep an eye on the health of the crops, and Global positioning system-guided equipment makes sure that field work is done correctly [4]. Farmers can grow a lot of crops with this technology while still using their resources better. Farmers can utilize variable rate technology to put the right amount of inputs where they are needed, which cuts down on waste and damage to the environment [5]. Global positioning system guidance keeps field activities from getting in each other's way, which saves fuel and keeps the soil from being too hard. Farmers may now use AI and machine learning to look at a lot of data and make better decisions [6].

Sustainable agriculture

People have been arguing about what "sustainability" means for a long time without knowing about its actual meaning. The word was initially employed to describe industrial and agricultural systems that mitigated or eradicated the environmental damage typically associated with the economic activities. Hartwick (1978) and Solow (1974) described it as the ability to keep the consumption or productivity stable by using artificial capital and natural resources in production. In this context, "manmade capital" refers to anything that was made by people, such as structures, tools, knowledge, and information. Pearce and Atkinson (1993, 1995) assert that the environment is defined by the notion that natural resources and human-made capital synergistically contribute to the production process, necessitating the conservation of the natural resources as they represent the limiting element in production [7]. The United Nations gave a more complete definition of sustainability in 1972. They said "it refers to the process that meets the needs of the present generation without compromising the ability of future generations to utilize this and meet their own needs. Recently, sustainability has been linked to a detailed study of the social, cultural, environmental, and economic effects of any development (Caffey et al., 2001) (Figure 7.1).

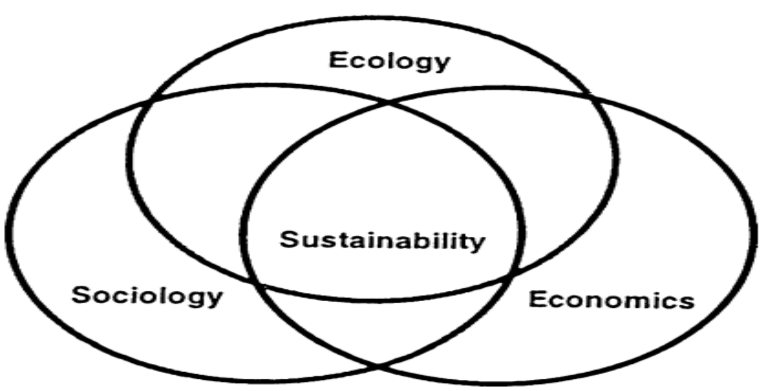

Fig 7.1 Sustainability as described by the intersection of three disciplines: ecology, economics and sociology.

The American Society of Agronomy (1989) defines "Sustainable Agriculture" as agriculture that, over the long term, improves the quality of the environment and the resources that agriculture relies on; meets basic human needs for food and fiber; is economically viable; and improves the quality of life for farmers and society as a whole.

Precision agriculture

Site-specific management means doing the correct thing at the right time and place. This idea has been around since farming began, but when farming became mechanized in the 20th century, there was a lot of economic pressure to use the same farming methods on big fields. Lowenberg-DeBoer and Swinton (1997) characterize Site-specific management as "electronic monitoring and control utilized for data collection, information processing, and decision support regarding the temporal and spatial distribution of inputs for crop production." They point out that the main focus is on agronomic crops, but the same reasons may be made for horticultural crops and for electronically tagging livestock [12]. The main idea behind precision agriculture is to use inputs as efficiently as possible, reduce waste, lower environmental consequences, and get the most money back. This is very similar to the ideas behind sustainable agriculture. Precision agricultural systems can greatly reduce the overuse of fertilizers, pesticides, and water while keeping or even increasing crop output by using the proper number of inputs at the right time and place. This focused method not only cuts down on production expenses, but it also makes farming activities less harmful to the environment.

Improvements in precision agriculture towards sustainability

The aspects of precision agricultural systems that deal with technology work together to provide full farm management solutions. Global Positioning System-guided tractors and tools make sure that work in the field is done right and that there are no overlaps or gaps in how inputs are used. Soil sampling and mapping technologies create detailed geographical databases of soil properties that make it easier to apply lime and fertilizer at different rates. Remote sensing platforms like satellites, airplanes, and unmanned aerial vehicles can tell you in real time how healthy your crops are, how stressed they are, and how they are growing. This helps us decide when to water and how to deal with pests. When you put these technologies together, you get a lot of data that needs to be looked at and comprehended in a fairly advanced way. Modern precision agriculture systems use the latest machine learning algorithms like classification algorithms and regression algorithms, data analytics, and artificial intelligence to look at this data and give farmers meaningful advice. Cloud-based platforms help people share information and keep a watch on things from a distance. Farmers can quickly get field data and tools to assist them make choices with mobile apps (Fig 7.2).

Fig 7.2 Monitoring crops through mobile application

The economic reasons for using precision agriculture are higher input costs, higher land values, a lack of workers, and a growing need for food that is grown in a way that is good for the environment. Environmental regulations and customers' desire for eco-friendly agricultural methods further promote the usage of precision agriculture technologies. In many places, farmers can follow precision agriculture as part of bigger initiatives to make farming more sustainable.

And those initiatives were supported by government programs and subsidies. The scientific ideas that explain how to manage and use the resources more efficiently are what make the precision agriculture systems function better. The 15–25% decrease in fertilizer use is based on Liebig's Law of the Minimum and the premise that various portions of a field need varying amounts of nutrients. Integrated Pest Management and economic threshold theory explain the 20–35% reduction in pesticide consumption. It only gets rid of the pests when there are so many of them that hurt the production and economy. Precision scouting, variable rate sprays that target insect hotspots, and predictive modeling are all used to do this. We can improve the efficiency of the water consumption by 10% to 30% by using the evapotranspiration mechanism, soil moisture monitoring, and the deficit irrigation plans. This is based on the idea of how much water crops consume and the idea of the soil-plant-atmosphere continuum. Yield gap analysis, which means using the resources wisely and then planting seeds in the proper places, can increase yields by 5–15%. By using the nitrogen cycle dynamics to match the supply with the needs of the crops, we may minimize the nitrogen loss by 20% to 40%. Using the Universal Soil Loss Equation and conservation tillage methods can cut soil erosion by 50% to 90%. Economic optimization theory says that reducing over-application and operational overlaps can save $15 to $50 per acre on input costs. These foundations are validated through randomized controlled trials, meta-analysis, and comprehensive uncertainty analysis (Table 7.1).

Table 7.1 Precision Agriculture Performance Metrics

parameter	Traditional agriculture	Precision agriculture	Improvement (%)
Fertilizer use reduction	Baseline	15-25% reduction	15-25%
Pesticide application	Baseline	20-35% reduction	20-35%
Water use efficiency	60-70%(sprinkler)	85-95% precision	10-30%
Yield improvement	Baseline	5-15% increase	5-15%
Nitrogen loss reduction	Baseline	20-40% reduction	20-40%
Input cost savings	Baseline	$15-50 per acre annually	Variable

The scientific principles of precision agriculture's environmental benefits explain how these technologies became prominent through enhancing farming while preserving and protecting the environment. By applying fertilizer only to the areas where and when crops require it, precision agriculture reduces waste and stops nitrogen from leaking into groundwater or escaping into the atmosphere, which leads to an increase in nitrogen use efficiency by 15–25% [7]. Farmers can identify the exact locations of the pests and spray only those areas instead of spraying entire fields, so that the use of pesticides was reduced by 20–35% [8]. There are several ways to reduce greenhouse gas emissions: conservation tillage techniques help soil store more carbon, Global Positioning System-guided equipment uses less fuel and produces less carbon dioxide, and using less fertilizer reduces nitrous oxide emissions from soil [9]. By using less tillage, keeping crop residues on the soil surface for protection, and using Global Positioning Systems to control the movement of farm equipment, precision agriculture significantly reduces soil erosion by 50–90% [4] (Table 7.2).

Table 7.2 Comparison son of Environmental Impacts between Traditional and precision farming

Environmental factor	Traditional farming	Precision farming	Improvements
Nitrogen use efficiency	Baseline	15-25% improvement	Leaching is reduced
Application of Pesticide	100%	60-80% of baseline	20-35% reduction
Emission of greenhouse gases	Baseline	Reduced	Variable reduction
Soil erosion	Baseline	10-50% of baseline	Reduced by 50-90%
Energy Efficiency	Baseline	12-18% improvement	Fuel and input savings

Precision agriculture improves water quality by controlling soil erosion that carries pollutants to water bodies, applying nutrients when crops need them most, and reducing the number of pesticides and fertilizers that can run off fields into streams and lakes [6]. Because Global positioning system guidance prevents overlapping passes in fields, farmers use less fuel through reduced tillage, and precise input application lowers the overall number of materials that must be produced and transported, so that the energy efficiency increases by 12–18% [3]. Scientific studies comparing precision agriculture to traditional farming practices have demonstrated these advantages, with researchers tracking real improvements in the environmental quality over time and across various farming systems and geographical areas [15] (Table 7.2).

ADVANTAGES AND POSITIVE IMPACTS OF PRECISION AGRICULTURE

Enhanced Resource Use Efficiency

One of the best things about precision agriculture technology is that it makes it easy to employ all of the primary inputs in farming. Farmers can use variable rate technology to apply fertilizers, herbicides, seeds, and water at the appropriate rates for each field condition, rather than using the same quantity on all fields. Studies have shown over and over that adopting precision spraying methods can minimize fertilizer use by 15% to 25% while keeping or even improving crop yields [5]. Farmers can only use fertilizers where they are needed and at the proper rates since they can see where nutrients are accessible in varying amounts by analyzing and mapping the soil. This speeds up the procedure. Precision irrigation systems that employ soil moisture sensors, weather data, and crop growth models to figure out when and how long to water can cut water use by 10% to 30% [6]. These methods stop both under-irrigation, which slows down crop growth, and over-irrigation, which wastes water and can wash away nutrients. Drip irrigation systems can utilize over 90% of the water they need when they are used at the right time. Regular sprinkler systems only use 60–70% of the water they need. One may acquire the best plant populations for our soil productivity zones, moisture availability, and topography by placing seeds in the proper areas and utilizing different seeding rates. This exact strategy will help you use seeds more efficiently by 5 to 15 percent and also help you identify the ideal spacing for plants to produce the highest yield. Global positioning system-guided planting tools make sure that the rows are placed appropriately and that there are no gaps or overlaps that make the field less productive.

Environmental Protection and Sustainability

Precision agriculture benefits the environment in many ways, such as keeping ecosystems healthy for a long time. Using less fertilizers means that releases less nitrogen and phosphorus into the environment which will wash into water bodies. This helps in keeping the lakes, rivers, and coastal areas from being too nutrient-rich. Research indicates that precision nutrient management can reduce nitrogen losses to groundwater by 20–40% compared to traditional uniform application approaches [7]. This decrease in nutrient contamination keeps drinking water pure and protects aquatic ecosystems. Precision application technologies that only treat some areas of the pest infestation instead of the whole field can reduce pesticide usage by 20–35% [8]. Precision agricultural technologies improve integrated pest management systems by using real-time monitoring of the insect populations, weather conditions, and the crop growth stages to find the best times to apply pesticides and reduce the wasteful treatments. This targeted method holds less pesticide residue on food and has less effect on beneficial insects, soil creatures, and other species that aren't the target. It's healthier for the soil if you don't till it as much, and Global Positioning Systems accurate planting tools make this possible. Precision agricultural technology that enables no-till and reduced-till methods helps keep the soil's structure, adds more organic matter to the soil, and reduces the erosion rates by 50% to 90% compared to traditional tillage systems [9]. These activities also help farmland soils to keep carbon, which helps fight climate change. Precision agriculture technologies help to reduce greenhouse gas emissions in a lot of different ways. So less nitrous oxide is emitted into the air when we use less fertilizer. Nitrous oxide makes up to 60% of the greenhouse gasses that arise from farming. When farm equipment has Global positioning system-navigation and better field operations, it consumes less fuel and emits less carbon dioxide. Conservation tillage methods that help keep carbon in the soil also assist lower the quantities of greenhouse gases in the air.

Economic Benefits and Profitability

Precision agricultural technology helps farmers make more money by lowering their input costs, increasing their yields, and making their operations more efficient. Depending on the type of crop, the state of the land, and how much technology is used, input cost savings usually vary from $15 to $50 per acre every year [10]. These savings come from using the right amount of fertilizer, pesticides, and seeds so that crops stay productive without wasting or overusing them. Precision agriculture strategies that improve growing conditions and cut down on factors that limit production sometimes leads to yield improvements of 5-15% [11]. Better pest control, better fertilizer management, healthier plant populations, and better water management all lead to these higher yields. Farm profitability and return on investment go up a lot when input costs go down and yields go up., which helps fight climate change. Precision agriculture technologies help to reduce greenhouse gas emissions in a lot of different ways. So less nitrous oxide is emitted into the air when we use less fertilizer. Nitrous oxide makes up to 60% of the greenhouse gasses that arise from farming. When farm equipment has Global positioning system-navigation and better field operations, it consumes less fuel and emits less carbon dioxide. Conservation tillage methods that help keep carbon in the soil also assist lower the quantities of greenhouse gases in the air.

Data-Driven Decision Making

Using a huge number of data sources in precision agricultural systems enables farmers to make decisions based on facts, which leads to better farm management results. Farmers can get all the information they need to make their field work better by keeping an eye on the weather, soil moisture, crop conditions, and the equipment performance in real time through apps which are associated with precision farming technologies. Historical data analysis shows long-term trends and patterns that help with planning and making the investment decisions. Farmers can use predictive analytics to analyze problems and their consequences before they happen. This enables them to take proactive steps to avoid the yield losses and lower the input costs. Machine learning algorithms will take huge amounts of data to find the best times to sow, water, and harvest crops based on the weather and the past performance data in that particular area.

Technology Integration and Automation

Modern precision agricultural systems integrate many technologies into all-in-one farm management platforms that will automate simple activities and help in decision-making. Internet of Things sensors keep an eye to monitor the state of the field, the equipment, and the environment all the time. Cloud-based data tools enable farm teams to work together to make decisions and access agricultural information from anywhere. Artificial intelligence and machine learning algorithms deal with complicated datasets and come up with useful suggestions for the farmers. These systems keep learning from the fresh data and getting better at making predictions over time. Farmers may get the field information right away and make changes to field operations in the real time with mobile apps.

DISADVANTAGES AND NEGATIVE IMPACTS OF PRECISION AGRICULTURE

High Capital Investment and Economic Barriers

The biggest problem with adopting precision agriculture is that it requires a lot of money to buy and set up the technology. The cost of the first set of equipment for a full precision agricultural system is usually between $50,000 and $200,000 per farm, depending on the size of the farm and how advanced the technology is [12]. Global Positioning Systems for tractors cost between $15,000 and $30,000, while variable rate application equipment costs between $20,000 and $50,000 more. For extensive research, soil sample and mapping services cost $8 to $15 per acre. This will represent significant upfront costs for large farming operations. The high capital needs make things especially hard for the small and medium-sized farms that may not have enough money or credit to get those technologies. Traditional agricultural lenders may not want to fund precision agriculture investments since they don't know how the technology works and aren't sure how much money they'll get back from investment i.e.; simply Return on Investment. This financial barrier makes it harder for the big businesses to embrace new technologies than for the small family farms, which might make differences in the agricultural productivity and profitability. Depending on the size of the farm, the types of crops grown, and the local economy, the return on investment for precision agricultural systems usually takes 3 to 7 years [13]. These payback periods are usually fine for agricultural investments, but farmers need to keep making money and have cash flow for a long time. Market instability, weather concerns, and fluctuating commodity prices can impact the investments on precision agricultural technologies. Ongoing technology expenditures include paying for the software licenses, managing data, fixing equipment, and getting new technology updates on a regular basis. The cost of the software and services each year can be between $5 and $15 per acre. Maintenance and calibration of the equipment need specialized technical help that may not be easy to find in the rural locations. These costs that are incurred on them again and again need to be taken into account when making the long-term economic plans. They can also make it hard for the farms to stay within their budgets when the commodity prices are low.

Technical Complexity and Training Requirements

Precision agriculture systems use advanced technology that need a lot of technical knowledge and abilities to run and operate it well. Farmers need to know how to use the Global Positioning Systems, Geographic Information System software, data analysis methods, and the complicated equipment calibration methods. The learning curve for adopting precision agriculture can be steep, especially for the older farmers who may not be used to computers and digital technologies. Training needs go beyond just learning how to use the equipment. Comprehensive training programs can cost $5,000 to $15,000 per farm and take a lot of time, which may not fit into the hectic agricultural schedules. The absence of the uniform training programs and the certification procedures results in disparities in the farmer knowledge and system efficacy. In rural villages or remote locations, where the precision agriculture service providers may not be nearby in such a situation getting technical support might be a bigger problem. Equipment failures or software failures occurring during important times for farming might cause big delays and money losses if technical support isn't easy to get. Modern precision agriculture systems are typically very complicated; therefore, they need professional technicians who may know much about how things are done on local farms using these precision technologies.

Technology Reliability and Maintenance Issues

Precision agriculture systems depend on advanced electrical devices that can be damaged by environmental stress, mechanical failure, and by becoming outdated. In severe agricultural settings with dust, moisture, vibration, and extreme temperatures, Global Positioning System receivers, sensors, and computer systems may not work well. Equipment breakdowns may occur during important farming tasks which may cause big delays, lower production, and money loss. Calibration needs for the precision agriculture equipment are complicated, time-sensitive and require regular adjustments to maintain accuracy and performance. It is important to calibrate the soil sensors with respect to the specific soil conditions in the area. Variable rate application equipment also needs to be calibrated often to make sure that the right amount of input is delivered. If you don't calibrate your equipment correctly, you can use too much or too little of the inputs, which defeats the purpose of precision agriculture systems. When precision agriculture systems connect equipment from different manufacturers that use different data formats, communication protocols, and software platforms, they can have problems with the software compatibility.

Data Privacy and Security Concerns

Precision agricultural systems can store and manage a lot of sensitive information about the farms, like where fields are, how much crops yield is there, how inputs will be applied, how much money is made, and how farms will run. Farmers might not want to disclose this information to the tech companies, equipment makers, or service companies because it is incredibly useful to businesses and gives them an edge over their competition. Data ownership rights and the usage agreements are not often clear, and they often support the tech companies over the farmers. The risks to cybersecurity are growing as precision agriculture tools become more connected and depend more on cloud computing and online services. Cyberattacks on farming systems could stop the farms from working, steal private information, or reduce the performance of the equipment. Farms were easy targets for cyber-attacks in the past because the agricultural sector did not know anything about cybersecurity or had the tools to protect itself. When farmers want to transfer technology providers or connect systems from the different manufacturers, they have trouble moving and sharing the data. Because of proprietary data formats and closed systems, farmers may be stuck with certain technology platforms. This makes it tougher for them to be flexible and work out deals with service suppliers. Over time, this may boost costs and make it tougher for the farmers to choose their own technology.

Environmental and Social Concerns

Precision or modern agriculture has many benefits for the environment, however there are certain negative effects and worries have been found. Using more technology and electronic devices generates more electronic waste and demands the energy-hungry production processes. The environmental impact of making and getting rid of precision agriculture technology may eliminate some of the profits that come from better farming techniques. One effect of precision agricultural systems on rural jobs is that they could replace workers because they automate traditional farming chores and lower the number of workers needed. Precision agriculture may provide new technical occupations, but these professions frequently need different skills and levels of education than regular agricultural work. This could mean that some rural laborers are out of work or not working enough. Farmers may have less freedom and be more vulnerable to problems with their supply chains, service interruptions, or changes in business connections if they rely on technology businesses and outside service providers. Farmers could rely on proprietary technologies and services owned by big companies instead of being independent and self-sufficient in their work.

APPLICATIONS OF PRECISION AGRICULTURE TECHNOLOGIES

Crop Production and Management Systems

1. Precision agriculture technologies

Precision agricultural technologies are most useful in systems for producing the crops, because they make every part of the growing process better, from preparing the soil to harvesting the crop. Variable rate seeding applications use Global positioning systems-guided planters with the advanced control systems to change the placement, depth, and number of seeds according to the soil, the shape of the land, and with the past production data. These systems may change the seeding rates by 20% to 50% from field to field, which helps plants grow in the best way possible for the highest yield while lowering seed costs in regions that aren't as productive.

2. Precision nutrient management systems

Precision nutrient management is one of the most advanced and commonly used techniques of precision agricultural technology. Soil sampling grids using Global positioning systems coordinates make detailed nutrient maps that help with the variable rate fertilizer applications. Advanced systems use soil test findings, crop removal data, yield targets, and environmental factors to figure out the best fertilizer rates for each management zone in a field. This method has been used successfully in big crop production systems like corn, soybeans, wheat, cotton, and specialty crops.

3. Precision pest management applications

Precision pest management solutions integrate the real-time monitoring systems, predictive models, and targeted application technologies to make the best use of pesticides while still keeping the pests under control.

4. Scouting applications

Scouting apps on the mobile devices enable field workers to record pest sightings with Global positioning systems coordinates, making the spatial databases of pest pressure that help them to decide how to handle the problem. Drone-based imaging systems can find the pest infestations, disease outbreaks, and weed populations with the high spatial resolution. This makes it possible to find-treat areas, which reduces the pesticide consumption by 30-60% compared to the broadcast applications.

5. Precision irrigation systems

Precision irrigation systems use soil moisture sensors, meteorological data, crop growth models, and variable rate irrigation equipment to make sure that water is applied evenly across the fields with different types of soil, slopes, and crop conditions. With the variable rate technology, center pivot irrigation systems can change the water consumption by fields in real time based on how wet the soil is and how much water the crops need. These systems consume 85–95% less water while providing the best conditions for the crops to grow.

Livestock Management and Monitoring

1. Precision agriculture technologies-livestock management

More and more, precision agricultural technologies are being used on farms with animals. These technologies help with monitoring the health of the animals, making sure they get the right amount of food, managing their reproduction, and running the farm more efficiently overall. Electronic ear tags can be used to identify individual animals and then keep track of their whereabouts, activity patterns, food habits, and their health condition at all times. These systems can pick up on early indicators of the disease, estrus cycles, and behavioral changes that show when the treatment is needed.

2. Precision feeding systems

Precision feeding systems use automated feed delivery equipment, software for modeling nutrition, and monitoring of each animal to find the best feed ratios for each animal or group based on their stage of the production, body condition, and their performance goals. These systems can reduce feed expenditures by 10% to 20% while making animals work better and decreasing the negative effects on the environment from the nutrient excretion.

3. Dairy precision agriculture applications

Automated milking systems, individual cow monitoring, and milk quality analysis are all examples of dairy precision agriculture technologies that improve animal welfare and also increase milk production. Robotic milking systems using sensors can keep track of each cow's milk yield, composition, and quality. They can also find health problems and change the milking schedule to fit each cow's demands.

Soil Conservation and Management

1. Soil conservation

Precision agriculture technologies are very important for protecting the soil and using it in a way that is good for the environment. Precision tillage systems use Global positioning system guidance, soil sensors, and variable depth control to make the tillage operations work best for the soil conditions, residue levels, and compaction patterns. These methods can make the tillage less intense in places with good soil structure and more intense in regions with the compacted soil. This makes the soil better for growing the crops and lowers the soil erosion.

2. Precision conservation practices

Precision conservation approaches use comprehensive topographic maps, soil erosion models, and Global positioning system-guided tools to put in places where it requires specific conservation measures including contour farming, strip cropping, and buffer strips. These precision systems enable farmers to put conservation strategies in the best places and design them in the best way to provide the most erosion control benefits while having the least effect on the crop production and farm operations.

3. Crop management applications

Applications for managing crops by use of variable rate planting, species selection, and termination timing according to the soil conditions, crop rotation plans, and conservation goals. Precision agriculture technology helps the farmers to set up and manage cover crops in the best way for the soil health while causing the least amount of trouble for cash crop output.

Specialty Crop Production

1. Precision agriculture applications-specialty crop production

Precision agriculture applications in specialty crop production meet the needs of high-value products such fruits, vegetables, nuts, and ornamental plants. Precision orchard management systems use Global Positioning Systems mapping, canopy sensors, and variable rate application equipment to make pruning, thinning, fertilizing, and pest control in tree and vine crops as effective as possible.

2. Greenhouse and controlled environmental agriculture applications

Greenhouse and controlled environment agriculture uses environmental sensors, automated control systems, and data analytics to make the best growing conditions for the best crop quality and output. These systems keep a close eye on and adjust the temperature, humidity, light levels, Carbon dioxide levels, and nutrient solutions. This makes it possible to grow high-quality crops all year long.

3. Precision vegetable production systems

Global positioning system-guided transplanters, variable rate fertilization, and automated harvesting equipment are all used in precision vegetable production systems to make sure that production is as efficient as possible and that the crops are of the highest quality. These systems are very useful for processing vegetables since they need to be regular and on time for harvest and processing to work.

Research and Development Applications

1. Precision agriculture technologies as tools

Precision agriculture technologies are useful research tools for the scientists and researchers that investigate the crop productivity, the effects of farming on the environment, and how to make the farming systems work better. Small-plot research applications use Global positioning systems-guided tools, automated data collection systems, and statistical analysis software to do very accurate field experiments with a lot of control and reproducibility.

2. On-farm research networks

Precision agriculture technologies are used by on-farm research networks to do large-scale studies on many farms and in many circumstances. This creates strong datasets that can be used to analyze how well new varieties, management approaches, and technology work in different situations. These networks give technology development and extension programs useful information.

3. Breeding program applications

Precision phenotyping technology like drones, sensors, and automated measuring systems are used in breeding program applications to look at a lot of the genetic lines for traits that affect yield, stress tolerance, and quality. These technologies speed up the process of breeding and make the genetic evaluations more accurate.

4. Environmental monitoring applications

Environmental monitoring applications utilize the precision agriculture sensors and data collection systems to examine the ecological effects of various farming practices, yielding scientific evidence for the formulation of policies and regulatory choices concerning agricultural sustainability and environmental conservation.

RESULTS AND DISCUSSION

The use of precision agriculture technologies in different types of the farms has produced a lot of performance data that shows both the benefits and the drawbacks of these methods. Data from more than 500 precision agriculture projects throughout the world show that performance outcomes vary a lot depending on the size of the farm, the types of crops grown on the farm, the extent of technology adoption, and the conditions in a particular area. Compared to traditional farming, the precision agriculture methods are 12–18% more energy efficient. This is mostly because they use less tillage, better field traffic patterns, and better equipment. Global positioning guiding systems eliminates the gaps in the field work, which lowers the fuel use by 8 to 15% and makes the operations more accurate. Variable rate technology applications make the best use of inputs, which means less energy is required to make and move the fertilizers and pesticides. Economic performance analysis shows that 75–85% of the farms that use precision agriculture get positive returns on their investments. The average payback period for the full systems is 4.2 years, and for individual technology components is 2.8 years. Larger farms (more than 1000 acres) make more money because of economies of scale of production, but smaller farms may have trouble in justifying the high expenses of technology. Specialty crop enterprises frequently make the most money because they can get the profits out of their inputs and increase their quality. Environmental impact evaluations show that the precision agriculture systems reduce nutrient losses, pesticide use, and the greenhouse gas emissions by a lot. Using 20% to 35% less pesticides keeps pests under control while also reducing pollution to the environment and harm to the crops. Precision conservation methods and less tillage work can reduce soil erosion by 30% to 60% compared to traditional farming. Patterns of technology adoption show big differences depending on things like the type of farm, the infrastructure in the area, and the state of the economy. When it comes to the basic precision agriculture technology, large commercial farms have adoption rates of 60 to 80%, while small family farms only have the adoption rates of 15 to 25. Regional and locality differences show how different technology infrastructure, technical support, and economic incentives for adoption are available.

According to performance studies, the successful implementation of precision agriculture needs thorough training, continuing technical assistance for farmers, and the integration with the current farm management systems. Farms that have their own precision agriculture specialists can get 25–40% better than farms that only use the equipment operators to manage technology.

CONCLUSION

Precision agriculture technologies are an innovative way to farm sustainably that handles many of the biggest problems that traditional agriculture is being faced. This review from the study shows that when precision agriculture is used and managed correctly, it may greatly improve the efficiency of resource utilization, minimize the environmental consequences, and increase farm profits. The technology's capacity to diminish the fertilizer usage by 15-25%, lower the pesticide application by 20-35%, and enhance water use efficiency by 10-30% while sustaining yields establishes it as an essential instrument for the sustainable intensification of the agricultural output i.e. returns on investment. But for precision agriculture to be widely used, major problems such as high capital costs, technical complexity, and limited access for the small-scale farmers need to be solved. The economic advantages of precision agriculture are particularly evident in larger enterprises capable of realizing economies of scale of production, but the smaller farms may find it challenging to rationalize the significant investments which are necessary. This disparity in the technology could make the differences in agricultural productivity and profitability even worse. Future advancements in artificial intelligence, machine learning, robots, and Internet of Things technologies are expected to improve precision agriculture even more, and they may also make it cheaper and easier to use. Bringing these new technologies together could help fix some of the problems with precision agriculture and make it easier for the smaller businesses and developing areas to use. To fully realize the potential of precision agriculture in establishing sustainable, productive, and ecologically responsible agricultural systems that can meet the food security issues of the 21st century, we will need to keep doing research, development, and policy work.

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