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REVIEW ARTICLE

Climate action: Impact of precision farming technologies on the sustainable conservation and management of its resources and nature preservation

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Abstract

In the phases of technology, precision technology is a very important parameter to check the rice crop production in an efficient way. Nowadays, satellites are also playing a very important role in the agriculture sector by providing help through global positioning system (GPS), remote sensing (RS), yield analysis devices and helping to improve the optimum use of resources. Water is a lifesaver in agriculture, as we know, without water, life is not possible anywhere. The optimum use of water is most recommended in the agricultural sector, so the water application is completely monitored by precision agriculture (PA). In the next generation, the use of fertilizers and pesticides is also contributing to a major role in agricultural production. The excess use of fertilizers is always causing a major issue in the soil environment and causing soil to be more acidic in nature, which is not suitable for the maximum crops. The application of precision technology is helping to reduce the use of chemicals more than the recommended dose. Recent research showed the reduction in water wastage by using specific irrigation systems that monitor the humidity level in the soil and plants and promote the ecological balance. The satellites provide high-definition images, enabling effective decision-making to maintain control over diseases and insect pest infestations and maximize yield, which is limited due to the world population. The farmers are not aware of all these technologies. To overcome all these challenges, training and education are the best strategies to solve these problems.

Keywords: climate action; decision support system; ecological balance; reduced fertilizer; variable rate technology

Introduction

The world agricultural scenario has experienced tremendous changes, which have been marked by increased population growth, climate fluctuation, depreciation of natural resources and increased environmental interests. The challenges have forced the adoption of sustainable agriculture systems that can meet the rising appetite for food at the same time reducing negative environmental impacts. The introduction of precision farming (PF) has emerged as a practical tool to address these hard challenges that have been known as precision agriculture (PA) or smart farming. This paper discussed the details of PF, its innovations and significant impacts in sustainable agriculture. The fact that the global population continues to grow has aggravated the problem of feeding billions of people without compromising the already scarce resources on planet Earth. The agricultural sector has a two-fold responsibility: to increase food supply and avoid developing an unsustainable environment (1). Precision farming is thus an emerging disruptive strategy that has transformed the traditional farming practice through the adoption of new and improved farming approaches that employ high technology and data-oriented approaches. Agricultural management: PA is a radical change in agricultural management. It is intended to balance the growing food demands, as well as the imminent need to protect the ecosystems, biodiversity and natural resources. Precision farming takes the view that a field is a unique and dynamic thing, the model for which is the need to develop different solutions because of the specifics of soil structure, climatic conditions and the condition of crops. The main idea of PF is gathering information, interpreting and using massive amounts of data related to crops. With the latest technology, such as global positioning system (GPS), geographic information systems (GIS), remote sensing (RS), drones and sensor networks, farmers gain an unquestionable understanding of their farming regions as illustrated in Fig. 1. Such an approach based on the information allows them to make informed decisions that can ensure and guarantee proper and efficient resource allocation (2).

Why PA?

Precision agriculture technologies (PATs) are changing the agricultural industry with a proliferation of improved productivity, efficiency and sustainability. One of the most advanced tools that these technologies employ is the use of GPS, Internet of Things

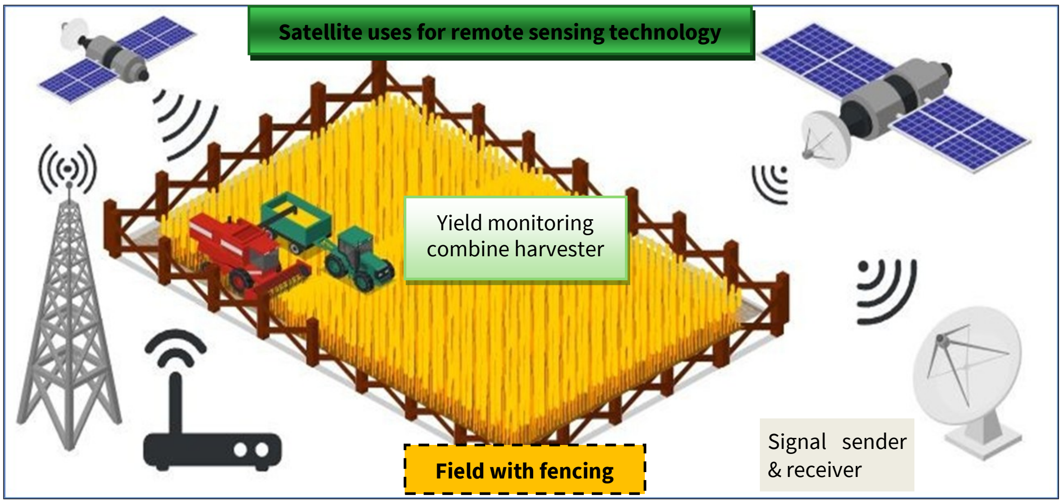


Fig. 1. Advanced technologies of PF and RS technology.

(IoT), drones and data analytics tools in order to facilitate close supervision and the optimization of crop production within any field. Precision agriculture (PA) increases the input of factors such as water, fertilizers and the use of pesticides, to reduce waste material, environmental impact and promote sustainable agricultural practices. This approach increases agricultural productivity and, at the same time, ensures environmental sustainability by conserving the available natural resources and reducing pollution. The world trend of consuming PATs is rising because they target concerns such as climate change, resource shortage and food security. In the developed countries, massive work has been carried out on research and infrastructure, which has led to widespread use of these technologies and has led to a more sustainable and stronger agricultural economy. Also, emerging economies are slowly embracing the use of PA, albeit at a pace that is not so fast due to high initial costs and the technical expertise that is needed. Precision agriculture in poorer countries has great potential in terms of commitment to transforming the agricultural scene on the continent. International organizations, as well as local governments, strive to apply new technology such as GPS, IoT and drones to agriculture, which leads to the spread of adoption. Technology allows developing agriculture 4.0, which creates a more intelligent, efficient and environmentally friendly industry, focusing on economic as well as social and ecological sustainability. Agriculture 4.0 boosts the efficiency of production, supply chain and logistics by enabling the use of modern technologies to receive and process data on an ongoing basis, analyze it and make decisions in an ethically healthy way. Agriculture 4.0 aims at extending the sustainability scope of agri-food systems by reducing food losses and wastes as well as improving food security to eliminate global poverty and malnutrition. The purpose of the study was to discuss the application of PATs to achieve agricultural product sustainability and environmental sustainability (3).

Sustainability and PF

Sustainability has been subject to a lot of discussion in terms of what constitutes it. Sustainability was originally used to mean agricultural and industrial innovations alleviated or prevented the degradation of the environment that has many times been witnessed through economic processes. A hypothesis of environmental sustainability states that natural resources in combination with manufactured capital are complementary in the production process; therefore, they must be safeguarded as they represent the parameter of limitation in the production process (4). The United Nations offered a relatively short definition of sustainability and it focuses on the fact that there is a dire need to ensure that the present generation can fulfill its needs without violating the ability of future generations to fulfill their satisfying needs. The American Society of Agronomy applies the same thing in agriculture by naming sustainable agriculture as a practice that, in the long run, meets human needs of essential food and fiber, improves environmental quality and resource base fundamental to agriculture, ensures economic returns and lifts the living standards of farmers and society. The principle of doing the right act at the right place and the best time is known as site-specific management (SSM). This notion came earlier, before the practice of agriculture, but was subjected to a lot of economic pressure in the 20th century by the modernization process of agriculture as a way of efficiently handling the large terrains successfully. Information technology can automate SSM using PA, thus promoting its relevance in commercial farming. Precision agriculture is the integration of all agricultural production practices that apply information technology in tracking or altering input applications to achieve the determined outputs. These include such devices as the yield monitors, variable rate application (VRA) and RS. It is known as SSM, the electronic monitoring and control used in the collection of data, decision support and information processing, so that the inputs used in agricultural production may be allotted to time and geography. Precision agriculture could be beneficial to producers in terms of improved management tools involved in supplying the input needed on the farm. The use of PA enables farmers to be more precise in their administration of pesticides and fertilizers, rather than administering it uniformly in large regions. The claim often heard with regard to PA has been that they can replace some of the externally applied physical compounds with information and knowledge and that by doing so, they can perhaps move the farm closer to the ideal form of a biological equilibrium. The functioning of PA depends on external knowledge, such as information technology and expertise. The objective of PA is to reduce disturbance to natural ecology processes, as opposed to uniformity, where physical inputs are used (5).

Global status of precision technology for agriculture

The rate, scope and necessary factors of sustainable agricultural development are uneven across many developing nations, regarding their status as well as limitations. The massive changes in the socioeconomic life of many of the emerging countries are opening new avenues of public administration. The urban population of the world during the 20th century doubled and most of this growth was in the low or middle-income countries and the latter includes India (6). The United States is one of the world's leaders in many spheres of modern technology. The same can be applied to PA technologies. In the world, about 90 % of the yield monitors were concentrated in the United States (7). In 2003, combines were installed with a yield monitor with approximately 45000 combines retrieving 46 % of maize, 15 % of wheat and 36 % of soybeans. The United States contained about 90 % of the yield monitors in the world. Recently, the application of automated guidance technology in different states and regions has reached 60 - 80 %. Despite variable rate sensors and monitoring of yields that dominated in the past (8), auto sectional controls and auto steering techs have also become more dominant in the last ten years. Automatic guidance systems such as those offered with the help of GNSS (Global Navigation Satellite System) have a lot of benefits that deliver to farmers such as the increased accuracy in works in the field, faster and easier work, working at night, working in a variety of weather conditions, less operator fatigue, quick installation, fewer overlaps and misses, lack of need in foam markers on the ground and reduced (or even no) input costs (9). The availability of fuel, pesticides, fertilizers, seeds, and other inputs means that auto-guiding may soon become a standard feature in modern, highly efficient farm tractors. Moreover, most of the industrialized nations, particularly the United States, are undertaking a series of tests on the autonomous driverless tractors. Other European Union countries, such as Germany, Finland, Sweden and Denmark, in addition to the United States and Canada, have also partially adopted PA technologies (10). Tractor auto guidance was used by 56.4 % of the Turkish farmers in the Adana region and these farmers cultivated more than 100 hectares of land. The countries with the highest levels of employing the PA technologies include South Africa, Argentina, Brazil and Turkey. It is worth noting that other countries might be using the PA technologies that have not appeared in the publications (11). Among the surveyed farmers in Canada/Western, 98 % affirmed that they were using GPS guidance, 84 % utilized at least one technology in PA, 84 % had access to yield monitoring, 73 % had auto section controls and 75 % were interested in applying more PA approaches in the future. Radical progress is taking place in the use of PF in countries like India, Korea, Bangladesh, Sri Lanka and China, where the average landholding is lower than that of 4 hectares. Small and inefficient land pattern characterizes the agricultural sector in India (12). About 85 % of the total farmland is divided into smaller segments of less than 10 hectares. It is known that 60 percent of the agricultural land globally occupies less than 4 hectares. Geographic information systems are currently being developed to be used in the small-scale farms of Japan, Taiwan and South Korea, with the governments in those countries encouraging the use of GIS technology through web-based applications (13). The whole world is working in PF to lead and save agriculture in the future (Fig. 2).

Principles of PF

The conventional production modes often adopt standard treatments in large areas to cover broad spaces, which translates to unproductive resource allocation and poor production. The main concern of PF is the production of a higher yield and lower ecological effects and thus is the force of the sustainable agriculture movement. Precision farming is essentially a data-intensive agricultural management approach that aims at ensuring that the farming activities are best managed depending on site-specific data. It tries to treat one field like it is a unique field with its differences in qualities of soils, terrain and healthy crops (14). The key principles of PF include:

Data collection

The process of PA is initiated by data gathering, which should involve the collection of data on the properties of the soil, the level of soil moisture, nutrient level, vitality of the crops and the weather patterns. Some of the technologies used in collecting data include soil sensors, drones, satellites, meteorological stations and sensors on the land (15).

Data analysis

The data obtained is filtered and processed with the help of the latest artificial intelligence-machine learning (AI-ML) algorithms and advanced software. The analysis reveals patterns, trends and correlations, which can enable farmers to make knowledge-based decisions (15).

Automation and precision equipment

Precise farming relies on more advanced machinery and equipment that includes GPS and various other things. These tools help promote the correct navigation, sowing, fertilizing and harvesting with reduced human mistakes and promote resource consumption (16).

Tools and technologies used in PF

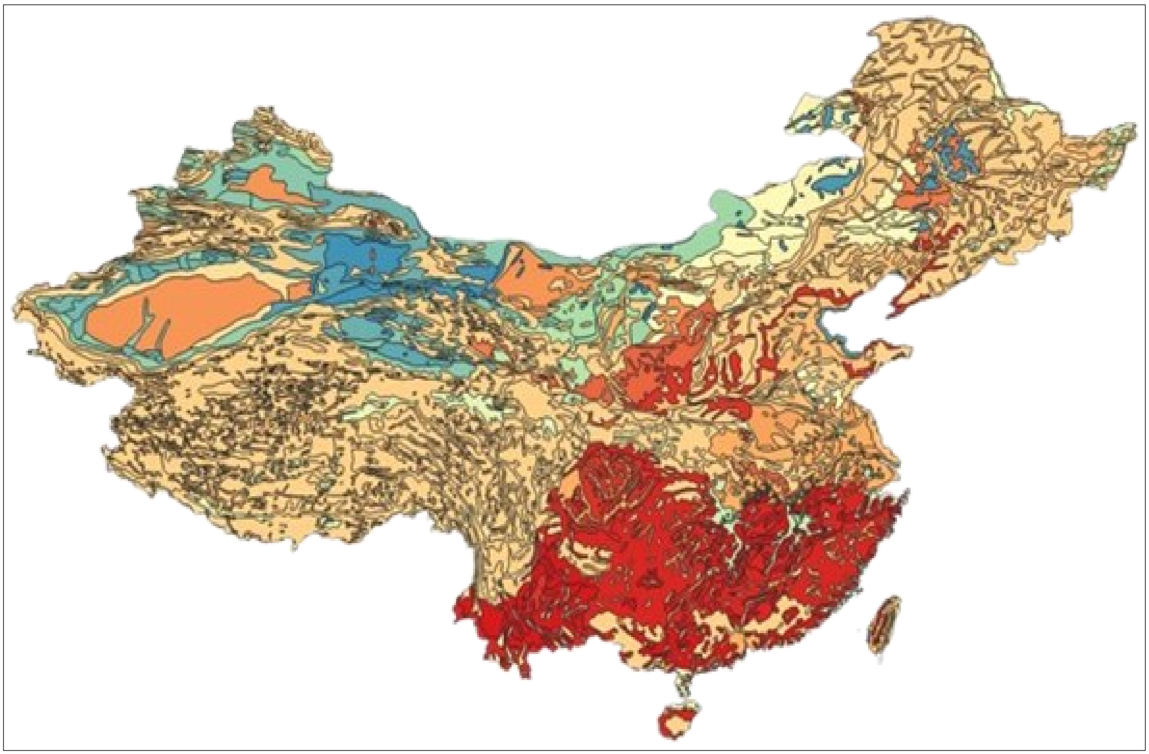
Technologies cover a wide range of hardware, software and apparatuses, which are represented in Fig. 3.

Global positioning system (GPS)

Global positioning system is a satellite navigational system which gives a precision of location (longitude, latitude and elevation) within a margin of 100 - 0.1 m. Through the phrase, GPS, agriculturalists can locate field information like the nature of soil, the existence of insects, the distribution of weeds, the presence of water, limits and obstacles. There are also an automated operating system and an antenna, together with light or sound reception equipment and a differential global positioning system (DGPS). Technology can also be used by the farmers to precisely define the fields because this will help in the application of the resources (seeds, herbicides, fertilizers, insecticides and irrigation water) based on the performance requirement and prior input applications of fields (17).

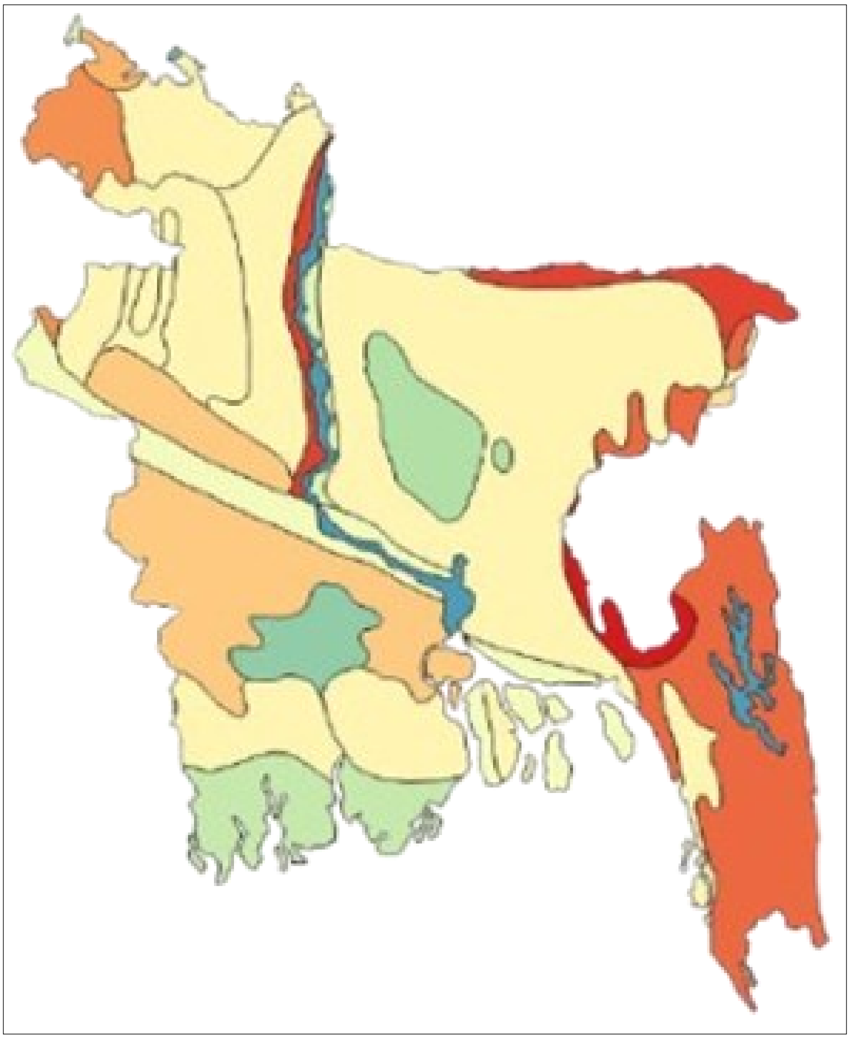
Differential global positioning system (DGPS)

A technique of increasing the accuracy of a GPS which uses the virtual range differences at a known point to improve the measurements made by multiple GPS receivers in close vicinity. Global positioning system has the capability of detecting the location of farming equipment in the field down to 1 m using a widespread global network of military satellites. It is desirable to achieve mm-level (or even sub-mm-level) levels of accuracy in location because: it allows one to check the locations of soil samples in combination with laboratory results using a soil map; to make recommendations on the use of fertilizer and pesticide use based on soil conditions (it may depend, among others, on the concentration of clay and organic matter) and characteristics



China

Precision agriculture market valued at $548 million in 2021, with an annual growth of 18.7 %.



Bangladesh

Estimated that around 70 % area comes under agriculture land by minimum use of PF.

India

Precision farming, cover around 9.2 million hectares.

Malaysia

Agriculture land accounted for 26.09 % of the total land area.

Fig. 2. Countries that are using PF techniques (Source: QGIS software version 3.32.1).

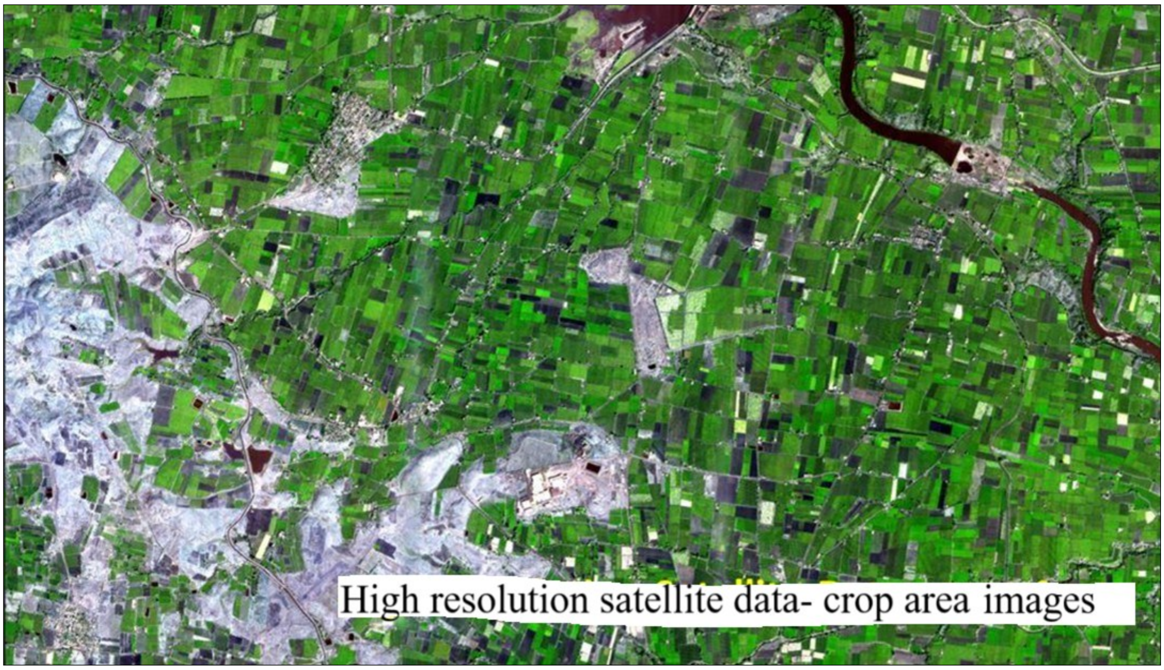


Fig. 3. Green color for vegetation area under cultivation with satellite (Source; NRSC-national RS center).

(relief, drainage, etc.); to correct tillage patterns as field conditions change; and to record yield information as one passes through the field (18).

Geographic information systems (GIS)

Geographic information systems are software, hardware and methods that capture, store and extrapolate enough information about the characteristics of a thing and its place to make maps. Geographic information systems centralizes its data in a single place, which can be expanded when the need arises. In computerized GIS maps, several layers of data are available, which yield data, soil survey maps, rainfall statistics, crop information, soil nutrient level and occurrence of insects are not available in the conventional maps. Geographic information systems is a form of digital mapping application, largely used in geographical and statistical analysis of people as well as places. Geographic information systems stores the data at a single point and has the capacity to be expanded whenever the requirement arises. Geographic information systems is a computerized mapping program mainly used to analyze population and locations in terms of geographical and statistical data. An agricultural GIS database contains data about crop production, topographic data related to fields, soil, drainage of water on the surface, drainage of water beneath the surface, soil analysis and irrigation (19). Geographic information systems can evaluate a wide range of management scenarios, as well as being able to preserve data and present it visually by blending and altering a number of data layers.

Remote sensing

Remote sensing is simply the process of getting information about an object without the need to touch it. Remote sensing has been used in mapping soil, geographical evaluation, crop stress mapping, production mapping and determination of organic matter in soils but on a scale above the scope needed in PA, as demonstrated in Fig. 4. The advantage of high-resolution RS can also be a valuable contribution to PA because of the ability of such technology to observe spatial variations. Satellite RS in PF aims at gathering both temporally and spatially variant information to detect and map crop and soil differences within fields (14).

Variable rate technology (VRT)

It includes a variable rate applicator, which consists of three parts. These include the control computer, actuator and locator. The application map gets installed on the computer at a variable -rate applicator. The device, which uses the application map and a GPS receiver, operates a goods-delivery controller to modify the amount and/or type of product entered into the application map (20). Yield monitors will always quantify and record the flow of grain in a clean grain elevator. The yield maps require certain data, which can be obtained with a yield monitor that is integrated with a GPS receiver.

Sensors technology

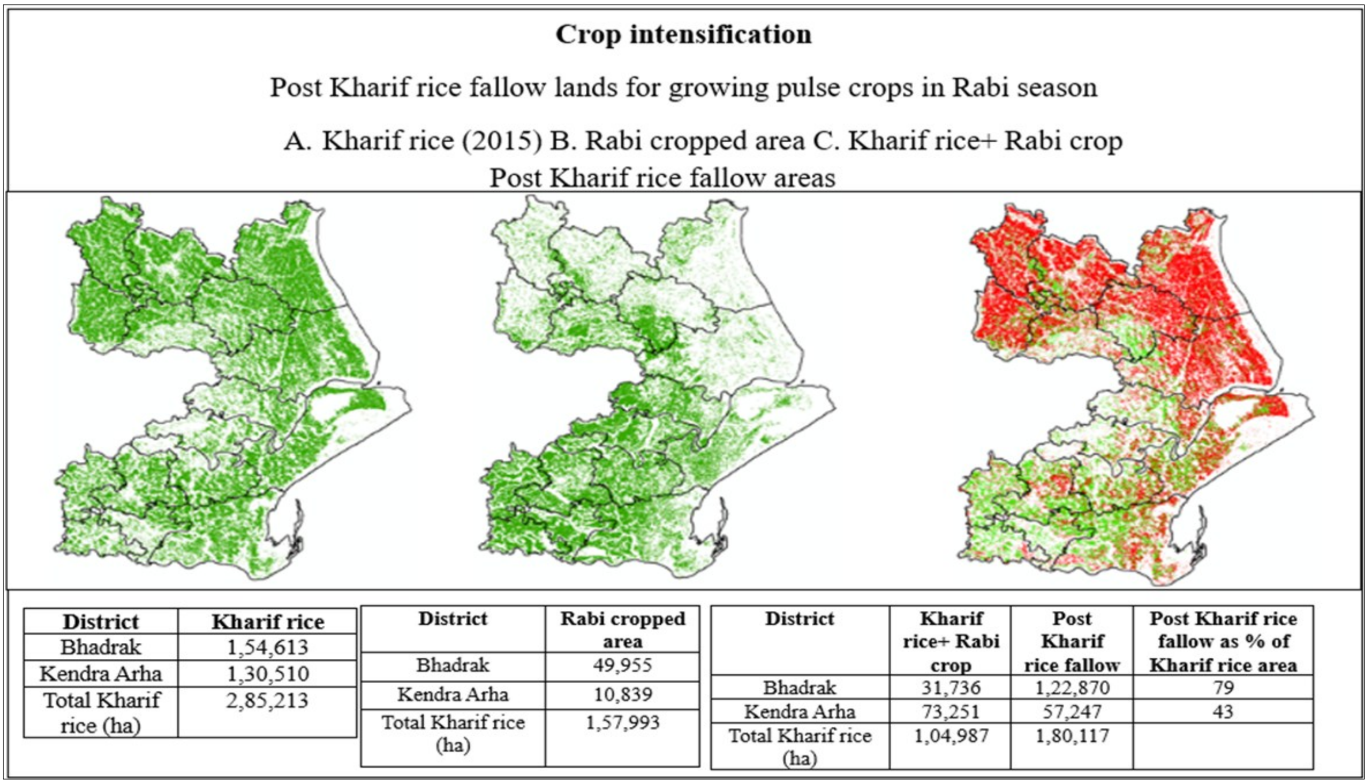
The use of different techniques, including electromagnetic waves, electrical conductivity, photoelectricity and ultrasonic vibrations, is applied to measure moisture, vegetation, temperature, structure, physical properties and conductivity. Remote sensing information can discriminate among the different crop species, identify the stress points, detect the weeds and pests, investigate the soil moisture conditions and assess the vegetable status. Sensors can be used to collect data without the need to send it to the lab.

Soil and plant sensors

Sensors are also applied to pass information about soil attributes, plant growth and water conditions that have been well documented. Precision agriculture technologies requires sensor technology. An overview analysis of existing sensors and the characteristics that ought to be included in the future sensors (21). Another common method of describing soil variability is a survey of the field with the use of an actual electrical conductivity (EC) sensor, which continuously measures conductivity by moving across the surface of the ground. Such sensors render an excellent platform to carry out site-specific management because of the sensitivity of electrical conductivity to variability in soil texture and salinity.

Rate controllers

Rate controllers keep a check on the use rate of the chemical inputs, such as fertilizers and pesticides that take a liquid or granular form. These rate controllers adjust the flow rate and



Crop intensification

Post Kharif rice fallow lands for growing pulse crops in Rabi season

A. Kharif rice (2015) B. Rabi cropped area C. Kharif rice+ Rabi crop

Post Kharif rice fallow areas

District	Kharif rice
Bhadrak	1,54,613
Kendra Arha	1,30,510
Total Kharif rice (ha)	2,85,213

District	Rabi cropped area
Bhadrak	49,955
Kendra Arha	10,839
Total Kharif rice (ha)	1,57,993

District	Kharif rice+ Rabi crop	Post Kharif rice fallow	Post Kharif rice fallow as % of Kharif rice area
Bhadrak	31,736	1,22,870	79
Kendra Arha	73,251	57,247	43
Total Kharif rice (ha)	1,04,987	1,80,117	

Fig. 4. Kharif, Rabi and post Kharif rice percent with the help of RS application in agriculture in crop intensification in Punjab during the whole year as per NRSC.

pressure of the material (in case of liquid form) and the movement of the tractor/sprayer over the terrain and make real-time adjustments in the supply to maintain the required pace. The rate controllers are quite old and they were highly used as standalone systems (22).

Software

The PATs are widely utilized to accomplish a huge number of functions, such as display-controller interfaces, data layer mapping, pre- and post-data processing evaluation and analysis, input accounting, field-specific and many more. The main types of software belong to the filtering of the acquired information, the preparation of variable rate maps of applications (fertilizers, chemicals, lime, etc.), the development of yield and soil maps, overlapping the maps of many maps and providing important geostatistical properties (23).

Yield monitoring

The yield monitors are composed of several parts. The task computer tends to have a variety of sensors installed in the tractor, often located in the tractor cab and most tend to deal with the interaction and integration of multiple sensors and components. It acts as a device to store information, as a user interface (display and keypad) and as well as others. The sensors determine the type of grain, the weight or volume of the grain flow, the speed of the separator and the ground speed. The grain yield is always measured to indicate the force of the grain flow when it collides in the calibrated plate sitting in the clean grain elevator of the combine. A mass flow sensor that has been newly developed measures the level of energy reflected when it meets the flow of the seeds flowing through the chutes. It conspires in sending beams of microwave radiation. Whether production monitors are mounted on the factory floor or on the shop floor, they all use GPS receivers to show the location and the shrinkage of the production data. Another kind of yield monitoring equipment is machinery used in fodder crotches to measure volume, moisture and other data per bin (24).

Internet resources

The quantity of information about modern technologies in agricultural production is large on the Internet. Many companies that produce agricultural equipment, GPS devices, sensors and other PAT products use this media to inform growers about innovation in products and science (10).

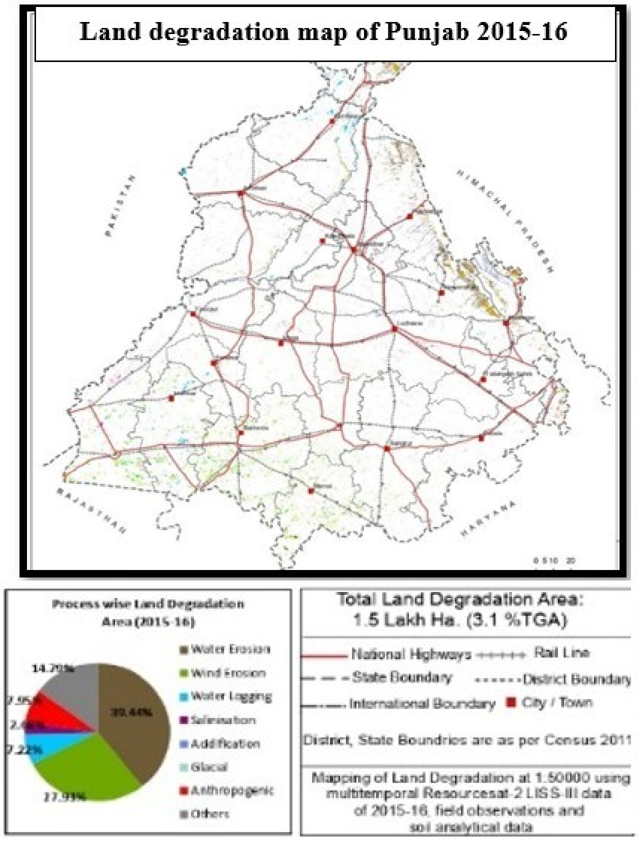
Grid sampling

It is a sampling technique in which a field is subdivided into grids (0.5 to 5 hectares). It is necessary that the soil be sampled in the grid to arrive at the required amount of fertilizer (10).

Overview of the applications of PA for sustainable crop production

Soil management

Precision farming makes use of new technologies such as GPS, RS and other IoT-enabled devices to change soil management to enable farmers to implement site-specific treatment. This is also an effective method in situations where the characteristics of the soil, the pH, nutrient and moisture content can be thoroughly mapped in different parts of a field. The farmers are thus able to craft their own soil management techniques to fit the needs of any particular area, thus maximizing inputs such as water and fertilizers. This targeted approach increases yields and quality of agricultural production, maximizes the use of resources and minimizes the impacts on the environment through nutrient run-off and groundwater pollution. The map shows land degradation in Punjab (Fig. 5). Being able to detect early signs of soil erosion, attack by pests, or deficiencies of specific nutrients allows sensors and drones to enable timely action. Machine learning and data analytics predict the behavior of soils and they help farmers reduce their issues before they develop (25). It is therefore evident that PA



S.No	Process	Code	Land Degradation Class	Symbol	Area Ha.
1	Water Erosion	A1	Sheet erosion - Slight	🟫	12447
2		A2	Sheet erosion - Moderate	🟫	25280
3		A3	Sheet erosion - Severe	🟫	7871
4		A4	Rills	🟨	3019
5		A5	Gullies	🟨	8452
6		A6	Ravines-Shallow	🟧	4548
7		A7	Ravines-Deep	🟫	951
8	Wind Erosion	B1	Sheet erosion - Slight	🟩	42
9		B2	Sheet erosion - Moderate	🟩	31982
10		B3	Sheet erosion - Severe	🟩	2
11		B4	Stablized Dunes	🟩	4669
12		B5	Partially Stablized Dunes	🟩	7470
13		B6	Un-Stablized Dunes	🟩	146
14	Water logging	C1/C2	Surface ponding - Seasonal/Permanent	🟦	10832
15		C3	Subsurface waterlogged	🟦	615
16	Salinisation / Alkalisation	D1-D3	Saline - Slight/Moderate/Severe	🟪	3642
17		D4-D6	Sodic - Slight/Moderate/Severe	🟪	25
18		D7-D9	Saline Sodic - Slight/Moderate/Severe	🟪	585
19		D10	Rann		
20	Acidification	E1/E2	Acidic – Moderate/Severe		
21	Glacial	F1	Frost heaving		
22		F2	Frost Shattering		
23	Anthropogenic	G1	Industrial effluent affected areas		
24		G2	Mining and dump areas	🟪	442
25		G3	Brick kiln	🟥	12172
26	Others	H1	Mass movement / mass wastage		
27		H2	Barren rocky / Stony waste	⬛	62
28		H3	RiverineSands/Sea Ingress etc	🟦	23401

Fig. 5. Land degradation map of Punjab according to 2015-2016 year as per NRSC, ISRO data.

not only continues to sustain soil production, but it also encompasses the long-term health of soil, hence increasing sustainable agricultural activities and food security.

Water management

Water management in agriculture has been significantly enhanced in PA, which is a standard farming management that uses technology to optimize agricultural activities. This approach will employ a combination of data obtained through numerous data sources that include soil moisture probes, meteorological predictions, satellite images and IoT gadgets to ease informed decisions about irrigation plans. Exact estimation of the moisture needs of individual zones of a field helps farmers to use water more efficiently and avoid wastage, ensuring that the crops receive an optimal amount of moisture (26). The process not only saves water but also enhances the agricultural output, as well as reducing the chances of waterborne illnesses. Moreover, the introduction of PA into water management involves the use of advanced irrigation systems, such as drip irrigation and variable rate irrigation (VRI). Components of data-driven systems, such as the correct water distribution, minimize the evaporation and run off, whereas VRI adapts the application rates to the specific areas of the field. Such precision enables efficient operation of low water resources, creation of sustainable farm work and minimization of the ecological impacts of farming. Sustainability and efficiency of water management are some of the primary functions of PA (27). Also, the flood inundation areas of the river basins were determined by satellite images that minimized the risk of flood as indicated in (Fig. 6 & 7).

Crop monitoring

Precision agriculture has transformed crop monitoring through the utilization of new technology, including GPS, RS and IoT devices**.** These technologies allow farmers to gather precise data regarding their fields, encompassing soil health, moisture levels and crop conditions. Farmers can utilize satellite imaging and drones with multispectral cameras to monitor crop health in real time, detecting regions impacted by pests, illnesses, or nutritional deficits (28). The granular data provide targeted actions, including variable rate application of fertilizers and insecticides, optimizing inputs and reducing environmental effects. Thus, PA improves production and fosters sustainable farming practices by minimizing chemical usage and preserving resources. Moreover, precision agricultural systems frequently incorporate data analytics and ML algorithms to forecast crop performance and discern trends. By examining historical data in conjunction with real-time observations, these systems can furnish farmers with actionable insights to enhance yield forecasts and optimize planting schedules. Predictive models can anticipate weather trends and provide ideal planting periods to circumvent unfavorable situations (29). This proactive strategy mitigates the likelihood of crop failure and enhances overall agricultural efficiency. Moreover, smartphone applications and cloud-based systems provide effortless data exchange and remote monitoring, allowing farmers to make educated decisions from any location. Ultimately, PA optimizes decision-making, increases production and improves the sustainability and profitability of contemporary farming (30).

Nutrient management

Precision agriculture, utilizing advanced technology like GPS, RS and data analytics, is transforming nutrient management into agriculture. This method facilitates the accurate administration of fertilizers and soil amendments according to specific, site-related data regarding soil nutrient concentrations and crop requirements. Agriculturalists can generate variable rate application maps by synthesizing data from soil analyses, crop yield monitors and aerial imagery. Remote sensing offers a non-

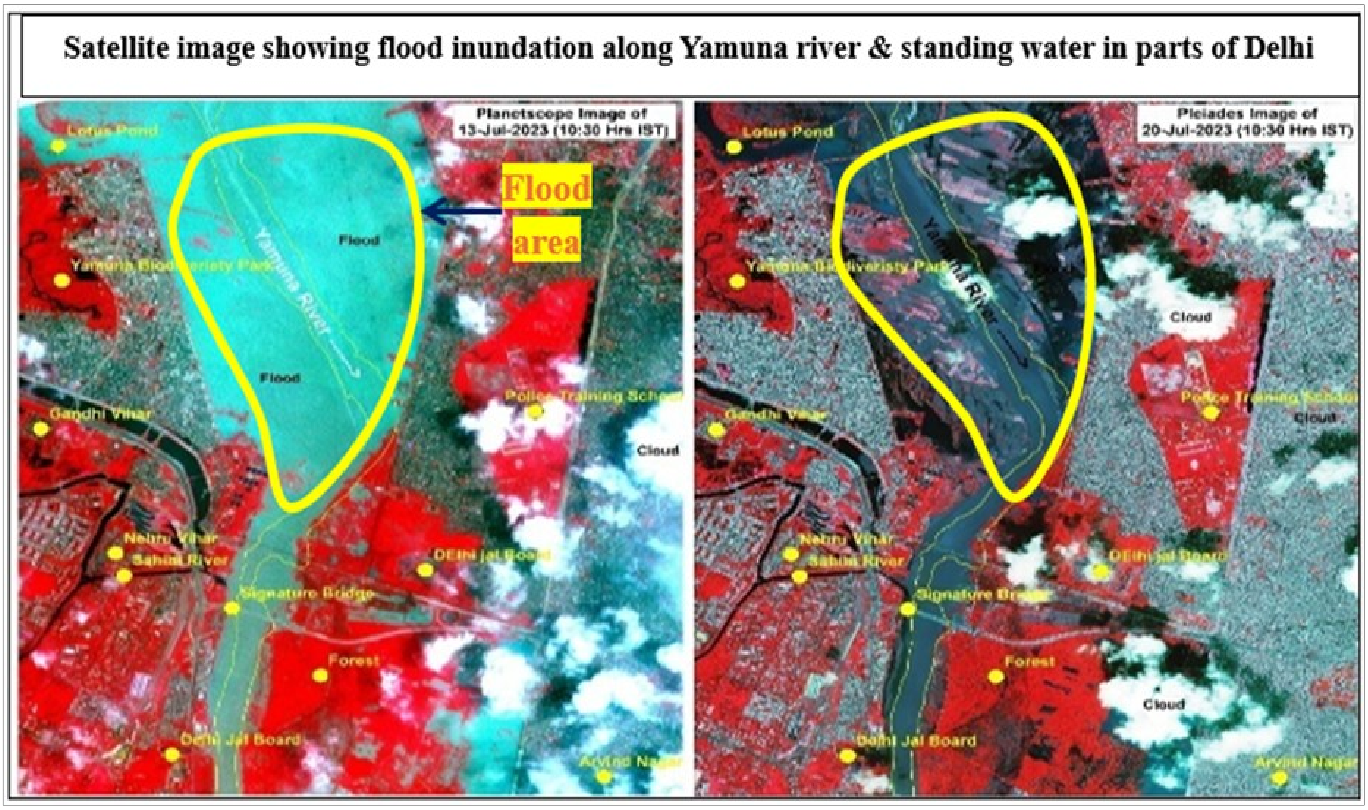


Fig. 6. Illustrates the satellite images of flood inundation along the Yamuna river and standing water in parts of Delhi as per the year 2023 (Source: NRSC)

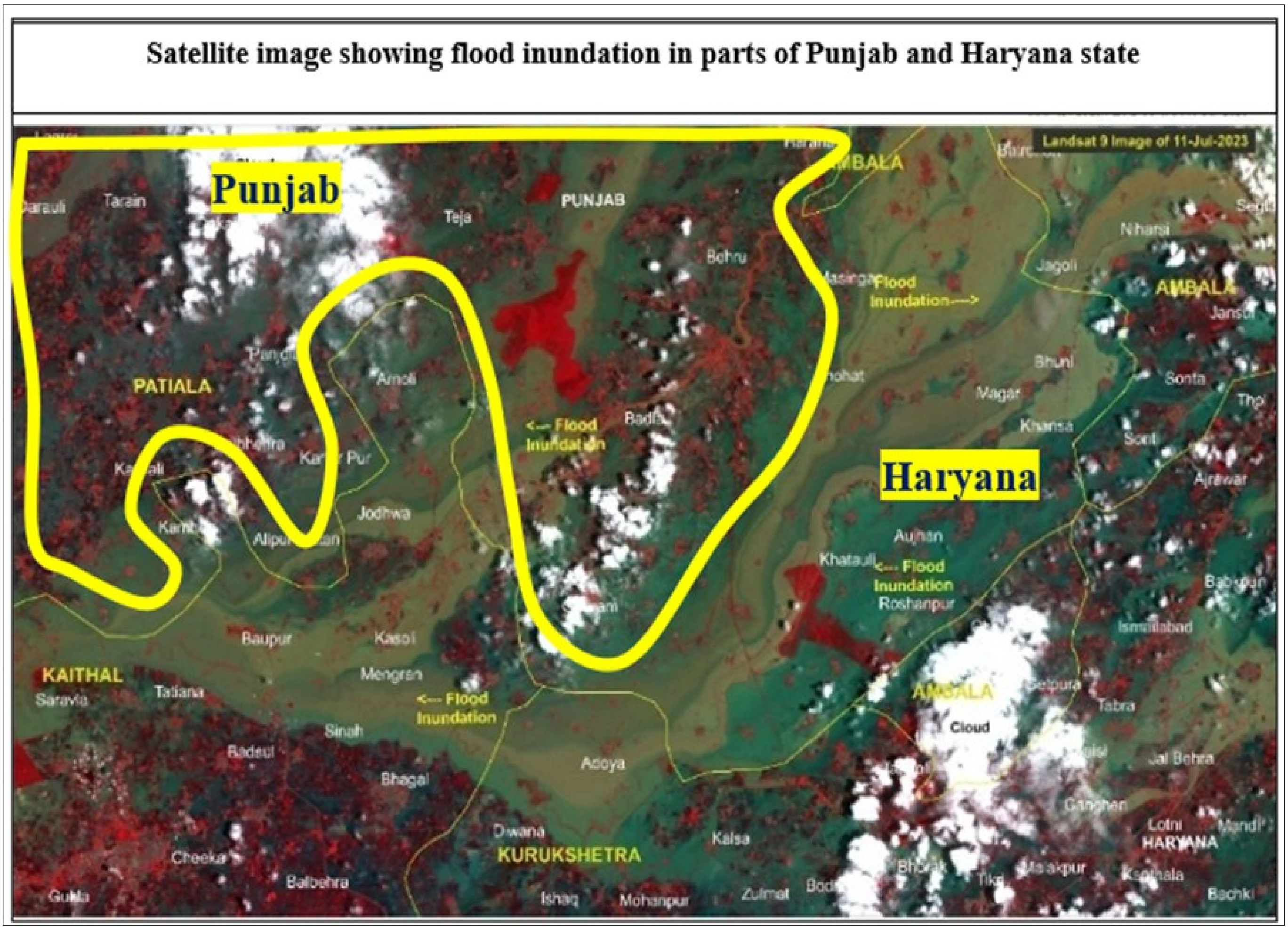


Fig. 7. Satellite image related to flood inundation in Punjab and Haryana state (Source: NRSC).

invasive and cost-effective approach to acquiring essential data regarding crop health and the nutrient composition of soil or plants. Employing RS to identify nutrient deficiencies and incorporating this information into a GIS can facilitate targeted fertilizer and soil amendment applications in India (31). This would subsequently enhance fertilizer use efficiency and diminish nutrient losses. Precision agriculture integrates data from soil analyses, RS technologies and historical yield records to build nutrient management strategies customized for distinct field zones. This method guarantees the application of fertilizers at optimal rates and timings, enhancing crop nutrient absorption while reducing nutrient runoff and leaching. Furthermore, PA improves environmental sustainability by alleviating the adverse effects of traditional farming methods. Targeted application of fertilizers reduces runoff into waterways, hence mitigating algal blooms and other ecological issues. Moreover, it diminishes greenhouse gas emissions linked to fertilizer production and utilization (32).

Pest and disease management

Precision agriculture employs sophisticated technologies and data management strategies to improve pest and disease control in agriculture. Farmers can utilize systems like GPS, RS and GIS to monitor and manage crop health with exceptional precision. These technologies facilitate the prompt identification of pest infestations and disease outbreaks by delivering comprehensive geographical and temporal data. Remote sensing can detect minute variations in crop color and vigor, signaling stress or infection that may be undetectable to the unaided eye. Utilizing such data enables farmers to execute targeted interventions, minimizing the necessity for indiscriminate pesticide applications and thereby fostering more sustainable agricultural practices. A notable advantage of PA in pest and disease management is the capacity to administer treatments with greater efficiency and efficacy (33). Variable rate technologies facilitate the accurate application of herbicides and fertilizers according to the distinct requirements of various zones within a field. This focused strategy enhances resource efficiency and mitigates environmental harm by decreasing chemical runoff and soil pollution. Moreover, PA can use predictive modeling, utilizing historical data and current conditions to anticipate pest and disease impacts. This enables farmers to implement preventive strategies, such as modifying planting schedules or choosing resistant crop varieties to alleviate possible problems before they escalate. Alongside enhancing immediate pest and disease management, PA promotes enduring agricultural resilience (34). Through the ongoing collection and analysis of data, farmers can get profound insights into the patterns and determinants affecting pest and disease dynamics. This understanding facilitates the formulation of integrated pest management (IPM) strategies that prioritize ecological equilibrium and sustainable practices. Farmers can recognize beneficial insect populations that naturally regulate pests and modify their management practices to support these advantageous species. Overall, PA improves the efficiency and efficacy of pest and disease management, contributing to the sustainability and resilience of agricultural systems (35).

Planting and harvesting

The transformation brought by PA in planting and harvesting is that efficiency and production are better and the wastage of resources is minimized because of the use of technology in this operation. Precision agriculture makes use of sensitive techniques like the GPS-guided tools and the VRT to locate seeds in the right depths and spacing in the right manner, therefore promising uniformity across the field. By interpreting the information about the soil, including nutrient concentration and levels of moisture, farmers can tailor their planting strategies to maximize the production of every crop. Such a narrow approach not only enhances the farmer's ability to produce more but also decreases input costs through decreased use of seed and fertilizer. Precision agriculture has continued to play a significant role in maximizing activities and improving output during harvest. Other technologies, such as the yield monitoring systems and RS, help a farmer to evaluate the health and maturity of crops in real time, thus helping determine the optimal harvest time (36). Combining meteorological forecasts with edaphic statistics, farmers will be able to plan the harvest better and prevent harvest losses caused by severe weather conditions or plant stresses. Besides, the fact that advanced machinery is combined with sensor and automation technologies makes the harvesting process efficient, reduces the amount of required labor and increases the overall production. The use of such PA applications in planting and harvesting converts the traditional practices of planting and harvesting to improve productivity, sustainability and profitability. With the agricultural sector embracing innovation, there is an impending role that PA is likely to play in ensuring that the blooming global population is maintained without depleting natural resources that could be needed in the future (37). The ability to increase the efficiency of resources and improve the production of crops is largely recognized as a critical tool in the climate adaptation strategies of agriculture. One of the major aspects of global warming is the way it impacts meteorological patterns, which include changes in precipitation levels, temperature levels and extreme weather conditions. The use of PATs (such as sensors, drones and satellite imaging) allows farmers to better understand and prepare educated responses to changing circumstances, as these technologies also monitor and collect data in real-time. Sensors could be used to check how moist the soil is; therefore, farmers could adjust the timing of the irrigation to fit the changes in the precipitation cycles, thus saving on water consumption and minimizing the chances of drought. This is shown to maximize resource productivity, reduce environmental degradation and enhance the resistance towards climatic changes (38). Moreover, crop breeding programs can be made more effective by using the information gathered with the help of precision agricultural systems, to produce varieties that are better with respect to climate change challenges, such as heat and drought resistance.

Data management and analysis

In PF, data processing plays a crucial role in maximizing the variety of information collected from different sources. This includes soil sensors, satellite images, weather predictions and crop wellbeing systems and is fronted into cloud systems to check ongoing access and projections by farmers. The technologies organize the data and ensure their accuracy and reliability and provide farmers with a solid framework on which they can base their assertions (39). On the other hand, predictive analytics use such identified patterns to make predictions, like agricultural yields or pest invasions. Through this advanced knowledge of the agricultural systems.

Sustainable land management

The optimization of inputs and the maximization of yields through PA have increasingly become a dreadful tool in the sustainable management of land. This precision supports the precise use of resources such as water, fertilizers and insecticides, thus reducing wastage and reducing environmental consequences. A critical element of PA is the increased soil health and protection based on the field variability mapping, so that farmers can adjust the approaches to the unique needs of a particular site (40). Precision agriculture will therefore play an important role in promoting methods of sustainable land management, which balance out the needs of farmers and the environment, as well as future generations, in the successful utilization of the land through the land cover map, as indicated in Fig. 8.

Carbon and energy management

To achieve PA, the traditional process of farming is redefined in a way that integrates high-tech technologies and data-driven approaches to improving the efficiency of used resources and minimizing the impact on the environment. The application is based on a precise observation and control of the inputs, both water, fertilizers and pesticides, with the use of advanced technologies, RS, GPS-based equipment and data analytics systems. Such a well-thought-out plan maximizes crop production and minimizes wastage of farm resources, thus reducing the carbon footprint associated with farming. Other than resource efficiency, PA allows the implementation of environmentally friendly measures that will increase carbon sequestration and energy conservation rates. Such practices as conservation tillage, cover cropping and crop rotation, based on soil and environmental data, increase soil status and carbon sequestration. A strike to reduce the emission of greenhouse gases, improve soil condition and improve the resilience of the soil is a reduction in reliance on chemical inputs and any increase in land use by farmers (41) is represented in Table 1.

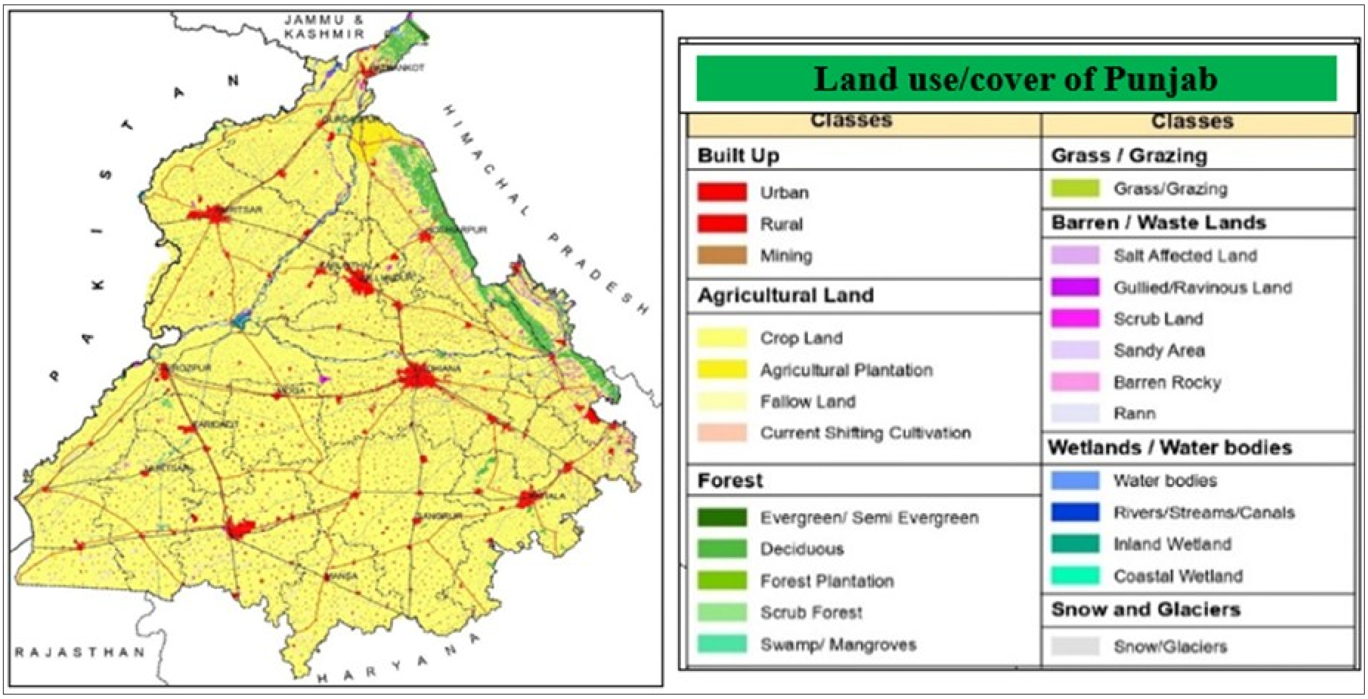


Fig. 8. Punjab land use cover area under agricultural land, forest, barren land and wetlands.

Table 1. Represents the PF application across various fields for PF

Precision farming application	Quantitative benefits	Local barriers addressed	References
Enhances soil health and resource efficiency using advanced technology to promote sustainable crop production	Soil health improvements by 20 - 30 %; resource use efficiency up by 15 %	Poor soil fertility; inefficient resource use	(42)
Conserves water using sensor technology and data analysis to optimize irrigation for sustainable crop growth	Water usage reduction by 30 - 50 %; crop yield increase of 10 - 20 %	Water scarcity; inefficient irrigation systems	
Uses drones, satellite imagery and IoT sensors for real-time crop monitoring to enhance decision-making and yields	Yield improvement by 10 - 25 %; reduction in input costs by 15 %	Lack of real-time crop data; high input costs	
Optimizes nutrient usage through data-driven techniques for sustainable crop production	Nutrient use efficiency went up by 20 %; fertilizer costs reduced by 25 %	Overuse of fertilizers; high nutrient costs	
Manages pest and disease outbreaks using data-driven strategies and RS	Pest/disease reduction by 20 - 40 %; crop loss reduction by 15 - 25 %	Pest and disease management challenges	(46)
Optimize planting and harvesting with GPS guidance and data analysis for efficiency and yield	Yield increases by 15 - 30 %; fuel savings of 10 - 20 %	Inefficient planting/ harvesting; high fuel costs	
Use climate data and predictive modeling to adapt crop management practices to climate change	Improved crop resilience by 20 %; adaptation costs reduced by 10 %	Climate change impacts: adaptation costs	
Maximizes crop production through advanced data management and analysis techniques	Crop production increases by 15 - 25 %; data management efficiency is up by 20 %	Low productivity; inefficient data management	(49)
Uses technology to optimize resource use and minimize environmental impact	Land degradation reduction by 20 %; resource use efficiency up by 15 %	Land degradation; inefficient resource use	(50)
Minimizes carbon emissions and optimizes energy usage for sustainable agriculture	Carbon emissions reduction by 15 - 25 %; energy use reduction by 10 - 20 %	High carbon emissions; high energy costs	(51)

Practical applications of PF technologies in rice crop

Early disease and stress detection

Remote sensing of early disease identification also helps in sustainable environmental methods during rice production, (Fig. 9). It is more common to have traditional approaches that rely on systematic applications of agro-chemicals in combating pests and diseases without respect to the actual existence of threats. Through the application of aimed interventions according to or based on specific and timely information acquired by remote sensors, farmers will be able to decrease chemical application, hence decrease environmental degradation and add to integrated pest management solutions (52). This not only makes the whole agricultural system healthier but keeps the production of rice economically feasible by scaling down expenditure on the inputs and making consumers trust the rice they are getting more.

Enhances optimum use of water and nutrients

The overall task of enhancing RS technology used in rice production vastly benefits the initial disease identification abilities as well as the overall discussion related to sustainable agricultural production. Application of resources in rice farming can be maximized by the inclusion of RS technologies, which ensure optimal distribution of resources like fertilizers and water. Precision agriculture practices, along with GIS and remote data sensing information, empower farmers to effectively exploit their resources strategically in a manner that becomes compatible with a particular harvest with distinctive developmental phases. This guided management reduces wastage of inputs as explicated (53). Advantages of this form of precision are not only limited to the efficiency of using the available resources; It is also very important in enhancing the soil fertility and the gain of crops in general income. Points towards the significance of such correlation imply that application of resources optimally through RS not only brings in additional income but also enhances the management of soil nutrients, leading to sustainable agriculture. Having the data obtained from the resource of RS enables a finer resolution of knowledge concerning the health of soil, the degree to which it is moist and its nutrient status throughout different geographies within rice and the farmer makes their optimum decision on how to integrate resources (53).

Landsat, sentinel and MODIS

Agricultural surveillance through satellite technologies has been a revolutionary idea in the production of rice, where accurate information on the growth of crops, the goodness of land and the amount of water is required to ensure sustainability. Some of the most powerful satellite systems are Landsat, Sentinel and MODIS. Through these platforms, high-resolution and detailed records are made available, thus enabling researchers and farmers to evaluate multiple required parameters to enhance rice output whilst ensuring environmental sustainability. Long-term continuity of data of the Landsat satellites may be regarded as a valuable source of information about the dynamics of the cultural growth as well, since there is an analysis of the normalized difference vegetation index (NDVI), other spectral indexes. This feature was vitally important in phenological warning in activities on rice crops and stress, so that it was able to assist in agricultural interventions at an opportune moment. Observation of the health of cultures and the forecasting of yields can be taken to an in-

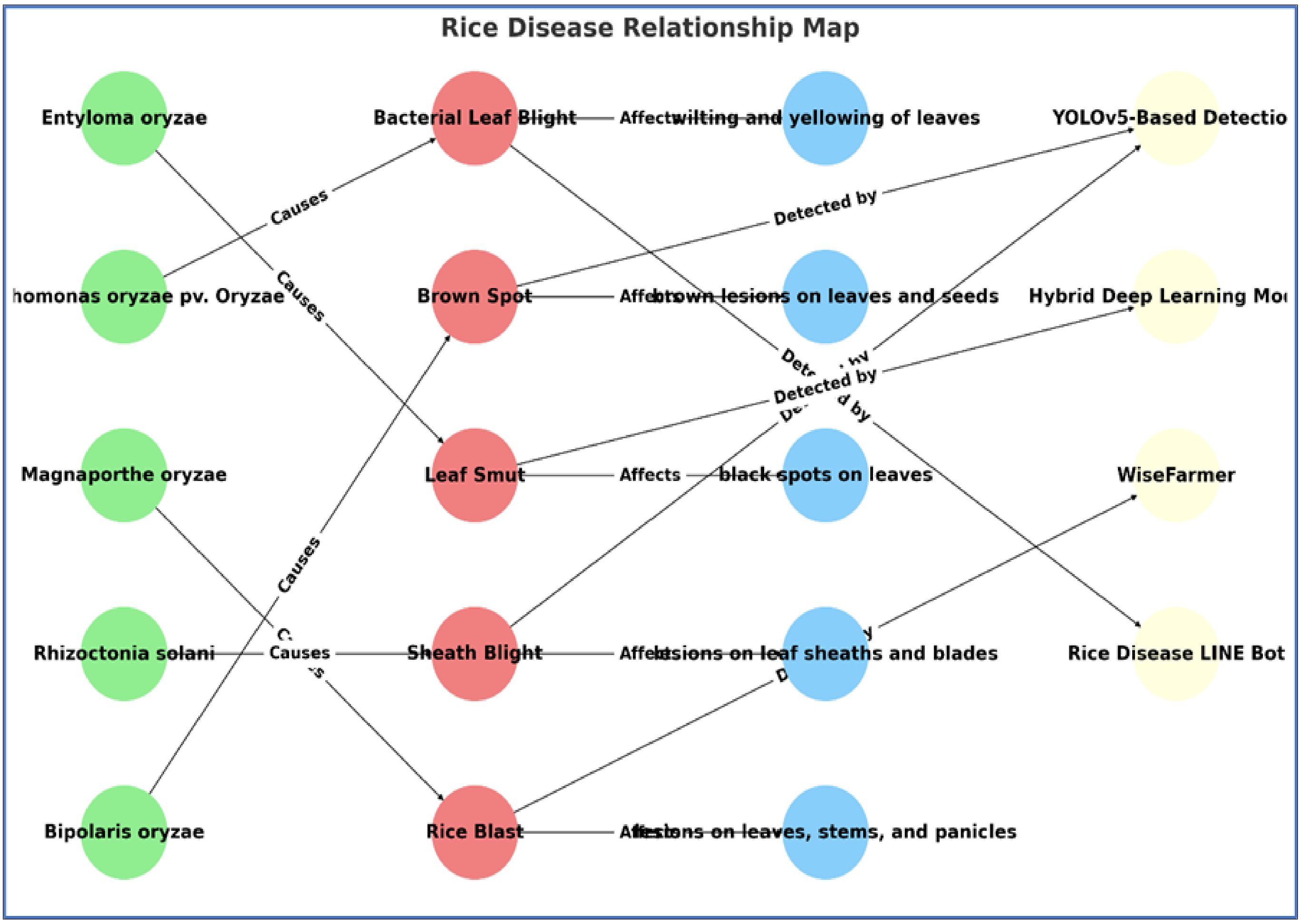


Fig. 9. Interrelationship map of different rice diseases.

depth level with Landsat multispectral imagery. The Sentinel satellite series has recently played a great role in agriculture monitoring, as its space resolution and spectral capabilities are better and higher than those of the Landsat satellite series. As an example, Sentinel-2 imaging was applied successfully to determine the salinity of soils in irrigated rice lands that React TY BM 2020-07-02T02:03:05.529Z (54).

Regional-level monitoring

Precision technologies in agriculture have grown to be an important instrument to maximize crops in rice, especially regionally, as illustrated in Fig. 10 (a, b, c, d, e and f). Such innovations exploit the practices based on data that favor sustainability as well as enhancing productivity. Such technologies as RS and data collection systems used in the field are very important as they provide farmers with an opportunity to make informed decisions concerning fertilization, irrigation and control of pests. The efficiency of the confluence of the smartphone measures and the Sentinel-2 satellite measurements to include the concrete fertilization of the field in rice systems. This will not only increase the yield of the crops but also ensure little or no destruction is caused to the environment due to the overdose of fertilizers. Intelligent agricultural practices have become increasingly embraced in various areas and this comes about the panorama of the large-scale rice agriculture in Japan. Their results highlight the possible advantages of applying PA through the advanced monitoring technologies that offer a more effective distribution of the available resources and enhance their sustainability. With the increasing demand for rice, the utilization of these monitoring technologies on the regional level is becoming more fundamental in dealing with the issue of climate change and, even more so, the problem of resources and their scarcity. Data-driven adoption of such practices enables the farmer to streamline his/her processes, at the same time ensuring environmental management (55).

Analysis of real-time

Presence of high-resolution imaging in a real-time analysis is a great addition in the management of rice crops by enhancing the decision-making process. It can be used to detect diseases earlier and crop conditions can be accurately monitored. Influencing the real-time detection of rice phenology with high accuracy via convolutional neural networks fed by feeds relayed by portable cameras achieves such a goal. This technological advancement enables farmers to notice important growth periods and they can undertake mid-cycle interventions. Accuracy in PA involves the use of drones that enable the surveillance of rice fields in detail. The low altitude of drones' RS is efficient to distinguish rice weeds in real-time identification and an enhanced semantic segmentation model is applied. These capabilities not only make sense in managing the weeds, but also in the efficient use of resources, the effect of which has been an increase in yields and a decrease in the cost of entry. There are still challenges despite the advantages. Issues involved in data processing abilities, cost and the lack of trained staff to read high-resolution images may stop mass adoption (56).

Normalized difference vegetation index (NDVI) spectral indices

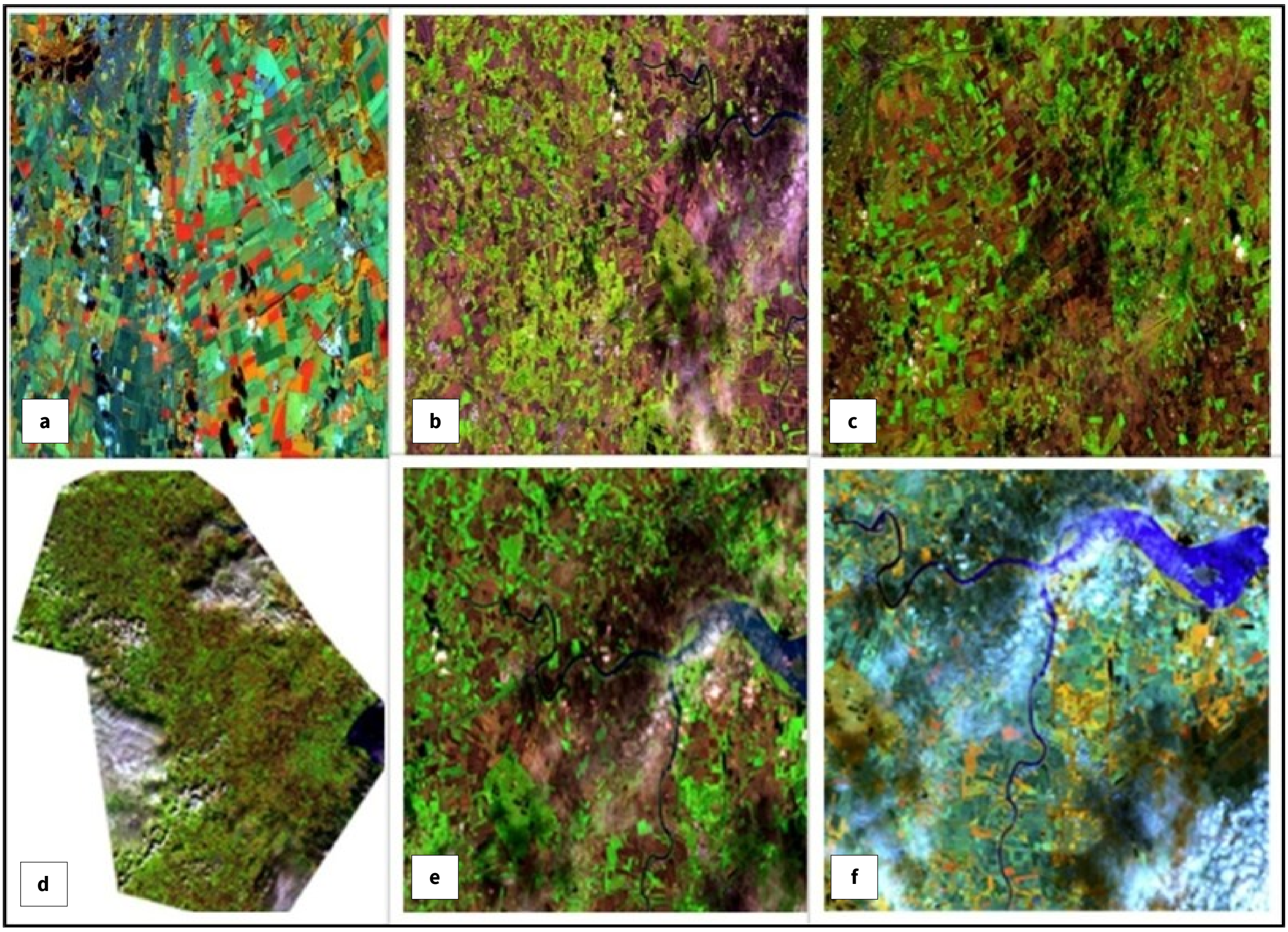


Fig. 10. Landsat satellite images (a) agricultural field, (b) uncultivated area, (c) vegetation cover, (d) urban area, (e) atmospheric corrections and (f) water bodies.

Normalized difference vegetation index as emerged as a major tool to identify rice crops and one can get information of health and production of the crops based on spectral data analysis as can be seen in Fig. 11 (a, b, c & d). Normalized difference vegetation index makes use of the near and infrared red wavelength to determine the viability of vegetation and in this case it can be useful as rice requires close monitoring since it is susceptible to water shortage and deficiency of nutrients. Various studies have revealed that NDVI is strong in forecasting rice performance owing to its capability of reflecting changes in chlorophyll abundance and photosynthetic efficiency. This confirms the truth that NDVI is a reliable tool in assessing different stages of rice development and eventually assists the farmers and agronomists in coming up with informed decisions on how to handle their crops. Added advantage favoring the usefulness of NDVI. The study proves the importance of NDVI in the accurate monitoring of agriculture, as it reacts to changes that happen to rice plant physiology in relation to environmental factors. The performance of NDVI, however, is not free of limitations (57).

Spectral indices based on chlorophyll content

The spectral indices have become effective tools to measure the content of chlorophyll and assess the health of crops in rice, which is crucial for PA and optimization of yields, as per Fig. 12 and Table 2. These clues use RS technologies to analyze the reflectance properties of the sheets, providing information on

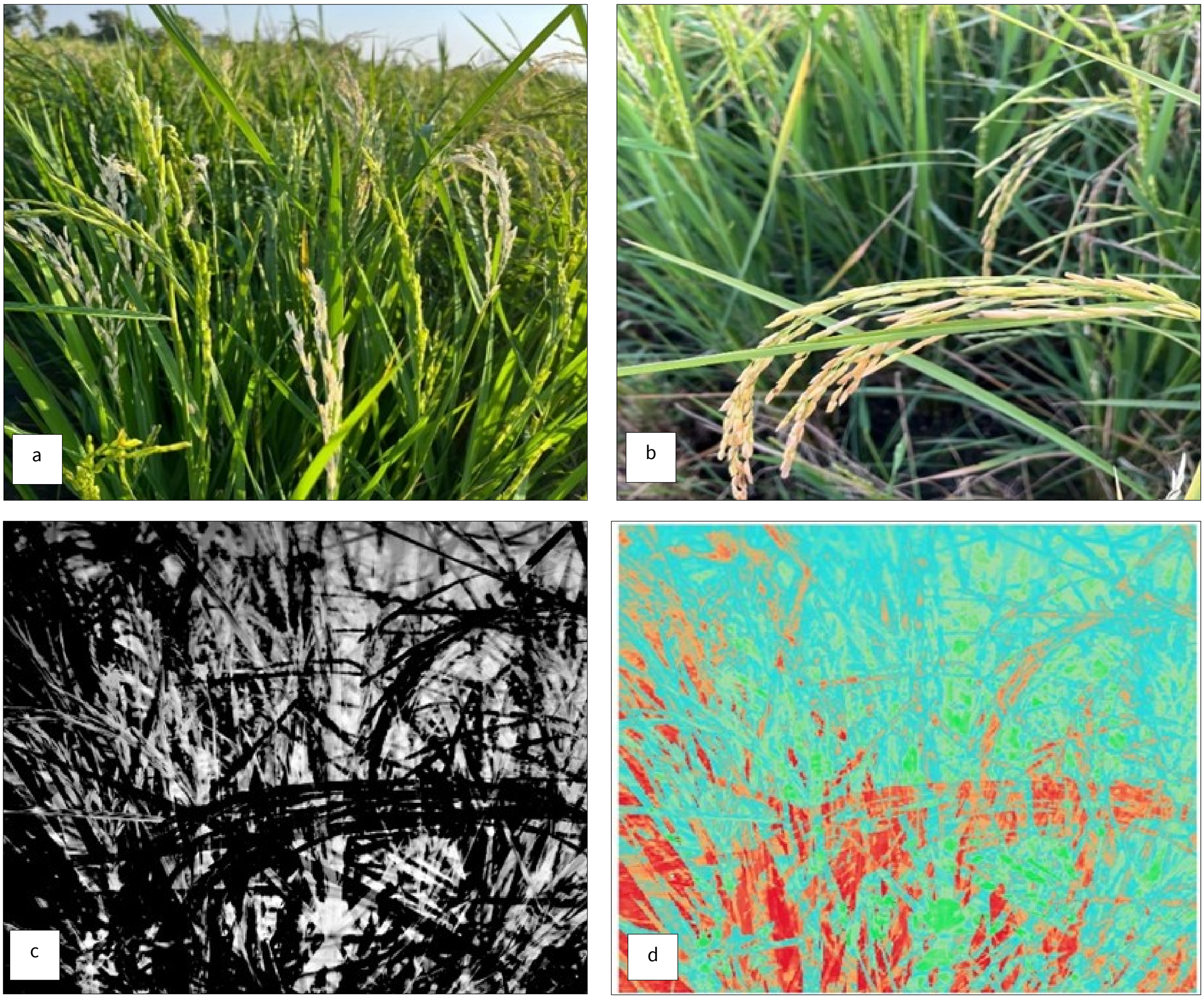
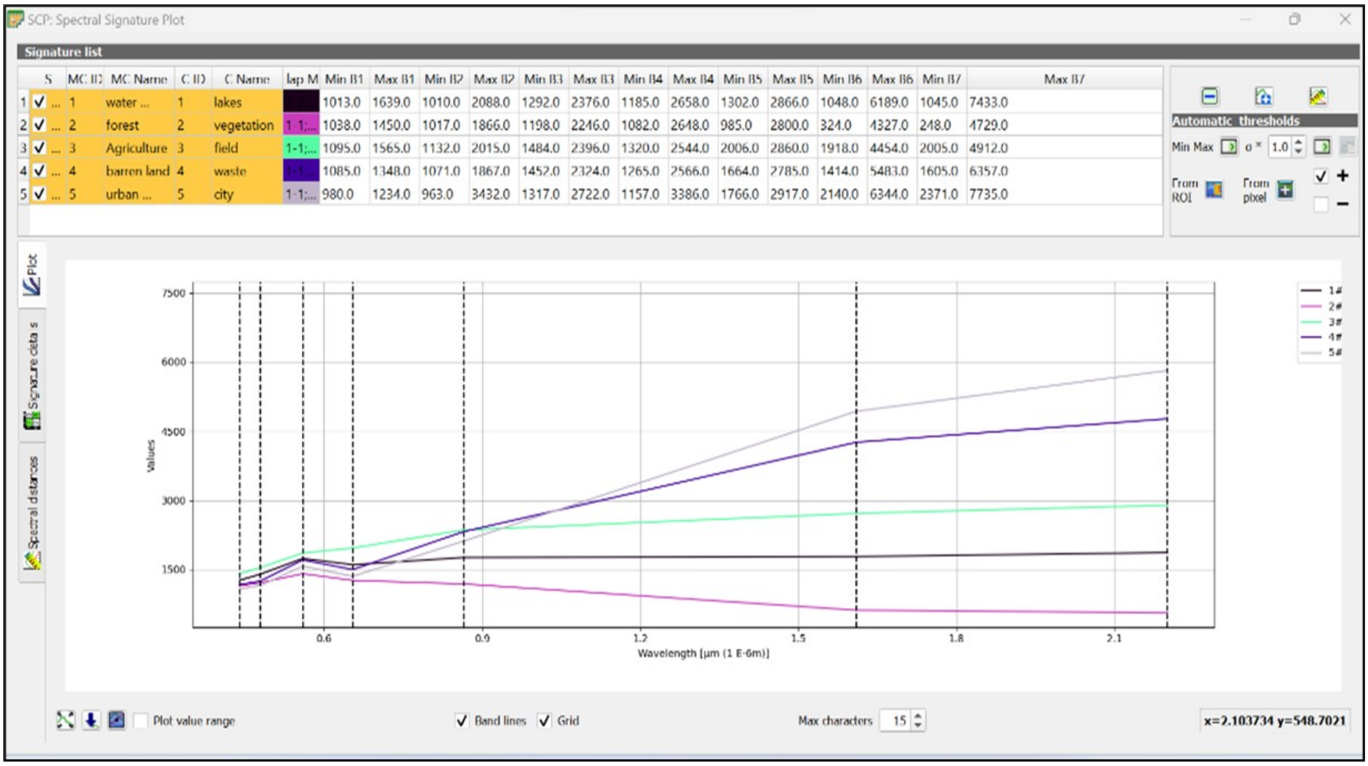


Fig. 11. Different images of rice udbatta (*Balansia oryzae-sativae*) disease and NDVI calculation of images through QGIS software. Image (a, b) rice panicle with empty grains, (c) image color change into single grey band pseudo color, (d) showing NDVI calculations by using QGIS software.

Table 2. Spectral indices used in RS for rice farming

Index	Formula	Application
NDVI	(NIR - Red) / (NIR + Red)	Crop vigor and health assessment
EVI	2.5 * (NIR - Red) / (NIR + 6 Red - 7.5 Blue + 1)	Improved vegetation monitoring with atmospheric correction
SAVI	(NIR - Red) / (NIR + Red + L) * (1 + L)	Used in areas with a high soil background influence
NDWI	(NIR - SWIR) / (NIR + SWIR)	Water stress and irrigation monitoring

*NDVI (Normalized Difference Vegetation Index), EVI (Enhanced Vegetation Index), SAVI (Soil-Adjusted Vegetation Index), NDWI (Normalized Difference Water Index), NIR (Near Infrared), SWIR (Short-Wave Infrared)



	S		MC ID	MC Name	C ID	C Name	lap M	Min B1	Max B1	Min B2	Max B2	Min B3	Max B3	Min B4	Max B4	Min B5	Max B5	Min B6	Max B6	Min B7	Max B7
1	✓	...	1	water ...	1	lakes		1013.0	1639.0	1010.0	2088.0	1292.0	2376.0	1185.0	2658.0	1302.0	2866.0	1048.0	6189.0	1045.0	7433.0
2	✓	...	2	forest	2	vegetation	1-1;...	1038.0	1450.0	1017.0	1866.0	1198.0	2246.0	1082.0	2648.0	985.0	2800.0	324.0	4327.0	248.0	4729.0
3	✓	...	3	Agriculture	3	field	1-1;...	1095.0	1565.0	1132.0	2015.0	1484.0	2396.0	1320.0	2544.0	2006.0	2860.0	1918.0	4454.0	2005.0	4912.0
4	✓	...	4	barren land	4	waste	1-1;...	1085.0	1348.0	1071.0	1867.0	1452.0	2324.0	1265.0	2566.0	1664.0	2785.0	1414.0	5483.0	1605.0	6357.0
5	✓	...	5	urban ...	5	city	1-1;...	980.0	1234.0	963.0	3432.0	1317.0	2722.0	1157.0	3386.0	1766.0	2917.0	2140.0	6344.0	2371.0	7735.0

Fig. 12. Spectral indices graph showing the measurement of crop, water bodies, forest area, barren land and urbanization.

the dynamics of chlorophyll (58).

Challenges in the adoption of PA

Objections to the use of PA are the high initial investments in machinery, inadequate infrastructure such as high-speed internet connexon, inadequate technical skills and training of farmers and proprietorship, privacy and security of data. These are aggravated by the fact that there are other challenges such as small or fragmented landholdings that can render the investment less viable economically (Fig. 13).

Review gaps and future directions

- Findings of the systematic literature review of PATs show major gaps in the accessibility and uptake of the technologies, especially in developed and developing countries. Some obstacles, such as language differences, poor Internet access and illiteracy among people in many developing countries, such as Africa and Asia, are some of the hurdles that hinder the implementation of PA in those regions. Such obstacles can be bad infrastructure, lack of funds and technical skills. Current literature is largely devoted to developed nations, whose agricultural environments, inputs and infrastructure are highly differentiated as compared to developing areas. The aim of this concentration is the existing knowledge gap that cannot solve the special agricultural conditions and problems of farmers in the less developed regions. The review gap is represented in Fig. 14.
- Future studies should therefore emphasize developing cost-effective and scalable solutions to PA to eliminate these gaps by considering the needs of resource-constrained environments.
- Low-cost sensors: A variety of low-cost sensor designs that can be conveniently incorporated into the current farming methods.

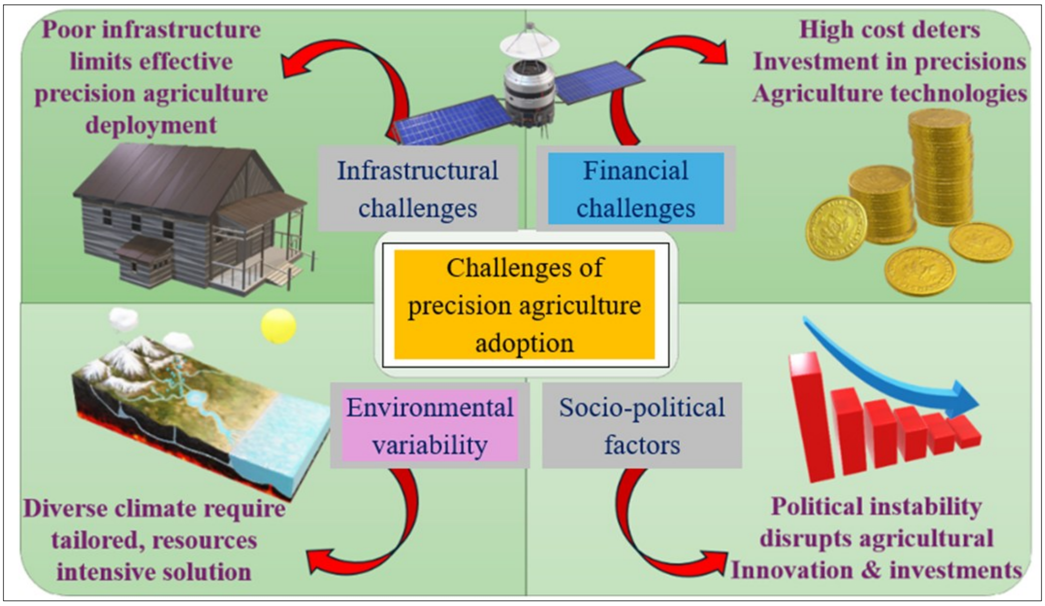


Fig. 13. Challenges in the adoption of PA.

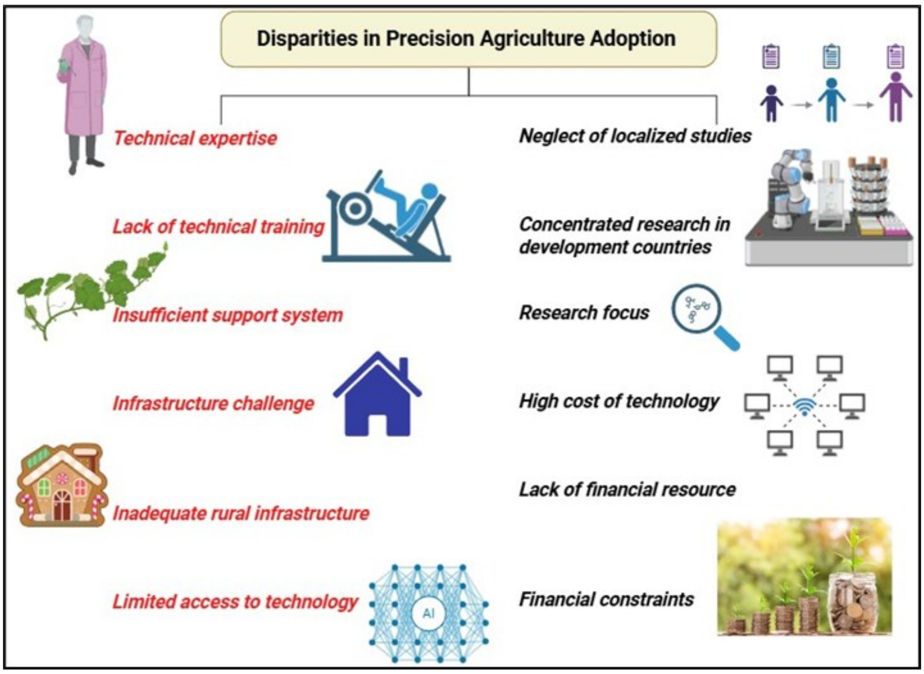


Fig. 14. Research gaps in the adoption of PF.

Conclusion

The usage of PATs in crop production and environmental sustainability has great opportunities. Precision agriculture has led to increased crop yield, resulting in the optimized use of inputs using GPS-equipped machines, RS and VRT. Technology enables site-specific management, as resources like water, fertilizers and pesticides will be used only where and when it is needed. Not only does this enhance crop yields, but it also reduces wastage and the cost of input. Moreover, the practice of PA is helping to make the environment more sustainable by discouraging excessive use of agricultural chemicals, therefore, avoiding their adverse effects on the health of the soil, the water supply and the biodiversity level. Nevertheless, adoption of PATs entails certain challenges, among them being that it is costly to adopt, it requires specialized knowledge and training and in the case of smallholder farmers in the developing world, PATs will be costly to adopt as they have infrastructural and financial limitations. The application of PATs should be enabled by subsidies and governmental service provision, especially toward small-scale farmers. The cooperation of the governmental and business spheres could help to make PATs more affordable and lead to the improvement of innovations. Through such suggestions, sustainable agricultural production and an ecosystem will be possible and this will lead to food safety and ecosystem balance not only for the country but for the whole globe.

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Authors' contributions

LM, GS and AS wrote the paper. SS and ST did the corrections. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors do not have any conflicts of interest to declare.

Ethical issues: None

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