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Assessment Model for Sustainable Smart Agricultural Areas Based on Digital Technology, Irrigation, And Land-Use Planning in Merauke Regency

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ABSTRACT: Merauke Regency is a strategic agricultural area in South Papua Province that contributes significantly to regional rice production. However, the development of agricultural areas should not focus solely on land expansion and increased production; it must also consider digital technology readiness, irrigation and drainage infrastructure, accessibility, and land-use planning. This study aims to develop an assessment model for sustainable smart agricultural areas in Merauke Regency, integrating digital technology, irrigation, and land-use planning. A mixed-methods approach was employed, utilizing an assessment model development design. The research stages included indicator identification, expert validation, indicator weighting via the Analytical Hierarchy Process (AHP), and the formulation of an area readiness index. The assessment aspects comprised digital technology, irrigation and drainage, and land-use planning. The study produced a draft assessment model capable of measuring the readiness level of sustainable smart agricultural areas. The model positions digital technology as a support for data-driven decision-making, irrigation and drainage as the foundation for production sustainability, and land-use planning as the mechanism for integrating production zones, access, and supporting facilities. This assessment model is expected to serve as an initial instrument for local governments, agricultural extension workers, and stakeholders in prioritizing the development of Merauke's agricultural areas in a more targeted, adaptive, and sustainable manner.

KEYWORDS: smart agricultural zone, digital technology, irrigation, land-use planning, sustainable agriculture, Merauke Regency

INTRODUCTION

Agriculture is a strategic sector for supporting national food security, particularly in regions with vast land potential and a significant role in regional food production. Merauke Regency in South Papua Province is a key agricultural area due to its dominant contribution to rice production in the South Papua region. According to data from Statistics Indonesia (BPS), the harvested rice area in South Papua Province in 2025 reached 79,433.92 hectares, with a production volume of 362,542.11 tons of milled dry grain. Of this total, Merauke Regency accounted for a harvested area of 79,428 hectares, a productivity rate of 45.64 quintals per hectare, and a production volume of 362,515 tons. These data indicate that rice production in South Papua is essentially concentrated in Merauke Regency [1], [2].

Merauke's position as a strategic agricultural zone is further reinforced by various agricultural land development and optimization programs. The government is promoting increased production through the expansion of planting areas, optimization of swampland, strengthening of agricultural infrastructure, and modernization of production systems. Several districts—namely Merauke, Jagebob, Malind, Tanah Miring, Kurik, and Semangga—have been designated as central areas for agricultural development. However, the development of agricultural zones depends not only on land expansion but also on technological readiness, water infrastructure, accessibility, and integrated land-use planning [3], [4].

In the context of Merauke's agricultural zones, key challenges requiring attention include water availability and management, the condition of irrigation and drainage networks, the risk of inundation or flooding, access to farm roads, and the integration of land-use planning. Local government efforts also emphasize the importance of water supply for paddy fields, the repair of irrigation channels, the construction of sluice gates, and the reinforcement of primary and tertiary canals leading to the rice plots. This situation indicates that agricultural infrastructure is a crucial factor in determining the sustainability of regional productivity, particularly in areas characterized by wetlands, swamps, and rainfall patterns that require precise water management [5].

On the other hand, the advancement of digital technology opens up new opportunities for managing agricultural areas. The concept of "smart agriculture" leverages technologies such as the Internet of Things (IoT), soil moisture sensors, satellite imagery, drones, Geographic Information Systems (GIS), artificial intelligence, and monitoring dashboards to enhance resource-use efficiency, support decision-making, and strengthen the sustainability of agricultural production [6], [7]. Digital technology also enables farmers and area managers to monitor land conditions, water requirements, potential crop threats, and infrastructure distribution more rapidly and on a data-driven basis.

However, the implementation of smart agriculture cannot be viewed solely through the lens of digital technology. Smart and sustainable agricultural areas must be developed through the integration of digital systems, irrigation and drainage infrastructure, production access roads, land-use patterns, and agricultural support facilities. Many studies on smart farming still focus primarily on the use of sensors, applications, or automation systems, while spatial aspects and physical infrastructure readiness are not always central to assessment models. Yet, in regions like Merauke, the success of agricultural transformation is heavily influenced by the interconnectedness of technology, water, land, and infrastructure [8], [9].

Given these conditions, there is a need for an assessment model capable of comprehensively measuring the readiness of sustainable smart agricultural areas. Such a model should evaluate not only the presence of digital technology but also the condition of irrigation, drainage, accessibility, land-use planning, and area infrastructure support. Thus, this research offers a novel approach by integrating three key aspects—digital technology, irrigation, and land-use planning—to serve as the foundation for developing a sustainable smart agricultural area assessment model in Merauke Regency.

The objective of this research is to formulate an assessment model for sustainable smart agricultural areas in Merauke Regency based on the integration of digital technology, irrigation, and land-use planning. This model is intended to serve as an initial instrument for identifying the readiness level of agricultural areas, pinpointing aspects requiring improvement, and providing recommendations for developing agricultural areas that are productive, adaptive, and sustainable. The research findings are also expected to contribute to the development of interdisciplinary studies—integrating informatics engineering, architecture, and civil engineering—in support of the transformation of agricultural areas within strategic food zones.

LITERATURE REVIEW

A. Sustainable Smart Agriculture

Sustainable smart agriculture is a farm management approach that integrates technology, resource efficiency, productivity, and environmental sustainability. This concept emphasizes not only increasing production yields but also prioritizing the efficient use of water, energy, land, and labor, as well as the agricultural system's capacity to adapt to climate change and shifting food demands. Within the context of agricultural areas, sustainable smart agriculture should be understood as a system linking digital technology, physical infrastructure, land-use planning, and institutional capacity to support more effective and sustainable production processes [6], [7].

Smart agriculture has evolved alongside the adoption of digital technologies in cultivation, land monitoring, water management, crop mapping, and data-driven decision-making. Technologies such as the Internet of Things (IoT), soil sensors, drones, Geographic Information Systems (GIS), satellite imagery, artificial intelligence, and monitoring dashboards help improve the accuracy of field data and accelerate responses to agricultural needs. Consequently, smart agriculture serves as a crucial approach for enhancing productivity and efficiency in agricultural areas, particularly in regions with extensive landholdings, such as Merauke Regency [8], [9].

B. Digital Technology in Agricultural Areas

Agricultural digital technology serves as a key instrument in establishing data-driven agricultural systems. Soil moisture sensors can monitor crop water requirements, while drones assist in land mapping and crop condition monitoring; meanwhile, geographic information systems (GIS) enable the analysis of land distribution, irrigation networks, production roads, and potential environmental risks. Furthermore, monitoring dashboards allow farmers, extension workers, and policymakers to quickly assess area conditions in an integrated manner [10], [11].

However, the successful implementation of digital technology depends not only on the availability of devices but also on communication network readiness, user capabilities, data availability, system integration, and operational sustainability. In large-scale agricultural areas, digital technology must bridge information needs across land, farmers, infrastructure, and management institutions. Consequently, in this study, digital technology is viewed not merely as a production tool but also as a component for assessing the readiness of sustainable smart agricultural areas [12].

C. Agricultural Irrigation and Drainage Infrastructure

Irrigation is a key component in supporting sustainable agricultural production, particularly for rice, a crop that relies heavily on water availability and management. An effective irrigation system enables controlled water distribution, mitigates drought risks, and enhances water use efficiency. Conversely, suboptimal irrigation conditions can lead to planting delays, low cropping intensity, reduced productivity, and an increased risk of crop failure [13].

In addition to irrigation, drainage systems play a vital role in agricultural areas, especially in regions prone to waterlogging or flooding, or those with wetland characteristics. Proper drainage helps manage excess water, maintain soil conditions, and ensure land accessibility. Within the context of smart agriculture, irrigation and drainage are not viewed merely as physical infrastructure; they can also be integrated with sensors, sluice gates, pumps, weather data, and monitoring systems to facilitate more adaptive water management [14], [15].

D. Agricultural Land Spatial Planning

Agricultural land spatial planning encompasses the organization of land use, the distribution patterns of rice fields, access to production roads, the location of supporting facilities, irrigation and drainage networks, and farmer settlements, as well as the linkages between production and distribution zones. Effective spatial planning can enhance agricultural efficiency, shorten distribution routes, mitigate land-use conflicts, and strengthen the area's sustainability. Conversely, unplanned spatial arrangements can hinder accessibility, inflate production costs, and weaken the connectivity between different components of the agricultural area [16].

In the development of sustainable agricultural areas, the assessment of spatial planning must consider land suitability, infrastructure availability, accessibility, ecological functions, and environmental carrying capacity. Land suitability is crucial because distinct land-use types entail different requirements and characteristics. Therefore, evaluating an agricultural area requires more than merely measuring land area or production output; it also necessitates an assessment of whether the area's spatial structure supports efficiency, sustainability, and adaptation to environmental risks [17].

E. Assessment Model for Sustainable Smart Agricultural Areas

An assessment model is an instrument used to measure the condition, readiness, or performance of an object based on specific indicators. In this study, the assessment model for sustainable smart agricultural areas is designed to integrate three key aspects: digital technology, irrigation and drainage infrastructure, and land-use spatial planning. Integrating these three aspects is crucial because agricultural areas require not only technological innovation but also physical infrastructure support and appropriate spatial arrangements.

The developed assessment model is expected to provide an overview of the readiness level of agricultural areas in Merauke Regency. The assessment results can be used to identify areas of strength and weakness, as well as priorities for area development. Through this approach, the study not only yields a descriptive analysis but also offers an evaluation tool that can serve as a basis for planning, decision-making, and the development of sustainable smart agricultural areas [18].

RESEARCH METHODS

This study employs a mixed-methods approach with an assessment model development design. This approach was chosen because the research aims not only to describe the conditions of agricultural areas but also to formulate an assessment instrument capable of measuring the readiness of sustainable smart agricultural zones based on the integration of digital technology, irrigation, and land-use planning aspects. The assessment model is developed through stages involving indicator identification, expert validation, indicator weighting, and the construction of an area readiness index.

The research is located in Merauke Regency, South Papua Province, focusing on rice farming areas linked to the development of food production hubs, irrigation networks, farm-to-market access roads, and the utilization of agricultural technology. Observation sites may include agricultural hub districts such as Kurik, Semangga, Tanah Miring, Jagebob, Malind, or other districts characterized by productive agricultural land. Site selection is conducted purposively, taking into account land area, the presence of irrigation networks, accessibility, the intensity of agricultural activities, and the potential for digital technology implementation.

The research data comprises both primary and secondary data. Primary data is obtained through field observations, targeted interviews, assessment questionnaires, and expert validation. Observations are used to assess the condition of irrigation infrastructure, drainage, production roads, land-use layouts, and supporting facilities within the agricultural areas. Interviews are conducted with farmers, extension workers, area managers, or relevant stakeholders to gather information regarding land management constraints, technology utilization, and infrastructure needs. Questionnaires are used to obtain assessments for each indicator of area readiness. Meanwhile, secondary data is sourced from statistical documents, government publications, area maps, planning documents, agricultural reports, and relevant scientific literature.

The primary variables in this study consist of three assessment aspects: digital technology, irrigation and drainage, and land-use planning. The digital technology aspect encompasses internet network availability, the use of agricultural applications, sensor utilization, the use of drones or spatial imagery, the availability of land data, and agricultural monitoring systems. The irrigation and drainage aspect encompasses the availability of irrigation and drainage channels, sluice gates, pumps, and embankments, as well as the condition of the water network, inundation control, and water distribution efficiency. The land spatial layout aspect covers land use suitability, access roads for production, connectivity between the land and supporting facilities, land distribution patterns, the location of warehouses or storage facilities, and the integration of production and distribution areas.

The indicators were formulated through a literature review and adapted to the specific characteristics of the Merauke agricultural area. Preliminary indicators were subsequently validated by experts representing the fields of informatics engineering, architecture, civil engineering, agriculture, and/or regional planning. Expert validation was conducted to assess the relevance, clarity, and feasibility of each indicator. Indicators deemed less relevant could be revised, merged, or eliminated, resulting in a final set of indicators better suited to the requirements of the assessment model.

Indicator weighting was performed using the Analytical Hierarchy Process (AHP) method. This method is used to determine relative priorities among aspects and indicators through pairwise comparisons. AHP was selected for its ability to systematically structure multi-criteria decisions and generate priority weights based on expert judgment [19]. The assessment hierarchy comprises a primary objective—namely, the readiness of the sustainable smart agricultural area—followed by three main aspects (digital technology, irrigation and drainage, and land-use planning) and the specific indicators associated with each aspect.

Field assessments utilized a 1–5 Likert scale. A score of 1 indicates a very low condition or non-existence; 2 indicates a low condition; 3 indicates a moderate condition; 4 indicates a good condition; and 5 indicates a very good condition. The value of each indicator was then multiplied by its corresponding AHP-derived weight to obtain a weighted score. Finally, the scores for each aspect were aggregated to produce the readiness index value for the sustainable smart agricultural area.

The index calculation is performed using the formula:

$$\mathbf{IKKPCB} = \Sigma\,(Wi \times Si)$$

Note:

IKKPCB is the Sustainable Smart Agricultural Area Readiness Index;

Wi is the weight of the i-th indicator;

Si is the assessment score of the i-th indicator.

The resulting index values are categorized into five levels of readiness: very low, low, moderate, high, and very high. These categories facilitate the interpretation of assessment results and help prioritize recommendations for area development. Areas with low scores indicate a need to strengthen fundamental aspects, such as water infrastructure, road access, or digital connectivity. Conversely, areas with high scores demonstrate greater readiness to transition toward the implementation of sustainable smart agriculture.

Data analysis was conducted using both quantitative and qualitative descriptive methods. Quantitative analysis was employed to calculate indicator weights, weighted scores, and the area readiness index value. Qualitative analysis was used to describe field conditions, implementation challenges, and development recommendations based on observations and interviews. The study concludes with a sustainable smart agriculture area assessment model that can serve as an initial evaluation tool for agricultural area development in Merauke Regency.

RESULTS AND DISCUSSION

A. General Conditions of Agricultural Areas in Merauke Regency

Merauke Regency is a primary agricultural area in South Papua Province. Based on 2025 data, the harvested rice area in South Papua reached 79,433.92 hectares, with a production of 362,542.11 tons of milled dry unhusked rice. Of this total, Merauke Regency accounted for a harvested area of 79,428 hectares and a production of 362,515 tons. This situation indicates that rice production in South Papua is almost entirely supported by Merauke Regency [1], [2]. Consequently, the development of agricultural areas in Merauke plays a strategic role in supporting both regional and national food security.

Agricultural development in Merauke is also supported by land optimization programs in several key food-producing districts, including Merauke, Jagebob, Malind, Tanah Miring, Kurik, and Semangga. These programs aim to increase cropping intensity and rice production through land enhancement, mechanization, and agricultural infrastructure support [3], [4]. However, agricultural area development cannot rely solely on land expansion or increased production. Agricultural areas must also be assessed based on digital technology readiness, irrigation and drainage conditions, and land-use planning to ensure a more targeted transformation toward sustainable smart agriculture.

In the context of Merauke, water management is a critical factor. The local government emphasizes the need for paddy field water supply, the improvement of irrigation channels, and the construction of sluice gates, main canals, and tertiary channels leading to individual paddy plots [5]. This demonstrates that the readiness of sustainable smart agricultural areas is determined not only by the adoption of digital technology but also by the robustness of basic infrastructure and the area's spatial layout.

B. Assessment Model Structure for Sustainable Smart Agricultural Areas

The assessment model developed in this study comprises three key aspects: digital technology, irrigation and drainage, and land-use layout. These three aspects were selected because they represent the integration of information systems, physical infrastructure, and the spatial structure of the area. The digital technology aspect reflects the area's capacity to utilize data and digital tools to support agricultural management. The irrigation and drainage aspect represents the readiness of water infrastructure, which serves as the foundation for sustainable rice production. Meanwhile, the land-use layout aspect reflects the orderliness of land use, accessibility, and the connectivity between production areas and supporting facilities.

Figure 1. Conceptual model for the assessment of sustainable smart agricultural areas.

The model in Figure 1 demonstrates that a sustainable smart agriculture zone cannot be understood merely as an area utilizing digital technology; it requires the integration of digital systems, water infrastructure, and land-use planning. If digital technology is available but irrigation is inadequate, the implementation of smart agriculture will not be optimal. Similarly, if irrigation infrastructure exists but land-use planning is not integrated with access to production roads and supporting facilities, the zone's efficiency will remain low.

C. Assessment Model Indicators

The assessment indicators are structured around three main aspects. Each aspect comprises indicators that can be evaluated through observation, questionnaires, interviews, and document review. These indicators are designed for practical application in the Merauke agricultural area.

Table 1. Assessment Indicators for Sustainable Smart Agricultural Areas

Assessment	Indicator	Data Source	Assessment Technique
Digital technology	Availability of internet networks in agricultural areas	Observation & interviews	Scale 1–5
Digital technology	Use of agricultural applications or information systems	Interviews & documents	Scale 1–5
Digital technology	Utilization of sensors, drones, or spatial imagery	Observation & interviews	Scale 1–5
Digital technology	Availability of land data and monitoring dashboards	Interviews & documents	Scale 1–5
Irrigation and drainage	Condition of primary and tertiary irrigation canals	Observation	Scale 1–5
Irrigation and drainage	Availability of sluice gates, pumps, and embankments	Observasi, & dokumen	Scale 1–5
Irrigation and drainage	Inundation and flood control capability	Observation & interviews	Scale 1–5
Irrigation and drainage	Efficiency of water distribution to rice paddies	Observation & interviews	Scale 1–5
Land-use planning	Agricultural land use suitability	Maps and documents	Scale 1–5
Land-use planning	Availability of access to production roads	Observation	Scale 1–5
Land-use planning	Connectivity between the site and the warehouse/supporting facilities	Observation & interviews	Scale 1–5
Land-use planning	Integration of production and distribution areas	Observations & documents	Scale 1–5

Table 1 shows that the assessment indicators are structured across multiple disciplines. Digital technology indicators relate to informatics engineering, irrigation and drainage indicators to civil engineering, and land-use planning indicators to architecture and area planning. Thus, this model can serve as a collaborative instrument for assessing the readiness of agricultural areas in a more comprehensive manner.

D. Initial Assessment Simulation

To illustrate the model's operation, a preliminary assessment simulation was conducted using a 1–5 scale. While this simulation does not represent the final field survey results, it serves to demonstrate the index calculation mechanism. Aspect weights were determined using the AHP approach, taking into account the relative importance of each aspect regarding the readiness of sustainable smart agricultural areas [19].

Table 2. Simulation of Weights and Scores for Assessment Aspects

Assessment Criteria	Weight	Simulation Score	Weighted Score
Digital technology	0,30	2,80	0,84
Irrigation and drainage	0,40	3,20	1,28
Land-use planning	0,30	3,00	0,90
Total Index	1,00		3,02

Based on the simulation in Table 2, the readiness index value for the sustainable smart agricultural area is 3.02 on a scale of 1–5, placing it in the moderate category. This indicates that the agricultural area possesses a sufficient foundation for development but still requires strengthening in certain aspects, particularly regarding digital technology and the integration of monitoring systems. The irrigation and drainage aspect received the highest score, as it represents the most visible fundamental component in the management of rice farming areas. However, this score still requires verification through actual observation, specifically concerning the condition of canals, sluice gates, and pumps, as well as the capacity for managing inundation.

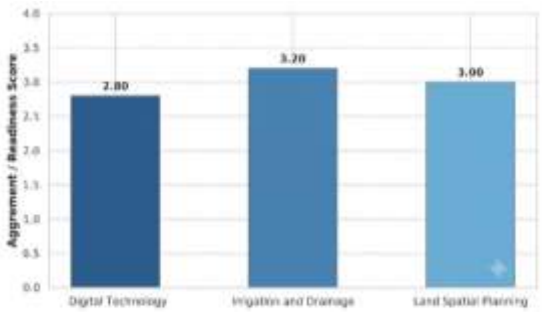

Figure 2. Simulation graph of area readiness aspect scores.

Simulation graphs indicate that the digital technology aspect scores the lowest compared to other aspects. This suggests that the development of smart agriculture in Merauke needs to focus on enhancing digital connectivity, utilizing spatial data, deploying sensors, employing drones, and developing area monitoring dashboards. Digital technology should be positioned as a tool to support decision-making, rather than merely as an add-on device.

E. Model Interpretation and Development Priorities

Simulation results indicate that the development of a sustainable smart agricultural area in Merauke should be carried out in stages. The first priority is strengthening irrigation and drainage infrastructure, as this aspect is directly linked to water availability, flood control, and the sustainability of rice production. Such strengthening can be achieved through the repair of irrigation channels, construction of sluice gates, optimization of pumps, reinforcement of embankments, and maintenance of drainage networks [20].

The second priority is the strengthening of digital technology. Smart agriculture development should begin with fundamental requirements, such as spatial data-based land mapping, irrigation network inventory, land information systems, and simple monitoring dashboards. In subsequent stages, technologies such as soil moisture sensors, drones, and flood early-warning systems can be implemented gradually, aligned with the area's readiness and user capacity.

The third priority is land-use planning and area accessibility. Factors such as the availability of farm access roads, warehouse locations, drying facilities, distribution infrastructure, and connectivity between plots must be considered to ensure the agricultural area is not only productive but also logistically efficient. Effective land-use planning can strengthen the linkages between production plots, water infrastructure, farming settlements, and markets [21] [22].

Thus, this assessment model can serve as a tool to identify the area's readiness level, determine intervention priorities, and formulate strategies for sustainable smart agriculture development. The model can be further refined by incorporating spatial, hydrological, and productivity data, as well as field assessment results, to generate a more accurate index.

F. Research Implications

The theoretical implication of this study is the development of an assessment approach for sustainable smart agricultural zones that goes beyond a mere focus on digital technology to integrate irrigation infrastructure and land-use planning. This approach broadens the understanding that smart agriculture should be viewed as a zonal system rather than simply the application of digital tools to farmland.

In practical terms, this model can be utilized by local governments, extension agents, agricultural zone managers, and other stakeholders to conduct preliminary evaluations of agricultural zone readiness. The assessment results can help identify priority areas for action, such as strengthening water infrastructure, providing access roads for production, or developing data-driven agricultural information systems.

Figure 3. Assessment Model of Sustainable Smart Agricultural Areas Merauke

CONCLUSION

This study develops an assessment model for sustainable smart agricultural zones in Merauke Regency, integrating digital technology, irrigation, and land-use planning. The model was created because Merauke’s agricultural zones play a strategic role in rice production for South Papua; however, their development requires an approach that goes beyond merely expanding land and increasing output to also address digital system readiness, water infrastructure, accessibility, and the spatial integration of the zones.

The resulting assessment model comprises three key aspects: digital technology, irrigation and drainage, and land-use planning. The digital technology aspect encompasses internet network readiness, agricultural applications, sensors, drones, spatial data, and monitoring dashboards. The irrigation and drainage aspect covers the condition of canals, sluice gates, pumps, embankments, water distribution, and inundation control. Meanwhile, the land-use planning aspect addresses land-use suitability, access to production roads, connectivity with supporting facilities, and the integration of production and distribution areas.

The development of the model demonstrates that the assessment of sustainable smart agricultural zones requires a multidimensional approach. Smart agriculture should not be viewed merely as the adoption of digital technology; it must also be supported by adequate irrigation infrastructure and integrated land-use planning. Consequently, this model can serve as a preliminary tool for measuring zone readiness, identifying areas of weakness, and establishing development priorities for agricultural zones in Merauke Regency.

In practical terms, the model can assist local governments, agricultural extension officers, zone managers, and stakeholders in formulating strategies for sustainable smart agriculture development. Development priorities could focus on strengthening irrigation and drainage networks, enhancing connectivity and agricultural information systems, utilizing spatial data, and organizing production access roads and supporting facilities. Future research should involve field testing using a broader set of primary data—engaging both farmers and stakeholders—and integrating spatial and hydrological data to ensure greater accuracy in the resulting zone readiness index.

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