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Precision agriculture as a viable means of enhancing sustainable agricultural production

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Abstract:
Effective management of finite resources in precision agriculture requires efficient technologies to generate reliable data about crops, pastures, soil, water sources, climate, pests, diseases, and other variables. These data enable farmers to make informed decisions to enhance efficiency and make their production more sustainable. This review aimed to assess the technological advances in precision agriculture in terms of their benefits, constraints, and potential for sustainable farming practices.

A total of 132 scientific papers were selected, analyzed, and discussed to explore the current status and the future of precision agriculture in relation to sustainable development. This review covers technologies utilized in planting, crop monitoring, resource management, decision support systems, and automation.

The application of artificial intelligence (AI)-driven technologies, including machine learning, computer vision, and sensor technologies, transforms traditional farming and contributes to resolving its limitations by providing farmers with real-time data and actionable insights. Ethical considerations, data security, and the digital divide are among the key challenges needing attention. Interdisciplinary collaboration is also needed to tackle complex issues associated with the sustainable implementation of advanced technologies, including AI in precision agriculture.

Precision agriculture technologies have a transformative impact on traditional farming. The integration of AI contributes to higher productivity and efficiency, as well as long-term sustainability of farming practices, ensuring food security for the growing population.

Keywords: Precision agriculture, sustainability, advanced techniques, production efficiency, technology adoptability

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INTRODUCTION

Early forms of agriculture were predominantly subsistence-oriented and confined to small areas. However, as specialization gained momentum and farmers acquired more scientific knowledge, as well as mechanical ability, they enlarged their plots and improved techniques using standardized approaches. Thus, agriculture developed in the following stages: the pre-agricultural revolution [1], agricultural mechanization [2], the green revolution [3], and sustainable agriculture involving organic and precision farming [4, 5]. Each stage had its characteristics, benefits, and drawbacks (Table 1). Launched in the 1960s, the green revolution was based on a set of technical improvements aimed at eradicating hunger and malnutrition linked to exponential population growth [3]. In general, it has partially resolved the food security problems but also has had environmental implications. The agricultural intensification has increased due to the use of irrigation, fertilizers, pesticides, antibiotics, and growth promoters for animals. However, this has degraded the soil structure, polluted the ecosystems, and decreased agricultural and wild biological diversity due to its reliance on only a few high-yielding varieties of crops. These environmental shortcomings have

Table 1 Stages in the evolution of agriculture

Development phase	Characteristics	Advantages	Disadvantages	Reference
The pre-agricultural revolution (before 1900)	Domestication of animals and plants, combining human and animal labor (draught power)	Economical; Minimal impact on the environment	A prolonged period of work; Low production (subsistence farming); Increased deforestation	[1]
Agricultural mechanization (1900–1930)	Use of machines (tractors, harvesters etc.) to mechanize the processes of cultivation and breeding, as well as the primary processing and transportation of products	Easier and more efficient operations; Larger cultivation area; Human labor freed up for lighter and/or more productive work	Increased environmental pollution from waste (exhaust gases, fuel vapors, antifreeze, brake fluid, soot); Loss of local biodiversity (in nature and agriculture); Higher cost of agricultural production	[2]
The green revolution (the 1960s)	Genetic modification of plants; Mechanization of production; Intensive use of chemicals (fertilizers and pesticides); Introduction of modern technology for planting crops, irrigation and harvesting processes	Increased production per unit area; Reduced food insecurity in the world; Improved quality of life	Mass production of cereals and legumes; High yields, but not enough nutritional value; A dramatic increase in energy consumption in agriculture; Contamination of the environment by high concentrations of chemicals (pesticides, fertilizers, etc.); Loss of genetic diversity in food crops and locally raised animals; High production costs	[3]
Sustainable agriculture (the 1980s), organic farming	Prohibition of pesticide use, genetically modified organisms, growth hormones, antibiotics, food additives; Use of adaptive varieties and breeds, special crop rotations, green manures, biological plant protection systems, probiotics, renewable energy and various near-natural technologies	Low/no pollution; Preserved health of plants, humans, animals and the entire planet (sustainable agriculture); Restored natural soil fertility, improved agrobiocenoses and ecosystems	Lower yields compared to farms using fertilizers and pesticides; Higher price of organic products	[4]
Precision agriculture (from the mid-1980s to date)	Use of geographical positioning system (GPS), geographic information systems (GIS), accurate field mapping, parallel driving systems, global navigator satellite systems (GNSSs), etc.	Increased awareness of variation in soil and crop conditions; Higher profitability and sustainability of agricultural operations; Lower negative environmental impact; Improved quality of the work environment and better awareness of the social aspects of farming, ranching, and relevant professions	Fuel saving; Work too difficult to adopt optimization; High production costs; Conservation of renewable and non-renewable resources; Environmental sustainability not assured	[5]

led to a shift towards sustainable agriculture, including organic and precision farming.

Precision agriculture emerged due to agriculturalists' ongoing efforts to lower unit costs and boost output per unit of input while considering the ecological principles [6, 7]. The main prerequisites for its rapid development were global positioning systems based on satellite and aerial photography, weather forecasting, variable rate fertilizer application, and plant health indicators. Another factor was the introduction of machines (used in data analysis and artificial intelligence) to predict crop planting even more accurately. Precision farming's defining feature is its reliance on cutting-edge technologies to achieve agronomic optimization at the plant or animal level or at the intra-plot level. Its advantages are tied to the farmer's increased yields and/or enterprise profitability. Other advantages include enhanced animal welfare, better working conditions, and the potential to improve various aspects of environmental management. Precision farming thus contributes to the overall goal of sustainable agricultural production [7–10].

Unlike traditional farming methods, precision agriculture combines satellite navigation for unmanned aerial and proximal vehicles equipped with sensors and detectors which collect crop or livestock monitoring data. They are linked to computing platforms that process the pooled data and enable a decision that is adapted to an organism's need without increasing labor [5]. The data include information about stem size, leaf shape, hydrophysical and chemical properties of the soil, applied technology, and micro-climatic conditions around the plant. This information is transmitted to a computer via fixed or robot-mounted sensors and camera-equipped drones as images and individual plant data used for monitoring biotic and abiotic stresses. This individual plant information is made available to growers in real time as feedback so that they can make decisions about the distribution of water, pesticides, or fertilizers at a calibrated rate to the required specific area or site. In the same manner, it also helps in the planting, sowing, and harvesting processes [7, 11].

Despite the benefits of precision agriculture, farmers have not yet significantly embraced this technology. This could be due to lack of knowledge among farmers, inadequate financial means to start initial investments, or insufficient economic feasibility of investments due to small plot sizes [12, 13]. These aspects also affect the ratio of the technology's accessibility and availability, skilled mechanization workers, and maintenance costs.

The present review included the following stages: 1) determining the scope of the paper; 2) designating keywords that fit within the scope; 3) developing search strings based on the set keywords; 4) selecting literature databases to apply the developed search tools in; and 5) assessing the papers for their consistency with the defined scope. A total of 132 papers were selected, analyzed, and discussed exploring the current status as well as the future of precision agriculture in relation to sustainable development. Modern software was used to effectively illustrate the concepts explored in the paper. Thus, we reviewed the application and potential of precision agriculture for enhanced sustainable agricultural production.

RESULTS AND DISCUSSION

Overview of agriculture. Global agriculture is facing several major challenges caused by demographic issues, accelerated urbanization, epiphytotic diseases (fungi, bacteria, viruses, and nematodes), etc. [14–16]. One of these challenges is the supply of food for a burgeoning population while reducing its ecological carbon footprint and preserving natural resources for future generations. It was estimated that the current world population of about 8 billion could reach 10 billion by 2050 and would continue to increase by 1 billion every 12 years [17, 18]. This will increase the demand for energy and food, posing a serious threat to agriculture and the environment (Fig. 1).

According to the Population Reference Bureau and the United Nations Department of Economic and Social Affairs, the demographic growth puts pressure on the environmental resources (including their irrational use) in a quest to meet ever-increasing needs. This leads to other global problems such as environmental pollution, depletion of naturals resources, etc. [17, 18]. Another major

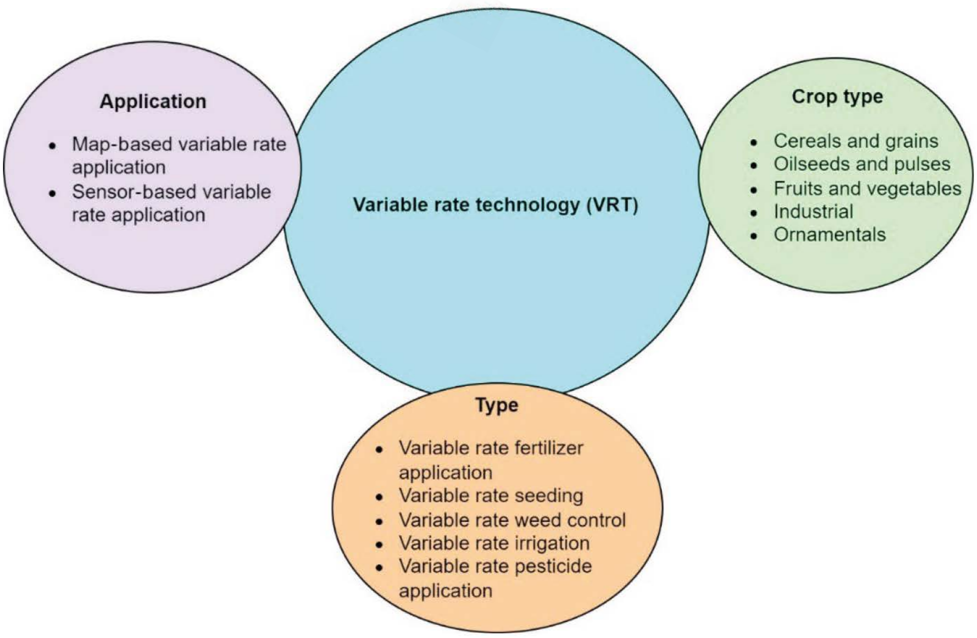

Figure 1 Segmentation analysis of the global variable rate technology market

consequence of the population growth is a shortage of food resources, which requires an increase in production through sustainable intensification (Fig. 2). Increasing the use of agricultural inputs can aggravate the problem of keeping the ecological balance. Therefore, there is a need to find ways to remediate soil cultivation and interrelationships between production systems and natural ecosystems. Unsustainable intensification in crop production can also lead to significant changes in the phytosanitary situation, which therefore requires proper adjustments and plant protection. These problems could cause changes in the populations of pathogens, pests that previously had no economic significance (including changes in their biological properties such as virulence), as well as beneficial flora and fauna [15, 16].

Another key problem is the anthropogenic activities which have led to the destruction of most natural ecosystems [19]. Furthermore, the rapid growth of human population and anthropogenic activities in the 20th century have contributed to an increase in desertification, pollution, and erosion, as well as a decrease in soil fertility. According to the United Nations Convention to Combat Desertification, about 33% of the world's soils are moderately or severely degraded due to erosion, salinity, intensified agriculture, deforestation, overgrazing, industrial pollution, uncontrolled irrigation systems, tillage practices, acidification, and nutrient depletion [20].

Beginning in the 1970s, urbanization has led to dramatic changes in the demand for agricultural products, diminishing agricultural land and causing labor shortage [21]. This phenomenon has its own characteristics in different regions and countries of the world.

Climate change has affected agricultural activities directly and indirectly in several ways. Its main impacts include the shifting of cropping calendar, increased susceptibility to biotic and abiotic stresses, and the spread of harmful microorganisms (as well as changes in their bioecological properties and interaction with plants) [22, 23]. According to Zhao *et al.* [24], each 1°C increase in the global mean temperature could reduce average global yields of wheat, rice, maize, and soybean by 6.0, 3.2, 7.4, and 3.1%, respectively.

Another limitation to agricultural production is caused by the proliferation of weeds [25], fungal diseases [26, 27], bacterial diseases [28], viral diseases, and pests, as well as the increased frequency of abiotic stresses (e.g., drought) in most farming systems [29]. According to the Food and Agriculture Organization, up to 40% of the world's food crops are destroyed by pests and diseases annually. This loss is estimated at $220 billion, causing famine for millions of people and negatively impacting agriculture, the main source of income for poor rural communities [30]. Weeds have also been reported to cause an average yield loss of 16 to 34% for spring wheat, rice, corn, potatoes, and soybeans [31]. According to Brás *et al.* [32], drought and heatwaves account for around 9 and 7.3% of cereal yield losses, respectively, as well as 3.8 and 3.1% of non-cereal yield losses, respectively.

The emergence and evolution of herbicide resistance in weeds since 1957 and fungicide resistance in many fungal and oomycete pathogens has become a serious problem since the introduction of site-specific inhibitors in the 1970s [33–35]. Several scenarios can lead to the

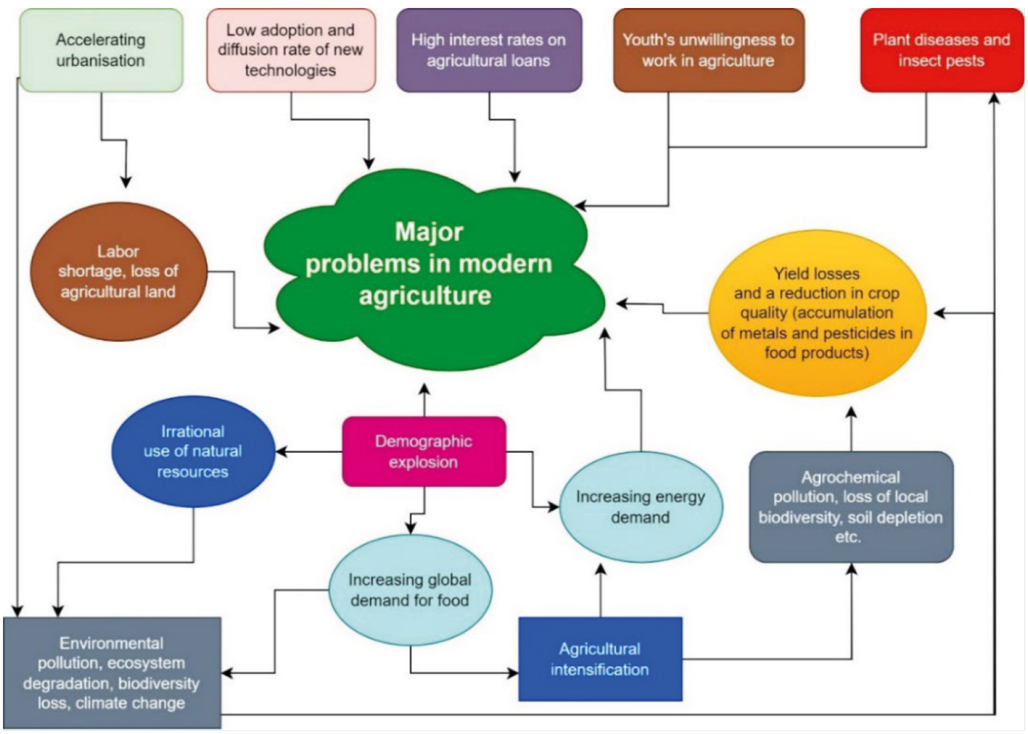

Figure 2 Major problems in modern agriculture

development of resistance: the repeated application of the same active ingredient in a field, the application of a reduced rate of pesticide, or the application of pesticides where the infestation is severe and the field cannot be recovered. According to the Health, Engineering and Agriculture Program (HEAP), about 245 species from 136 genera and 30 families of weeds are considered herbicide-resistant [37]. In the United States alone, crop losses directly due to pesticide resistance are estimated at about $1.5 billion annually [38].

Yield stability and reliable supply of high-quality seed are major challenges in agriculture. In Russia, the proportion of elite and first-generation (F1) hybrid seed represents about 5% of commercial malting barley crops, with over 90% of these varieties being 20–30-years-old [39]. Over time, the varieties lose their valued qualities and resistance to biotic and abiotic factors during long-term cultivation [40].

Improving the yield quality of agricultural products is one of the most important issues in agronomy, especially in Africa and Asia. According to Saquee *et al.* [23], micronutrient deficiencies in soils have led not only to crop loss but also to a decline in the nutritional status of most crops. Moreover, the yield and grain quality are also affected by climate change, the contamination of grains by heavy metals [41] and mycotoxins [42], as well as poor storage conditions [43, 44]. The accumulation of these toxic substances leads to yield losses, alters the product quality, and can therefore be found throughout the food value chain.

Precision agriculture can make an important contribution to solving the above problems. It can also be part of an environmentally sustainable agricultural system while maintaining profitability [8, 10].

History, concept, and advances in precision agriculture. Small landholdings were typical for agricultural production before technological advances. Farmers had a general understanding of their production system but did not measure variability. Mechanization and profit pressures led to the development large-scale, consistent, standard farming techniques. Accelerated agricultural development due to technological advancements occurred in the late 20th and early 21st centuries. As the agricultural market's profitability declines, producers seek technologies that minimize costs without reducing production [45, 46]. Thus, precision agriculture emerged in the early 1990s, taking various forms and depending on the knowledge and technology available at each stage. The first adopters of precision agriculture were the United States, Germany, United Kingdom, Netherlands, Denmark, Japan, and China, followed by Eastern Europe and Russia [9, 11, 12, 47]. In 1999, Dr. P. Robert, the "father of precision agriculture", defined it as an information- and technology-based farm management system aimed to identify, analyze, and manage differentiated spatial and temporal variations in the soil within a single field to optimize costs and increase production, as well as ecological stability, within a production system [48].

In recent years, precision agriculture has been extended to the dynamic sector of animal husbandry – precision animal husbandry, with its branches of precision dairy farming, precision pig farming, and precision poultry production. In similar terms, McBratney *et al.* [49] proposed that precision agriculture at the farm level aims to increase the number of better decisions per unit of space and time and their net benefits. The International Society of Precision Agriculture defines this method as a systematic production strategy that pools or aggregates spatial, temporal, and individual data. These data are processed and analyzed to produce information essential for making quality support management decisions, hence enhancing productivity, product quality, enterprise profitability, and sustainability of agricultural operations [50]. In addition, coordinated (precision) agriculture is a set of technical devices, software and hardware complexes, navigation, geo-information, and telecommunication technologies aimed at capturing, processing, and applying coordinated-related information to optimize agro-technological solutions for crop production [51].

Since the advent of precision agriculture, various advances have contributed to increased crop production and improved crop quality and profitability. One of such advances is artificial intelligence (AI). The application of AI in precision agriculture draws on advanced computational techniques, machine learning algorithms, computer vision, and sensor technologies to facilitate data-driven decision-making processes [52]. The paradigm shift from traditional, uniform farming techniques to a more personalized and adaptive approach marks the centrality of integrating AI in precision agriculture [53]. The advent of AI-driven technologies (including drones, satellites, and ground-based sensors) has empowered farmers with better understanding of crop health, soil conditions, and environmental factors. Using this information, they can make informed decisions on irrigation, fertilization, and pest control, thereby minimizing waste, optimizing resource allocation, and reducing the environmental footprint of agriculture [54].

Aerial photography from drones offers several tools to address these problems faster, leading to lower costs and higher sustainability [5, 55, 56]. Drones can handle a wide range of tasks in agriculture. In particular, they can monitor herds and agricultural plots, identify local areas of vegetation suppressed by various adverse factors in the field, and detect outbreaks of weeds, plant pathogens, and pests. They can also identify areas of fields subject to water erosion, detect agricultural engineering errors, specify microrelief maps of agricultural land, and provide technical support for implementing technologies. Drone sensors provide a wide range of accurate data on nitrogen, chlorophyll, biomass, moisture, and water stress. According to Dengeru *et al.* [57], mounted aerial vehicle spraying effectively reduces and mitigates farmers' health risks (exposure to toxic chemicals) during field spraying with handheld sprayers. Keshet *et al.* [58] demonstrated that drones could be used to help farmers determine the presence of Levant voles and their damage in crop fields. They can better control the rodents using precision farming methods, e.g., apply rodenticides in specific areas, thereby increasing efficiency and decreasing the number of pesticides used.

The AI autonomous technologies and robotics play multifaceted roles in precision agriculture. Smart machines equipped with AI algorithms revolutionize the farming operations spanning from planting and crop maintenance to harvesting [59]. These technologies enhance operational efficiency and address constraints associated with labor shortages, thereby contributing to a more sustainable and economically viable future for agriculture. As precision agriculture is increasingly becoming data-centric, critical issues emerge that necessitate action, such as equitable access to technology, data security, and ethical considerations [60].

The incorporation of Machine Learning (ML) with Decision Support Systems (DSSs) contributes to the overall sustainability of farming practices and enhances resource management and informed decision-making for farmers [61], thereby empowering them with data-driven insights and predictive analytics. The ML algorithms are proficient in processing huge datasets, extracting meaningful patterns, and generating predictions. For instance, these algorithms provide more precise and localized weather predictions, compared to the traditional methods, by analyzing historical weather data, satellite imagery, and real-time meteorological information [62]. Accurate and reliable weather forecasts facilitate optimizing irrigation schedules, planning for adverse weather events, and mitigating the impact of climatic variations on crop yields [52]. In addition, the ML models can identify optimal planting dates and predict crop yields, as well as potential threats (e.g., disease outbreaks) by using weather patterns, crop-specific parameters, and historical datasets. The decision support systems enhance farmers' capabilities to make data-driven decisions based on historical data, current conditions, and predictive analytics [63]. These capabilities permit a deeper understanding of how crop rotations, soil conditions, and pest prevalence affect agricultural outcomes. As a result, farmers can adjust their practices and enhance long-term sustainability. The ML-driven decision support systems significantly optimize agricultural resources [64] by analyzing soil health, nutrient levels, and water usage datasets and making recommendations for precise fertilization and irrigation strategies.

Effective resource management is another useful application of AI for sustainable and efficient agriculture. Integrating AI technologies in precision agriculture has contributed to optimum utilization of water, fertilizers, and pesticides [65, 66]. The AI-driven smart irrigation systems leverage real-time data on soil moisture, weather forecasts, and crop requirements to precisely control the timing and amount of irrigation [67]. Through the dynamic adjustment of water delivery based on actual crop needs, smart irrigation minimizes water wastage, promotes water conservation, and ensures optimal crop hydration [68]. The AI contributes to precision agriculture by optimizing the application of fertilizers. The ML models analyze soil nutrient levels, composition, and historical yield data to recommend personalized fertilization plans for different sections of a field [69]. The use of AI in resource management makes the agriculture sector more environmentally sustainable [70, 71] by reducing water and fertilizer wastage and therefore minimizing environmental pollution, soil degradation, and the eutrophication of water bodies.

Advances in AI currently involve the integration of robotics and autonomous vehicles to further enhance the efficiency of resource management. AI algorithms enable farmers to apply resources precisely according to real-time data, reducing their reliance on manual labor. Incorporating AI technology in resource management has contributed to a transformative shift towards precision agriculture [72]. These interventions increase agricultural efficiency and productivity, promoting environmentally sustainable and resilient farming practices in the face of changing climate patterns.

Autonomous vehicles leverage AI algorithms to plant seeds at optimal depths and spaces, contributing to uniform crop growth. During harvesting, advanced sensors and robotic arms of these vehicles permit timely and selective picking, reducing waste and increasing overall yield efficiency [73]. Autonomous vehicles equipped with robotic systems and AI-driven algorithms identify and target pests or weeds with precision. They can perform automated weeding by distinguishing between weeds and crops. This technology reduces environmental impact by lowering the use of herbicides and pesticides, as well as addresses labor shortages, making weed management more sustainable and cost-effective [74]. Applying autonomous machines for repetitive tasks permits human labor to be directed towards more skilled and complex aspects of farming, increasing overall operational efficiency. Although the initial investment in automation technologies is high, it offers long-term economic viability benefits such as lower labor costs, higher productivity, and better yield quality. The integration of Internet of Things (IoT) technologies permits seamless connectivity between agricultural equipment and robotic systems [75, 76]. With these technologies, farmers can remotely monitor and control robotic systems, making adjustments based on real-time data and varying conditions. This level of control ensures that farming operations can be fine-tuned for real-time data exchange, adaptive decision-making, and optimal outcomes even from a distance [77].

Connectivity plays a crucial role in precision agriculture. It involves the integration of technologies and data exchange systems to create a networked ecosystem that transforms traditional farming practices. Connectivity, with advances in communication and sensor technologies, is a key contributor to precision agriculture [78]. For instance, the deployment of smart sensor equipment and IoT technologies enables farmers to collect real-time data on soil moisture, temperature, and crop health [79, 80]. Interconnected technologies provide a continuous generation and flow of valuable information on irrigation, fertilization, and pest control. This forms a foundation for data-driven decision-making in precision agriculture. Connectivity technologies (including drones and satellites) provide a comprehensive view of the entire farm, aiding in crop monitoring, disease detection, and assessment of overall field health [81]. Connected systems leverage ML algorithms to analyze integrated data based on historical patterns and real-time inputs that enable the prediction of future trends for crop yields, weather conditions, and pest outbreaks [82]. Connectivity fosters information sharing on best practices, emerging technologies, and local insights among farmers, researchers, and agricultural experts through online platforms. Connectivity software enables farmers to plan, optimize resource, and implement sustainable farming practices by integrating data on crop rotation, resource usage, and yield history [83, 84].

The global satellite navigation system collects spatial information in the fields and allows the targeting of resources [8, 11]. It enables a number of precision agriculture technologies that can be divided into several categories based on the role they play in management decision-making and their level of complexity. In particular, they include positioning (e.g., georeferencing of field information), diagnostics and data management (e.g., soil sampling and yield monitoring), and application (e.g., variable rate technologies) technologies. Satellite geo-positioning (GPS) and geographic information systems (GIS) are the leading technologies used for many purposes, such as livestock and crop tracking, field monitoring and management, or geolocation at exact levels [26, 85, 86]. For instance, crops can be traced using satellite imagery, while drones can study soil moisture. Other geolocation tools facilitate the detailed tracking of livestock and pastures. Precision agriculture also draws on some other technologies such as sensors, big data, artificial intelligence (AI), visualization, the Internet of Things (IoT), and networks [87], as demonstrated in Fig. 3.

According to Loudjani *et al.* [8], the global market for precision farming technology has averaged €2.3 billion and is expected to grow by an average of 12% each year. Precision agriculture technologies can be divided into ground, aerial, and satellite. The ground technology suits production planning, mapping, scouting, and machine

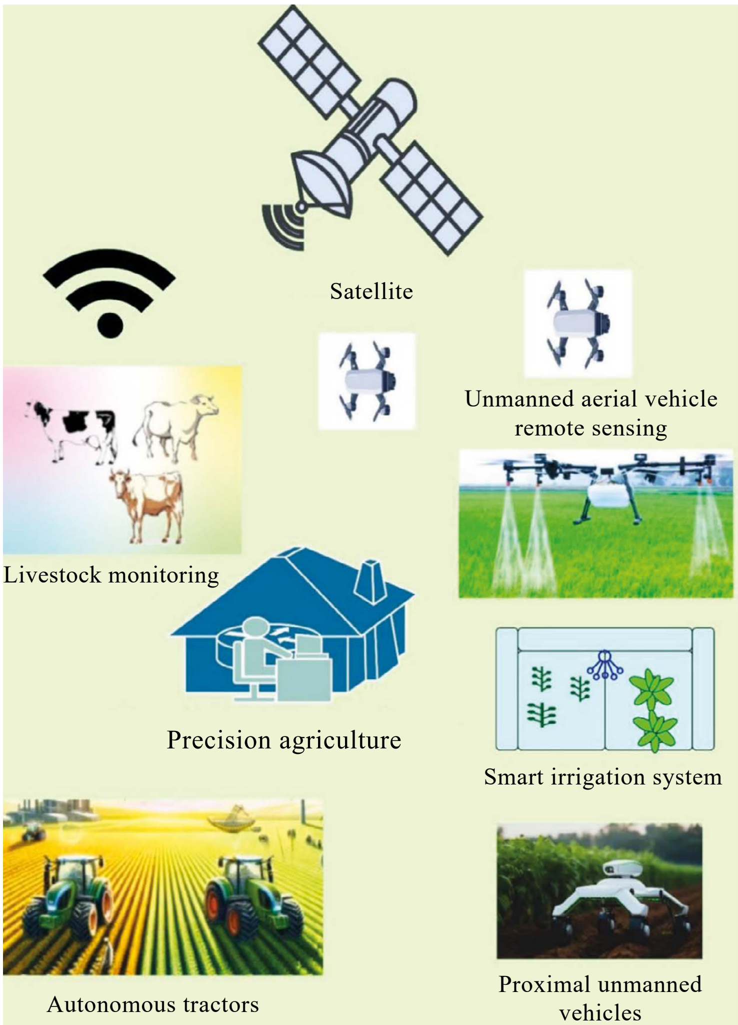

Figure 3 Precision agriculture concept

control. Aerial and satellite technologies are useful in resolving global problems, such as real-time yield state analysis from anywhere.

Remote sensing is a technique that allows growers to monitor yield health using satellite imagery. It provides up-to-date information on moisture stress, disease, structural anomalies, and nutrient levels. Modern precision agricultural satellite imaging has high spectral resolution, allowing growers to collect the most accurate data. Remote sensing enables visual observations to be recorded via digital media and georeferenced in a GIS database. Precision agriculture uses aerial photography and videography, with digital capture being the most common remote sensing method. According to Bill *et al.* [88], remote sensing has enormous potential for crop production at the farm level. Satellite remote sensing generates the General Yield Unified Reference Index (GYURI) by analyzing data from the Advanced Very-High-Resolution Radiometer (AVHRR), the Sentinel-2A/B satellite, and the Landsat 8 multispectral satellite. It has proven to be a valuable tool to estimate yield at the field level for spring barley, winter wheat, corn, and oilseeds [89, 90]. Therefore, remote sensing information can resolve many soil and crop management issues. In addition, this tool is more cost-effective than GPS or UAVs because it lacks extra fuel and labor costs.

There are different forms of ***variable rate technology (VRT)***. The map-based VRT corrects the amount of applied fertilizers, pesticides, herbicides, and other products depending on the previously developed area map. The sensor-based VRT studies the soil in real-time and can assist in determining nitrogen insufficiency. The control system then determines the required quantity of inputs. VRT is a tool that enables farmers to apply the correct quantity of seeds, fertilizers, and crop protection products, leading to a positive environmental impact. In other words, VRT helps reduce losses resulting from the over- or underuse of agricultural resources by implementing precision application technologies [91]. The variable rate technology can be applied for variable rate fertilization, plant protection, seeding, and irrigation (Fig. 3).

Electronic field mapping is a land inventory tool that determines the resource potential of agricultural land. It allows farmers to accurately calculate the application rates of fuel, lubricant, fertilizer, and crop protection products on an area basis. An electronic map (raster or vector) and a related database are the best means of organizing farmland information in precision agriculture. In addition to showing field boundaries, a road network, and dwellings, electronic terrain maps include all the information about the terrain such as soil conditions, the application of fertilizers and crop protection products, crop rotation, yields, the amount of precipitation per year, etc. [91–93]. These maps have a multi-layer structure: fields, grasslands, pastures, orchards, disturbing objects (poles, trees, wells, etc.), soil agrochemical properties, measurement and sampling points, roads, etc. Each layer stores specific information in the form of objects. The lowest layer is usually a satellite image of the terrain. There are three main methods of collecting input data to produce these maps: 1) field measurement using a high-precision GNSS receiver (a more accurate method); 2) processing high-resolution satellite imagery (a less accurate but often faster and cheaper method); and 3) a combined method (an electronic map created from space imagery and edited in the field using a high-precision GPS receiver) [11].

Varying nutrient concentrations in the soil have been responsible for variation in crop yield. Proximal soil sensing allows farmers to obtain soil characteristics quickly and with less cost. This technique bridges the data gap between high-resolution point data and low-resolution remote sensing data. Intensive soil sampling is costly and time-consuming, labor-intensive and limited to point measurements [94]. Valente *et al.* [95] confirmed a need for a high soil sampling density to effectively determine the spatial variability of the soil's physical and chemical properties. Tripathi *et al.* [96] revealed that efficient, cost-effective, and easy-to-use tools are needed for specific soil management. For example, proximal soil sensors can acquire high data density rapidly and continuously, which is essential for delineating development areas. These sensors offer increased measurement density and complete coverage of the terrain. They can be divided into different categories depending on the type of sensor used, namely electrical, electromagnetic, optical, radiometric, mechanical, acoustic, pneumatic, and electrochemical [55, 56]. Proximal soil sensors are set near, or in direct contact with, the soil to measure its properties directly or indirectly. Electromagnetic induction uses the electromagnetic field induced in the soil column to calculate apparent electrical conductivity to indirectly establish the variability of different soil properties such as texture, moisture, and salinity [57].

Benefits of precision agriculture. Precision agriculture allows for an environmentally friendly way of farming by preventing overuse of fertilizers and crop protection chemicals, reducing climate and weather risks, achieving planned yields, and protecting the environment from pollution. The cutting-edge technologies in precision agriculture can optimize the usage of traditional resources. As a result, this agricultural management system contributes to the development of sustainable farming by addressing both economic and ecological problems. The main goal of precision agriculture is to increase the efficiency, productivity, and sustainability of farming operations. By having accurate information about soil moisture, nutrient levels, and pest infestations, farmers can apply fertilizers, irrigation, and pesticides in a more targeted and precise manner, thereby reducing waste and decreasing environmental impacts [51, 52]. With the precision agriculture techniques, farmers can make informed decisions based on real-time information, promoting more efficient, productive, and sustainable farming practices. The benefits of precision agriculture can be divided into three groups: agronomic, economic, and ecological benefits.

Ecological benefits of precision agriculture. Sound ecological principles need to be utilized to reduce the anthropogenic impacts and create scientific and technical support, as well as favorable conditions, for sustainable development in agriculture. Precision agriculture technologies enable farmers to mitigate the ecological footprint of agricultural activity through a more targeted use of inputs. They can also reduce losses due to overapplication, nutrient imbalances, weed escapes, insect damage, etc. [97, 98]. Precision agriculture addresses some of the key issues of the late 20th and early 21st centuries such as environmental impact, risk, and degradation. This management practice also aims to ensure global sustainability and food security [8, 10]. Depending on the type of technique used, precision agriculture reduces the loss of soil fertility, with 30–50% of residual nitrogen in soils, as well as erosion, flood risk, soil compaction, carbon and ammonia emissions, water pollution, water consumption, and the use of herbicides (Table 2). Thus, the material and technical resources are used more rationally, with a positive environmental effect [8, 10].

However, the environmental benefits of precision agriculture are difficult to quantify for objective reasons. For instance, the complex nature of its implementation and impact on the agro-ecosystems makes it difficult to determine the environmental efficiency (reduction of production costs such as fuel, fertilizers, and plant protection products). Another reason is that the environmental conditionality of this technology by landscape and climatic conditions makes it possible to generalize the results obtained in the precision agriculture experiments. For this reason, precision agriculture techniques are not widespread, and it is quite difficult to obtain specific data confirming their effectiveness on a real-world scale. Furthermore, the ecological effects of precision agriculture depend on the level of a farm's intensification, and their evaluation can also be determined by the choice of technologies or farming systems used for comparison [99].

The ecological effects of precision farming technologies are measured by comparing differentiated single-field work with traditional continuous work (with the same level of applied effort), regardless of differences in fertility. Reducing the intensity of tillage (considering depth differentiation in a single field) offers, above all, a possibility of reducing fuel consumption. The ecological effect of differentiated seeding technology based on field heterogeneity is likely to be smaller than that of differentiated tillage, and quantifying it is much more difficult [8, 98, 99]. As a result, precision farming ensures savings in seed/planting material, fertilizer, and crop protection products, reducing the need for seeding zones. Obviously, this has little environmental potential. For example, smart sensor systems have resulted in nitrogen fertilizer savings of 10–80%, while residual nitrogen fertilizer levels in the soil have been reduced by 30–50% albeit maintaining wheat yield and grain quality [100]. In olive cultivation, the use of potassium, phosphate, and lime fertilizers was reduced by 31, 59, and 86%, respectively. This reduction in input use significantly lowered the environmental impact [101]. Precision technologies based on the spectrometric methods of soil and plant characterization can be used to optimize the seeding and fertilizer application rates without compromising crop yield and quality. The variable rate fertilizer application in individual soil fertility zones showed a higher tillering coefficient (up to 6.74%), higher grain yield (up to 14.55%), more ears per square meter (up to 27,6%), more protein (up to 6.2%), more grain (up to 12.56%), and a lower 1000 grain weight (up to 8.61%) compared to conventional flat-rate fertilization [102]. In addition, the site-specific seeding and variable rate fertilizer application saved approximately 14 kg N ha^{-1} compared to the conventional site-specific seeding and uniform rate fertilizer application [102].

Differentiated fertilizer application has a higher positive ecological effect. This precision method reduces the consumption of non-renewable energy and the deposition of heavy metals (uranium, cadmium) contained in fertilizers into the soil [99]. Quantifying these effects is difficult though. Furthermore, in some cases, the application of precision farming technologies is associated with an increase in fertilizer rates to enhance the economic efficiency of adaptive landscape farming. In Italy, the application of precision agriculture has led to a decrease in labor costs (–20%) and pesticides (–53%) while increasing the amount of nitrogen (+11%) and seeds distributed across the field (+5%) [48]. This indi-

Table 2 Expected environmental benefits of precision agriculture processes and techniques

Task	Technique	Environmental benefits
Fertilizer application	Soil nutrient mapping; Crop vegetation index; Micro-dams	Reducing environmental pollution; Increasing soil fertility; Reducing erosion
Irrigation	Soil texture mapping; Soil moisture sensors	Reducing erosion; Lower water consumption by meeting crop water requirements needs more precisely
Pesticide application	Disease detection using multi-sensor optics and volatile sensors	Improving soil condition and reducing erosion through reduced tillage; Lower risk of biodiversity loss; Reducing environmental pollution due to lower greenhouse gas emissions; Lower resistance
Yield quantification	Crop vegetation index	Higher yields due to precision spacing (pass to pass, headland rows) and speed; Reducing amount of residual pesticides in agricultural produce

cates that, in the face of a significant increase in total costs due to the capital invested in the technology, the farm aims to intensify production rather than reduce agricultural inputs [103].

Effective management of crop population ensures an optimized level of yield potential. As such, precision agriculture technology opens up additional opportunities to manage pest populations' resistance to plant protection agents. In practice, it is possible to implement the envisaged weed control strategies. Van Evert *et al.* [101], who studied precision agriculture technologies in potato production, reported a 23% reduction in pesticide use and a 15% reduction in nitrogen fertilizer use. Site-specific spraying can reduce herbicide usage by up to 70% while maintaining 100% weed control [104, 105]. In another study, the real-time sensor-based precision spraying system reduced the volume of pesticides (including herbicides, insecticides, and fungicides) applied to soybean and corn crops. Adopting this technology reduced costs 2.3 times compared to applying pesticides to the entire area with a conventional sprayer [51]. Thus, precision agriculture is a primary tool for protecting valuable agricultural landscapes and ensuring environmental stability in a single field and neighboring biomes. This provides additional opportunities to protect rare species of wild flora and fauna. The practical realization of its ecological potential depends largely on the choice of agro-technological policy and state legislative acts [99].

Economic and agronomic benefits of precision agriculture. The application of precision farming technologies requires additional costs to cover data collection and control (maps, global positioning systems, sensors, equipment, and software), as well as precise execution of agricultural practices and navigation (GPS-controlled machines and equipment). When introducing a system of precision farming, it is necessary to consider the expected costs of many factors and circumstances that ultimately provide the effect. Generalized data from global experience with individual precision agriculture technologies are given in Table 3 [99, 106].

Some cost-oriented measures are implemented once every 5–10 years, others annually. The attractiveness of precision agriculture technologies, as well as other innovations, is determined by the economic efficiency of an agricultural enterprise. When analyzing the economic efficiency of applying precision technologies, the expense of purchasing equipment and other production costs is compared to the level of expense reduction or yield gain over conventional technologies [99].

The use of economic analysis in precision agriculture is limited by the difficulty of identifying and quantifying positive and negative effects. The positive effects include: (a) a reduced workload and simplified processes for machine operators due to automation; (b) improved efficiency of product marketing due to transparent and accessible control of the entire process; (c) better general management of agricultural technologies based on information; and (d) improved conditions for managing individual processes and the entire farm [99, 107]. For example, German farmers, who implemented elements of precision agriculture, achieved a 30% increase in yield and a cost reduction of 30% for mineral fertilizers and 50% for inhibitors [108]. Precision farming can help farmers make the most of their resources without increasing their workload, thus improving efficiency. One method is to use a mapping tool that allows farmers to monitor field conditions and determine the optimal planting schedule [99, 107, 109].

Table 3 Precision agriculture technologies

Precision technology	Description	Merit
Parallel driving	Automatic control system; executive board; software; staff training costs	Time and fuel savings (driver can perform other tasks); improved overall productivity and quality of work
Differential seeding	Soil maps; seeders for differential seeding, depth and density changes; DGPS/RTK systems	Increased yields through improved seed density and distribution; reduced seed costs
Differential fertilizer application	Differential fertilizer application system; integrated GIS system; aerial photos; yield mapping; soil samples; soil map; staff training costs	Increased yields; time and fertilizer savings
Differentiated spraying based on weed map	Integrated injector sprayer; soil samples (soil map); personnel training costs; weed mapping with stand-alone weed visualization systems	Herbicide and time savings; increased yields
Differential irrigation	Water management software; drip irrigation piping; sensors	Water and nutrient conservation
Soil map differentiated tillage	Soil maps; sensors to determine soil composition; tillage tools	Increased yields; energy and time savings; improved machine efficiency
Measurement of crop chlorophyll content prior to harvest	Sensors for chlorophyll mapping of plants; yield mapping	Improved product quality; optimal time to start harvesting; improved grain quality with optimal moisture content
Harvesting logistics	Unified vehicle management system; new vehicle system; yield maps; logistics optimization system; auxiliary software tools for harvest scheduling	Increased yields; optimized harvest; fuel savings; reduced crop moisture content; time savings in transportation
Information management	Field map processing software	Reduced research costs in time and manpower; improved quality of the data obtained

From an economic perspective, a review of 234 studies published between 1988 and 2005 showed that precision agriculture was profitable in 68% of the cases [110]. Gusev and Volkova [111] analyzed 41 agricultural organizations in the Sverdlovskaya region and proposed a system of indicators to evaluate the effectiveness of precision technologies. Satellite-based vehicle monitoring systems are among the most commonly applied technologies. According to the authors, their use contributed to saving 6.3% on fuel consumption, with a total economic effect of 60.8 thousand rubles and a payback period of 0.64 years. The accurate application of agricultural technologies reduced the rates of seeds, fertilizers, and plant protection products by 1.1; 3.1; and 3.6%, respectively [111]. The most widespread are precision agriculture technologies that are relatively easy to use, do not require large investments in preparation or equipment, and have a short payback period [112].

In another study, precision agriculture reduced the costs of fertilizers, seeds, fuel, and lubricants by an average of 30% [99, 112]. The use of real-time kinematic navigation by Kelc *et al.* [113] saved 15.7% of time and 8.66% of fuel on a 3-meter-wide tillage machine, as well as 12.6% of time and 8.28% of fuel on a 6-meter-wide tillage machine.

In addition to reducing costs and increasing yields, precision farming enhances the physical and agrochemical properties of the soil and makes the shape of the field more suitable for performing agricultural operations. AquaCrop's automated multi-patterning can also contribute to farm-wide water savings due to reduced infiltration and drainage. This increases the final yield in the variable field due to a higher water content in the root zone [114].

Precision agriculture also has some benefits for social and working conditions. For example, automated systems are available for different models of tractors, which makes the work less tiring [113]. Similarly, the precision dairy farming technology improves automatic applications for individual cow management, thus reducing labor costs such as twice-daily milking. There is also an argument for improving animal welfare [8].

When introducing new precision machinery or technology, farm managers and workers need to improve their skills and master new specialized knowledge [115]. Training costs can vary considerably depending on the digital competence of a farmer. It was assumed that an "expert" only needed half the average learning time. According to Munz and Schuele [107], the farmers who were not at all familiar with digital technologies needed three times as much time for initial training. Overall, the proportion of learning costs in implementing the technology was very small (0.9–1.5%) and therefore was not considered an economically decisive determinant of success for a digital technology-driven operation.

Most modern approaches to the economic analysis of precision farming technology are limited to the evaluation of applied machinery and proper technologies in a single crop. At the same time, the overall agro-economic effect of integrating precision technologies at the farm level, considering synergistic effects, will be higher than the use of individual technology complexes [99].

The farm's size has a much greater effect on the economic success of technology application than changes in the product or input prices that cannot be controlled. Price-related ranges of variation become smaller as the farm size increases. This means that larger farms have greater resilience to market changes due to economies of scale in terms of added costs [107]. Small farms, however, can generally afford precision farming technologies only if they subcontract service companies, rather than buy the necessary equipment themselves. Applying a model-based sensitivity analysis to three farms of different sizes (11, 57, and 303 ha), Munz and Schuele [107] proved that larger farms had greater resilience to external factors due to economies of scale. Balogh *et al.* [115], who conducted 604 interviews and 30 semi-structured interviews in Hungary, also found that small farm size is a barrier to the faster spread of precision agriculture [115]. Therefore, the farms interested in adopting digital technologies need to (a) know their status quo well (e.g., the cost structure of the farm), (b) collect relevant data in sufficient detail during and after adoption (changes resulting from the implementation), and then (c) make changes based on the collected data. Since these approaches are often costly in practice, small farms (< 30 ha) are recommended to use service providers, while medium farms (30–70 ha) can join machine pools (resource pooling). Beyond that, government subsidies can help with the acquisition of these technologies [107]. In addition, the economic efficiency of precision farming technologies can be influenced by the range of machines selected, the comprehensiveness of their technological use, the level of their integration into the farm, and the rational use of the technology complex as part of business management [99]. Furthermore, economic efficiency can be affected by other factors such as the management system used in the farm or the prices of the initial set of information, production facilities, and manufactured agricultural products.

Unlike other innovation processes such as genetic engineering, public and consumer attitudes towards precision agriculture are generally positive or neutral [111, 115]. The knowledge-intensive nature of agricultural production and the attractiveness of agricultural professions are increasing, especially among the younger generation of farmers and specialists. However, the adoption of precision technologies into agricultural practice is relatively slow.

Factors affecting precision agriculture. ***High initial investment costs.*** The implementation of precision agriculture in crop production depends on the sociodemographic, financial, and contingent factors [116]. According to Mizik [117], the top five constraints to adopting small-scale precision technologies are a small land size, a high cost of adoption, technology challenges, a lack of professional support, and a lack of supportive policy. Le Hoang Nguyen *et al.* [118] examined

59 high-level journal articles to determine the factors that facilitate or hinder the adoption rate of precision agriculture technology. Of the reviewed studies, 63% reported driving factors at the farm level and 37%, at the individual level. The individual factors included the relative benefits of the technology, its observability and testing capability; the farmer's education, knowledge, and experience in using the technology; as well as the farmer's age, risk tolerance, and the complexity of the technology.

A smart irrigation control system costs about 54,540.8 USD without transportation and labor costs, which could limit its direct use by the farmers [109]. In another study, more than half (62.75%) of the respondents identified excessive cost as the main barrier to the adoption of precision farming technology in Italy [119]. Similarly, Pandeya *et al.* [120], who surveyed the farmers in Kentucky, reported high cost (20% of the respondents) as the main barrier, followed by complexity (15%) and lack of profitability (12%). Due to capital-intensive initial investment associated with precision farming technology, their adoption is mainly limited to large farms, while the expected benefits per hectare are not high enough to make a justifiable investment for small farms [121]. Moreover, there is a lack of information on precision farming technology. The information is mainly provided by equipment manufacturers, who are more interested in selling the equipment rather than in its economic efficiency. Jacobs *et al.* [122] conducted a survey in the Schweizer-Reneke region of South Africa and found that the adoption of precision agriculture was limited not only by high costs and a small size of cultivated area, but also by homogeneous fields.

Lack of skills and information asymmetry. The accuracy of methods using remotely sensed data (satellite, airborne, and drone) depends on many factors, including image resolution (spatial, spectral, and temporal), weather conditions, cultural and terrain conditions (e.g., growth stage, land cover), and analysis method (e.g., regression-based, machine learning, physical modeling). Given the complexity of image processing methods and the amount of technical expertise required for their application, a simple and robust workflow should be explored and developed for image pre-processing analysis and real-time applications. Major challenges and gaps remain in the development of tools and frameworks that can facilitate the use of satellite data by end users for real-time applications [123]. Another major barrier to adoption is the compatibility of precision farming equipment with conventional machinery, as well as between different components of precision farming technologies [124].

In addition, the following limitations to adoption are highlighted: (a) the farmers' inability to analyze and use the vast amount of data provided by precision agriculture technology; (b) the lack of scientific procedures to determine variable rate inputs; (c) the lack of evidence of the benefits of precision agriculture; (d) costly and time-consuming collection of data; and (e) the need to improve technology transfer [13].

Another barrier to adoption that requires significant investment is the lack of knowledge and skills to use the complex precision farming technologies and analyze the data [116, 124, 125]. Kendall *et al.* [126], who studied 27 Chinese farmers in Hebei and Shandong provinces, showed that although the farmers were open to engagement, they had limited knowledge about the use of precision technologies. Many of them highlighted the need for more professional information-sharing platforms and a greater role for extension agents. The farmers had doubts about the reliability and performance of technologies, including drones, due to battery issues and chemical efficacy.

In another study based on pilot interviews, 10 participants from the Beijing area found it difficult to discuss precision agriculture technologies due to their limited experience [127]. On a personal level, a farmer's decision to adopt precision farming technology also depends on their values and motivation. Not only subjective factors such as risk aversion affect their decision, but also such aspects as the farm's size and production conditions [47].

Poor collaboration among relevant stakeholders. No technological development can provide a total solution to the user until it has been commercialized as a service for extensive use. The interest in, and introduction of, precision agriculture has resulted in a mismatch between technological capabilities and scientific understanding of the relationship between input and output. The development of precision agriculture has been largely market-driven, but its future growth requires collaboration between the private and public sectors. The private sector must take responsibility for business development, product credibility, and consumer satisfaction. The public sector needs to coordinate the development and implementation of precision agriculture by providing support programs to meet the objectives [128]. Synergies between government, academia, and business are essential to facilitate the transfer and adoption of this technology by end users. The potential of this technology has already been demonstrated, but in practice, meaningful distribution is difficult as it requires large-scale commercialization to realize its benefits.

The utilization of AI technologies in precision agriculture is fraught with challenges. The creation of a unified and reliable dataset for AI algorithms is constrained by the quality and integration of diverse data sources such as satellite imagery, historical and sensor data. The biases that may inadvertently be introduced during model training lead to unfair outcomes with a complex interpretability challenge. The challenge of data privacy and security remains critical, especially as the amount of sensitive agricultural data increases. Another challenge is to provide farmers with equitable access to AI technologies, particularly smallholder farmers who may lack the resources or digital literacy required for effective adoption. Poor network connectivity or access to advanced hardware may also hinder the widespread adoption of AI-driven precision agriculture, particularly in the regions with limited technological infrastructure [52].

The vast amount of data generated through AI-driven technologies raises concerns about data privacy. Stakeholders including farmers must securely manage sensitive data and ensure proper control over data usage. Another ethical constraint is the ownership and sharing of agricultural data. Farmers, researchers, and technology service providers should establish clear guidelines on data ownership rights and mechanisms for fair data sharing without compromising individual interests. Advanced monitoring technologies, including drones and satellite imagery, are useful for farm surveillance and crop health, but the farmers' privacy needs to be protected against unwarranted intrusions. Ethical considerations regarding the impact of monitoring on individuals and local communities should be sensitive to cultural norms, community consent, and potential consequences of data collection. The adoption of AI technologies by farmers should ensure equitable access to these technologies to address the existing disparities. Insufficient digital literacy among farmers may pose ethical challenges. Through training and support, they can effectively navigate, and make informed decisions in, the AI-driven agricultural landscape [52].

Despite these constraints, various mitigating strategies have been noted. The explainable AI (XAI) techniques can resolve the constraint of algorithmic interpretability and provide the farmers with a better understanding of the recommendations provided by AI systems. The development of holistic and sustainable solutions to the multifaceted constraints of AI in precision agriculture necessitates the integration of expertise from diverse fields such as agriculture, computer science, ethics, and policy-making. The block chain technology can enhance data security and privacy by providing a decentralized and tamper-resistant system for managing agricultural data. Edge computing technologies contribute to resolving the infrastructure limitations by reducing the reliance on centralized computing resources and activating data processing closer to the source. Collaborative platforms for research and knowledge sharing help overcome the constraint of data quality and provide a collective understanding of best practices in AI-driven precision agriculture. Comprehensive policies and regulatory frameworks can serve as useful guides for the ethical and responsible implementation of AI in agriculture in terms of data privacy, security, and fairness. The digital divide among farmers can be overcome by fostering inclusive technology adoption programs that prioritize digital literacy and provide support for smallholder farmers [52].

Potential of precision agriculture for sustainable agricultural production. The potential of precision agriculture in sustainable development is quite broad. Since this form of advanced agriculture thrives on information technology, it enhances efficiency in the fields reducing the negative impacts associated with farming [92, 106]. For instance, accurate information on temporal and spatial weather conditions, crops type, and pest population enables the farmers to determine when to spray the pesticide and how much to apply, which increases efficiency and reduces the amount of pesticide released into the environment [42]. This then has a ripple effect and reduces the impact of pesticides on non-target species like bees (*Apis mellifera* L.), which play an important role in pollination [128]. Furthermore, variable rate fertilizer application allows for the provision of nutrients tailored to the different soil strata across the field. Unlike methods such as blanket fertilizer application or using the rough rule of thumb, this technology ensures that the nutrient-rich areas of the field do not receive excessive fertilizer. This reduces the risk of eutrophication whereby excess nitrates are deposited into surrounding water resources, consequently polluting them and adversely affecting marine life [129]. The acidification of the soils is also slowed this way.

In the context of climate change, specifically frequent droughts due to the El Nino Southern Oscillation effect in the global South, variable rate irrigation has been of tremendous benefit in high-value crop enterprises such as blueberry (*Vaccinium corymbosum* L.) farms. This technology enables the farmers to meet the crop water requirements while conserving water.

Precision agriculture and sustainable development have certain economic benefits [93]. As each stage of the industrial revolution has had profound effects on enhancing agricultural production, the fourth industrial revolution (information era), on which precision agriculture is premised, not only increases the returns but also potentially lowers the costs of production. The increased efficiencies in the fields allow for the optimum allocation of resources per unit area. In essence, this gives the farmers financial leverage to expand their operations and produce more, thus enhancing profitability of the enterprises.

CONCLUSION

Advances in precision agriculture have led to judicious use of energy and resources (labor, fertilizers, plant protection products, water, etc.) that could be exploited for increased agricultural production and productivity. The integration of machine learning with decision support systems, robotics, and artificial intelligence autonomous technologies in precision agriculture has contributed to higher yields and quality, as well as lower risks to humans and the environment. The utilization of satellite imagery, drones, ground-based sensors, and machine learning algorithms has enabled the farmers to analyze real-time data for proactive and informed decision-making. The precision obtained through efficient crop monitoring allows for early detection of diseases and pests, minimizing the environmental impact of interventions and contributing to higher crop productivity. The characteristic predictive analytics of machine learning and its decision support systems have enhanced the farmers' ability to analyze historical data, weather patterns, and crop-specific parameters that provide invaluable insights for resource optimization and long-term sustainability. Resource management, a critical aspect of sustainable agriculture, has been revolutionized through AI technologies.

The reduction of environmental impact through smart irrigation systems and precise fertilization strategies reveals AI's potential in addressing the constraints of resource scarcity and environmental degradation. The integration of automation and robotics in farming operations has led to a paradigm shift, enhancing economic viability and labor efficiency. Robotic systems, autonomous vehicles, and connected machinery streamline tasks (such as planting, crop maintenance, and harvesting), serving as the cornerstone for a more technologically-induced, productive agricultural sector. The application of connectivity in precision agriculture through interconnection between devices and data integration has demonstrated the significance of a holistic approach to farming. The real-time monitoring and exchange of knowledge among stakeholders at the collaborative platforms contribute to continuous sharing of useful information and sustainable practices. However, careful attention should be paid to the ethical issues of data privacy associated with these technological advancements, as well as the digital divide and the impact of automation on employment. The equitable distribution and alignment of the benefits of AI in precision agriculture are crucial for ethical considerations.

Based on this review, we see the future of the agricultural sector in harmonizing technological progress with the principles of environmental stewardship and societal well-being. Advances in explainable AI, edge computing, and inclusive technology offer exciting prospects to overcome the constraints of precision farming and shape a more resilient and equitable agricultural sector. The application of AI in precision agriculture is a technological evolution that provides a pathway to a more sustainable and productive future. Collaborative networking among stakeholders, interdisciplinary research, and responsible innovation are critical to harness the full potential of AI for the benefit of farmers, communities, and food systems. The lack of skills and information asymmetries that challenge precision agriculture can be resolved by engaging consultants and technical services providers. These consultants can serve as skills transfer agents to help farmers adopt precision technologies. They can fill the information gap related to the socioeconomic factors such as age, level of education, and farming experience.

Roundtable discussions in 2016 with 32 scientists, administrators, and stakeholders from the public sector and industry (mainly from the United States but also from Brazil, Canada, Germany, Israel, New Zealand, South Korea, and the United Kingdom) resulted in the key steps to guide future efforts in precision agriculture. It is essential to strengthen research on sustainable agricultural practices through increased documentation, involvement of non-governmental organizations, and balanced funding (short- and long-term, basic and applied). It is also important to facilitate IP-neutral public-private partnerships, adapt research to the needs of small farms, encourage collaboration with diverse stakeholders, support emerging scientists, and promote projects aligned with sustainable agriculture goals [130]. Decision support systems should be tailored to the needs of local farmers involved in various farming enterprises. Considering the novelty of precision agriculture, these decision support systems need to be user-friendly. Another step towards precision farming is to increase the level of automation by installing on-board sensors so as to have diagnosis and variable rate application occurring simultaneously in real-time.

To overcome the challenge of landholding sizes and economies of scale, small farmers can pool their resources and acquire the equipment together as cooperatives to reduce the capital investment per farmer. Another benefit of common use is that the farmers can share their skills, knowledge, and experience with each other.

Policy implications are indispensable to precision agriculture adoption since policy drives all the other productive factors. There should be financial incentives for the early adopters of precision farming technologies. These incentives can be in the form of tax cuts, subsidies, or lower interest rates for the farmers acquiring these technologies for their farms.

CONTRIBUTION

All the authors were involved in the experimentation, data collection, management, and writing of the paper, as well as its reading and approval, prior to submission.

CONFLICT OF INTEREST

The authors declared no potential conflict of interest regarding the research, authorship, and/or publication of this article.

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