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Food estate vs. smart farming: Rice production strategies for national food security

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ABSTRACT

Background: Indonesia's food security faces complex pressures due to climate change, environmental degradation, and a high dependence on rice as the staple food. The government has responded to these challenges through the food estate program, which is based on large-scale land extensification. Various studies indicate that this program has low productivity, high ecological risks, and is unable to make a significant contribution to long-term food security. On the other hand, smart farming, which has been successfully implemented in countries such as Japan, Malaysia, and Brazil, demonstrates that technology-based precision intensification has significant potential to improve production efficiency without land expansion. **Methods:** The method used is a qualitative descriptive-comparative approach through the analysis of academic literature, policy documents, national statistical data, and international studies related to smart farming. **Findings:** The results show that productive food estate cultivation land accounts for less than 5% of the target and only produces 5.1–5.2 tons/ha (lower than the potential of intensively managed land), accompanied by ecological impacts such as peat degradation, deforestation, and land conflicts. In contrast, smart farming has the potential to increase national rice productivity by 10–20%, add up to 3 million tons of unhusked rice (milled dry paddy) if applied to 50% of existing rice fields, save water by 20–50%, and reduce chemical fertilizer use by around 20% through precision application. **Conclusion:** This study provides conceptual and empirical evidence that strengthening Indonesia's food security may benefit from complementing land expansion policies with precision agricultural intensification supported by digital technologies, stronger farmer institutions, and the utilization of domestic research and innovation. It also opens opportunities for further research on designing smart farming implementation models for smallholder farmers and institutional strategies to accelerate its adoption. **Novelty/Originality of this article:** This study introduces a paradigm shift from land-expansion food estates toward inclusive precision intensification, integrating smart farming, farmer institutions, and digital agriculture as sustainable strategies for Indonesia's future food security transformation.

KEYWORDS: agricultural policy; food estate; food security; land extensification; smart farming.

1. Introduction

The global food system is currently under increasing pressure due to climate change, the depletion of natural resources, geopolitical instability, and market volatility (FAO, 2021). These conditions have led to rising risks of global food insecurity and malnutrition, which are often more focused on quantity rather than nutritional quality (Kennedy et al., 2021). At the same time, in efforts to meet food quantity demands, climate change exacerbated by anthropogenic factors has increased uncertainty in crop production, thereby highlighting the urgency of developing more adaptive and predictive production models and strategies to strengthen global food security (Taniushkina et al., 2024). In

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response to this complexity, in 2016 the Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO) initiated a transformation by promoting food systems that are sustainable, healthy, equitable, and resilient to crises, ensuring availability, accessibility, affordability, and desirability (Kennedy et al., 2021; WHO, 2016). These pillars have since become the foundation for many countries in restructuring their food production, distribution, and consumption systems at both national and global levels.

Various countries have implemented diverse solutions to strengthen food security, particularly in the agricultural sector. These efforts include the application of True Cost Accounting (TCA) to assess the environmental and social costs of food production; increasing productivity through Climate-Smart Agriculture (CSA); the adoption of smart farming based on digital technology and the Internet of Things (IoT); the development of agroecology through organic farming and agroforestry to integrate food crops with trees; as well as agricultural extensification through the expansion of new land (Enyew & Gobie, 2025; FAO, 2023; Hashim et al., 2024); Supriyanto et al., 2025). In addition, several countries rely on substitution strategies through food import policies to maintain food supply stability, particularly when domestic production cannot meet population needs (FAO, 2014). However, the literature emphasizes that food security solutions cannot stand alone, as they should not focus solely on increasing production quantity while neglecting environmental and social sustainability aspects. The selected strategies must consider ecosystem carrying capacity to avoid long-term negative impacts (Fanzo et al., 2021). The choice of food production strategies will determine a country's contribution to achieving Sustainable Development Goals (SDG) 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land).

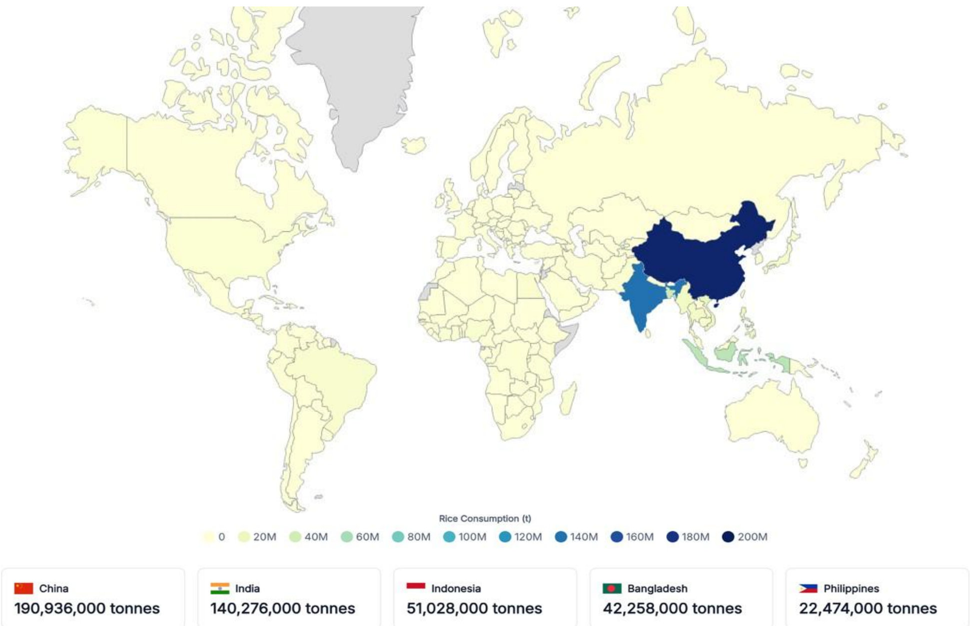

Fig. 1. The 5 countries with the highest rice consumption
(USDA, 2025)

Globally, staple food consumption patterns are still dominated by cereal groups such as rice and wheat. Rice is the primary staple food in most developing countries (Pimentel, 2009). Over the past 20 years, both production and consumption have generally increased due to population growth, rising food demand, and improvements in agricultural practices (Hashim et al., 2024). In 2022, the five countries with the highest rice consumption were dominated by Asian nations, namely China, India, Indonesia, Bangladesh, and the Philippines (USDA, 2025). This highlights the critical importance of rice production stability in maintaining food security, particularly in the Asian region.

Indonesia, with a population of approximately 284 million people, has a high level of rice consumption and a strong dependence on rice as the primary source of nutrition (Ministry of Agriculture, 2024; Central Statistics Agency, 2025b). In 2024, household rice consumption reached 1.521 kg per capita per week (Central Statistics Agency, 2024). Based on the Indonesia Rice Supply and Demand Balance 2024, national rice demand reached 2,635,526 tons, while supply from domestic production and imports amounted to 12,302,285 tons in 2024 (Ministry of Agriculture, 2024). These figures indicate that rice availability is actually sufficient, further supported by a declining consumption trend from 103.73 kg/capita in 2019 to 93.15 kg/capita in 2024. However, to maintain long-term production stability, the government has launched the food estate program, which aims to increase food production through extensification by expanding agricultural land on a large scale (Supriyanto et al., 2025).

Although the food estate program was introduced to strengthen national food security through agricultural land expansion, its implementation has generated diverse perspectives regarding its productivity, environmental implications, and long-term sustainability (Benedicta & Subekti, 2024; Meilinda et al., 2025). Several studies have reported implementation challenges in some locations, including agricultural development on peatlands and areas with high ecological sensitivity (Margono et al., 2012; Tsujino et al., 2016). At the same time, advances in precision agriculture and smart farming have attracted increasing attention as alternative approaches to improving agricultural productivity through digital technologies and resource-efficient management (Hashim et al., 2024). Both approaches therefore represent different pathways toward achieving national food security, each with distinct opportunities and challenges that require systematic evaluation.

While previous studies have examined food estate development and smart farming separately, limited research has provided an integrated comparison of these two approaches within Indonesia's food security context. Existing studies generally focus either on evaluating the implementation of food estate programs or on the technological potential of smart farming, without systematically assessing their relative effectiveness, environmental sustainability, and institutional suitability within Indonesia's agrarian structure and policy landscape. Consequently, evidence remains limited regarding how these two approaches compare as alternative strategies for strengthening national rice security. Accordingly, this study addresses the following research question: "What are the relative strengths and weaknesses of land-extensification (food estate) and technology-based intensification (smart farming) as strategies for enhancing Indonesia's national rice security?". To answer this question, the study compares both approaches in terms of productivity, environmental sustainability, implementation requirements, and their suitability within Indonesia's agricultural context.

Food plays a crucial role in maintaining economic and political stability (Wuryandani, 2021). In the aftermath of the pandemic crisis, the Indonesian government has promoted a national food reserve program through the food estate initiative (Benedicta & Subekti, 2024). As a national strategic program, based on the Regulation of the Minister of Environment and Forestry Number 7 of 2021 concerning Forestry Planning, Changes in the Allocation and Function of Forest Areas, and the Use of Forest Areas (Permen LHK 7/2021), a food estate is defined as a large-scale food production system that utilizes natural resources through human efforts, capital, technology, and other resources to produce food products in an integrated manner covering food crops, horticulture, plantations, livestock, and fisheries within a forest area. The food estate program, which involves land expansion, is not a new initiative in Indonesia. It has been implemented since 1995, with land expansion reaching 1.45 million hectares. However, despite large-scale land clearing, production outcomes have remained relatively low across different periods of government (Supriyanto et al., 2025).

Food estate is implemented through agricultural land extensification practices in peatlands, wetlands, and forest areas, supported by mechanization using heavy equipment (United Tractors, 2025), multi-commodity cultivation (rice, corn, and sugarcane), and centralized management led by the government (Supriyanto et al., 2025). These efforts aim to rapidly increase food production on a large scale, reduce dependence on food imports, and achieve food self-sufficiency (Rasman et al., 2023). Food estate is closely associated with land cover change, particularly agricultural expansion in forest, peatland, and swamp ecosystems (Benedicta & Subekti, 2024; Meilinda et al., 2025). The expansion of agricultural land in these vulnerable ecosystems can lead to deforestation, hydrological degradation, biodiversity loss, and high economic costs (Rasman et al., 2023; Redi & Mizuno, 2025). Thus, food estate can be understood as a food production approach oriented toward accelerating output through land expansion, but accompanied by significant ecological and governance consequences. This underscores the need for comparative studies with alternative approaches that are more sustainable.

Table 1. Implementation of food estate across different presidential administrations

The presidential era				
	Soeharto	Susilo Bambang Yudhoyono	Jokowi	Prabowo
Implementation Period	1995–1998	2008–2014	2015–2024	2025–2029
Planned Land Expansion	1.45 million ha	1.23 million ha	1.23 million ha	3 million ha (target)
Planned Locations	–	Merauke (Papua); Bulungan (North Kalimantan); Ketapang (West Kalimantan)	Merauke (Papua); Keerom (Papua); Gunung Mas (Central Kalimantan)	–
Realized Area & Locations	3,000 ha (0.2% of planned area), Central Kalimantan	140,000 ha (8.6%), Merauke (Papua); Ketapang (West Kalimantan); Bulungan (North Kalimantan)	30,000 ha (2.4%), Central Kalimantan; North Sumatra; East Nusa Tenggara; South Sumatra; Papua	150,000 ha in 2025, Merauke (Papua); South Sumatra; Central, South, and West Kalimantan
Budget Allocation	IDR 13.3 trillion	IDR 8.09 trillion	Data not available	IDR 105.9 trillion

(Supriyanto et al., 2025)

Climate change has increased the variability of rainfall, extreme temperatures, floods, droughts, and the emergence of pests and diseases, thereby threatening the stability of global food production. As a result, agricultural adaptation requires a transformation of production systems to remain resilient under climate pressures (Enyew & Gobie, 2025). On the other hand, several rice-producing countries have experienced substantial increases in output driven by technological advancements, irrigation systems, and improved farming techniques (Hashim et al., 2024). The use of technology in agriculture, commonly referred to as smart farming, provides benefits such as improved efficiency in fertilizer and pesticide use, increased farmer profitability, and contributions to more sustainable agricultural practices (Ewert et al., 2025).

Smart farming is often referred to as smart agriculture, Agriculture 4.0, or precision agriculture. Smart farming is an overarching concept that encompasses various digital technologies and automation, while precision agriculture is a data-driven approach that emphasizes site-specific land management. Meanwhile, Agriculture 4.0 refers to a comprehensive digital transformation involving the Internet of Things (IoT), sensors, cloud computing, robotics, big data analytics, Artificial Intelligence (AI), and satellite data to optimize agricultural production (Ali et al., 2023; Ewert et al., 2025). The fundamental principle of this approach is the more effective and efficient use of resources, enabling increased productivity, reduced operational costs, and support for sustainable agricultural practices. Through the integration of computing devices and automated monitoring systems, smart farming aims to transform traditional agricultural practices into more precise, adaptive, and sustainable systems (Ali et al., 2023). The fundamental differences between traditional agriculture and smart farming are illustrated in Figure 2.

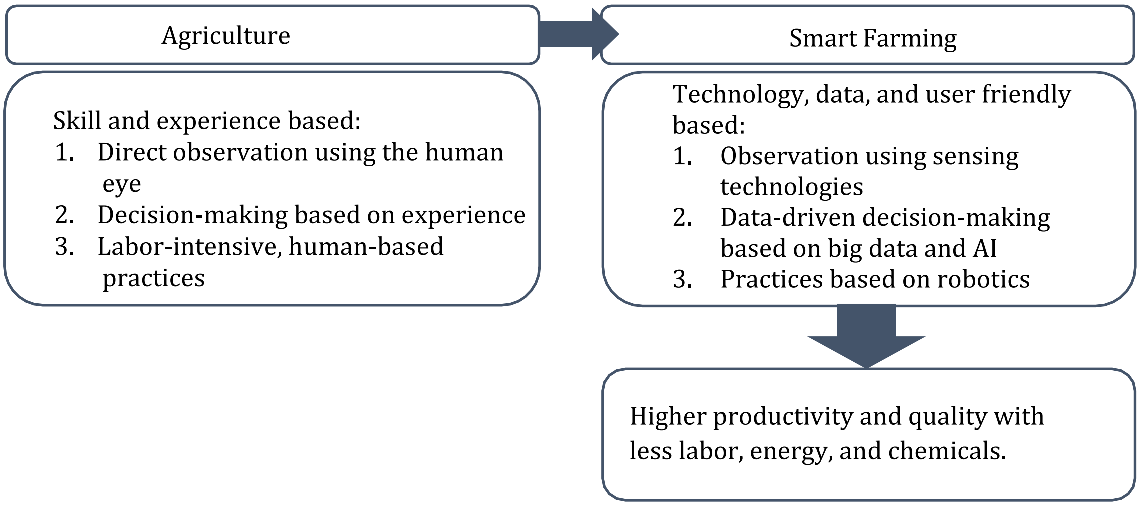

Fig. 2. Comparison between traditional agriculture and smart farming
(Inoue, 2020)

In rice production, smart farming is applied in yield estimation, smart irrigation systems, monitoring of plant growth and diseases, as well as predicting the quality and classification of harvests (Hashim et al., 2024). Yield estimation is essential for farmers to make crop management decisions in order to maintain stable yields and ensure sustainable production amid climate challenges (Hashim et al., 2024). The use of technology in yield estimation enables real-time, data-driven monitoring, allowing farmers to optimize resource management such as water, fertilizers, and pesticides and make timely decisions to improve overall efficiency (Jabed & Murad, 2024). The main technologies commonly used in yield estimation include the integration of Variable Rate Technology (VRT), real-time monitoring sensors, drones for crop monitoring and spraying, yield monitors on combine harvesters, and IoT systems with real-time data simulation (Ali et al., 2023; Jabed & Murad, 2024). These key technologies are summarized in Table 2.

Table 2. Technologies used in yield estimation

Technology	Main function in yield estimation
VRT (Variable Rate Technology)	Adjusts input application (fertilizers, seeds, water), predicts and optimizes yield in a site-specific manner, and reduces waste by up to 20–30%.
Real-time Monitoring Sensors	Continuously measure soil parameters (moisture, nutrients, pH) and weather conditions to support yield prediction models with accuracy >85% through IoT integration.
Drones for Monitoring and Spraying	Utilize NDVI imagery to detect early crop stress and enable precision spraying, with yield prediction accuracy reaching RMSE <10% in heterogeneous fields.
Yield Monitor on Combine Harvester	Measures actual yield in a georeferenced manner during harvesting to validate predictions and map yield variability per hectare.
IoT and Real-time Data Simulation	Collect and simulate data from sensors and drones for AI-based prediction models, supporting “what-if” simulations for different climate scenarios.

(Ali et al., 2023; Hashim et al., 2024; Jabed & Murad, 2024)

The implementation of smart irrigation systems contributes to more efficient water use and cost reduction (Ali et al., 2023; Getahun et al., 2024). This approach integrates soil moisture sensors, climate and temperature data, and crop data with cloud-based systems supported by the internet to enable real-time monitoring and analysis (Hashim et al., 2024). The main technologies commonly used are summarized in Table 3.

Table 3. Technologies used in smart irrigation systems

Technology	Main function in smart irrigation systems
Soil Moisture Sensors	Detect real-time water needs of crops.
Drip and Sprinkler Irrigation Systems	Regulate precise water application to crops.
Naïve Bayes, Support Vector Regression, Fuzzy Logic	Predict water requirements based on data and environmental conditions.
Internet of Things (IoT)	Control irrigation systems to improve water efficiency compared to traditional irrigation.
Data Platforms and Mobile Applications	Monitor and manage irrigation systems in real time.

(Ali et al., 2023)

The implementation of smart irrigation requires several integrated steps and technologies, such as automated drip irrigation, sprinkler systems, and irrigation control based on soil moisture sensors, along with water demand prediction using algorithms such as Naïve Bayes, Support Vector Regression, and fuzzy logic. This system also integrates climate and soil temperature data to optimize water use. In addition, the use of wireless sensor networks and automated controllers enables precise irrigation adjustments, improving crop yields while reducing water consumption compared to traditional systems. With these technologies, farmers can monitor field conditions and manage irrigation more intelligently and efficiently, reducing manual labor while conserving water resources (Ali et al., 2023).

Table 4. Technologies used in disease identification and rice growth monitoring

Technology	Main function in disease identification and growth monitoring
GPS, Remote Sensing, GIS	Monitor crop health spatially and detect changes in plant conditions.
VRT (Variable Rate Technology)	Regulate the application of fertilizers and pesticides according to specific crop needs.
Drones	Identify the distribution of pests and diseases and assess their severity levels.
Data-based Predictive Modeling	Project pest and disease pressure based on environmental and historical data.
Electronic Nose	Predict rice shelf life based on aroma analysis.
Convolutional Neural Networks (CNN)	Classifying disease types with 99.7% accuracy.

(Getahun et al., 2024; Hashim et al., 2024)

Disease identification and crop growth monitoring enable farmers to quickly detect constraints in the field, allowing timely and appropriate interventions based on existing problems (Ali et al., 2023). Identification can be carried out using various technologies (see Table 3), such as GPS, remote sensing, and Geographic Information Systems (GIS), which provide spatial information on changes in plant color and vigor. These indicators can signal stress or infection that may not be visible to the naked eye, enabling farmers to take rapid and accurate action. In addition, recent studies show that the RicePest-DETR model developed in China is capable of detecting small-scale rice pests with high accuracy using an end-to-end transformer approach, thereby improving the speed and precision of automated pest identification in the field (Liu et al., 2025). The application of these technologies also supports ecological balance by identifying and protecting beneficial insect populations in line with the Integrated Pest Management (IPM) approach (Getahun et al., 2024).

Table 5. Technologies used in rice quality prediction and classification

Technology	Main function in quality prediction and classification
Hyperspectral Sensing Techniques	Identify rice varieties based on spectral characteristics.
Electronic Nose	Predict rice shelf life based on aroma analysis.
Machine Vision	Classify rice quality and detect physical defects in grain shape.
Radio Frequency (RF) Tomography and Transceivers	Measure moisture distribution within rice grains.

(Hashim et al., 2024)

Rice quality significantly influences its market price (Mohidem et al., 2022), making it essential to anticipate and reduce post-harvest losses (Hashim et al., 2024). Such anticipation can be achieved through a combination of image processing, electronic sensors, and machine learning algorithms to improve the accuracy, efficiency, and speed of rice quality classification and prediction (Hashim et al., 2024). The application of these technologies in quality prediction can help farmers increase the added value of the rice they produce. The application of smart farming is not merely conceptual but has demonstrated measurable real-world impacts. Quantitatively, smart farming provides various benefits, ranging from improved resource-use efficiency to increased crop yields and reduced environmental impacts (Table 6).

Table 6. Quantitative benefits of implementing smart farming

No.	Technology application	Quantitative benefits
1	Improving soil health and resource efficiency using technology	Soil health improvement of 20–30%; resource efficiency increased by 15%
2	Water-saving through sensors and data analysis for irrigation practices	Water use reduced by 30–50%; yield increased by 10–20%
3	Real-time crop monitoring using drones, satellite imagery, and IoT sensors	Yield increased by 10–20%; input costs reduced by 15%
4	Data-driven optimization of nutrient (fertilizer) use	Fertilizer use efficiency increased by 20%; fertilizer costs reduced by 25%
5	Pest and disease management using data and remote sensing	Pest/disease reduced by 20–40%; crop loss reduced by 15–25%
6	Optimization of planting and harvesting using GPS and data analytics	Yield increased by 15–30%; fuel savings of 10–20%
7	Use of climate data and predictive modeling to adapt crop management practices	Food resilience increased by 20%; adaptation costs reduced by 10%
8	Use of data management and analytical techniques to maximize production	Crop production increased by 15–25%; data management efficiency improved
9	Optimization of resource use and environmental impact	Land degradation reduced by 20%; resource-use efficiency increased by 15%
10	Minimizing carbon emissions and optimizing energy use	Emissions reduced by 15–25%; energy use reduced by 10–20%

(Getahun et al., 2024)

2. Methods

This study employs a qualitative descriptive-comparative approach based on a literature review to examine food estate and smart farming as alternative rice production strategies for strengthening Indonesia's national food security. This approach was selected because it enables a systematic comparison of the characteristics, implementation contexts, and potential contributions of both strategies while synthesizing evidence from previous studies. Data collection was conducted through a review of academic literature, policy documents, national and global reports, as well as statistical data. Descriptive analysis was used to identify the key characteristics, operational principles, and implementation contexts of smart farming and food estate. Furthermore, comparative analysis was then conducted using three international smart farming case studies representing different implementation models: a high-technology model (Japan), a low-cost technology model for smallholder farmers (Malaysia), and a data-driven precision agriculture model based on remote sensing (Brazil). These cases were selected to evaluate the potential applicability of smart farming in Indonesia in terms of productivity improvement, resource-use efficiency, institutional readiness, and environmental sustainability. Finally, the findings were synthesized to develop conceptual policy recommendations regarding the relative roles of land extensification through food estate and precision intensification through smart farming in supporting sustainable national food security.

3. Results and Discussion

3.1 The implementation of food estates in Indonesia for rice production

The implementation of the food estate program as a strategy to increase rice production in Indonesia has been carried out since 1995 using a large-scale land extensification approach. According to the FAO Agro-Ecological Zoning (AEZ) framework, agricultural land expansion can contribute to food security when implemented on agro-ecologically suitable land and supported by appropriate land evaluation, planning, and governance (Ahmad et al., 2019). This program has opened a total of 6.91 million hectares of land across various regions, including Central Kalimantan, West Kalimantan, North Kalimantan, South Sumatra, North Sumatra, East Nusa Tenggara, and South Papua. The land utilized generally includes peatlands, existing rice fields, and forest areas, including protected forests that are permitted for cultivation activities under Regulation of the Minister of Environment and Forestry No. 7/2021. Although legally permitted, the use of such areas carries ecological consequences, including hydrological degradation, biodiversity loss, and high carbon emissions resulting from peatland conversion (Benedicta & Subekti, 2024; Rasman et al., 2023). On the other hand, Regulation No. 7/2021 does not provide clear limitations on the extent to which protected forests can be classified as "partially non-protective," raising concerns about potential expansion of cultivation into forested areas, which may accelerate deforestation (Benedicta & Subekti, 2024).

Empirically, the extent of land opened has not been accompanied by adequate productivity. The area that is truly productive is only around 323,000 hectares, or less than 5% of the total planned area (Supriyanto et al., 2025). Production yields range from 5.1–5.2 tons per hectare, which is lower than the national potential of 6–7 tons/ha, and far below the optimal potential of 7–10 tons/ha in intensively irrigated fields (Sulaeman et al., 2024). In addition to low productivity, various studies have documented the emergence of land conflicts, uncertainty in land-use status, and shifts from food production to non-food commodities.

The food estate program in Central Kalimantan, for example, has been further undermined by land conflicts involving local communities, corporations, and authorities; the dominance of large-scale business interests that shift the focus away from food security; unclear spatial planning and land status not aligned with the Regional Spatial Plan (RTRW); as well as the marginalization of indigenous communities and local farmers who lose their livelihoods and access to land (Ayu, 2022). Meanwhile, in North Sumatra, the food estate program has instead reduced rice production, as communities were compelled to shift to other commodities such as potatoes, garlic, and shallots, leading to rice shortages at the household level. A similar situation has occurred in Merauke, where large-scale agricultural projects involving investors have shifted toward non-food commodities such as oil palm (Kamin & Altamaha, 2019). Furthermore, the Minister of Agriculture has openly stated that the Merauke food estate area serves as a source of raw materials for ethanol and biodiesel. This indicates a shift in the original objective of food estate land development.

Narratively, the food estate program is often promoted as a driver of food security, an attractor of investment, and a means to increase farmers' income. However, various studies indicate that these benefits are overshadowed by risks such as land conflicts, environmental degradation, deforestation, and shifts in agricultural practices that may actually weaken food sovereignty (Redi & Mizuno, 2025). In general, the low level of success is largely influenced by weaknesses in planning and implementation processes (Rasman et al., 2023), as well as the failure to align ecological, economic, and socio-cultural interests. It is also associated with the lack of participatory and inclusive approaches that take into account local knowledge and indigenous rights (Meilinda et al., 2025).

In other words, this program has been developed without adequate land suitability analysis, particularly regarding water availability, soil characteristics, climate conditions, and the readiness of agricultural infrastructure. In fact, in addressing environmental pressures and climate change, the food estate program should prioritize research, especially related to soil quality (Fiantis et al., 2022). The mismatch of crop varieties, the use of planting methods that are not aligned with local ecological conditions, and the lack of technological support for farmers have also become significant constraints. In addition, synergy between the government, local farmers, and other stakeholders is often weak. Many farmers are unfamiliar with new farming systems, receive limited training, or bear high production risks when outcomes do not meet expectations (Rasman et al., 2023; Redi & Mizuno, 2025). Farmers are even frequently bound by contracts as suppliers in agribusiness schemes, indicating that the food estate program is driven more by political and economic interests than purely by the goal of increasing local food production (Hidayaturrahman et al., 2025). This situation suggests that land expansion alone may be insufficient to strengthen long-term rice production, highlighting the need to complement extensification with strategies that improve productivity, resource efficiency, and environmental sustainability. Overall, the implementation of food estate in Indonesia indicates that land extensification alone is insufficient to achieve sustainable rice production. Its effectiveness depends not only on expanding cultivated areas but also on appropriate land selection, comprehensive planning, adequate infrastructure, good governance, and the integration of ecological, social, and economic considerations. These observations highlight the importance of complementing land expansion with approaches that enhance productivity and resource efficiency, which are discussed in the following section.

3.2 Smart farming in various countries

The implementation of smart farming in various countries demonstrates diverse approaches depending on socio-economic contexts, land structures, and technological capacities. Japan, for instance, has faced unsustainable agricultural conditions due to climate change, limited land availability, and a significant decline in the number of farmers (Fuhrmann-Aoyagi et al., 2024). In response to these challenges, various efforts have been undertaken to enhance the productivity and sustainability of agriculture, forestry, fisheries, and food industries in Japan through innovation, policy support (Fuhrmann-Aoyagi et al., 2024), and the adoption of smart farming practices supported by advanced technologies (Inoue, 2020). Japan utilizes an integration of high-resolution satellite imagery (WorldView-2/3, SPOT-6/7, RapidEye), multispectral and thermal drones, and AI-based crop diagnostic algorithms for precision management in rice fields. These technologies support accurate yield estimation, precision fertilization based on CCC and CNC mapping, early detection of pests and diseases, and irrigation management based on plant water stress. The quantitative impacts are significant: fertilizer use is reduced by 10–17%, yields increase by 10–15%, rice quality improves, and land management efficiency is enhanced despite highly fragmented paddy field structures (Inoue, 2020).

Meanwhile, Malaysia has initiated smart farming practices focused in the Selangor region. Unlike Japan, its implementation is not conducted on a large scale but rather among smallholder farmers. The technologies used are simpler and more cost-effective, including drones for fertilization, spraying, seeding, and disease detection, as well as decision support systems such as PADDY-GIS, which integrates remote sensing, GIS, and GPS for precision mapping. These technologies have generated significant impacts, including improved time and labor efficiency, greater accuracy in input application, faster disease detection, enhanced land management, and reduced labor requirements. Although quantitative data are not yet available, qualitative findings indicate that smart farming improves the effectiveness of rice management and enhances farmers' readiness to face production challenges (Zaman et al., 2023).

In Brazil, significant progress has been demonstrated through the use of remote sensing based on satellite imagery and deep learning for precise rice mapping. The technologies applied include Sentinel-2 imagery, CNN and U-Net algorithms, as well as multiband spectral processing to generate high-resolution rice land cover maps. This approach improves mapping accuracy to over 90%, enabling more precise identification of cropping patterns, actual cultivated areas, and growth dynamics. The impacts are particularly significant in major rice-producing regions such as Rio Grande do Sul, where accurate spatial information supports governments and farmers in irrigation planning, production forecasting, flood risk mitigation, and more efficient resource management (Islam et al., 2025).

Comparatively, these countries demonstrate diverse applications of smart farming: Japan excels in high-precision technologies with clear quantitative impacts; Malaysia stands out in the adoption of low-cost technologies suitable for smallholder farmers; while Brazil maximizes the use of remote sensing and deep learning for data-driven planning and policymaking. These findings indicate that improving productivity and input efficiency does not necessarily require large-scale mechanization. In fact, Malaysia and Brazil show that smart farming can also be successfully implemented on small plots and through strengthened information systems, making this approach particularly relevant for Indonesia, where rice farming is predominantly small-scale and fragmented. However, large-scale implementation would require substantial initial investment in digital infrastructure, agricultural equipment, connectivity, and farmer capacity building. Therefore, smart farming should be introduced gradually through phased adoption, cooperative-based service models, and public support to reduce financial barriers for smallholder farmers. Compared with large-scale land expansion, this approach provides an opportunity to enhance productivity while minimizing additional environmental pressure.

3.3 Estimated increase in Indonesia's rice productivity through smart farming technology

In 2024, Indonesia had a total paddy field area of 10.05 million hectares, with total rice production reaching 53.14 million tons of unhusked rice (Gabah Kering Giling, GKG) (Central Statistics Agency, 2025a). On average, national productivity ranges from 5.2–5.3 tons/ha, comparable to the food estate output of 5.1–5.2 tons/ha. However, this figure remains lower than the potential of intensively managed irrigated fields, which can typically reach 6–7 tons/ha. If traditional practices are enhanced with smart farming technologies—such as real-time crop monitoring using drones, satellite imagery, and IoT sensors—productivity can increase by approximately 10–20% (Getahun et al., 2024). Using a baseline productivity of 6 tons/ha, this improvement could raise yields to around 6.6–7.7 tons/ha, thereby increasing national production without the need for land expansion as in the food estate approach. This improvement is also more sustainable, as it optimizes the use of existing agricultural land. In addition, recent studies have developed IoT-based models for monitoring soil fertility and pest rates with an accuracy of up to 99% (Widanti et al., 2024).

In terms of water efficiency, rice water consumption varies across genotypes and varieties; however, under the assumption of 200,000 clumps per hectare, water requirements range from 3,639 to 4,827 m^3/ha (Supijatno et al., 2012). This amount can be reduced by 30–50% through the use of sensors and big data analytics (Getahun et al., 2024). Meanwhile, a study in Indonesia shows that the development of water-saving irrigation control based on fuzzy logic can reduce water use by 20.32% (Saputra, 2022). Thus, if applied, average water consumption could decrease to approximately 2,899–3,955 m^3/ha. Smart farming also has the potential to reduce the use of chemical fertilizers. Under low productivity conditions (±6 tons/ha), conventional practices with low soil nutrient status typically require around 300–400 kg/ha of urea, 100 kg/ha of SP36/TSP, and 100 kg/ha of KCl. With a data-driven approach, fertilizer efficiency can increase by up to 20% due to application based on actual crop needs (Getahun et al., 2024). Consequently, urea requirements can be reduced to approximately 240 kg/ha, SP36/TSP to 80 kg/ha, and KCl to 80 kg/ha. This reduction is important to minimize nutrient loads on soil and water systems.

At the national level, if 50% of Indonesia's rice fields (approximately 5 million hectares) adopt smart farming with a minimum productivity increase of 10%, the additional production would reach: 5 million ha × 0.6 tons/ha = +3 million tons of unhusked rice (GKG). This increase would be sufficient to close import gaps in certain years without the need for land expansion. The environmental impact of smart farming is significantly lower than that of food estate, as it does not require deforestation, reduces the use of fertilizers and water, and prevents peatland degradation. Therefore, precision intensification through smart farming offers a more efficient, sustainable, and low-emission strategy for increasing production compared to the extensification approach of food estate.

3.4 Challenges in implementing smart farming

Although smart farming offers promising technical and environmental advantages, its adoption in Indonesia is influenced not only by technological readiness but also by broader policy priorities. The continued implementation of the food estate program illustrates that agricultural development decisions are shaped not only by technological effectiveness but also by political and economic considerations. Food estate projects have gradually expanded beyond food production objectives to support broader policy agendas, including regional development, investment attraction, infrastructure expansion, and downstream agro-industries such as bioenergy. These multiple policy priorities help explain why land extensification continues to receive substantial policy attention despite documented challenges in productivity, environmental sustainability, and social outcomes (Hidayaturrahman et al., 2025; Kamin & Altamaha, 2019). Consequently, the transition toward smart farming involves not only overcoming technical and financial barriers but also strengthening policy support and aligning public investment with long-term productivity and sustainability objectives.

The implementation of smart farming in Indonesia faces structural constraints typical of developing countries. More than 50% of farmers in Indonesia are smallholders managing land areas of less than 0.5 hectares (Central Statistics Agency, 2023). This condition makes investments in IoT sensors, drones, and other technologies difficult to afford. In addition, internet usage in Indonesia, although reaching 72.78% (Central Statistics Agency, 2025b), remains unevenly distributed, which hampers the implementation of cloud-based and real-time technologies. From an economic perspective, farmers face price volatility of unhusked rice, high input costs, and limited access to financing, making precision technologies appear high-risk and difficult to prioritize as investments.

Technical barriers are also significant, including limited digital capacity among farmers, inadequate energy infrastructure in agricultural areas, and a lack of data availability. This data limitation causes many technology-based solutions to remain isolated (Project Mizu, 2023). Moreover, environmental challenges such as droughts, floods, and soil degradation require more adaptive smart farming systems, while most farmers still rely on traditional farming practices. However, these traditional practices—largely based on experience are becoming less relevant under current climate crisis conditions (Project Mizu, 2023).

Experiences from other countries show that the various barriers to smart farming can be overcome through strong institutional support. Malaysia has successfully adopted low-cost technologies such as drones and GIS systems among smallholder farmers, supported by subsidies, field training, and service models such as "drone-as-a-service" (Zaman et al., 2023). Japan demonstrates successful agricultural productivity despite land limitations through the adoption of high-standard technologies supported by national policies (Fuhrmann-Aoyagi et al., 2024). Meanwhile, Brazil has maximized the use of remote sensing technologies and spatial modeling for crop planning and data-driven decision-making by the government (Islam et al., 2025). These lessons are highly relevant for Indonesia, whose agricultural structure is similar to Malaysia's, but which requires strong institutional support like Japan and spatial data integration as implemented in Brazil. In the policy context, given the substantial public investment of approximately IDR 127 trillion in the food estate program, the limited productive area, modest yield improvements, and the environmental and social challenges discussed in this study suggest that a comprehensive evaluation of future investment priorities is warranted. Greater investment in smart farming technologies and agricultural digitalization may offer a more cost-effective and sustainable pathway to increasing national rice production than continued reliance on large-scale land expansion.

4. Conclusions

The findings of this study indicate that strengthening Indonesia's food security cannot rely solely on large-scale land expansion through the food estate approach, given the limited productive outcomes, environmental risks, and implementation challenges identified in this study. In contrast, a comparative analysis of Japan, Malaysia, and Brazil demonstrates that smart farming, through both high-precision and low-cost technologies, offers a promising pathway to increase productivity, improve input-use efficiency, and reduce environmental pressures. The analysis suggests that adopting smart farming on only a portion of Indonesia's existing rice fields could increase national rice production by approximately 3 million tons of unhusked rice (GKG), while simultaneously reducing water and fertilizer use through data-driven management.

The successful adoption of smart farming, however, depends not only on technological innovation but also on addressing structural and institutional barriers. Land fragmentation, limited farmer capacity, inadequate digital infrastructure, and policy incentives that continue to prioritize land extensification remain major constraints. Therefore, the transition toward smart farming requires stronger governance, cross-sectoral coordination, and a shift from a predominantly top-down policy approach toward farmer-centered institutional arrangements that strengthen extension services, technology adoption, and long-term investment. Rather than being implemented nationwide at once, smart farming should first be introduced through pilot projects in major rice-producing regions, followed by gradual scaling based on technical, economic, and institutional evaluation.

From a policy perspective, rather than focusing predominantly on expanding cultivated land, future agricultural investment should prioritize integrating national agricultural data systems, strengthening agricultural digitalization, expanding rural digital infrastructure, reinforcing research and extension services, and empowering farmer organizations to ensure inclusive technology adoption. These measures should complement continuous evaluation of large-scale land expansion programs to ensure that future public investment generates higher productivity and sustainability outcomes.

This study contributes to the literature by providing a comparative conceptual assessment of food estate and smart farming as alternative strategies for strengthening Indonesia's food security. However, this study is based primarily on a literature review and comparative analysis; therefore, its conclusions should be interpreted within the scope of a conceptual analysis. Future research should undertake field-based empirical validation to evaluate the technical feasibility, economic performance, institutional readiness, and social acceptance of smart farming under different agroecological and socio-economic conditions in Indonesia. Such evidence will provide a stronger empirical basis for evaluating the relative effectiveness of food estate and smart farming as alternative rice production strategies for achieving Indonesia's long-term national food security.

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Author Contribution

The author was responsible for conceptualization, methodology, data collection, analysis, interpretation of results, manuscript preparation, revision, and final approval of the submitted manuscript.

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The author declares no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the author used ChatGPT (OpenAI) to assist in improving the clarity, grammar, academic writing style, and organization of the manuscript. After using this tool, the author reviewed, revised, and edited all content as needed and took full responsibility for the accuracy and integrity of the manuscript.

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References

Ahmad, A., Khan, M. R., Shah, S. H. H., Kamran, M. A., Wajid, S. A., Amin, M., Khan, A., Arshad, M. N., Cheema, M. J. M., Saqib, Z. A., Ullah, R., Ziaf, K., ul Huq, A., Ahmad, S., Ahmad, I., Fahad, M., Waqas, M. M., Abbas, A., Iqbal, A., … & Khan, I. A. (2019). *Agro-ECOLOGICAL ZONES OF Punjab Pakistan*. FAO. https://openknowledge.fao.org/items/1cad58c4-6fd3-400c-aa08-9da0cd4cea46

Ali, A., Hussain, T., Tantashutikun, N., Hussain, N., & Cocetta, G. (2023). Application of smart techniques, internet of things and data mining for resource use efficient and sustainable crop production. *Agriculture*, *13*(2), 397. https://doi.org/10.3390/agriculture13020397

Ayu, K. P. (2022). Kebijakan perubahan lahan dalam pembangunan food estate di Kalimantan Tengah. *Journal Ilmu Sosial, Politik Dan Pemerintahan*, *11*(1), 24-36. https://e-journal.upr.ac.id/index.php/JISPAR/article/view/4203

Benedicta, S. J., & Subekti, R. (2024). Problematika kebijakan food estate terkait pemanfaatan kawasan hutan lindung. *Konsensus: Jurnal Ilmu Pertahanan Dan Ilmu Komunikasi*, *1*, 130–139. https://doi.org/10.62383/konsensus.v1i1.231

Central Statistics Agency. (2023). *Jumlah petani pengguna lahan pertanian dan petani gurem menurut wilayah, Indonesia*. https://sensus.bps.go.id/topik/tabular/st2023/215/98808/0

Central Statistics Agency. (2024). *Rata-rata konsumsi per kapita seminggu beberapa macam bahan makanan penting, 2007–2022.*

Central Statistics Agency. (2025a). *Jumlah penduduk menurut kelompok umur dan jenis kelamin 2025*. https://www.bps.go.id/id/statistics-table/3/WVc0MGEyMXBkVFUxY25KeE9HdDZkbTQzWkVkb1p6MDkjMyMwMDAw/jumlah-penduduk-menurut-kelompok-umur-dan-jenis-kelamin--ribu-jiwa-.html?year=2025

Central Statistics Agency. (2025b). *Statistik telekomunikasi Indonesia 2024*. https://www.bps.go.id/id/publication/2025/08/29/beaa2be400eda6ce6c636ef8/statistik-telekomunikasi-indonesia-2024

Enyew, S., & Gobie, W. (2025). Adoption of climate smart agricultural practices impact on food security of smallholder farmers in North Western Ethiopia. *Discover Sustainability*, *6*(1). https://doi.org/10.1007/s43621-025-01793-7

Ewert, F., Baatz, R., & Finger, R. (2025). Agroecology for a sustainable agriculture and food system: From local solutions to large-scale adoption. *Annual Review of Resource Economics*. https://doi.org/10.1146/annurev-resource-102422

Fanzo, J., Haddad, L., Schneider, K. R., Béné, C., Covic, N. M., Guarin, A., ... & Moncayo, J. R. (2021). Rigorous monitoring is necessary to guide food system transformation in the countdown to the 2030 global goals. *Food Policy*, *104*, 102163. https://doi.org/10.1016/j.foodpol.2021.102163

FAO. (2014). *New FAO guidance on risk based imported food controls*. https://openknowledge.fao.org/items/44783b6a-c0af-4fb5-af27-dd0c41204aad

FAO. (2021). *Strategic Framework 2022-31*. https://www.fao.org/strategic-framework/en

FAO. (2023). The State of Food and Agriculture 2023. *The state of food and agriculture 2023*. https://doi.org/10.4060/cc7724en

Fiantis, D., Rudiyanto, Ginting, F. I., Utami, S. R., Sukarman, Anda, M., Jeon, S. H., & Minasny, B. (2022). Sustaining the productivity and ecosystem services of soils in Indonesia. *Geoderma Regional*, *28*. https://doi.org/10.1016/j.geodrs.2022.e00488

Fuhrmann-Aoyagi, M. B., Miura, K., & Watanabe, K. (2024). Sustainability in Japan's agriculture: an analysis of current approaches. *Sustainability*, *16*(2), 596. https://doi.org/10.3390/su16020596

Getahun, S., Kefale, H., & Gelaye, Y. (2024). Application of precision agriculture technologies for sustainable crop production and environmental sustainability: A systematic review. *Scientific World Journal (John Wiley and Sons Ltd)*. https://doi.org/10.1155/2024/2126734

Hashim, N., Ali, M. M., Mahadi, M. R., Abdullah, A. F., Wayayok, A., Saufi, M., Kassim, M., & J., & A. (2024). *Smart farming for sustainable rice production: An insight into application, challenge, and future prospect*. https://doi.org/10.1016/j.rsci.2023.08.004

Hidayaturrahman, M., Handrito, R. P., Putu Sugiantiningsih, A. A., Ubaid, A. H., Haris, R. A., &, & Suprianto, S. (2025). Food estate development: Political-economic and legal perspectives. *Indonesian Journal of Advocacy and Legal Services*, *7*(2), 467–506. https://doi.org/10.15294/ijals.v7i2.31423

Inoue, Y. (2020). Satellite- and drone-based remote sensing of crops and soils for smart farming–a review. *Soil Science and Plant Nutrition (Taylor and Francis Ltd)*, *66*(6), 798–810. https://doi.org/10.1080/00380768.2020.1738899

Islam, M. S., Garcia, A. D. B., Sanches, I. D., Prudente, V. R., & Cheng, I. (2025). Remote sensing-based rice mapping in Brazil: Identifying the best approach for segmenting different spectral compositions using deep learning. *Remote Sensing Applications: Society and Environment*, *40*. https://doi.org/10.1016/j.rsase.2025.101770

Jabed, M. A., & Murad, M. A. A. (2024). Crop yield prediction in agriculture: A comprehensive review of machine learning and deep learning approaches, with insights for future research and sustainability. *Heliyon*, *10*(24). https://doi.org/10.1016/j.heliyon.2024.e40836

Kamin, A. B. M., & Altamaha, R. (2019). Modernisasi tanpa pembangunan dalam proyek food estate di Bulungan dan Merauke. *BHUMI: Jurnal Agraria Dan Pertanahan*, *5*(2), 163-179. https://doi.org/10.31292/jb.v5i2.368v

Kennedy, E., Webb, P., Block, S., Griffin, T., Mozaffarian, D., & Kyte, R. (2021). Transforming food systems: the missing pieces needed to make them work. *Current Developments in Nutrition*, *5*(1), nzaa177. https://academic.oup.com/cdn/article-abstract/5/1/nzaa177/6030026

Liu, J., Zhou, C., Zhu, Y., Yang, B., Liu, G., & Xiong, Y. (2025). RicePest-DETR: A transformer-based model for accurately identifying small rice pest by end-to-end detection mechanism. *Computers and Electronics in Agriculture*, *235*. https://doi.org/10.1016/j.compag.2025.110373

Margono, B. A., Turubanova, S., Zhuravleva, I., Potapov, P., Tyukavina, A., Baccini, A., Goetz, S., & Hansen, M. C. (2012). Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010. *Environmental Research Letters*, *7*(3). https://doi.org/10.1088/1748-9326/7/3/034010

Meilinda, S. R., Salman, D., & Muhammad, S. (2025). Conflict and compromise, discourse and action: political ecology in the complexity of land management in Central Kalimantan, Indonesia. *Forest and Society*, *9*(2), 422–448. https://doi.org/10.24259/fs.v9i2.40301

Ministry of Agriculture. (2024). *Buletin Konsumsi Pangan Semester I 2024*.

Mohidem, N. A., Hashim, N., Shamsudin, R., & Che Man, H. (2022). Rice for food security: Revisiting its production, diversity, rice milling process and nutrient content. *Agriculture*, *12*(6), 741. https://doi.org/10.3390/agriculture12060741

Pimentel, D. (2009). Energy inputs in food crop production in developing and developed nations. *Energies*, *2*(1). https://doi.org/10.3390/en20100001

Project Mizu. (2023). *Water-agriculture nexus: Forefront of climate adaptation*. Nexus. https://www.water-energy-food.org/es/resources/report-water-agriculture-nexus-forefront-of-climate-adaptation

Rasman, A., Sinta Theresia, E., & Fadel Aginda, dan M. (2023). Analisis implementasi program food estate sebagai solusi ketahanan pangan Indonesia. *Holistic: Journal of Tropical Agriculture Sciences Riset*, *1*(1). https://doi.org/journal-iasssf.com/index.php/HJTAS

Redi, A., & Mizuno, K. (2025). Benefits and costs of legal policy for the food estate program in Indonesia. *Law Reform*, *21*(1), 58-80. https://doi.org/10.14710/lr.v21i1.62903

Saputra, R. (2022). *Pengembangan sistem kendali irigasi hemat air berbasis logika fuzzy pada implementasi system of rice intensification (SRI).* Universitas Gadjah Mada. https://etd.repository.ugm.ac.id/penelitian/detail/209560

Sulaeman, Y., Aryati, V., Suprihatin, A., Santari, P. T., Haryati, Y., Susilawati, S., ... & Yasin, M. (2024). Yield gap variation in rice cultivation in Indonesia. *Open Agriculture*, *9*(1), 20220241. https://doi.org/10.1515/opag-2022-0241

Supijatno, S., Chozin, M. A., Sopandie, D., Trikoesoemaningtyas, T., Junaedi, A., & Lubis, I. (2012). Evaluasi konsumsi air beberapa genotipe padi untuk potensi efisiensi penggunaan air. *Indonesian Journal of Agronomy*, *40*(1), 7793. https://doi.org/10.24831/jai.v40i1.13198

Supriyanto, R., Maharani, A., & Alta, A. (2025). *Menafsir ulang food estate Indonesia: Jejak, dinamika, dan masa depan ketahanan pangan nasional*. https://doi.org/10.35497/619003

Taniushkina, D., Lukashevich, A., Shevchenko, V., Belalov, I. S., Sotiriadi, N., Narozhnaia, V., ... & Maximov, Y. (2024). Case study on climate change effects and food security in Southeast Asia. *Scientific reports*, *14*(1), 16150. https://doi.org/10.1038/s41598-024-65140-y

Tsujino, R., Yumoto, T., Kitamura, S., Djamaluddin, I., & Darnaedi, D. (2016). History of forest loss and degradation in Indonesia. *Land Use Policy*, *57*, 335–347. https://doi.org/10.1016/j.landusepol.2016.05.034

United Tractors. (2025). *Peran alat berat food estate di program pangan Indonesia*. https://products.unitedtractors.com/id/berita/peran-alat-berat-food-estate-di-program-pangan-indonesia/

USDA. (2025). *Rice consumption by country 2025*.

WHO. (2016). *FAO/WHO conference stresses need for transformation of food systems across all sectors*. https://www.who.int/news/item/02-12-2016-fao-who-conference-stresses-need-for-transformation-of-food-systems-across-all-sectors

Widanti, N., Alamsyah, A., Albus, A., Ikhsan, A. N., Lestari, S. W., Handini, W., & Raharjo, S. A. (2024). Design smart farming in rice field for monitoring soil fertility and pest rate using internet of things. *Jurnal Penelitian Pendidikan IPA*, *10*(8), 5782-5788. https://doi.org/10.29303/jppipa.v10i8.8288

Wuryandani, D. (2021). Food estate untuk ketahanan pangan nasional. *Majalah Tempo*. https://www.tempo.co/info-tempo/food-estate-program-ketahanan-pangan-yang-sukses-di-masa-pandemi-481879

Zaman, N. B. K., Raof, W. N. A. A., Saili, A. R., Aziz, N. N., Fatah, F. A., & Vaiappuri, S. K. N. (2023). Adoption of smart farming technology among rice farmers. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *29*(2), 268–275. https://doi.org/10.37934/araset.29.2.268275

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