Recent innovation in precision agriculture and their impact on crop and soil health

Abstract

The maintenance of soil fertility and on-farm research or demonstrations might be enhanced by precision agricultural technologies. Using state-of-the-art technology, precision agriculture boosts agricultural output without negatively affecting the environment. Utilising cutting-edge technology and data analysis, precision agriculture aims to boost production, minimise waste, and maximise crop yields. This might be a viable approach to addressing some of the main problems facing modern agriculture, such feeding an expanding global population while lessening its impact on the environment. The application of precision agriculture starts with the collection of real-time data from various sources, such as satellite imagery, remote sensing, global positioning systems, geographic information systems, drones, soil sensors, and weather stations. Precision agriculture has become essential in addressing the challenges posed by a growing global population, climate change, and resource constraints. Recognising within-field variability and providing chances for differentiating treatment of sections within a field or industrial unit are what fuel demand for precision agriculture. Precision agriculture technology plays an important part in sustainable soil and crop management in modern agriculture by lowering crop production inputs and managing lands in an ecologically responsible way.

Keywords: precision farming; smart farming; agricultural technology, site-specific management, soil and crop management, sustainability

1. Introduction

Soil and water resources, which are increasingly important to use effectively, are major determinants in agriculture productivity and maintaining human existence [1]. The impact of climate change and the growth of metropolitan centres are placing strain on these resources. As the world's population grows and living standards rise, so does the need for food. With its finite amount of arable land and natural resources, the globe must expand food production to feed more than the projected 9 billion people by 2050 [2]. The introduction of new technology, such precision agriculture (PA), will have a big influence on our capacity to raise agricultural production globally in a sustainable way. "The science of enhancing crop yields and supporting management decisions using high technology sensor and analysis tools" is how PA is defined [3]. It is the art and science of using cutting-edge technologies to increase agricultural productivity, profitability, and efficiency while lowering environmental pollution. Examples of these technologies include remote sensing, geographic information systems (GIS), global navigation satellite systems (GNSS), farm management information systems (FMIS) and Internet of Things (IoT) [4].

Precision agriculture, often referred to as smart farming or precision farming, is a ground-breaking method that uses data-driven methods and state-of-the-art technology to revolutionise conventional agricultural techniques. This creative approach recognises that no two fields are the identical and aims to maximise production, efficiency, and sustainability while optimising all facets of agricultural operations, from planting to harvesting [5]. In the past, agriculture depended on one-size-fits-all techniques, applying water, fertiliser, and pesticides consistently to whole fields regardless of the circumstances that varied within them. But a new age of precision agriculture has been brought about by the application of cutting-edge technology seeking to adapt agricultural methods by considering the distinct qualities of various sections within a field. In order to learn more about soil health, moisture levels, insect infestations, and crop performance, real-time data must be gathered from a range of sources, including weather stations, drones, and soil sensors. Farmers are able to make well-informed decisions about specific measures such as timely pest management, targeted irrigation, and customised fertiliser use by analysing this data.

Enhancing the sustainability of agriculture requires sustainable crop and soil management [6]. Researchers and scientist contemplate employing many approaches to achieve agricultural sustainability, such as integrated soil management [7], climate-smart farming [8], sustainable intensification [9], and precision farming [10]. In order to do this, it is necessary to use the best management practices (BMPs) of the agroecosystems cumulatively. This ensures that resources are used as efficiently as possible, that soil health and quality are maintained, and that current environmental and social benefits are guaranteed without compromising future benefits [11,12]. According to many studies, PA technologies may guarantee optimal resource utilisation, lowering variable costs, raising farm revenue and productivity at the same time as lowering environmental impact [13].

2. Precision Agriculture Approaches, Applications, and Impacts

Precision agriculture entails data-driven management choices that enhance the efficiency of resource utilisation, leading to cheaper agricultural expenses and a decrease in the environmental effects of agriculture [14]. In order to engage in three essential agricultural steps—diagnosis, decision-making, and performance—precision agriculture relies heavily on data and data collecting systems, decision support tools, data-driven equipment, and input changes [15]. Information and communication technology (ICT) was introduced into agricultural machinery and devices to collect actual data prior to the introduction of smart technologies. Here, agricultural methods included the use of robotics, drones, autonomous vehicles, GPS, telematics, automated hardware and software, and remote sensing.

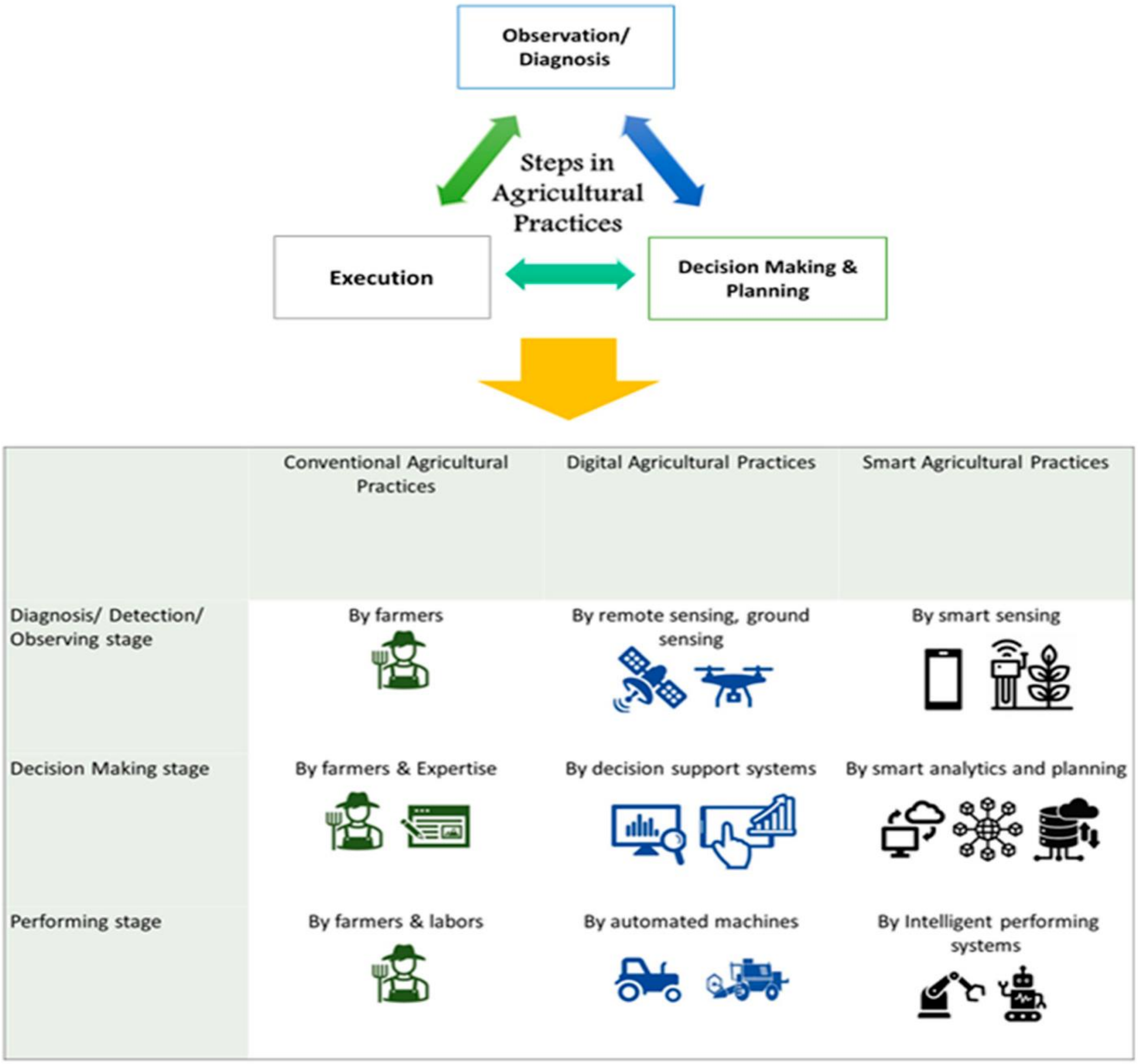
2.1 Data Collection and Acquisition

Identification and diagnosis of numerous areas of agriculture depend on data, data collecting, and decision support technologies. Precision farming involves gathering information on specific fields and crops by observation, measurement, and sensing using various sensors, yield and soil monitors, and remote sensing instruments including imagery from drones, personnel, aeroplanes, or satellites [16,17]. As a result, "sensing"—observing specific information and delivering data on climatic conditions, soil conditions, fertiliser requirements, water availability, pest and disease pressures, and other field parameters—is a crucial precision agriculture management tool [17]. Data on crops and soil conditions are gathered via remote-sensing technology, including drones, personnel, aeroplanes, satellites, and other ground-based sensors [15]. The discovery of geographical patterns of plant signatures that correlate with soil properties and pest or disease stressors is made possible by remote sensing [18]. Global navigation satellite system (GNSS)-equipped unmanned aerial vehicles (UAVs) have been used recently for mapping, data collection, land surveying, agricultural spraying, and animal monitoring [2]. Soil maps are essential decision-making tools in precision agriculture [17] because they provide important insights into the spatial distribution of the physical and chemical qualities within a specific area [21]. This importance arises from the fact that crop output is generally influenced by the physical and chemical properties of the soil, including bulk density, porosity, nutrient availability, water availability, and nutrient-holding capacity [19].

2.2 Planning, Decision Making, and Execution

Decisions are made by evaluating the information that has been acquired, and then data-driven machinery is used to carry out the decisions that have been made. In terms of illnesses as well as soil and climatic characteristics, most fields are not homogeneous [20]. However, precision agriculture has demonstrated that it is feasible to enhance environmental quality and performance in agricultural areas by applying technology to regulate the spatial and temporal variabilities [21]. Depending on the unique requirements of each section of a field, precision agriculture's variable rate technologies administer inputs including fertilisers, water, seeds, and crop protection agents (weedicides and pesticides) at different rates [22]. A field's detected heterogeneity may be used to identify and apply the right quantities of water, fertiliser, herbicides, insecticides, and lime.

This site-specific management supports the conservation of agricultural inputs and lowers costs along with environmental consequences [23], while also increasing the number of accurate judgements per unit area per unit time connected to net benefits [21]. Grid sampling, another strategy for management, likewise includes dividing fields into grids and gathering data at each grid crossing. This method gives representative data on all the variance within a field [18], and with such data, site-specific crop and soil management may be done to accurately optimise resources. As a result, despite adding automated machinery for exact performance, humans have employed digital tools to improve diagnostic and decision making [24]. With the help of these digital technologies and the rapidly evolving diagnostic and decision-making processes may now be gradually automated, requiring human intervention mainly for monitoring (Figure 1) [25]. In order to increase productivity, the main goals of this revolution are variability management and optimal agricultural practices. Nevertheless, "more production" shouldn't be the only strategy used to meet the need for food. It should also be seen as "less wastage" of the agricultural production's inputs and outputs [26] and improving the soil health for better environmental sustainability.



	Conventional Agricultural Practices	Digital Agricultural Practices	Smart Agricultural Practices
Diagnosis/ Detection/ Observing stage	By farmers	By remote sensing, ground sensing	By smart sensing
Decision Making stage	By farmers & Expertise	By decision support systems	By smart analytics and planning
Performing stage	By farmers & labors	By automated machines	By Intelligent performing systems

Fig. 1 Emerging approaches and application of advanced technologies for Precision agriculture

3. Revolutionising Farming through Precision Agriculture

Precision farming is a key component of the third modern farming revolution that the world is on the verge of. During the first farming revolution, which took place between 1900 and the 1930s, agriculture was mechanised and each farmer could now produce enough food for 26 people. Long afterward, the second revolution—also referred to as the Green revolution—took place in the 1990s. As a result of technological advancements, more recently developed genetically modified crops that are resistant to pests and require less water were introduced, enabling each farmer to feed 155 people. By 2050, there will be 9.6 billion people on the planet, meaning that twice as much food would need to be produced as is now done in order to feed everyone. The third revolution will mostly involve continually evolving IoT capabilities, such as precision agriculture technology, and advanced analytical skills.

By using precision agricultural technologies and practices, farmers can no necessarily forced to apply inputs (such seeds, fertiliser, and pesticides) evenly throughout the field; instead, they may target specific portions of the field that require them most by utilising precision agriculture technology and methods. Farmers may save money on inputs and improve crop quality and output by using this focused strategy and also improve the soil health through site specific soil testing of available nutrients. Furthermore, farmers may monitor and manage their crops more efficiently with the use of precision agricultural technologies, which enables them to react swiftly and effectively to possible issues (such pests or diseases). To properly apply fertilisers at the correct rate and place, farmers can make use of mapping tools and sensors. Moreover, farmers may optimise their irrigation techniques with the use of precision agriculture technology, saving water and energy. Farmers' approaches to their operations must fundamentally change in order to use precision agriculture. It requires a blend of data analytics skills, technology infrastructure, and in-depth knowledge of agronomy. In order to optimise agricultural yields, minimise resource waste, and lessen environmental effect, farmers need to adjust to this data-driven paradigm.

4. Application of Precision Agriculture (PA) for crop and soil health management

Efficiency, economy, and environmental concerns are currently the key drivers of modern agriculture methods, which mostly include PA. In agricultural field settings, PA provides ways to choose and implement BMPs for crop production. Sustainable soil and crop management methods will be implemented primarily by means of the technological expertise and knowledge linked with PA technologies. Soil sample, geostatistics and GIS, farming by soil, site-specific farming, management zones, GPS, yield mapping, variable nutrients rate, herbicides rate, irrigation rate, remote sensing, automated tractor navigation and robotics, proximal sensing of soils and crops, and profitability and adoption of precision farming are some of the important components of PA that are in line with the sustainability of soil and crop management [27,28].

4.1 Site-specific soil and crop management

The goal of site-specific crop management is to maximise profitability, sustainability, and environmental protection by identifying, analysing, and managing site-soil spatial and temporal variability within fields via the use of information and technology (Robert et al. [29]). Creating and maintaining SSMZs, or sub-zones, is the most common strategy to handle this kind of spatial diversity in soil properties [30]. These production level SSMZs, or sub-regions, are homogeneous, with comparable traits and yield-limiting variables, and thus have an equivalent potential for productivity [31]. In a sizable field, Khosla and Alley [32] optimised a soil sample grid approach utilising homogeneous management zones. Nutrient maps for VRT nutrient application were created by Fleming et al. [33] based on production management zones. Finding spatially coherent sections within the field can also help delineate the geographic variability of soil properties [34]. It can be easier to control variations across multiple zones when a big field's management zones are well defined [35].

According to a recent research, the best spacing for defining production management zones in medium- and small-scale farms is 50 metres for soil sample [36]. According to Wells et al. [37], in one of the three sites, precision deep tillage at a depth of 400 mm outperformed deep tillage at 400 mm in terms of crop productivity and farmer benefits. Using PA technology can initiate and accelerate these benefits. Soil compaction measurement, mapping, modelling, and potential management are also conceivable with PA advancements and the use of remote sensing techniques [38]. According to a recent research conducted in the USA, 40% of farmland, or two out of every five crop acres, have embraced grid sampling practices related to site-specific fertiliser and lime treatment [39]. However, 43% and 59%, respectively, of sites adopted GNSS-assisted yield monitors for fertiliser and lime application. Research conducted in the United Kingdom revealed that autonomous PA equipment is both technically and financially possible. If implemented, this technology might result in cost savings for a large number of farms [40].

4.2 Remote sensing

Using satellite or aircraft-based cameras and sensor platforms, remote sensing technology is utilised to gather visual data. UAVs and other aircraft, as well as sensors on-board satellites, are examples of aerial remote sensing systems that have experienced a rise in use recently. These methods combine georeferenced field data (soil and crop) with spectral features of the soil measured by sensors to estimate and quantify a wide range of soil attributes. Comparing remote sensing data and machine learning algorithms to traditional approaches, Khanal et al. [41] found that the former provides a more economical and efficient means of spatially predicting soil parameters and maize production. These kinds of constraints can be circumvented via remotely sensed imagery, which can also enhance the temporal and geographical coverage of soil and agricultural production data. Drones, both aerial and ground-based, may be utilised for various tasks such as soil and field analysis, pesticide application, crop planting, crop monitoring, irrigation, and health evaluation [42]. A new business has created an 85% cost-saving UAV-based seeding method. Data on soil water availability, fertility, compaction, temperature, and crop growth rate—including leaf area index and temperature—as well as insect and disease infestation are collected via sensors.

4.3 Geospatial applications

The wide range of instruments used to provide geographic mapping and analysis of the Earth's surface and human activity is referred to as "geospatial technologies." Internet mapping, GIS, GNSS, and remote sensing are a few examples of the various geospatial technology kinds. A layered collection of maps may be created using GIS by assembling geospatial data, also known as geo-referenced data, which includes information on a piece of information's exact position on the surface of the Earth. Mapping and analysis of this geographical data are made possible by a collection of software tools known as GIS. In order to carry out crop production field activities, automated field technology is a necessity for contemporary agriculture [43]. These devices may be programmed to follow an ideal route using GIS and GNSS in order to accurately carry out fieldwork in accordance with the positional data that is supplied to them.

Proper data collection, analysis, and interpretation are essential for the success of geospatial technology. The surfaces of the Earth and human activity are imaged and data is collected using remote sensing technologies. It assists in monitoring and addressing issues and requirements by displaying finely detailed visuals at a resolution of one metre or less. Geospatial data may be seen and shared differently because to software like Google Earth and online capabilities like Microsoft Virtual Earth. The PA technologies for separating crops into discrete management zones rely heavily on GIS and GNSS. These divisions are carried out primarily on the basis of: a) soil characteristics, including types, pH, EC, MC, and availability of nutrients; b) crop characteristics, including crop density and canopy, infestations by insects and diseases, fertility requirements, responses to hybridization, and crop stress; and c) weather forecasts.

4.4 Variable-rate technology (VRT)

Frequently misunderstood, PA is thought to be an intricate technological advancement in industrialised agriculture. In less developed parts of the world, however, it has been demonstrated to be lucrative. For instance, cereal grain yields in Africa increased after microdosing fertilisers to nutrient-starved soils [44]. Case studies showed that Chinese farmers profited from controlling in-field variability [45]. An agricultural property's soil parameters are analysed spatially using geostatistical techniques [46]. The implementation of soil science management (SSM) to sustain crop and soil production while reducing costs and environmental effect is made easier with a thorough understanding of the geographical distribution of soil attributes [47].

Sustainable soil nutrient management works effectively to prevent soil deterioration and increase crop yield [48]. This involves site-specific nutrient management with a thorough grasp of in-field soil and geographic variability. VRT application is essential in managing in-field soil variability since it is widely recognised that soil physical and chemical characteristics are spatially variable and may be influenced by agricultural techniques like irrigation and fertilisation [49]. The most mobile and dynamic nutrient is N, which is essential for optimising crop yields [50]. These changes may be recognised, measured, and mapped over the field terrain using GIS techniques. Research has demonstrated that by more effectively adapting N rates to crop demands, VRT N management may be able to increase the efficiency of N usage [51]. In comparison to traditional farming, a recent research showed that site-specific P and K management may optimise target crop output and save 21 kg ha^{-1} and 30 kg ha^{-1} of P and K, respectively [52]. Consequently, one of the primary advantages of PA is the application of the appropriate goods at the appropriate time and location, which is often achieved with the use of VRT.

4.5 Yield monitoring and mapping

Integrated yield monitors are now a common feature on most new combine harvesters, making them an effective instrument for producing grains. It enables farmers to evaluate and distinguish how weather, soil characteristics, and management affect grain yield. According to Shearer et al. [53], the yield monitors have the following three main advantages: During harvest, yield data can be quickly viewed by an operator, transferred to a computer and summarised for the entire farm or for individual fields, and used with geographic reference to create yield maps that allow high- and low-yielding areas of a field to be compared year to year. However, to guarantee the accuracy of these devices, correct installation, calibration, and use are required. Comprehensive data on soil health may be obtained by soil sampling and laboratory studies, while yield monitors aid in comprehending the geographical fluctuations in crop productivity [54]. In order to manage in-field soil and geographic variability on the farm more effectively, PA encourages the better use of information [55]. The management of arable land is centred on the yield maps [55]. When precision farming is implemented, yield mapping and soil sample are often the first steps [56]. With the help of the yield monitoring system, it is possible to gather georeferenced yield data and create yield maps that show the variability in crop performance.

4.6 Agricultural robots

Agriculture has undergone a radical transformation thanks to robotics. The use of robotics in horticulture, forestry, and agriculture is still developing [57]. The application of robotic and autonomous technology will be necessary to refine agricultural production management decisions down to the level of individual plants. An increasing number of developing technologies are contributing to the PA's increased significance, including autonomous tractors, drones, crop harvesting robots, seeding equipment, and robotic weeding. From crop preparation to harvesting, autonomous platforms can be employed and offer more advantages than traditional machinery [58]. By using targeted applications of fertilisers and pesticides, consuming less energy, and using lighter vehicles, these platforms lessen the total environmental effect of crop production while also lowering soil compaction [59]. Producers, dealers, and merchants in the Midwest of the United States are becoming increasingly confident in the possibility of robotic weeding, scouting, and administering agricultural production inputs by UAV/drone [60].

5. Precision Agriculture in the face of Climate Change

Climate change poses a serious threat to agribusinesses. In many places, farming is getting harder and harder because of lower yields and more frequent extreme weather events like droughts and floods. Based on a National Academy of Science (NAS) research, worldwide agricultural productivity is predicted to decline by 17 percent by 2050 due to climate change. According to NAS, precision farming has the potential to significantly contribute to more sustainable agricultural practices without sacrificing yield or farmer income. The World Economic Forum estimates that by 2030, precision agriculture could increase global food production by 10–15%, while if 15–25 percent of farms implemented the technology, greenhouse gas emissions and water usage would drop by 10–20% and 20–20%, respectively. Two of the most often mentioned components of precision agriculture are variable-rate application (VRA) technology and site-specific field management. Reducing the impact of agriculture on the environment requires these actions.

6. Challenges and Barriers to Adapting New Technologies in Precision Agriculture

The agriculture sector might undergo a change thanks to high-tech innovations from the fourth industrial revolution, which would allow for more sustainable and productive methods while cutting down on resource waste. Since precision agriculture is still in its infancy when it comes to the adoption of these sophisticated, intelligent technologies, there are a number of obstacles that need to be overcome in order to expedite the transformation of precision agriculture. But in the context of the current agricultural operation, it is crucial to carefully analyse the unique requirements, difficulties, and implementation issues for each technology.

One of the main obstacles is a lack of multidisciplinary skills because big data scientists, analysts, and engineers do not have backgrounds in agriculture. However, even with their extensive expertise and practical knowledge, farmers lack the education necessary to manage advanced technologies such as artificial intelligence [61]. substantial-tech applications come with substantial manufacturing and development expenses, as well as capital expenditures associated with implementing them in actual agriculture [62]. Due to their high manufacturing and implementation costs, modern technologies may be out of reach for small-scale farmers who may not have the financial means to invest in them [63].

The lack of affordable technologies for small-scale farmers may also result in a "digital divide," whereby only large-scale, educated farmers may benefit from these innovations [64]. Due to the unequal distribution of resources worldwide, some groups find it difficult to access these new technological advancements. In many developing agricultural nations, implementing precision agriculture trends has become a challenging task due to a lack of funding, a lack of confidence in the technologies, a lack of proper infrastructure, a lack of necessary resources, etc. [65]. Additionally, the lack of sufficient energy in rural areas makes the use of new technologies difficult, even as science works to develop wireless power transfer methods and ambient. Establishing sustainable intelligent technologies in agricultural operations is further complicated by poor digital literacy, uneven access to digital technology in rural regions, and connection problems [66].

As new technologies boost the need for highly trained labourers while lowering prospects for unskilled workers, they might cause job displacement and unemployment. Trending technologies require technical competence that may not be available in some places. Family commercial farmers as well as small-scale farmers are affected by this [67]. Training may be necessary for farmers and service providers to use these technologies efficiently. The use of cutting-edge technologies in precision agriculture, however, may be constrained by the incompatibility of certain technologies with one another or with currently in use agricultural gear and equipment [67]. Given the financial benefit to farmers, another concern is the security and privacy of the data and information generated by PA technology [68]. In order for the organisations in charge of this information to participate in the production of value, it is crucial to grant ownership to this data and work outputs [69]. One of the most important ideas that has to be clarified in order to guarantee PA's effective adoption and implementation.

7. Way forward

Future advances in the development and execution of PA practices will call for new technological know-how and abilities as well as a shift in perspective among farmers and end users. Closing the knowledge gap between farmers and experts people is an important component. Better education and on-the-job training in cutting-edge technology applications can enable farmers to leverage new technologies efficiently. Governments have a big say in the development of precision agriculture by building the social, legal, economic, and physical infrastructure that makes it possible. Farmers may be encouraged to use these technologies by investments in energy and communication infrastructure, internet connection, service markets, consulting services, and loan markets.

It is critical to overcome the shortage of specialised agricultural sensors in order to advance precision agriculture even more. Communication between technologies is another important issue that must be taken care of. The development of new agricultural systems and improvements in breeding technologies like deep learning and machine learning also help to the overall progression of precision agriculture. The agriculture industry has a lot of hope for future developments in precision agricultural technologies. To fully utilise these technologies, it is imperative to get over the current obstacles and uncertainties. Our future in agriculture can be more productive, efficient, and sustainable if we prioritise education, infrastructure development, sensor technologies, communication networks, and innovative farming practices.

8. Conclusion

Precision agriculture converts conventional farming methods into intensive farming using data that varies both in space and time. It is fast turning into an essential part of productive agricultural operations in agroecosystems that are always changing. PA is the umbrella term for a group of linked technologies that work together to improve soil and crop production, boost agricultural input efficacy, and execute more precise cultivation operations. The number of fields and industries using PA technologies like remote sensing, GNSS, and GIS is still rising. Farmers today routinely monitor, record, and manage the spatial variability of their farms thanks to the use of remote sensing, GNSS, and GIS. SSM decision making, which maximises input usage efficiency, yield, and profitability while lowering environmental pollution, was made possible by the capacity to see this variability. Strong linkage among researchers, extension workers along with industry partners, and farmers are vital to the continuing evolution and adoption of PA technologies for enhancing the crop and soil health without compromising the environment sustainability.

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