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# State-of-the-art technologies in precision agriculture: a systematic review

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## Abstract

**BACKGROUND: The socio-economic status of the countries is ever-changing due to the increasing population. 'Green Revolution', a paradigm shift towards technology driven agriculture, has ensured a good quality of life to some extent for this increasing population. However, it brings in several negative impacts on the environment, which poses a threat to the sustainability of agriculture and natural resources. Precision agriculture (PA) is a state-of-the-art concept of site-specific farm management that helps to overcome this threat in a smart way using modern information and communication technologies. It reduces the indecorous use of resources, pollution and hence improves quality of life, which in turn helps to achieve sustainable development goals.**

**RESULTS: The objective of this systematic review is to understand the present status, benefits, and limitations of the state-of-the-art technologies used in PA. A total 67 articles are identified following the PRISMA guideline to inspect the technical innovations at different components of PA. The articles are examined based on the novelties, measured parameters, technologies, and field of applications.**

**CONCLUSION: This analysis results in a significant understanding about the present knowledge gap and identification of the potential future research opportunities for sustainable agronomy.**


**Keywords:** information and communication technology; precision agriculture; sustainable agronomy; systematic review

## INTRODUCTION

Population increase is a constant threat to the global food security.[1] Food security can be ensured with improved agricultural practice. Worldwide 1.3 billion (19%) people are engaged in agricultural pursuit.[2] In the process of agricultural practice, the green revolution is a milestone that evolved between 1930s to late 1960s.[3] Since then, it has helped to increase agricultural production worldwide using hybrid seeds with controlled irrigation, chemical fertilizers, and mechanization in cultivation.[3] These hybrid seeds require a lot of fertilizers to increase productivity. This indiscriminate and unscientific use of fertilizers over an extended period decreases the fertility of soil gradually, reduces the quality of cultivated products, causes health hazards, increases environmental pollution, and causes ecological imbalance.[4] Uncontrolled use of irrigation causes soil erosion and deterioration of soil salinity.[5] Besides that, in order to get rid of insects and weeds, pesticides and herbicides are sprayed at a constant rate all over the field. This reduces soil moisture and nutrient content[6] of the field. The level of weed distribution and insect infestation is not equal all over the field. Thus, the requirement of pesticides and herbicides is also not the same. The resources of agriculture are decaying with time due to natural calamities, global warming, and indecorous use of pesticides and herbicides.[6] All these imbalances throw a challenge to the sustainable development in agriculture.

Sustainable agronomy signifies agricultural resource management while preserving ecological balances and economic profit to fulfill human needs with the help of modern technology.[7] Precision agriculture (PA) helps in achieving sustainable agronomy with the automation and technological involvement to control the improper use of resources with precise variable rate application. According to the Board on Agriculture, National Research Council, Department of Agriculture Research Education and Economics, USA, – PA can be defined as a site-specific crop management concept that can monitor inter- and intra-field variability.[8] This variability helps to predict the field-specific optimum requirement of resources like irrigation, fertilizers, pesticides, and herbicides. Thus, PA controls the application rate of these resources, maintaining agronomic and ecological balance to increase productivity, which further leads to sustainable development in agriculture. So, it can be considered as an effective and smart farm management strategy, which uses modern information technologies to fetch field data from multiple sources and make decisions related to the crop production.[8] PA automates site-specific management and adjusts the usage of water, fertilizer, pesticides, herbicides to increase crop yield and control them through variable rate application (VRA). The concept of PA first emerged at the end of the 20$^{th}$ century.[9] Practical implementation of PA concept is done in three different stages[9] – Data Collection, Data Analysis and Decision Making, and Variable Rate Control.

The first component in the management process is data collection, which acquires parameters like soil type, irrigation uniformity,

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field topography, fertilizer uniformity, soil moisture, soil nutrient, soil salinity, pest and disease infestation, rainfall, temperature, radiation, sun light, weed, and yield.[9] The second component analyses the collected data to realize their interdependency. This analysis results in an accurate mapping of the crop, yield, weed infestation, pest, salinity, and site-specific variable rate application of resources.[9] The third component applies the decided amount of water, fertilizers, pesticides, and herbicides with automated machinery at field level in real time.[9] A single technology cannot fulfill the purpose of each of the PA components simultaneously. So amalgamation of diverse information techniques is required to address the components of PA with proper agronomic knowledge.

The objective of this systematic review is to find out the present status, benefits, and limitations of existing modern technologies used in PA. For this reason, the techniques are extensively reviewed according to the basic PA components. It also highlights the future opportunities of technical advancement in PA that encourage the researchers to use modern technologies for sustainable agronomy.

This review is organized as follows. The next section describes the methods used to select the articles for this review. The third section draws the results of the systematic review following the methodology according to the three basic components of PA. The fourth section highlights the limitation of this study and finally the last section concludes the review with future direction.

## METHODS

This systematic review follows PRISMA guideline,[10] which is an evidence-based framework for carrying systematic review using the standard protocol. Rayyan software[11] is used to implement this protocol and find the result. All the authors of this article have designed and approved the methodology following the PRISMA guideline for this systematic review including focused questions, search database, strategy, inclusion and exclusion criteria, data extraction procedure, and PRISMA flowchart.

### Focused questions

What are the key technologies used in PA for sustainable agronomy? What are the present status of these technologies? What are the limitations of these technologies? What are the technical breaches identified for future research area?

### Information sources

A systematic literature search following the PRISMA guideline was performed on 20 February 2019 in two digital scientific journal database: Science Direct and IEEE Xplore. Except searching these databases, some reference search was also done from sources like from the reference of selected papers in Science Direct and IEEE Xplore, and articles suggested by the expert which were not available in the searched database with the search string.[12–25] Relevant literatures were identified based on the eligibility criteria fixed by the authors.

### Search strategy

The search strategy terms include Precision Agriculture, Precision Farming, Smart Agriculture, Smart Farming, and Technology, respectively. The terms of the same group were combined with 'OR' and different groups were combined with 'AND'. The final search string for both the database (Science Direct and IEEE Xplore) was (('Precision Agriculture' OR 'Precision Farming' OR 'Smart Agriculture' OR 'Smart Farming') AND 'Technology'). These terms were selected based on the aim of this review. Since our main aim was to find the research works which focused on key technologies used in PA, so different terminology related to PA were grouped with 'OR' and 'Technology' term was added with 'AND'. As application of PA includes sustainable solution for agriculture, therefore, 'Sustainable Agronomy' term was not considered separately. The searched articles were restricted to the language 'English' and year 2013 to 2019. The original research articles including conference proceedings and journals were selected for this systematic review. The duplicate articles were removed using Rayyan software. After that, the unique articles were screened based on the title, abstract and full text of the paper using the inclusion and exclusion criteria.

### Eligibility criteria

This systematic review highlights the state-of-the art technologies used in the main components of PA namely Data Collection, Data Analysis with Decision Making and Variable Rate Control. The eligibility criteria for the reviewed articles were set according to the application of the key technologies in the domain of these three components of PA. The search produced a list of articles that included application of technologies in the smart farming and applied field related to PA. All these articles were screened according to the inclusion and exclusion criteria.

The exclusion criteria for this review were as follows: (i) articles including review of the technologies in PA; (ii) comparison and simulation based study; (iii) literature on pure theoretical framework of PA application; (iv) study on adoption strategies in PA; (v) study in the applied field of PA like food industry and other farm except agriculture; and (vi) full text articles not available.

The inclusion criteria for this review were as follows: (i) the study that focused on application of information and communication technologies for data collection in PA; (ii) literatures that build a Decision Support System based on miscellaneous modern (DSSM) technologies for smart farming; and (iii) literatures on designing a variable rate control system for field level application.

### Data extraction

After screening, 67 number of articles were considered for qualitative analysis based on the eligibility criteria. These articles were thoroughly reviewed to collect significant information about the technologies used in data collection, data analysis, decision making, and variable rate control. The information includes the state-of-the-art technologies, application of these technologies in PA per year (2013–2019), and limitations of current technologies. The studied literatures are compared based on the frequency of application of the technologies, the focused parameters in agricultural field, the advantages, and disadvantages of the technologies and the field of application.

### PRISMA flow chart

The flow chart (Fig. 1) represents the key findings of systematic review following PRISMA guideline. The flowchart contains four phases – Identification, Screening, Eligibility, and Included. Each phase is represented with different colour scheme in the flow chart.

## RESULTS AND DISCUSSIONS

This section describes the enabling technologies in PA and their applications in real field. The technologies are categorized according to the basic components, parameters and applied field. After

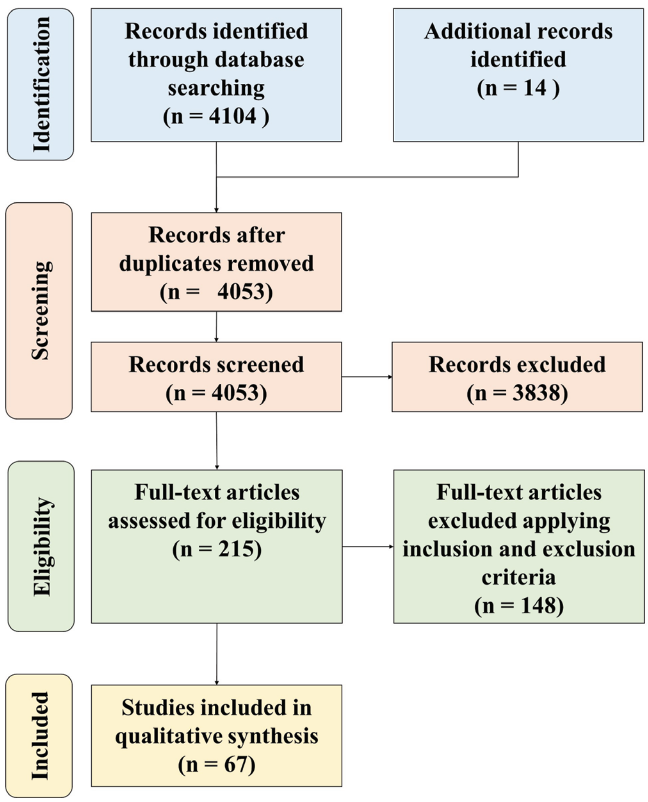


**Figure 1.** PRISMA flowchart of the systematic review on state-of-the-art technologies in precision agriculture.

that the results are summarized with the key findings following the research protocol.

### Studies' selection

According to this protocol a total 4104 number of articles were searched primarily from Science Direct and IEEE Xplore database. Another 14 articles[12–25] were identified from sources such as from the reference of selected papers, and articles suggested by the expert which were not available in the searched database with the search string. Therefore, a total of 4118 articles were first selected, then 65 duplicate articles were removed. The remaining 4053 number of articles were considered for screening by title, abstract and eligibility criteria. The screening resulted in the exclusion of 3838 number of articles on the basis of title and abstract using the eligibility criteria. The remaining 215 potentially significant full text articles were scrutinized methodically. Finally, 67 eligible articles were found for qualitative synthesis of their contents with the defined focus.

The extracted data discuss the present status of the reviewed technologies, their advantages, disadvantages, and the technical activities in PA per year and comparison of data collection technologies with respect to considered parameters within the years 2013–2019.

### Data collection: enabling technology

Data collection is a procedure of securely acquiring, transferring, and storing the data. Large fields are sub-divided into smaller management zones for precise data collection. Choosing appropriate zone of data collection is a vital point of PA. This is because the collected data should cover the entire field variability. There are mainly two types of variabilities, which directly affects the production – spatial and temporal variability.[26] Spatial variability measures soil and field-specific physical properties, yielding capability at different locations of land. Temporal variability measures the same variations with respect to time. Temporal variability also includes climate condition. The data collection should be done maintaining authenticity and reliability of data. Timely collection of correct and complete field level data is very important for taking the accurate decision for controlling the resources in the PA. Thus, it is required to develop a secure and time specific data collection and transmission process.

The technologies that can be used to measure all the parameters within the field and beyond the field and in the environment are Global Positioning System (GPS), Remote Sensing (RS), Wireless On-the Go Sensors (OTG_SENSOR) and Yield Monitors (YM).[8]

The technologies used in data collection for precision agriculture are summarized in Table 1. The summary concludes the following results for reviewed literatures – (i) real-time kinematic GPS (RTKGPS) is the mostly used real-time solution for positioning the agricultural vehicles to collect samples; (ii) airborne and remote sensing technology is used in maximum studies for observing the field and crop parameters; (iii) most of the wireless sensors are developed to measure soil and field parameters and very few are designed for monitoring crop and environmental condition; and (iv) yield monitor is mainly used for automated harvesting and yield measurement.

**Table 1.** Technology used in reviewed literatures for data collection: DGPS, differential global positioning system (GPS); RTKGPS, real-time kinematic GPS; UDGPS, user defined GPS; SRS, satellite-based remote sensing (RS); ANRS, airborne and near-field RS; SFP, soil and field parameter; CEP, crop and environmental parameter; CVYM, cereals and vegetables yield monitors (YM); FIYM, fruits and industrial crops YM

| | Technologies | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | GPS | | | RS | | OTG_SENSOR | | YM | |
| References | DGPS | RTKGPS | UDGPS | SRS | ANRS | SFP | CEP | CVYM | FIYM |
| 27 | √ | X | X | X | X | X | X | X | X |
| 12,13 | X | √ | X | X | X | X | X | X | X |
| 28,29 | X | X | √ | X | X | X | X | X | X |
| 14–16,30,31 | X | X | X | √ | X | X | X | X | X |
| 32–38 | X | X | X | X | √ | X | X | X | X |
| 17–19,39–51 | X | X | X | X | X | √ | √ | X | X |
| 20,21,52 | X | X | X | X | X | X | X | √ | √ |

**Table 2.** Comparative study of the reviewed papers based on collected parameters

| References | Parameters addressed | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | TP | SF | SPP | SCP | WI | CV | YD | WC | AV |
| 27,53 | √ | X | √ | X | X | X | X | X | X |
| 12,13,28 | √ | X | X | X | X | X | X | X | X |
| 29,30 | √ | X | X | X | X | X | √ | X | X |
| 15 | X | X | X | X | X | √ | X | √ | X |
| 16,17,22,33,39,54–58 | X | X | √ | X | X | X | X | X | X |
| 14,23,31,34,40,43,44,59–62 | X | X | X | √ | X | X | X | X | X |
| 45,63 | X | X | X | X | X | X | X | √ | X |
| 19,24,64,65 | X | X | X | X | X | X | X | X | √ |
| 32,35,36 | X | X | X | X | X | √ | X | X | X |
| 25,37,66,67 | X | X | √ | X | X | √ | X | X | X |
| 18,51 | X | X | √ | √ | X | X | X | X | X |
| 41,42,46,49,50,68–72 | X | X | √ | X | X | X | X | √ | X |
| 43,47 | X | X | √ | √ | X | X | X | √ | X |
| 20,21,52 | X | X | X | X | X | X | √ | X | X |
| 38 | X | X | X | X | X | √ | √ | X | X |
| 48 | X | X | X | X | X | X | X | √ | √ |
| 73 | X | X | X | X | √ | X | X | X | X |

Table 2 presents the comparison result of reviewed papers according to the measured parameters. Agricultural productivity depends on nine parameters[26] like Topological Parameters (TP) which help to analyse field structure and texture,[26] Soil Fertility (SF), Soil Physical Properties (SPP), Soil Chemical Properties (SCP), unwanted plant or Weed Infestation (WI), Crop Variability (CV), Yield Distribution (YD), Weather Condition (WC), Additional Variability (AV) like pest and crop disease infestation, hay damage, nematode infestation, damage due to natural calamities like wind, storm and flood, etc. This comparative study will help the researchers to discover the unexplored segment of data collection in PA. This analysis shows that interdependence among field and environmental parameters are ignored in most of the reviewed literature. It leads to develop automated control mechanism considering correlation among different parameters.

### Data analysis and decision making: enabling technology

Data analysis is a procedure of studying the data, cleaning incorrect, ambiguous, incomplete data, and reforming the data to extract useful information. In PA, data analysis is required to know the relationship among different fields and weather parameters. Prescription maps are generated based on this analysis. These maps plot site-specific requirement of the resources like water, fertilizer, pesticide, and herbicide, etc. Control decision is taken based on these maps at the right time and right place. The technology used for data analysis in PA are mainly Geospatial tools, Soft Computing (SC),[74] Modern Software (MS) and information technology. Geographic Information System (GIS)[75] software is used for geospatial analysis. Since 1950, Decision Support System (DSS)[76] with Information and Communication Technology (ICT) is popular for its capability of intelligent data modelling. Agricultural data are highly correlated. So, finding a pattern from these data on the mass scale and taking precise control decision about input resources is really a challenging task. In literature, technologies like GIS,[75] Fuzzy Logic (FL),[77] Machine Learning Technology (MLT),[77] Adaptive Neuro-Fuzzy Inference System (ANFIS),[77] nature inspired algorithms,[78] Cloud Computing (CC),[68] Internet of Things (IOT),[53] etc. are used to overcome these challenges.

**Table 3.** Technology used in reviewed literature for data analysis and decision-making

| References | GIS | ANFIS | Fuzzy | MLT | Soft | CC | IOT |
|---|---|---|---|---|---|---|---|
| 22,23,25,66,67,79 | √ | X | X | X | X | X | X |
| 54,69,70 | X | √ | √ | X | X | X | X |
| 51,70 | X | X | X | √ | X | X | X |
| 55,56,80 | X | X | X | X | √ | X | X |
| 57,58,68,81 | X | X | X | X | X | √ | X |
| 48–50,71,82 | X | X | X | X | X | √ | √ |
| 63 | X | X | X | √ | X | √ | X |
| 46 | X | X | √ | √ | X | X | X |
| 72 | X | X | √ | X | X | X | X |

Table 3 summarizes all these technologies used in data analysis and decision-making. From Table 3 we can draw a comparative analysis on different technologies used in developing DSS for PA application. In literature, most of the research works consider GIS software for making a decision about the agricultural field. Very few research works consider MLT and CC to build up a DSS. So future research can consider these technologies in making efficient DSS for PA. Moreover, secure data communication is a challenging part of PA applications. Very few researches address the security and reliability of data communication in the agricultural field. It opens a new direction of research in the PA field.

### Variable rate control: enabling technology

The final component of PA concept is Variable Rate Control (VRC) that implements management decisions at the right time and place.[9] VRC is a process of applying varying rates of inputs (water, fertilizer, pesticides, etc.) at proper zones throughout the field in an optimized way. This optimum utilization of resources helps to maintain economic profit ensuring sustainability and environmental safety. The technology used for variable rate control is known as Variable Rate Technology (VRT).[9]

**Table 4.** Technology used in reviewed literature for variable rate control

| References | Technologies | | | |
|---|---|---|---|---|
| | VRF | VRP | VRH | VRI |
| 59–62 | √ | X | X | X |
| 64 | X | √ | √ | X |
| 24 | X | X | X | X |
| 65 | √ | X | X | √ |
| 73 | X | X | √ | X |
| 83 | X | √ | X | X |

Variable rate technologies are briefed in Table 4. From Table 4 it is clear that most of the literatures concentrate on Variable Rate Fertigation (VRF). Very little work is done on the combination of four types of VRT – Variable Rate Irrigation (VRI), Variable Rate Fertigation (VRF), Variable Rate Pesticide (VRP), and Variable Rate Herbicide (VRH). It inspires the researchers to develop a single control unit that considers the correlation among different field and weather parameters and develop a combined VRT. This combined VRT can apply water, fertilizer, pesticide, and herbicide at a prescribed rate with a centralized controller.

### Comparative analysis of enabling technologies in PA

In this section, enabling technologies of PA are compared with respect to their frequency of used, advantages and limitations. The reviewed papers are arranged according to the year of publication to analyse the year, which was technically the most active one in the field of PA application (Fig. 2). Figure 2 shows that the major technical innovations in this field took place in the year of 2016.

Then the reviewed papers are arranged according to the technology considered, to figure out the most popular technology in PA. The graph in Fig. 3 represents the frequency of used technology in PA. This graph depicts that RS and OTG_SENSOR are the mostly used technology in PA application and yield monitor unit, GIS and soft computing-based decision-making are very rare in PA. Table 5 lists down all these technologies with their advantages and limitations. Table 6 compares the reviewed literatures with respect to the 'field of application' and 'concluding result'. From this comparison table it can be concluded that most of literatures worked on developing decision support system and variable rate technology. But they did not consider the reliability of collecting spatio-temporal variables from real field and interference of soil physical and chemical properties and weather condition at a time.

## LIMITATIONS OF THIS REVIEW

There are some limitations in this systematic review. It only considers the published literatures on the application of key technologies at three components of PA. There are various DSS available as app in play store to help the farmer based on the input parameters. These applications have not been considered in this study, as full descriptions of these applications are not available to understand their functionality. In contrast, full descriptions of applied technologies are found in the original research articles more clearly. Not only that, this research work also did not consider the theoretical framework of a PA application due to unavailability of field level experiment. The unpublished articles, unavailable full text articles, articles in other languages and articles not directly connected with the three components of PA are excluded in this study. Moreover, different number of articles may be found with different search strategies. Therefore, this review does not ensure the coverage of full list of technical innovations and their status in PA.

## CONCLUSION AND FUTURE SCOPE

PA is an eco-friendly solution for site-specific farm management. It is a state-of-the-art concept in agriculture for developing smart farming. Since the early 1990s, the agriculture of developed countries has benefitted with the practical implementation of this concept throughout the world. Extensive research is required to make it successful all over the world not only for large-scale farms in developed countries, but also for small-scale farms in developing countries. This encourage us to find the future key technologies for sustainable agronomy. In this review, the role of modern technologies at different stages of PA concept have

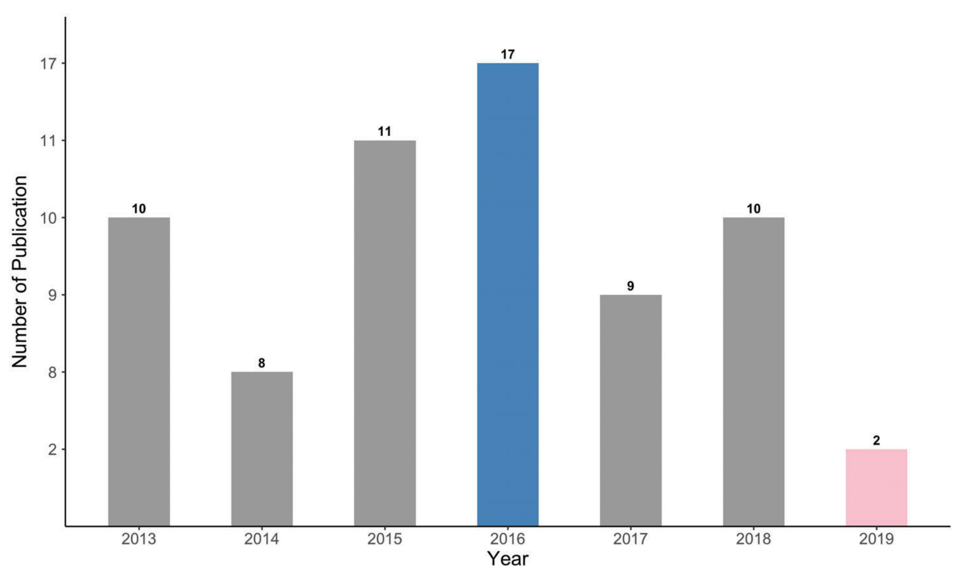


**Figure 2.** Classification of reviewed paper according to the year of publication.


  

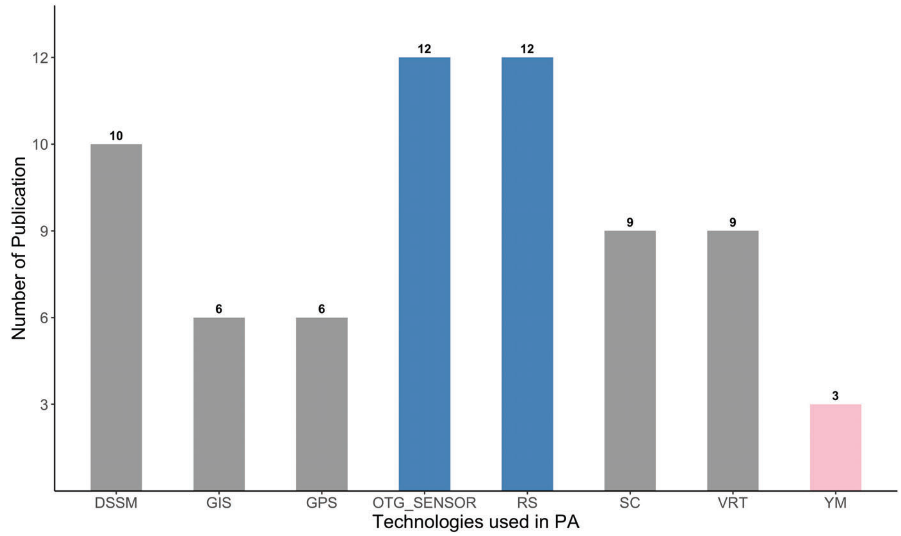


**Figure 3.** Classification of reviewed paper according to the state-of-the-art technologies in precision agriculture.

**Table 5.** Comparison of enabling technologies

| Technology | Benefits | Limitations |
|---|---|---|
| GPS | GPS provides positional information for precise data collection at real time for smart farming. | 1. It provides poor signal due to hindrance like a tree, building, storms etc.,<br>2. It is not a cost-effective solution for small-scale farm as power source is limited. |
| RS | It provides a visual representation of field status, monitors the health condition of crop and field. | 1. It uses costly and sophisticated instruments.<br>2. Expert is required to analyze the result of it.<br>3. Robust image and data analysis method are required.<br>4. The accuracy is low due to low resolution.<br>5. It provides low coverage area with a high cost.<br>6. Error in collecting data due to signal interruption caused by trees, buildings, weather condition, and natural calamities. |
| OTG_SENSOR | It ensures real-time continuous monitoring of field and weather condition and precise variable rate control. | 1. The wireless ground sensors are commercially unavailable.<br>2. High chance of data alteration during simultaneous data transmission by different sensors.<br>3. Data transmission maintaining integrity and security is a challenging task.<br>4. Limited battery life of the sensors. |
| YM | Yield monitor automates the process of yielding and helps to fetch yield related information for crops at real time. | 1. It is not a cost-effective solution for small-scale fragmented land structure as equipment's of yield monitor are very costly.<br>2. Technical expertise is required to operate it.<br>3. Accuracy of yield monitor is affected by various factors like − Incorrect swath width, Time delay through the threshing mechanism, GPS error, Grain loss, Sensor calibration. |
| GIS | It provides accurate geospatial information, topological texture of a field, a prescription map with layered architecture for resource allocation. | 1. GIS packages like ArcView, ArcGIS, and IDRISI, etc. are expensive.<br>2. It requires a large amount of geographic data to generate the layered map. This huge volume of data creates overhead in terms of storage space and processing time.<br>3. It does not provide a cost effective and real-time solution for PA application, as data processing and analysing time is high.<br>4. Technical expertise is required to analyse the prescription map. |
| DSS | It removes vagueness, inexactness, ambiguity from agricultural data by real-time analysis. | 1. Available DSS models concentrate mainly on large-scale and organized farms.<br>2. The experiment is required to find the applicability of existing models in fragmented, unorganized field structure.<br>3. Automated dynamic DSS for the fragmented land.<br>4. Building an efficient and flawless DSS model considering inter-dependency among spatial and temporal parameters for PA is a challenging task. |
| VRT | It reduces the wastage of resources, ensures healthy environment reducing the rate of pesticides and herbicides application. | 1. A single controlling unit is required for different sensing module considering the inter-dependency among soil parameters like soil type, water level, pH level, N-P-K content etc.<br>2. Research is required to design a cost effective variable rate control system for small-scale farmers. |

  

**Table 6.** Comparison of reviewed studies with respect to field of application and result

| References | Field of application | Result |
|---|---|---|
| 68 | Automated DSS for irrigation control. | Designed a cloud-based automated variable rate irrigation control system using Ruby and Amazon Cloud Services. |
| 53 | IOT-based Smart Farming. | Generate a prescription map to apply resources according to the requirement. |
| 27 | DGPS enabled unmanned aerial vehicular system for PA. | Generate a prescription map of field topography using RS. |
| 12 | RTKGPS enabled auto navigation system for PA. | An auto navigation tractor for farming in mountain area. |
| 13 | RTKGPS enabled vehicular guidance system for smart farming. | A low cost positioning system for agricultural vehicles. |
| 28 | Sampling position calculation for Precision Farming with a low cost positional device. | A low cost positioning system for precise farming. |
| 29 | Field monitoring system. | Collect field data to predict the yield with supervised learning method. |
| 14 | Field variable estimation from satellite data. | Estimate nitrogen status in rice field at key growth stage. |
| 30 | Field variable monitoring and yield mapping based on satellite data. | A monitoring and yield predicting system for PA. |
| 31 | Mapping soil reflectance pattern with other properties based on multispectral RS images. | A model to generate soil properties map with GIS. |
| 15 | Monitoring crop growth condition and environmental stress in oilseed rape from satellite data. | Developed a model to monitor crop physical condition by estimating the green leaf area index. |
| 16 | Estimation of water distribution in the field from satellite images. | A model to evaluate Water Distribution in field. |
| 32 | Remote data collection and analysis from an unmanned aerial vehicle. | A model to estimate crop canopy coverage, biomass, chlorophyll content and nitrogen deficiency in PA. |
| 33 | Soil moisture level measurement from airborne imagery. | Soil moisture level estimation model for pivot irrigation control. |
| 34 | Field nitrogen status monitoring from airborne imagery. | A model to estimate Site-specific nitrogen requirement. |
| 35 | Chlorophyll concentration measurement from high and multi spectral images. | A system to measure chlorophyll concentration from an unmanned vehicular system. |
| 36 | Crop health condition and water requirement monitoring from vegetation indices. | A dynamic model for water stress management from an unmanned aerial vehicle. |
| 37 | Water stress management from soil moisture level in sugar beet plant. | A model to evaluate water stress from thermal images captured using an unmanned aerial vehicle. |
| 38 | Yield distribution and crop variability monitoring from dynamic reflections pattern of the field from aerial sensor platform. | Developed an aerial sensor platform to monitor dynamic reflection pattern in real field using GPS navigated flights. |
| 39 | Soil moisture level monitoring at the top layer of soil. | Deployed a wireless sensor network with soil moisture and temperature sensors. |
| 40 | Soil fertility measurement from electrical conductivity and top soil depth. | Soil fertility estimation model using ultrasonic sensor. |
| 41 | Field monitoring based on temperature, soil moisture, and humidity data. | Developed a sensor-based field monitoring system. |
| 17 | Sensor-based soil moisture level estimation. | Designed an automated irrigation control system. |
| 42 | Water requirement prediction from soil moisture content and environmental condition. | A prediction model from historical and real-time data by support vector machine and relevance vector machine. |
| 43 | Sensor-based soil nitrogen status management. | Design an *in situ* soil nitrogen sensor network. |
| 43 | Irrigation control decision-based soil moisture, water flow, and temperature sensor's data. | Design an Arduino-based smart irrigation control system. |
| 44 | Sensor-based soil pH level estimation. | A model to measure soil pH level using pH sensor. |
| 18 | Water level estimation based on soil moisture and pH sensor values. | Design an automated water sprinkler. |
| 45 | Sensor-based field variability management. | Proposed an environmental parameter monitoring system. |
| 19 | Pest management. | Developed a smart ultrasonic sensor to detect farm pest. |
| 46 | Irrigation prediction model based on real-time soil moisture content and weather condition. | Proposed a weather model using fuzzy logic to generate hourly suggestions on water requirement of the field. |
| 47 | Wireless sensor network-based real-time and reliable field data collection for PA. | Proposed a reliable and cost-effective routing protocol APTEEN for PA. |
| 48 | Smart DSS based on field parameters. | Proposed a cost-effective, real-time, low powered monitoring system for the smart-phones. |
| 49 | Smart irrigation management based on weather condition and field parameters. | Proposed a real-time cloud-based information visualization system to predict irrigation requirement. |
| 50 | Smart irrigation control in PA. | Developed a three-layer mobile application for smart irrigation control based on IOT. First layer collects field, weather, and crop data, Second-layer analyses those data and third layer control the water level both automatically and manually by the user. |

**Table 6.** Continued

| References | Field of application | Result |
|---|---|---|
| 51 | Soil condition prediction system. | Proposed a soil toxicity prediction system based on soft computing algorithm. |
| 20 | Yield monitor. | Proposed a proximity sensor for YM. |
| 21 | Yield monitor. | Developed a mass flow sensor for YM. |
| 52 | Yield monitor. | Designed a cloud-based yield monitoring system. |
| 22 | Variable rate irrigation management based on soil moisture level. | Proposed a model to assess the pattern of soil moisture with respect to time using standard geo-statistical analysis. |
| 54 | Smart water requirement control system for PA application. | Proposed a fuzzy-based smart irrigation management. |
| 55 | DSS for smart harvesting and irrigation management. | Proposed a DSS to choose the best time for harvesting and predict water requirement. |
| 56 | Android-based DSS for smart farming. | Developed an information communication technology-based DSS. |
| 57 | A dynamic DSS based on heterogeneous field data. | Proposed a scalable cloud-based DSS, Agrilaxy for PA. |
| 58 | Cloud-based water management system. | Developed an application that can predict precise water requirement for PA. |
| 23 | Variable rate irrigation management based on estimated soil water content. | Estimated soil water content based on soil sample and geo-physical data. |
| 59 | Variable rate fertilizer management. | Proposed an optimized VRF based on the nature of explosion of fireworks. |
| 60 | Variable rate fertilizer management. | Developed an automated VRF. |
| 61 | Variable rate fertilizer management. | Developed an automated VRF. |
| 62 | Variable rate fertilizer management. | Designed a master slave control for VRF. |
| 63 | Crop characteristics prediction model based on environmental parameters. | Proposed a predictive model using machine learning and cloud computing technology. |
| 64 | Variable rate pesticide management. | Proposed a scheduling algorithm for VRP. |
| 24 | Variable rate herbicide management. | Developed a VRH classifying crop and weed with wavelet feature analysis. |
| 65 | Variable rate spraying system. | Designed a variable rate spraying system based on crop canopy and growth level. |
| 66 | Agricultural decision-making based on field parameters. | Developed a PA management system with IoT and GIS software. |
| 67 | Monitoring the effect of shadow length and planting angle in crop growth. | Developed a model to monitor the effect of plantation angle on crop growth. |
| 25 | Soil fertility status assessment from the spatial distribution of soil chemical properties. | Developed a model to calculate soil fertility status using geo-spatial method. |
| 69 | DSS for irrigation management based on weather and field condition. | Proposed a smart irrigation control model using fuzzy logic. |
| 70 | Water requirement prediction based on soil and environmental variables. | Proposed a smart Irrigation management model using Partial least square regression model and Adaptive Neuro Fuzzy Inference System. |
| 71 | DSS for irrigation control. | Designed an alert-based DSS using IOT and cloud computing technology. |
| 72 | Variable rate irrigation management. | Proposed a smart irrigation control system based on fuzzy logic. |
| 73 | Smart weed detection and variable rate herbicide management. | Proposed an artificial intelligent-based weed detection system for VRH. |
| 79 | Variable rate irrigation management with recycled water. | Developed an IOT-based variable rate irrigation model. |
| 80 | Variable rate irrigation and fertilizer management. | Developed a cost-effective mobile application for real-time monitoring of water and fertilizer in the field based on IOT. |
| 81 | Real-time agricultural decision-making platform. | Proposed a real-time DSS for smart farming using cloud computing technology. |
| 82 | Smart irrigation management. | Proposed a real-time irrigation management system using IOT. |
| 83 | Variable rate pesticide management. | Developed a mobile application which can detect the row of crop and activate the related sprinkler for optimized pesticide application. |

been discussed. These technologies are grouped according to the three key components of PA namely – Data Collection, Analysis, and Variable Rate Control. Information and communication technologies such as – GPS, GIS, Wireless Sensor Network (WSN), Yield monitoring system, RS, DSS, and VRT involved in these three stages of PA are reviewed with their technical advantages and disadvantages. A total of 67 relevant articles are found for these technologies in PA. At first enabling technologies used for data collection are comprehensively studied and further compared with respect to all available spatiotemporal variabilities. This helps in analysing the correlation among all the measured parameters for real-time analysis. In smart farming, real-time analysis is very crucial thus, this study helps in achieving the goal for sustainable development. Next, technologies used in agricultural decision making are reviewed to find out the open research areas in agricultural data analytics. This helps in developing dynamic decision support system by analysing huge agricultural data in real time. At last, different variable rate technologies are studied and compared.

After reviewing all these articles, we can conclude that this systematic review provides a detailed analysis of the key technologies in PA for sustainable agronomy thereby giving a useful insight about the ways of technical development in smart farming. This survey has a significant and useful contribution for emerging areas in PA research. To ensure the goal of sustainable agronomy, following future research areas are identified from this systematic review.

1 Site-specific farming in fragmented land structure using single controller.
2 Identifying the relationship among different field parameters simultaneously and developing the control mechanism based on that.
3 Designing cost effective variable rate controlling system.
4 Designing low power sensing module.

These challenges open a broad research area to develop new concept in sensor-based PA. Moreover, there are also some societal challenges that create obstacle in adopting PA concept for developing countries. These are small-scale farming, fragmented land with multiple ownership, heterogeneity of cropping systems, lack of experts, lack of knowledge, lack of technical involvement and market imperfections.

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## CONFLICTS OF INTEREST

The authors have declared no conflict of interest.

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