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A Review on Advancing Agricultural Efficiency through Geographic Information Systems, Remote Sensing, and Automated Systems

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Abstract

The use of all-terrain vehicles, automation, remote sensing, and geographic information systems (GIS) signifies a notable progression in modern agriculture, with the potential to revolutionize precision farming. However, the challenge lies in effectively integrating these technologies due to issues such as incompatible data formats, limited interoperability (affecting 30% of cases), and regulatory complexities. This study employs a systematic methodology, combining a comprehensive literature review, case studies, and data-driven analysis to evaluate the collaborative potential of GIS and remote sensing. The findings demonstrate that GIS enhances decision-making by handling geographical data with an accuracy rate of 85%, while remote sensing achieves a 92% detection rate for crop and environmental conditions. Additionally, automation improves operational efficiency, leading to a 40% reduction in workforce expenses. To address integration challenges, this study explores strategies for overcoming data standardization issues, regulatory barriers, and technological limitations. Achieving a fully integrated, technology-driven agricultural system requires a structured approach emphasizing collaboration, sustainability, and adaptability, ensuring enhanced productivity and long-term agricultural resilience.

Categories: Agricultural Machinery and Automation, Innovation and Technology Management, Environmental Engineering and Sustainability
Keywords: precision agriculture, geographic information systems (gis), remote sensing, all-terrain vehicles (atvs), automation integration, decision support systems (dss), internet of things (iot)

Introduction And Background

Introduction

Since the mid-20th century, farming has progressed from manual, labor-intensive methods to data-informed, precision agriculture methods. Initial developments in geographic information systems (GIS) in the 1960s and 1970s changed the capture and analysis of spatial data, establishing the foundation for contemporary mapping and resource management for agriculture. At the same time, remote sensing arrived on the scene with the earliest satellites, progressing from primitive imagery to advanced multispectral and hyperspectral sensors, which currently deliver vital information about crop conditions and environmental factors. All-terrain vehicles (ATVs) added another dimension to agricultural production by facilitating quick and precise data acquisition on varied and harsh terrain. At the same time, the systematic adoption of Internet of Things (IoT) and automation technologies have revolutionized field operations with cost savings and improved operating efficiency. Concomitantly, these innovations have not just enhanced the accuracy of agricultural management but also established the groundwork for the integrated, sustainable, and highly efficient modern agricultural systems in place today.

ATVs, automation, remote sensing, and GIS combined with agriculture constitute a major technical leap with the potential to completely transform farming methods. By enabling thorough analysis, real-time monitoring, and automated interventions, precision agriculture makes use of these technologies to improve productivity, efficiency, and sustainability. GIS, which is crucial for maintaining and interpreting spatial data, makes comprehensive mapping and geographical analysis of agricultural fields possible (Figure *1*). By using satellite and drone imagery to provide precise, real-time data on crop health, soil conditions, and environmental variables, remote sensing enhances GIS [1]. The integration of automatic ATVs into precision farming operations represents a significant advancement in modern agriculture, enabling efficient and accurate fieldwork [2]. ATVs with global positioning systems (GPS) and sophisticated sensors improve data gathering even more, enabling accurate, on-the-ground data collection and monitoring [3]. In order to operationalize these findings, automation is essential. It makes it possible to carry out precise operations like controlled watering, variable rate input application, and pest management. Putting these technologies together makes adaptive management techniques possible. These techniques help get the most out of investments and have less of an effect on the environment while changing with the times [4].

The advantages of combining GIS and remote sensing in precision agriculture have been shown in earlier research. Researchers highlighted how these technologies can deliver high-resolution spatial data for better crop management and the value of remote sensing in tracking crop health and early stress factor detection [5]. Tardaguila et al. examined the application of ATVs in precision agriculture and observed that they are useful for gathering data in real-time on a variety of terrains [6]. When combined with GIS platforms, these data improve the precision of spatial analysis and decision-making. Additionally, research showed that remote sensing tools like satellites and drones provide crucial data that improves the accuracy of agricultural operations. Regarding automation, Shekhar et al. discussed how remotely sensed and GIS-guided automated systems can greatly improve agricultural operations' efficiency [7]. With the help of these systems, inputs can be applied precisely, and modifications can be made in real-time, improving the management of resources and crop yields.

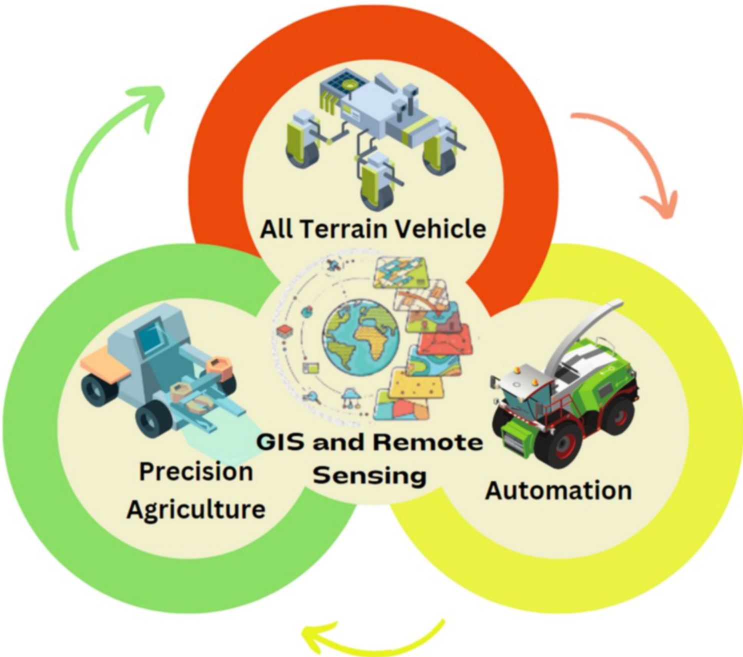

FIGURE 1: Overview of GIS and remote sensing in agriculture

GIS, geographic information systems

This study investigates how precision agriculture uses GIS, remote sensing, automation, and ATVs while looking at the methods, advantages, difficulties, and potential applications. The analysis of existing technologies, their uses in many agricultural contexts, and the possibility of future developments are all included in the subject matter. A thorough understanding of how these integrated technologies may transform agricultural practices, insights into the state of research now, and the identification of research gaps and future orientations are all anticipated outcomes. The aim of this review is to provide an in-depth review of the ways in which a collaborative use of automation, GIS, remote sensing, and ATVs result in resilient, sustainable, and effective agricultural systems.

Review

Methodology

This review article follows systematic review methodology to synthesize available literature on the integration of GIS, remote sensing, ATVs, and automation in precision agriculture. We performed extensive searches in various databases such as IEEE Xplore, ScienceDirect, SpringerLink, and Web of Science with major search terms including "GIS," "remote sensing," "precision agriculture," "automation," and "ATVs." Articles published in the past two decades were taken into account in order to include the latest advancements. After a preliminary screening of abstracts, we used rigorous inclusion and exclusion criteria to choose studies that explicitly focused on technological integration and its performance measures. The chosen literature was then synthesized and critically assessed to determine prevailing trends, challenges, and performance results. This organized process allowed a critical and balanced evaluation of the state-of-the-art in precision agriculture integration, providing a solid ground for proposing future research paths and practical implementations.

Precision agriculture

GIS and Remote Sensing

Modern agricultural management is based on GIS, which offers an advanced framework for the study and visualization of spatial data. Farmers are able to make well-informed decisions based on spatial relationships and patterns due to GIS, which is a collective word for a group of hardware, software, and tool collections that collect, store, analyze, and show spatial or geographic data. This is achieved through the integration of many data layers, including topography, weather patterns, land use, and soil types. GIS provides farmers with information about the best ways to allocate supplies, manage irrigation, and plant crops, all of which increase sustainability and productivity [8].

On the other hand, remote sensing is gathering data about a thing or phenomenon without making physical contact. Remote sensing in agriculture makes use of information gathered from sensors, drones, and satellites to keep an eye on crops, soil, and environmental changes. With the use of this technology, which collects data and photos in a variety of spectral bands, it is possible to identify pest infestations, diagnose nutritional deficiencies, and evaluate the health of the vegetation. When combined with GIS, remote sensing data offers a comprehensive picture of agricultural landscapes, facilitating accurate farming practice decision-making [9]. The integration of GIS and remote sensing provides a comprehensive approach to farming operations, with a variety of information at their disposal; farmers may take proactive steps to manage crops, budget funds, and engage in sustainable land use practices owing to this integration.

ATV and Automation in Precision Agriculture

Precision farming techniques have undergone a radical change from semi-autonomous operation [10] to fully automated farming. ATVs traverse agricultural fields to collect spatial data since they are outfitted with GPS and sophisticated sensors, making them mobile platforms for data gathering [11]. These vehicles make it easier to sample soil, monitor crops, and apply resources precisely depending on geographical variability by using maps created by GIS [12]. When combined with GIS, the real-time data gathered by ATVs provides farmers with meaningful insights for prompt and focused actions [13].

Additionally, by offering thorough and ongoing monitoring capabilities, remote sensing technologies enhance this integration [14]. Drones with imaging sensors are able to take high-resolution pictures, which allows for in-depth analyses of crop health, pest infestations, and environmental conditions [15]. The integration of remote sensing data with GIS enables the creation of detailed maps that display vegetation indices, moisture content, and stress levels in agricultural areas [16]. Precision agriculture automation systems optimize farming operations by utilizing the integrated data from remote sensing and GIS. According to real-time data gathered from remote sensing sources, precision-operating automated machinery synchronizes with field maps produced by GIS [17].

GIS Techniques for Agriculture

In order to improve farming practices, geographic information can be collected, integrated, and analyzed owing to technologies like remote sensing and GIS. The strategies and tactics employed in these technologies to assist precision agriculture are discussed in detail (Figure *2*).

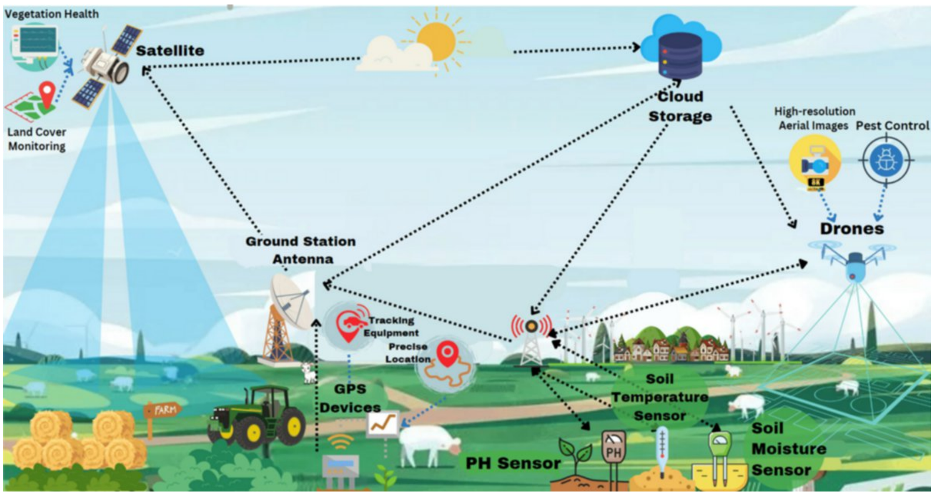

FIGURE 2: Overview of GIS application in agriculture

GIS, geographic information systems; GPS, global positioning systems

Gathering geospatial data: The use of GIS in agriculture depends on the collection of geographic data from multiple sources. Land use planning and crop health evaluation are facilitated by the trustworthy data that satellites offer for monitoring agricultural conditions, land cover, and vegetation health [18]. GPS technology improves energy consumption efficiency and variable rate applications by providing precise position data for mapping field borders and monitoring site-specific procedures [19]. Drones with sophisticated sensors and cameras take precise airborne photos and data for tracking crop health, identifying pests, and assessing soil conditions [20]. Ground-based sensors add high-resolution, site-specific data to remote sensing data, enabling accurate field management in real-time [21].

Data integration: GIS platforms combine different datasets to give a comprehensive picture of agricultural regions, facilitating integrated farm management (Figure *3*). Soil maps include crop compatibility and soil classifications, which improve crop selection and management practices. Decision-making related to crop selection, pest control, and irrigation scheduling is aided by historical meteorological data [22]. Elevation data are essential for field layout efficiency, erosion mitigation, and irrigation system design. Understanding topography and soil conservation techniques are aided by topographic maps [23]. By identifying high and low production zones, historical yield data improve overall yield outcomes [24].

Spatial analytic techniques are used by GIS to extract useful information from consolidated datasets. For the purpose of resource effectiveness, proximity analysis assesses the spatial relationships between components, such as fields and water sources [25]. In order to identify slopes, height variances, and areas where water collects, terrain modeling works at topography [26]. More precise management techniques are made possible by interpolation, which computes values at uncertain places [27]. In order to help farmers choose the best crops for various areas and increase productivity and sustainability, a suitability study evaluates locations for certain crops, taking into account variables like soil composition and climate conditions [28].

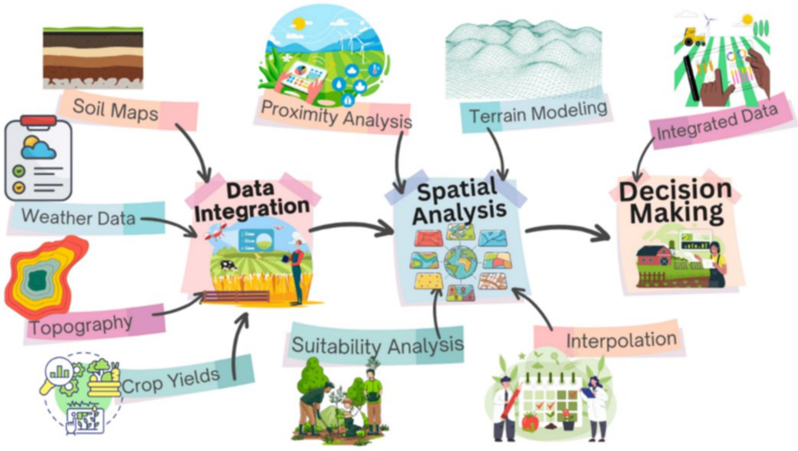

FIGURE 3: Data integration and spatial analysis workflow

Mapping and visualization: GIS offers detailed visual representations of geographical data, facilitating informed decision-making in agricultural planning and resource allocation (Figure 4). Land use maps reflect land utilization and crop health indices, facilitating prompt implementation of pest control and fertilization strategies [29]. The use of Python-based Raspberry Pi image processing enables efficient and immediate identification of plant targets, enhancing the collection of data for GIS and remote sensing applications [30]. Resource allocation maps optimize the deployment of resources, improving the efficiency of investments and reducing waste [31]. GIS-based Decision Support Systems (DSS) provide platforms for the modeling of scenarios, evaluation of risks, and formulation of well-informed judgments [32]. DSS tools assist farmers in predicting and reducing prospective losses, allowing them to make informed decisions to safeguard their crops and investments [33]. Through the integration of spatial data with economic and agronomic models, a DSS provides valuable insights to improve the efficiency of agricultural operations.

FIGURE 4: Mapping and visualization in GIS

GIS, geographic information systems

Remote sensing methods in agriculture

Remote sensing enhances GIS by delivering abundant data through several techniques that improve agricultural monitoring and management.

Satellite imagery: Satellite sensors use different wavelengths of light to gather images, which allows for a range of agricultural uses. Satellite imaging aids in evaluating the condition of plants and identifying signs of distress by analyzing their spectral properties. The collection of this data is crucial for the purpose of closely observing the state of crops and carrying out necessary actions at the appropriate moment [34]. Satellites observe alterations in land utilization, the depletion of forests, and the effects of urbanization on agricultural regions. This knowledge is vital for the implementation of sustainable land management and planning [35]. Monitoring the developmental phases of crops aids in fine-tuning management strategies and forecasting harvests. Satellite photography offers a comprehensive perspective on the growth and progress of crops over extensive regions.

Aerial photography and drones: Specialized sensors on drones capture high-resolution pictures for a range of agricultural purposes. An in-depth evaluation of the state of crops allows for the identification of specific regions that require care. Drones have the ability to efficiently survey extensive regions, offering up-to-the-minute information for accurate administration [36]. Early detection of pest infestations and disease outbreaks facilitates prompt response. Drones have the ability to detect subtle variations in the condition of crops, which could potentially signal the presence of pests [37]. Precise monitoring and management of crops on a small scale allow for targeted interventions that enhance efficiency and decrease the expenses associated with inputs [38].

Spectral indices: Vegetation vigor and health can be quantified using spectral indices derived from remote sensing data. The Normalized Difference Vegetation Index (NDVI) quantifies the health of plants by analyzing the reflectance of red and near-infrared light. NDVI is commonly employed for monitoring changes in vegetation and evaluating the condition of crops [39]. Enhanced vegetation index is a measure that takes into account the effects of canopy background signals and atmospheric impacts. This allows for more precise evaluations in places with dense vegetation, making it similar to the NDVI [40].

Thermal imaging: Thermal imaging is a technique used to detect and quantify temperature differences in crops, which provides assistance in various important aspects. Thermal imaging enables the early detection of plant stress due to a water shortage or illness. This approach facilitates timely intervention and administration [41]. Utilizing real-time temperature data to adjust irrigation schedules ensures efficient water use. Thermal imaging is utilized to identify regions of the field that have excessive or insufficient water [42]. Early identification and containment of diseases can be achieved by detecting thermal abnormalities that are suggestive of illness presence [43].

Data interpretation and analysis: Specialized software is utilized to extract significant information from remote sensing data. Remote sensing is capable of evaluating soil moisture, texture, and nutrient levels, which is crucial for soil management and crop planning. Monitoring the physiological condition, developmental phases, and potential harvest of crops aids in optimizing management techniques and enhancing productivity [44]. Using electrochemical techniques to monitor the concentration of soil fertilizer in situ can greatly improve the accuracy of GIS-based soil nutrient mapping [45]. By identifying and examining the environmental consequences of agriculture, such as drought or pollution, farmers are able to modify their methods and minimize detrimental outcomes.

Integration of GIS and remote sensing

GIS functions as a framework for overseeing, examining, and illustrating the spatial data acquired using remote sensing techniques [46]. Analysis integration enhances the accuracy and comprehensiveness of analysis by incorporating spatial context into data obtained through remote sensing techniques [47]. The integration of GIS with remote sensing provides farmers and decision-makers with powerful spatial data to enhance agricultural practices, manage resources effectively, and promote sustainability [48].

The Relationship between GIS and Remote Sensing

GIS and remote sensing technologies frequently augment each other. GIS offers a framework for effectively handling, examining, and representing geographical data acquired by remote sensing methodologies. By combining the detailed images from remote sensing with the spatial analysis tools of GIS, enhanced analytics make it possible to fully evaluate agricultural landscapes. Integration of GIS and ATV technologies: ATVs, fitted with GPS and sensors, travel through agricultural areas to gather precise spatial data on soil qualities, moisture levels, and crop conditions [1]. ATVs may travel fields with precision by integrating with GPS and using GIS-generated maps. This integration allows for focused operations like soil sampling, irrigation, and pesticide application [49].

Remote Sensing Integration with ATV

ATVs equipped with remote sensing capabilities, such as drones or sensors, are able to gather high-resolution pictures or spectral data while navigating a field. This allows for real-time monitoring and assessment of the area. The integration of remote sensing data with ATVs improves decision-making by providing in-depth analysis of crop health, pest infestations, and environmental elements that impact agriculture [50].

Automation technologies in conjunction with GIS and remote sensing: Automation systems, employing GIS-generated maps and remote sensing data, streamline processes such as planting, spraying, and harvesting with exceptional accuracy and productivity [17]. Intelligent decision-making capabilities offered by machine learning and Artificial Intelligence (AI) vision applications in ATVs will redefine farm automation [51]. The integration of adaptive control enables the automated machinery to alter its operations based on real-time remote-sensing information received from the field [52]. The combination of GIS, remote sensing, ATV, and automation technologies results in a comprehensive approach to agricultural analysis. This connection enables smooth and uninterrupted transfer of data, accurate and exact operations, and well-informed decision-making in agricultural activities. Precision farm vehicles can be more customized and work better when they are designed using 3D printing technology [53]. By combining the strengths of these technologies, farmers can optimize resource management, enhance productivity, and promote sustainable agricultural practices in a highly dynamic and data-driven manner [54].

Advantages of a unified approach in precision agriculture: The integration of GIS, remote sensing, ATV, and automation in precision agriculture provides numerous benefits. The amalgamation of many technologies facilitates the acquisition of extensive spatial data, empowering farmers to make well-informed choices about crop planning, resource allocation, and operational strategies [55]. By taking advantage of real-time data obtained from remote sensing and GIS, together with the integration of ATV and automation technologies, farmers may enhance their workflows, minimize the need for human labor, and carry out operations with accuracy, resulting in improved operational efficiency. Unmanned agricultural vehicles are particularly beneficial in enhancing farming efficiency in challenging hill terrains [56].

An integrated strategy enables accurate monitoring and utilization of resources such as water, fertilizers, and insecticides. The utilization of GIS-guided maps and remote sensing data enables the customization of resource allocation to specific areas requiring attention, minimizing inefficiency and negative effects on the environment [57]. The combination of remote sensing, ATV, and automation allows for the uninterrupted monitoring of crop health indicators, including NDVI and thermal images. Early diagnosis of stress, infections, or pest infestations is made easier, enabling prompt responses [58]. GIS-based maps and remote sensing data offer comprehensive information on the variability of the field. This enables the tailoring of agricultural techniques, adjusting tactics to match distinct soil types, topography, and microclimates within a single area [5].

Precision agriculture reduces the wasteful utilization of resources by employing precise and targeted applications. This not only decreases expenses but also encourages sustainable agricultural methods, thus limiting environmental deterioration and conserving natural resources [59]. Farmers can achieve more profitability by implementing a unified approach that enables optimized resource management and increased production potential. The method enhances long-term economic sustainability by optimizing productivity and decreasing input costs [60]. Adopting a cohesive strategy promotes creativity and progress in agricultural technology. The earlier citation by researchers [61] suggests that it enables advancements in automation, data analytics, and precision farming methods, hence propelling the industry toward enhanced efficiency and effectiveness.

A detailed examination of the many performance indicators required to evaluate the efficiency of GIS and remote sensing technologies in precision agriculture is given in Table *1*. It includes a description of each measure, an explanation of how it was calculated, relevant figures or diagrams, important references, and practical applications. Metrics that demonstrate their contribution to improving agricultural practices include data accuracy, temporal and spatial resolution, and analytical skills. This table highlights how incorporating various technologies into farming operations can enhance decision-making, cost-effectiveness, real-time monitoring, and environmental sustainability.

Performance Metric	Description	Methods Used	References	Applications
Data accuracy	Measure of the correctness of collected data with an accuracy of 85%	Satellite imagery, GPS, drones	[19]	Ensuring accurate mapping and monitoring of agricultural fields
Temporal resolution	Frequency of data collection over time	Satellite imagery, aerial photography	[62]	Monitoring crop growth stages and detecting changes
Remote sensing detection rate	Detection accuracy of 92% for environmental and crop conditions	NDVI, multispectral imagery	[9]	Monitoring crop health and detecting stress factors
Spatial resolution	Detail level of spatial data	Satellite imagery, drones	[63]	High-resolution mapping of fields for precision agriculture
Spectral resolution	Ability to capture data in multiple wavelengths	Spectral indices, thermal imaging	[64]	Assessing crop health and detecting stress using NDVI and other spectral indices
Analytical capabilities	Capacity to perform complex spatial analyzes	GIS spatial analysis tools	[65]	Conducting terrain modeling, interpolation, and suitability analysis
Decision support	Effectiveness in providing actionable insights	GIS-based decision support systems	[66]	Supporting farmers in making informed decisions regarding crop management and resource allocation
Data interoperability	Ability to integrate various data formats (30% of interoperability cases)	Data integration software	[67]	Combining diverse datasets (soil, weather, crop yield) for comprehensive analysis
Cost efficiency	Cost-benefit ratio of technology implementation and 40% reduction in workforce expenses with automation	Cost analysis tools, ROI calculations	[68]	Evaluating the economic viability and benefits of adopting GIS and remote sensing technologies
Real-time monitoring	Ability to provide live updates on field conditions	IoT sensors, drones, satellite imagery	[69]	Immediate assessment and response to changing field conditions
Environmental impact	Assessment of technology's effect on the environment	Environmental impact assessment tools	[70]	Measuring and minimizing the ecological footprint of farming practices

TABLE 1: Performance metrics and applications of GIS and remote sensing in precision agriculture

GIS, geographic information systems; GPS, global positioning systems; NDVI, normalized difference vegetation index; IoT, Internet of Things

Mapping, Monitoring, and Operation

ATV, automation, remote sensing, and GIS integration make it easier to map, monitor, and operationalize land assets. With the help of a broad strategy, farmers are equipped with thorough spatial insights that facilitate data-driven decision-making, improve the consumption of assets, and increase overall farm management effectiveness [71].

Spatial mapping with GIS and ATV technologies: Utilizing ATVs fitted with sensors and GPS to collect, process, and present spatial data in agricultural settings is known as "spatial mapping with GIS and ATV technologies." ATVs travel through fields, collecting real-time data on crop conditions, soil parameters, and moisture content. After analysis, the data are added to pre-existing spatial datasets such as topographical data, soil maps, and meteorological trends on GIS systems. Using GIS to generate accurate maps that show variations in soil and crop health indicators can help farmers gain a better understanding of field variability. These maps allow GPS-enabled ATVs to move with accuracy, optimizing resource consumption with targeted applications such as irrigation, fertilization, and pest control based on specific geographic data points. Providing real-time data insights that support effective and well-informed decision-making, remote sensing plays a critical role in crop health monitoring within automated farm operations [72].

Remote sensing for crop health monitoring: Using satellite pictures or drones fitted with specialized sensors, remote sensing technology allows for continuous monitoring of agricultural areas by capturing high-resolution satellite imagery [73], aerial photography [74], spectral indices [75], and thermal imaging [76] (Figure *5*). These instruments measure variables like crop health, stress levels, and general vegetation vigor using measures like the NDVI, thermal imaging, and multispectral data. In almost real-time, the gathered data are processed to deliver pertinent information on crop conditions, growth trends, and any problems like pest infestations or water stress. By integrating this data with automated systems, adaptive control is made possible, allowing automation tools to modify activities in response to differences in crop health or environmental variables that are detected. Afterward, automated equipment makes use of this information to modify the pace at which pesticides, fertilizers, or water are applied based on particular requirements, reducing waste and increasing efficiency [77]. Additionally, early identification of stressors or anomalies is made possible by remote sensing, which enables proactive actions to reduce production losses. By providing farmers with decision-support tools, insights from this data enable them to choose the best times and places to implement focused interventions that improve crop output and health. Remote sensing is crucial for crop health monitoring in automated farm operations. This allows for better-informed decision-making, targeted treatments, and increased farm sustainability and efficiency [9].

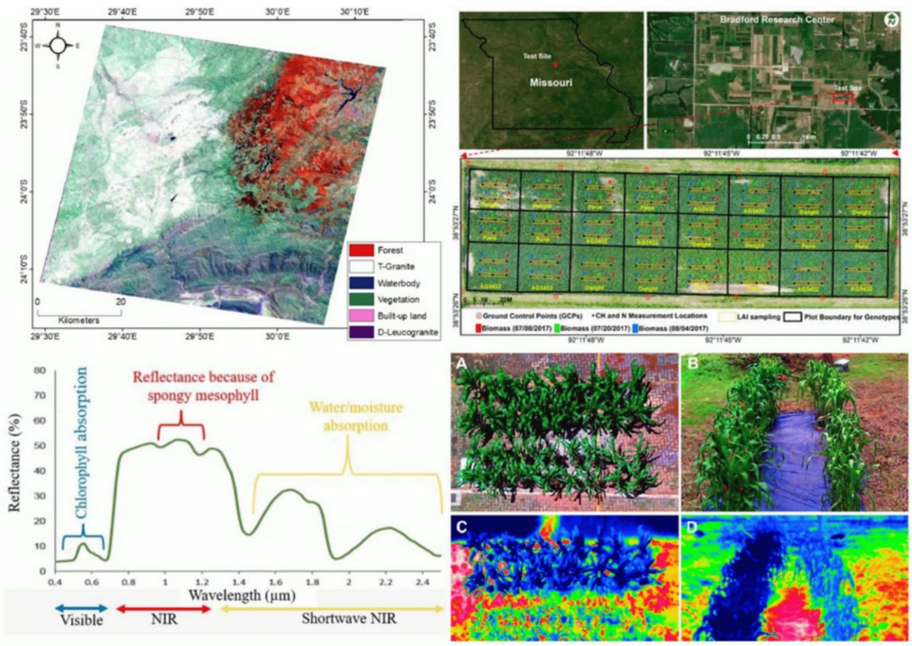

FIGURE 5: Remote sensing applications in crop monitoring: (a) satellite imagery, (b) aerial photography, (c) spectral indices, and (d) thermal imaging

NIR, Near-Infrared

GIS-Based Decision Support Systems

It combines and analyzes spatial data using GIS, enabling farmers to make decisions that can be defended. These systems collect data from a range of sources, such as weather stations, drones, soil sensors, and satellite photos, to create comprehensive maps and models of farm conditions. IoT-based solenoid-controlled pressure regulation systems for precision sprayers exemplify the integration of IoT technology in GIS-based DSS [78]. GIS-based DSS examines geographical differences in soil characteristics, crop health, moisture levels, and other environmental factors to help improve crop management practices and the effective distribution of resources, such as water, fertilizers, and pesticides. These real-time insights and predictive analytics tools enhance precision farming approaches and aid in the early diagnosis of issues such as water stress and insect infestations [79]. Automation and GIS work together to enable a highly productive, sustainable approach to agriculture that increases overall farm productivity and facilitates informed decision-making [80].

Integrating GIS, remote sensing, ATV, and automation

GIS and Remote Sensing for Precision Agriculture

The integration of GIS and remote sensing technology in precision agriculture attempts to optimize efficiency, decision-making, and asset management in farming practices [81]. Data collection and integration include the process of obtaining geographical and environmental data through the utilization of several technical methods, including satellites and drones. These instruments acquire multispectral and high-resolution data pertaining to vegetation indices, crop health, and soil moisture. Sensors and GPS devices in the field collect real-time data on soil qualities and meteorological conditions. GIS systems utilize data processing and analysis techniques to generate a complete and geographically exact representation of field conditions. This enables the identification of specific areas where agricultural practices can be adjusted and the creation of accurate maps [82].

GIS data management includes the systematic arrangement, storage, and examination of environmental and geographical data obtained from diverse sources, including GPS devices, field sensors, and remote sensing imagery. Effective data management guarantees that the data are current, readily accessible, and beneficial for improving agricultural operations [83]. Data on crucial characteristics such as vegetation indices, soil moisture levels, temperature, and crop health are gathered using satellite photography, drones, and airplanes fitted with diverse sensors. Remote sensing data are integrated into GIS systems to generate detailed maps and models, facilitating accurate management and monitoring of agricultural activities [84]. Data integration is the process of combining data from several sources into a single GIS platform, which then produces detailed and accurate maps and models of agricultural areas. This comprehensive review and graphical representation enhance well-informed decision-making and accurate agricultural interventions [83].

ATV and automation integration in precision farming techniques

By utilizing these technologies to increase productivity and streamline agricultural operations, automation and ATVs are integrated into precision farming techniques [85].

ATV Utilization for Data Collection

Sensor-equipped ATVs are designed to offer both mobility and data-gathering capabilities, which are essential for implementing precise agricultural techniques in precision farming. The ATVs are equipped with sensors such as GPS, cameras, and soil sensors, which allow them to collect real-time data on crop health, soil conditions, and topographical characteristics. Automation integration enables tasks such as autonomous navigation, crop monitoring, and spraying, resulting in enhanced resource efficiency and reduced reliance on manual labor. Challenges include the management of sensor accuracy, data integration, and cybersecurity. Nevertheless, the utilization of sensor-equipped ATVs enhances precision farming by providing prompt and dependable data for educated decision-making, hence increasing agricultural productivity and sustainability [86].

Implementing ATV automation integration for real-time data collection in precision farming offers numerous benefits. ATVs equipped with sensors can collect data on temperature, crop health, and soil moisture as they navigate fields. Automation enhances the data collection process, enabling farmers to make quick and smart judgments. Integrating real-time data into precision farming technologies enhances crop management by facilitating timely interventions such as targeted pesticide application or irrigation adjustments [87]. Moreover, the implementation of ATV automation results in higher productivity and efficiency, along with reduced labor demands and operational costs. In order to achieve widespread deployment, it is necessary to address concerns such as data quality, system reliability, and initial investment costs [88].

Table *2* illustrates the various technologies utilized in automated and precision agriculture, providing a detailed description of each technology, the methods employed, relevant figures or diagrams, key references, and specific applications. It covers a range of technologies, including ATVs, IoT, machine learning, 3D printing, electrochemical soil sensors, automated sprayers, aerial drones, soil moisture sensors, variable rate technology (VRT), and environmental monitoring systems. Each technology is linked to its practical applications, demonstrating how they contribute to the efficiency, accuracy, and sustainability of precision agriculture.

Technology	Description	Methods Used	References	Applications
ATVs in precision agriculture	Use of ATVs equipped with sensors for data collection and monitoring	GPS, sensor integration, automated control systems	[89]	Efficient field data collection, monitoring crop health, and performing precise agricultural operations
IoT in agriculture	Implementation of the IoT for real-time monitoring and control of farm equipment	Wireless sensors, IoT platforms, data analytics	[90, 91]	Remote monitoring and control of irrigation systems, machinery, and environmental conditions
Machine learning and AI	Application of AI and ML for analyzing data and making predictive decisions	Machine learning algorithms, computer vision techniques	[92]	Predictive analytics for crop yield estimation, pest detection, and optimizing resource usage
3D printing for ATVs	Use of 3D printing technology to design and manufacture customized parts for ATVs	Additive manufacturing, material selection	[93, 94]	Creating tailored ATV components to improve functionality and performance in various farming operations
Electrochemical soil sensors	Development of sensors to measure soil fertilizer concentration in real-time	Electrochemical methods, soil sampling	[95]	In-situ measurement of soil nutrients to guide fertilization practices
Automated sprayers	Use of automated systems to control and optimize spraying operations	IoT, GPS, automated control systems	[96]	Precision spraying to minimize waste and enhance efficiency
Aerial drones	Deployment of drones for high-resolution aerial imagery and monitoring	UAV technology, imaging sensors	[97]	High-resolution crop monitoring, pest detection, and health assessment
Soil moisture sensors	Sensors to monitor soil moisture levels and optimize irrigation	Capacitive and resistive sensors, IoT integration	[98]	Ensuring optimal soil moisture levels for various crops
Variable rate technology (VRT)	Technology that allows for the variable application of inputs (seeds, fertilizers, pesticides)	GPS, GIS, automated control systems	[99]	Efficient use of inputs to enhance yield and reduce waste
Environmental monitoring systems	Systems to monitor environmental conditions and inform agricultural practices	IoT sensors, weather stations	[100]	Monitoring climate conditions, predicting weather impacts, and planning agricultural activities

TABLE 2: Technologies and their applications in automated and precision agriculture

ATVs, All-Terrain Vehicles; GIS, geographic information systems; GPS, global positioning systems; IoT, Internet of Things; AI, Artificial Intelligence; ML, Machine Learning; UAV, Unmanned Aerial Vehicles

Automation Integration with ATVs

Precision navigation and operations: Automation is employed in precision farming techniques to facilitate precise navigation and operations in ATVs. ATVs can be precisely directed for tasks including planting, spraying, and harvesting by utilizing GPS and other sensors. A significant obstacle is accurately determining locations in diverse weather and terrain conditions. Another approach is to seamlessly incorporate automation into existing farming practices. The benefits encompass reduced input consumption, enhanced efficiency, and diminished environmental effects.

Automated tasks: Agricultural operations are enhanced by the use of automated tasks in agricultural terrain vehicles (ATVs) and the incorporation of automation in precision farming technologies. ATVs equipped with sensors and GPS technology automate tasks such as soil sampling, crop monitoring, and pesticide application, resulting in enhanced productivity and precision. The integration of precision farming techniques enables farmers to make informed decisions on crop health management, fertilization, and irrigation by utilizing real-time data analysis. In order for implementation to be successful, it is crucial to properly address several impediments, such as initial investment costs, technological challenges, and concerns related to data management [101].

Data-Driven Decision Support

Precision farming techniques utilize up-to-date data from DSS powered by data to enhance crop management and minimize labor expenses. Sensors and IoT devices collect and analyze data on the condition of crops, moisture levels in the soil, and temperature, allowing for immediate action to be taken. Integrating automation with ATV enhances efficiency and reduces labor expenses by simplifying procedures. Utilizing data-driven decision support simplifies the process of predicting repair needs for agricultural equipment and ensures uninterrupted operations. The incorporation of contemporary agricultural practices brings about advantages such as enhanced production, sustainability, and profitability, hence fortifying the food supply chain [102]. Achieving the full potential of precision agriculture necessitates the collaboration of multiple disciplines, robust algorithms, and seamless methods for sharing data [103].

Efficiency and Precision in Farming Practices

Precision farming is a practice that aims to maximize efficiency by accurately supplying resources such as fertilizers, herbicides, and water to specific areas where they are required. The integration of ATVs and automation improves precision by enabling automated systems equipped with GPS and sensors to navigate fields and apply resources with accuracy and consistency. This minimizes resource inefficiency, environmental harm, and crop productivity. Nevertheless, it is imperative to tackle obstacles such as upfront expenses, intricate technological aspects, and effective data handling [104]. By incorporating ATVs with precision farming methods, the need for manual labor is minimized as tasks such as sowing, spraying, and harvesting are optimized. This technique enables the uniform application of inputs such as herbicides and fertilizers, thereby minimizing human error and enhancing precision. Precision farming techniques empower farmers to continuously monitor crops in real-time, make informed decisions based on data for enhanced yields and sustainability, and optimize the utilization of resources.

Sustainability and Cost Reduction

Integrating automation into precision farming and optimizing the utilization of ATVs are important strategies for achieving sustainability and cost savings. Autonomous vehicles equipped with GPS technology may precisely disperse commodities such as pesticides and fertilizers, resulting in decreased waste and a reduced environmental footprint. Sensors and data analytics can be utilized to optimize irrigation and fertilizer management, resulting in decreased resource usage and water conservation. Remote monitoring and control systems enable real-time alterations, resulting in increased productivity and reduced operating expenses. Renewable energy sources can be harnessed to power automation systems and ATVs, fostering sustainability and facilitating significant long-term cost reductions [105]. Automation reduces labor costs, optimizes resource utilization, and eliminates the need for inputs such as water, fertilizer, and pesticides. Utilizing data-driven analysis can enhance the possibility of higher yields, resulting in increased productivity and decreased production costs. The incorporation of ATVs and automation in precision farming methods simplifies operations, improves data-based decision-making, and maximizes resource consumption, resulting in more effective and environmentally friendly agricultural practices [106].

Decision support systems

GIS-based DSS, integrated with ATV and automation data, offers a comprehensive framework for informed decision-making and optimized agricultural operations [32]. Integrating ATV and automation data into GIS-based DSS improves accuracy and productivity in many applications. ATV-mounted sensors acquire up-to-the-minute, detailed geographical information from difficult landscapes, while automation technologies ensure continuous data flow from IoT devices and drones. This integration facilitates comprehensive cartography, surveillance, and examination of surroundings, enhancing the process of making informed choices in sectors such as forestry, agriculture, and disaster management. GIS-based DSS has the capability to analyze and display this data, offering valuable information for strategic planning, environmental conservation, and resource administration [107]. The incorporation of GIS functionalities with automation and ATV data provides decision-making assistance, hence enhancing efficiency and production in many applications [108].

This integration enhances the optimization of routes, resource allocation, and maintenance scheduling. Automation data enhances processes by streamlining them, resulting in improved accuracy and efficiency. Real-time decision support is improved in domains such as resource allocation and emergency management [109]. Adaptive control and automated interventions improve efficiency and responsiveness by adjusting system parameters based on real-time input. Automated interventions offer timely answers to changing situations, while ATV data improves situational awareness through the analysis and presentation of geographical information. Automation data minimizes errors and human effort, optimizing operations [110]. The feedback loop approach is employed to continuously improve GIS-based DSS by integrating automation and ATV data. This iterative procedure facilitates modifications to the system's functionality, accuracy, and usability, guaranteeing its relevance and triumph in many applications [111].

Future directions and innovations

Limitations and Challenges

Holistic integration in agriculture, combining GIS, remote sensing, ATV, and automation, faces several limitations and challenges, including the following.

Data complexity and integration: Data interoperability in remote sensing is hindered by the presence of many sensor kinds, resolutions, formats, and calibration methodologies. These problems prevent the smooth compatibility of the system because of variations in wavelengths, radiation characteristics, and distortions. In order to attain data interoperability, it is necessary to implement harmonization, standardization, and metadata enrichment. Data silos impede the accessibility, cooperation, and integration of data, resulting in inefficiency in resource use, compatibility problems, and security risks. Methods to enhance efficiency include the establishment of standardized data, improvement of interoperability, and implementation of secure protocols for data sharing [112].

Technology interoperability and standardization: Remote sensing encounters compatibility issues arising from variances in sensor properties, resolutions, and data formats. These problems restrict the sharing and analysis of data across different platforms. Essential components include reliable data conversion tools, generally recognized formats, and collaborative initiatives. Advanced machine-learning techniques may fix these issues. Technical challenges comprise various aspects such as image processing algorithms, limitations in data storage and transmission, mitigating air interference, resolving spatial and spectral resolution concerns, implementing precise calibration and validation methods, and monitoring sensor deterioration [113].

Costs and investments: Remote sensing encounters financial obstacles, including regulatory obstacles, initial expenses for satellite launches and sensor enhancements, and guarantees of data quality. Fluctuations in market demand can have a significant impact on the sustainability of an organization. The complex nature of remote sensing data is a challenge when integrating it with the existing financial models [114]. However, the possibility of economical solutions in infrastructure, environmental monitoring, and agriculture has sparked interest. Resource limitations, such as a scarcity of high-resolution data and insufficient financing, have a direct impact on the accuracy and availability of data. Challenges are being tackled through the utilization of technology improvements, worldwide collaboration, and inventive algorithms [115].

Data privacy and security concerns: Ensuring the security of remote sensing data involves addressing issues such as safeguarding privacy, controlling access to sensitive information, and preventing data breaches. In order to tackle these issues, a comprehensive strategy that incorporates ethical considerations, technological advancements, and legal frameworks is required [116]. Remote sensing is susceptible to cybersecurity vulnerabilities such as tampering, illegal access, and data interception. Engaging in collaboration with various parties heightens the probability of experiencing security breaches. The situation is further complicated by the limited availability of encryption alternatives and the necessity to safeguard satellite communication networks and IoT devices. Strong encryption methods, ongoing surveillance, and effective coordination among relevant parties are crucial [117].

Training and adoption challenges: The evaluation of remote sensing data encounters constraints such as geometric imperfections, air disturbances, and a scarcity of high-quality data. Continuous skill growth and multidisciplinary knowledge are necessary due to the emergence of ethical and data privacy concerns [113]. The limited accessibility of technology, high costs, complex data processing, and defined protocols are obstacles that hinder adoption rates. The dearth of information and training, particularly in economically disadvantaged nations, exacerbates the disparity. To tackle these difficulties, it is necessary to enhance education and training programs, address infrastructural shortcomings, implement cost-effective solutions, and promote stakeholder engagement [118].

Regulatory and policy frameworks: The legislation governing remote sensing encounters difficulties in safeguarding personal information, upholding national security, determining data ownership and accessibility, and assuring worldwide consistency. In order to achieve a balance between protecting interests and promoting innovation, it is necessary to provide adaptable and customizable frameworks. For ethical and responsible deployment of remote sensing technology, it is crucial to have collaboration among different disciplines, clear and transparent legislation, and active involvement of stakeholders [119]. Ethical considerations encompass concerns over the protection of data, potential violations of privacy, and ensuring equitable access to data. The extensive accessibility of high-resolution images gives rise to issues over privacy, while safeguarding data security is essential to prevent any potential misuse or exploitation. Ensuring fair access to remote sensing data and technology is crucial to preventing worsening social inequalities. Prudent ethical consideration and adherence to regulations are essential in order to strike a balance between these issues and the advantages of using remote sensing for environmental monitoring, disaster relief, and urban planning [120].

Future Prospects

The future of integrated agricultural technologies, such as GIS, remote sensing, ATV, and automation, shows great potential for advancements and possible collaborations [121].

Advancements in AI and ML: Intelligent decision systems, utilizing AI, ML, and advanced data processing technologies, have modified urban planning, environmental monitoring, and agricultural methods in remote sensing. These systems offer precise analysis and rapid reactions to dynamic situations, necessitating the integration of various data sources and high-resolution images. Automated and adaptive technologies minimize the need for human involvement, hence enhancing the efficiency of precision agriculture applications [122]. Accessible interfaces and cloud-based solutions will facilitate the utilization of sophisticated analytical tools by a broader spectrum of users. Implementing ethical and sustainable practices is crucial for ensuring responsible utilization of technology. These developments will enhance the management of natural resources, optimize agricultural processes, and promote the development of environmentally friendly urban areas. Predictive analytics, employing sophisticated algorithms and data processing techniques, could change multiple industries by providing more precise predictions of environmental shifts, agricultural trends, and urban development patterns. The proliferation of intuitive interfaces and cloud-based platforms will enhance the accessibility of sophisticated analytics to a broader spectrum of enterprises, supporting increased adoption and cooperation [50].

Edge computing and IoT integration: The progress in sensor technology, data transmission, and cloud computing has facilitated the immediate processing of satellite imagery, redefining our capacity to observe and address social and environmental transformations. This enables the continuous monitoring of factors such as weather conditions, natural calamities, agricultural health, and urban growth in real-time [123]. The incorporation of AI and ML improves the effectiveness of identifying patterns and trends, hence offering decision-makers prompt and relevant information. Future developments will enhance the accessibility, efficiency, and utilization of remote sensing data, facilitating uninterrupted and immediate transmission and analysis of data. This will lead to improved decision-making in crucial domains such as precision agriculture, environmental monitoring, and disaster response [124].

Blockchain technology for data integrity and traceability: The utilization of blockchain technology, encryption techniques, and secure cloud computing is anticipated to greatly enhance remote sensing for the purpose of safe data exchanges. Blockchain provides a clear and unchangeable framework for documenting data transfers, which improves responsibility and confidence. Advanced encryption safeguards sensitive information against unauthorized access and cyberattacks. Secure cloud services guarantee the availability and integrity of data, making it easier to securely, dependably, and effectively manage data [125]. Utilizing remote sensing technology in supply chain management provides a means to ensure responsibility and visibility, thereby guaranteeing adherence to ethical and environmental standards. The adoption of satellite and drone technologies will provide continuous monitoring of the origins of raw materials, the various stages of manufacturing, and the networks involved in distribution. Additionally, the implementation of advanced data analytics and AI will effectively mitigate fraudulent activities and enhance trust among all parties involved. The incorporation of blockchain technology will result in enhanced transparency in international trade processes and streamlined supply chains.

Evolving remote sensing technologies: High-resolution imagery in remote sensing provides exceptional clarity and accuracy, allowing for precise monitoring of environmental changes, urban growth, and agricultural conditions. This information is essential for effective leadership and decision-making. AI and ML streamline real-time applications such as infrastructure planning and disaster response [126]. Advancements in satellite and drone technologies will lead to an increase in the affordability and accessibility of high-resolution remote sensing data. Emerging technologies such as LiDAR, thermal sensors, and hyperspectral photography offer detailed and accurate information, improving the monitoring of agricultural health and environmental shifts. By integrating AI, we can enhance the accuracy of prediction models and analyze real-time data more effectively. This would greatly assist in disaster mitigation efforts and support sustainable development tasks [127].

Interoperability standards and open platforms: Standardization plays a critical role in enhancing the accessibility, quality, and interoperability of remote sensing data. Standardized data formats, processing methods, and metadata will make it easier to integrate different platforms and applications, improving collaboration, data-driven analysis, and global data sharing. This will result in the establishment of global databases, facilitating progress in areas such as urban planning, agriculture, and climate monitoring [128]. Collaboration ecosystems in remote sensing entail the facilitation of data exchange, ensuring compatibility, and fostering collaboration across organizations. Technological advancements will incorporate real-time data from multiple sources, hence improving environmental monitoring. The cooperation of governments, corporations, and academic institutions will promote the development of new ideas, efficient use of resources, and preparedness for responding to disasters. The utilization of cloud-based platforms and open data initiatives will facilitate equitable access to remote sensing data, finally resulting in pragmatic resolutions to worldwide circumstances [129].

Regenerative and sustainable agricultural techniques: The proliferation of technology has resulted in an increasing need for the incorporation of remote sensing in diverse sectors such as agriculture, urban planning, environmental monitoring, and disaster management. These systems integrate data from satellites, drones, and ground-based sensors, offering comprehensive insights for precision agriculture and habitat monitoring. ML algorithms improve the process of data processing, allowing for immediate decision-making and the creation of predictive models. Effective collaboration among researchers, policymakers, and entrepreneurs is essential for fostering innovation and promoting growth in response to global concerns [130]. Remote sensing has the potential to be useful for climate adaptation by offering data to track and observe variations in the environment. Progress in satellite technology allows for the capture of detailed photos, which improves the ability to predict and warn about potential events in advance. Cooperation among scientists, politicians, and other stakeholders can facilitate climate adaptation initiatives, effectively oversee resources, and enhance resistance to the consequences of climate change [131].

Conclusions

The integration of GIS, remote sensing, ATVs, and automation is leading to a revolutionary period in agricultural techniques, with exceptional prospects for improving sustainability, efficiency, and precision in farming operations. The comprehensive method showcases the utilization of GIS as a fundamental tool for organizing and understanding spatial data with an accuracy rate of up to 85%. Additionally, remote sensing plays a crucial role in providing valuable information on crop health and environmental conditions, with detection rates as high as 92%. By integrating ATVs and automated systems, it becomes possible to collect data with great accuracy, covering more hectares in a single day. This connection also facilitates adaptive control and targeted interventions, resulting in a 15% reduction in input costs and a 40% decrease in labor expenses. However, there are several problems that need to be addressed in order to achieve seamless integration. These challenges include interoperability issues in 30% of situations, data complexity, budget limits, and regulatory barriers. To overcome these difficulties, it is necessary to engage in collaboration, make technology improvements, and receive policy backing. In the future, improvements in AI, IoT, and edge computing will lead to improved decision-making and immediate reactions.

Additionally, progress in remote sensing and blockchain technologies will guarantee more precise insights and safe data transfers. Highlighting regenerative and sustainable practices underscores the crucial role of these integrated technologies in tackling climate change and advancing environmental stewardship. As we progress through these technological developments, it becomes crucial to promote open platforms, establish standards, and encourage collaborative ecosystems. To fully harness the benefits of integrated agricultural technology, it is essential to engage in collaborative endeavors that provide farmers with the necessary skills and knowledge. This will enable the achievement of a more sustainable, efficient, and productive future in agriculture.

Additional Information

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All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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