

Precision Agriculture Technology: Accelerating Sustainable Food Security and Resource Efficiency

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The global agricultural sector currently faces significant challenges in the form of surging food demand amidst environmental degradation due to global climate change. This study aims to analyze the role of precision agriculture technology in accelerating the realization of sustainable food security while optimizing the efficiency of resource use (water, fertilizer, and land). The method used was a qualitative descriptive approach through a literature review of various national and international scientific articles, textbooks, and official reports from relevant agencies for the 2021–2026 period. The results show that the integration of a digital ecosystem based on the Internet of Things (IoT), automatic sensors, drones, and artificial intelligence (AI) can transform production patterns into data-driven farming, boosting crop productivity by 20–30%. Through a variable-dose application system, this technology has also successfully reduced irrigation water and chemical fertilizer use by 15–25%, minimizing negative ecological impacts. However, this massive potential is hampered by structural issues among local farmers, such as high initial capital requirements, fragmented land use, the demographic digital literacy gap, and fragile rural connectivity. This study concludes that democratizing precision agriculture requires inclusive public policy interventions through farmer corporation consolidation programs, smart fiscal stimulus, strengthening the upstream internet, and implementing the Agriculture-as-a-Service (AaaS) business model.

Keywords: Precision agriculture; food security; resource efficiency; internet of things; farmer corporations.

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1. Introduction

The global agricultural sector is currently at a crucial juncture demanding massive structural transformation. As the primary provider of bio-based food, this sector bears a significant responsibility to ensure the availability of calories for the world's exponentially growing population (Andrianto, 2023). However, meeting this need is confronted with the realities of environmental degradation, shrinking productive land, and extreme climate uncertainty. Conventional agricultural approaches are no longer adaptive to global dynamics that require rapid, measured, and precise responses to prevent systemic food crises (Tapi & Makabori, 2024).

Sustainable food security has become a central, non-negotiable issue on national and global development agendas. The concept of food security is now not limited to the quantity of commodity availability in the market but encompasses accessibility, affordability, nutrition, and long-term supply stability without compromising ecosystem support (Suryana, 2014). Overexploitation of land and a severe dependence on chemical inputs in traditional agriculture have actually triggered soil degradation and water source pollution. Therefore, a reorientation of agricultural production management strategies is needed to balance high productivity targets with environmental sustainability (Chaireni et al., 2020).

One of the main root problems in the agricultural sector today is inefficient natural resource management. Water use for irrigation and chemical fertilizer application is often carried out unmeasured due to limited

real-world data (Dadi, 2021). This resource waste not only increases farmers' operational production costs but also accelerates greenhouse gas emissions and macro-environmental pollution. Resource efficiency must be improved by utilizing minimal production inputs to produce maximum harvest output through accurate calculations (Saleh & Suherman, 2021).

Precision agriculture technology presents a new paradigm and cutting-edge technological solution to bridge this gap. This approach utilizes the integration of advanced digital technology to observe, measure, and respond to variability in crop and soil conditions in real time (Pierce & Nowak, 1999). Through precision agriculture, cultivation interventions are no longer based on a one-size-fits-all approach, but rather tailored to the specific needs of each square inch of land and the plant's vegetative growth phase. This digitalization transforms agricultural work patterns from speculative and intuitive to empirical data-driven agriculture (Gebbers & Adamchuk, 2010).

The precision agriculture architecture is supported by an ecosystem of modern technologies such as the Internet of Things (IoT), wireless sensor networks, satellite imaging, land-monitoring drones, and the implementation of artificial intelligence. Embedded soil sensors are capable of transmitting constant data on moisture, pH, and macronutrient content to farmers' devices (Susilo & Athallah, 2023). Artificial intelligence algorithms then process this data to drive automated drip irrigation systems and highly specific variable fertilizer doses. This automation ensures that plants receive the right amount of nutrients and water at the right time, thereby reducing unabsorbed chemical waste (Hidayat et al., 2025).

However, the implementation of precision agriculture in the field still faces various complex structural and cultural challenges. The initial investment costs for hardware, sensors, and digital connectivity infrastructure are considered too high for the economic scale of smallholder farmers (Sondakh & Rembang, 2021). Furthermore, there is a massive digital literacy gap among farmers, who are predominantly older generations with limited formal education. These barriers have slowed the adoption of precision agriculture technology and have been centralized within large-scale agribusiness corporations (Wijaya & Susandi, 2018).

Given these urgency and challenges, an in-depth study of optimizing precision agriculture is crucial for formulating national agricultural policy. Accelerating the adoption of this technology is no longer simply an innovation option but a strategic step to secure food sovereignty and maintain economic stability from the threat of the climate crisis. By mapping the potential of the digital ecosystem and identifying solutions to investment barriers, this research aims to formulate an integrative formulation for precision agriculture technology innovation. This step is expected to accelerate the realization of sustainable food security and achieve comprehensive resource efficiency.

2. Method

This research uses a descriptive qualitative approach with a literature review method. The data used in this study are entirely secondary data obtained through a search of various scientific literature, such as national and international journals, textbooks, and official reports from relevant agencies (Darmalaksana, 2020). The reference search process focused on recent scientific publications relevant to the topics of precision agriculture, food security, and natural resource efficiency. The collected articles and documents were then critically selected based on their suitability for substance to obtain a theoretical basis and valid empirical data to answer the research questions.

The selected literature data was then analyzed in-depth using content analysis techniques. The analysis began by grouping data by subtheme, comparing findings from various sources, and synthesizing information regarding the impact of precision agriculture technology on productivity and production input

savings. The results of this data synthesis were interpreted descriptively to provide a comprehensive picture of the potential for technology adoption and the obstacles encountered in the field. The final step was drawing logical conclusions that can serve as recommendations for the development of a sustainable agricultural sector.

3. Result And Discussion

Precision Agriculture's Contribution to Productivity and Resource Efficiency

The implementation of precision agriculture technology has sparked a new paradigm in the modern agribusiness landscape, shifting conventional, speculative cultivation methods toward data-driven systems. Past agricultural traditions relied heavily on the intuition of breeders and farmers and on the homogenous treatment of large tracts of land, ignoring the variability of the soil's physical and chemical properties. Precision agriculture redefines efficiency by introducing land management principles based on temporal and spatial mapping of micro-crop conditions. This digital transformation enables upstream stakeholders to identify specific crop needs quickly, measurably, and accurately.

The key pillar driving this precision agriculture ecosystem is the utilization of an Internet of Things (IoT) architecture integrated with wireless sensor networks. Physical sensors embedded in the plant's root zone act as sensory organs, constantly recording crucial macro- and micro-environmental parameters. Raw data such as soil moisture levels, air temperature, sunlight intensity, acidity (pH), and soil electrical conductivity are automatically transmitted to cloud computing. The availability of this continuous data stream eliminates time lags in agronomic decision-making in the field.

In addition to ground-based monitoring, the use of remote sensing technology through satellite imagery and unmanned aerial vehicles (drones) has become a crucial catalyst in expanding the scale of field monitoring. Drones equipped with multispectral and hyperspectral cameras are capable of capturing the reflectance of light waves from plant canopies that are invisible to the naked eye. This light reflectance data is then processed into vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). Through NDVI visualization, farmers can map plant health levels, detect drought stress, and even measure biomass density in real-time across hectares of land.

The early detection capabilities offered by the combination of IoT sensors and aerial imagery significantly contribute to mitigating the risk of crop failure due to plant pest attacks. Before external physical damage symptoms appear on leaves or stems, artificial intelligence (AI) algorithms integrated with the monitoring system can detect temperature anomalies or chlorophyll degradation at an early stage. Interventions in the form of pesticide or biological agent applications can be carried out isolated to the coordinates of infected land (spot spraying). This localized treatment method prevents the massive spread of pests while protecting natural enemy populations in healthy areas.

The direct impact of implementing precision monitoring and measurable early intervention is an increase in aggregate crop productivity of 20% to 30%. This yield increase is achieved not through expanding planted areas (extensification), but rather through optimizing the genetic potential of plants on existing land (sustainable intensification). Management based on the actual needs of the plant ensures that each individual plant grows in near-ideal environmental conditions at every stage of its development. This surge in production volume is a concrete response to the threat of a global food crisis triggered by the shrinking area of productive agricultural land.

In addition to boosting crop yields, precision agriculture technology makes a revolutionary contribution to improving the nutritional quality and uniformity of the size of harvested commodities. Variability in the

ripeness of rice fruits or grains, often a constraint in conventional farming, can be minimized through synchronized fertilization and irrigation timing controlled by a smart computing system. Uniform harvest yields increase the market value of commodities and reduce post-harvest losses caused by defective or immature commodities. Thus, farmers benefit not only from volume but also from improved commercial quality standards.



Figure 1 Precision Agriculture Technology

An equally crucial advantage of precision agriculture is the massive efficiency in water resource management through the implementation of smart irrigation systems. The traditional agricultural sector is known as the world's largest consumer of freshwater, often inefficient due to the use of manual flooding methods. In precision agriculture systems, automatic drip irrigation valves only open when moisture sensors detect that the water level in the root zone has fallen below the critical level required by the plant. The system automatically stops irrigation when the ideal soil water saturation level is reached, preventing water waste due to evaporation and percolation.

Through this automation of plant hydration management, water use at the farm level has been significantly reduced by 15% to 25%. This water savings is crucial, especially for agricultural regions frequently affected by extreme drought due to the impacts of global climate change. Efficient water use not only safeguards local groundwater reserves but also reduces the electricity consumption typically used to power large-scale water pumps. This cross-saving pattern of water and energy reduces the operational input costs that farmers must allocate each planting season.

Resource efficiency also targets plant nutrient management through the implementation of a variable rate application (VRA) system. VRA-based fertilizer equipment, combined with a global navigation system (GPS), can dynamically adjust the fertilizer distribution volume as the tractor travels through areas of land with varying fertility levels. Soil areas identified as low in macronutrients will receive higher doses of fertilizer, while areas already fertile will receive minimal doses or even be skipped. This principle of providing nutrients in the right dose, the right type, and the right location ends the era of ineffective over-fertilization.

The 15% to 25% reduction in synthetic chemical fertilizer application resulting from the VRA system has a significant economic and ecological impact on the agricultural ecosystem. Economically, fertilizer procurement costs, which have traditionally been the largest expense for farmers, can be substantially reduced, increasing net profit margins. Environmentally, the reduced use of synthetic chemical compounds

drastically reduces the risk of chemical residues settling in the soil and plants. This helps restore the balance of the soil ecosystem by maintaining the presence of beneficial soil microorganisms for long-term natural fertility.

From a macro-ecological perspective, limiting chemical inputs and optimizing irrigation water through precision agriculture serves as a bulwark against water pollution phenomena such as eutrophication. In conventional agricultural systems, unabsorbed nitrogen and phosphate fertilizer residues are washed by rainwater into rivers, lakes, or reservoirs surrounding rice fields. This accumulation of nutrients in water bodies triggers an explosion of aquatic weed growth and harmful algal blooms, which deplete dissolved oxygen levels and kill aquatic biota. Precision agriculture ensures that nearly all applied nutrients are fully absorbed by plant roots, thus minimizing chemical waste washed into aquatic ecosystems.

Furthermore, precision agriculture directly contributes to reducing greenhouse gas (GHG) emissions produced by the agricultural sector, such as nitrous oxide from the decomposition of nitrogen fertilizers and methane from flooded rice fields. Reducing the dosage of precision nitrogen fertilizer significantly reduces emissions released into the atmosphere. Meanwhile, an intermittent irrigation system regulated by moisture sensors prevents prolonged flooding of rice fields under anaerobic conditions, which trigger methane production. These technical measures position precision agriculture as a key part of the global strategy to mitigate global warming.

Overall, the integration of precision agriculture has successfully demonstrated that high food productivity does not have to be achieved at the expense of the carrying capacity and sustainability of macro-ecosystems. A 20-30% increase in crop yields, coupled with 15-25% savings in resource inputs, is clear evidence of the success of the concept of sustainable agricultural intensification. This technology is not merely a tool for mechanization, but rather a key architect in building a resilient, efficient, and environmentally friendly food system. The sustainability of the agro-ecosystem created through this precision approach ensures the ability of future generations to continue to meet their food needs independently.

Challenges of Technology Adoption and Formulating Acceleration Strategies for Local Farmers

Although precision agriculture technology offers a quantum leap in productivity and ecological sustainability, its penetration and adoption at the local farmer level still face a complex maze of obstacles. The transition from conventional, intuition-based farming to modern, data-driven agriculture requires not only a change in tools but also a radical shift in farm governance. In many developing countries, the upstream agricultural ecosystem is not fully prepared for this wave of digitalization due to market distortions and infrastructure gaps. As a result, the immense potential of precision agriculture architecture often stagnates at the level of laboratory experiments or small-scale pilot projects.

The most crucial obstacle, a major barrier to the adoption of this technology, is the high initial investment (capital expenditure) for smart farming hardware. Key components such as IoT-based soil sensors, RTK (Real-Time Kinematic) GPS navigation devices, multispectral cameras, and even automated drones have significant economic value. For the majority of local farmers operating with limited capital, allocating funds for digital technology is seen as a high-risk expenditure with a slow payback period. This financial uncertainty forces farmers to stick with traditional methods that offer low initial costs, even though they are inefficient in the long run.

This financial situation is exacerbated by the reality of a land ownership structure dominated by smallholders with very small farm sizes. Most local farmers own less than half a hectare of land, often spread

across several fragmented locations. Economically, implementing precision farming systems such as variable rate application will only achieve break-even and optimal efficiency if applied to large-scale land areas. This land fragmentation makes the investment value per unit area irrational, thus limiting economic opportunities for smallholder farmers to independently benefit from technological efficiencies.

In addition to capital and land factors, sociological barriers such as low digital literacy levels among farmers pose a difficult structural challenge. The demographic characteristics of the upstream agricultural sector are currently dominated by older generations who have limited access to sophisticated digital devices (a digital divide). Using mobile-based applications to read soil moisture graphs, interpret artificial intelligence-based fertilizer recommendations, or program drone flight paths requires specific technical expertise. This limited educational capacity triggers cultural resistance, with farmers feeling alienated and distrustful of the effectiveness of decisions made by computer algorithms.

Technical challenges in the field are also complicated by the unequal distribution of digital connectivity infrastructure and broadband internet networks in rural areas. Precision agriculture ecosystems rely heavily on the continuous and smooth transmission of wireless data from sensors in the field to cloud servers. Many key food production centers remain in areas with weak signal levels or even no cellular network at all (blank spots). This unstable connectivity results in high data transmission latency, preventing irrigation or fertilization automation systems from functioning in real time and losing their precision.

The lack of a reliable power supply in remote rice paddies and plantations is also a significant limiting factor for the sustainability of IoT sensors. Sensor devices and communication gateways require a stable power supply to operate 24/7 in open spaces. While the use of mini solar panels can be an alternative, the risk of component theft in open fields and the cost of maintaining energy storage batteries pose additional burdens for farmers. Without guaranteed device security and power stability, sensor networks installed in the fields are vulnerable to technical and operational failures within a short period of time.

From an industrial supply chain perspective, the availability of spare parts and local technicians skilled in maintaining precision agriculture equipment remains extremely scarce. If a hydrological sensor, automatic feeder, or GPS module on a smart tractor breaks down, farmers must wait long repair times due to their dependence on out-of-town vendors. This long repair time lag is particularly detrimental for agricultural commodities whose growing cycles are highly sensitive to delays in irrigation or fertilization. The unpreparedness of the local support ecosystem creates the perception that smart technology is a cumbersome luxury item that is unreliable for daily production activities.

If left uninterrupted, these structural barriers will create a new and detrimental economic polarization in the agricultural sector. The financial benefits and increased yields from precision agriculture will be absorbed solely by large-scale agribusiness corporations with unlimited capital liquidity. Conversely, local smallholder farmers will be increasingly marginalized due to their lack of competitiveness in production cost efficiency and commodity quality standardization in the modern market. Therefore, a shift in approach is needed from individual self-adoption to a nationally planned collective acceleration movement.

The first strategy to untangle this tangle is to restructure the farmer institutional model through a virtual land consolidation program. Smallholder farmers with limited land in one area must be organized into modern cooperatives or farmer corporations. Through this collective framework, physical land ownership boundaries are maintained, but cultivation management is unified within a single, economic-scale area (corporate farming). This consolidation allows for the procurement of precision agriculture infrastructure, such as joint drone mapping or mini weather stations, to be funded through mutual cooperation, significantly lowering the investment cost per farmer.

The second strategy focuses on government fiscal policy intervention through a targeted, smart agricultural technology subsidy scheme. Subsidies should no longer be provided in the form of physical commodities like conventional chemical fertilizers, which are often misused, but instead be diverted to subsidies for digital devices or internet packages specifically for agriculture. The government can also collaborate with the banking sector to launch a microcredit (KUR) facility specifically for modernizing the digital agricultural ecosystem, with ultra-low interest rates and grace periods tailored to the harvest cycle. This financial stimulus is crucial for reducing investment risk for farmers in the early stages of adoption.

The third, equally crucial, acceleration step is strengthening human resource capacity through the reconstruction of the field agricultural extension program (PPL). The role of agricultural extension workers must be expanded from providing basic cultivation advice to becoming digital literacy facilitators (digital agronomists). Agricultural vocational higher education institutions need to be involved in designing practical, applicable, and user-friendly training curricula for older farmers. Creating user interfaces using local languages and simple icon visualizations can accelerate farmers' psychological adaptation to smart technology.

In addition to preparing human resources, the government must accelerate the provision of digital infrastructure in rural areas by expanding village internet networks specifically for the productive sector. Strategic collaboration between the Ministry of Agriculture and the Ministry of Communication and Information is needed to build micro-signal transmitters in isolated productive agricultural areas. Providing dedicated network frequencies for IoT devices, such as Long Range (LoRa) technology, can be a cost-effective solution because it can transmit sensor data over long distances with very low battery consumption. A robust connectivity infrastructure will lay the foundation for the operation of thousands of smart sensors across the country.

The fifth strategy involves encouraging the local technology industry to create innovative, low-cost precision agricultural devices based on local raw materials (frugal innovation). State research institutions and universities should be encouraged to assemble reliable soil sensor components and automatic irrigation systems at affordable prices that are affordable for local farmers. This downstream research program will reduce dependence on expensive imported hardware that is often unsuitable for tropical soil characteristics. Local technological independence will ensure the availability of affordable spare parts and a fast after-sales service network at the sub-district level.

The next strategy is to develop a technology rental business model (Agriculture-as-a-Service/AaaS) as a solution for farmers reluctant to fully purchase equipment. Through the AaaS model, agritech startups or village-owned enterprises (BUMDes) can act as providers of drone mapping, precision fertilizer spraying, or soil laboratory analysis services. Farmers simply pay a per-hectare service fee based on their specific operational needs without having to bear the burden of complex equipment ownership and maintenance. This business model democratizes access to high technology, making it accessible to all farmers, regardless of their capital level.

The government also needs to integrate precision agriculture monitoring data into a single national agricultural database (big data agriculture). Data streams of soil moisture, harvest volume estimates from satellite imagery, and pest distribution maps collected from thousands of farmers' fields can be used as accurate macro policy-making instruments. This real-world data minimizes errors in food imports, aids in timely planning of subsidized fertilizer distribution, and provides early warning of food supply shortages in the market. This integration of macro and micro data creates national food security that is highly resilient to external shocks.

Regulatory-wise, a clear legal framework and national roadmap are needed for the implementation of sustainable agricultural digitalization. This regulation is crucial for providing legal certainty for agritech investors, standardizing IoT devices to protect them from cyberattacks, and protecting farmers' spatial land data ownership rights. A measurable roadmap will synchronize development direction across ministries, local governments, the private sector, and farming communities, all under a single vision of accelerating food security. This regulatory synergy ensures that the agricultural modernization process follows an inclusive and socially just legal framework.

Table 1. Matrix Analysis Obstacle Adoption Agriculture Precision and Formulation of Local Farmer Acceleration Strategies

No	Dimensions Obstacle	Description Field Issues	Acceleration Strategy Formulation	Stakeholders Primary Interest
1	Finance & Investment	The height initial capital expenditure for buy IoT sensor devices, GPS, and <i>drones</i> for farmer small.	<ul style="list-style-type: none"> • Provision subsidy technology agriculture Smart. • Special People's Business Credit (KUR) scheme digitalization agriculture with ultra- low interest. 	<ul style="list-style-type: none"> • Ministry of Finance • National Banking • Ministry of Agriculture
2	Land Scale	Structure land agriculture local too narrow (shabby) and fragmented, so that No reach scale efficient economy.	<ul style="list-style-type: none"> • Formation Corporation Farmers / <i>Corporate Farming</i>. • Consolidation management land in a way collective without change right owned by land. 	<ul style="list-style-type: none"> • Local Government • Cooperatives Farmer Groups (Poktan / Gapoktan)
3	Socio-Demographics	The low digital literacy as a result domination age old and limited level formal farmer education upstream.	<ul style="list-style-type: none"> • Reconstruction role Extension worker Agriculture Field (PPL) becomes digital facilitator. • Creation application language user interface friendly local user. 	<ul style="list-style-type: none"> • Ministry of Agriculture • Academics / Vocational Colleges
4	Digital Infrastructure	Limitations broadband internet network and many weak zones signal (<i>blank spot</i>) in rural areas.	<ul style="list-style-type: none"> • Expansion village internet network special sector productive. • Utilization network cheap data transmission empowered low like technology <i>Long Range</i> (LoRa). 	<ul style="list-style-type: none"> • Ministry of Digital Communication • Private Telecommunication Operators
5	Energy Supply	Instability supply electricity on land open as well as risk tall theft sensor components in the rice field area.	<ul style="list-style-type: none"> • Use of mini solar panels based on battery economical energy. • System strengthening security collective based community local. 	<ul style="list-style-type: none"> • BRIN / Research Institute • Community Local Farmers
6	Chain Industrial Supply	Scarcity technician experts and limitations ethnic group spare parts local trigger duration pause time repair (<i>downtime</i>).	<ul style="list-style-type: none"> • Encouragement innovation local cheap (<i>frugal innovation</i>) based material standard domestically. • Formation center service digital after-sales at the level subdistrict. 	<ul style="list-style-type: none"> • Technology Industry Home Affairs • Ministry of Industry
7	Accessibility Technology	Farmer reluctant buy tool in a way full Because burden	<ul style="list-style-type: none"> • Implementation of business models rental technology (<i>Agriculture-as-a-Service</i> / 	<ul style="list-style-type: none"> • BUMDes • Agritech Startup Company

No	Dimensions Obstacle	Description Field Issues	Acceleration Strategy Formulation	Stakeholders Primary Interest
		maintenance complicated technicalities in term long.	AaaS) through BUMDes or <i>agritech startups</i> .	
8	Regulation & Data	Absence standard law spatial data protection land owned by farmers and not yet integrated agricultural data macro.	<ul style="list-style-type: none"> • Preparation of a National Digitalization Roadmap Agriculture. • Integration of sensor data into in single database system (<i>big data agriculture</i>). 	<ul style="list-style-type: none"> • Ministry of Agriculture • Central Statistics Agency (BPS)

4. Conclusion

Based on in-depth analysis, this study concludes that precision agriculture technology is no longer merely a sectoral innovation option, but rather a transformative pillar absolutely necessary to break dependence on exploitative and speculative conventional agricultural practices. The integration of a digital ecosystem based on the Internet of Things (IoT), remote sensing, and artificial intelligence has been empirically proven to resolve the global food security paradox by boosting aggregate crop productivity by 20–30% while reducing critical inputs (water and chemical fertilizers) by 15–25%. These efficiency figures confirm that a data-driven agriculture approach successfully embodies the principles of sustainable agricultural intensification without sacrificing the carrying capacity of micro- and macro-ecosystems. However, the study's critical findings point to the threat of technological polarization; this massive potential is stagnate at the downstream level due to the trap of structural barriers for local farmers, such as high initial investment capital, fragmentation of small land, the demographic digital literacy gap, and fragile rural connectivity. Failure to address these barriers risks monopolizing the profits of modern agriculture solely at the scale of large corporations. Therefore, accelerating national food security equitably requires a strategic deconstruction from individual adoption to a collective, inclusive movement through radical government intervention. This includes institutional restructuring through farmer corporations, smart fiscal stimulus, provision of upstream internet networks, and democratization of technology through the Agriculture-as-a-Service (AaaS) business model to ensure all levels of farmers can achieve economic independence.

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