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BLUE-GREEN FOOD REVOLUTION: SMART FARMING INTEGRATIVE DEVELOPMENT MODEL FOR SPIRULINA CULTIVATION AS A PILLAR OF FOOD SECURITY IN INDONESIA

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Abstract

Introduction/Main Objectives: This study aims to develop an integrative smart farming model for Spirulina (Arthrospira plantesis) cultivation to improve production efficiency and support Indonesia national food security agenda. Background Problem: Global food security is its bioresources richness, requires sustainable solutions. Novelty: This research introduces a smart farming system for Spirulina within the blue-green economy framework, integrating IoT-Based control and simulation modeling. Methods: The study applies a literature review, IoT-Based environmental monitoring, and dynamic system modeling. Experiments were conducted at lab and field scale using real-time control for environmental parameters. Finding/Results: The prototype system improved Spirulina biomass yield and demonstrated reduced environmental impacts compared to traditional methods. Conclusion: The study shows that smart farming can increase productivity efficiency, contribute to sustainable food systems, and inform policy for national-scale adoption, aligning with Indonesia's blue-green economy goals.

Keywords: Blue-green economy, Smart farming, Spirulina, Food security, Superfood

Introduction

Background

Indonesia faces serious challenges in achieving food and nutritional security. Data from the Ministry of Health of the Republic of Indonesia (Ministry of Health RI, 2023) indicate that the prevalence of stunting among children under five is 21.6%, meaning that nearly one in four Indonesian children suffers from growth impairment due to chronic malnutrition. Furthermore, the Global Hunger Index 2024 ranks Indonesia 77th out of 127 countries, with a hunger score of 16.9, classified as "serious" (*Global Hunger Index*, 2024).

This situation is exacerbated by climate change, agricultural land conversion, dependency on food imports, and insufficient promotion of alternative nutrient-rich food sources, all of which threaten national food security. Spirulina, a nutrient-dense blue-green microalga, has been scientifically recognized as a potential superfood to address nutritional deficiencies. It contains 60-70% protein with all essential amino acids, making it a high-quality plant-based protein source, particularly valuable in protein-deficient regions (Ahda et al., 2023). Additionally, Spirulina is rich in B-complex vitamins, vitamin E, beta-carotene, and minerals such as iron, magnesium, and calcium, which play crucial roles in metabolic function and micronutrient deficiency prevention (Saraswathi & Kavitha, 2023). Its antioxidant compounds, such as phycocyanin, have demonstrated anti-inflammatory and protective effects against oxidative stress, contributing to overall health improvement (Calella et al., 2022). Recent studies further highlight Spirulina's potential to support immune function and reduce the risk of chronic diseases (Ahda et al., 2023).

Despite its potential, Spirulina cultivation in Indonesia remains limited, often relying on conventional methods and underutilized across diverse environments, including marginal lands and household gardens. Key cultivation challenges include the need for specific environmental conditions stable pH (8.01–9.02), optimal temperatures (28–31°C), and sufficient lighting which are difficult to consistently maintain in tropical climates (Boukid & Castellari, 2023). High production costs for essential nutrients (nitrogen, phosphorus) and energy-intensive aeration and mixing processes pose further barriers, particularly for small-scale farmers (Natasha et al., 2024). Additionally, contamination risks, technical knowledge gaps, and inadequate infrastructure hinder commercial-scale cultivation (Luo et al., 2024).

Leveraging smart farming technologies offers an innovative pathway to enhance productivity and efficiency in Spirulina cultivation (Wahyu et al., 2024). Smart farming enables the development of environmentally friendly and sustainable agricultural systems (Lisowski et al., 2023). Specifically, IoT-based precision farming allows real-time monitoring of key parameters temperature, pH, irrigation, and nutrient levels (Pokhrel, 2024).

Studies indicate that smart farming can boost Spirulina productivity by up to 30% and reduce operational costs by 20%, thereby contributing to sustainable agriculture and national food security (Lisanty et al., 2022).

Based on this context, this study proposes the development of an integrative smart farming model for Spirulina cultivation as a pillar of Indonesia's food security strategy.

Formulation of the problem

2.1 How can an integrative smart farming development model improve the efficiency and productivity of Spirulina cultivation?

2.2 What are the challenges and opportunities in implementing smart farming for Spirulina cultivation in Indonesia?

2.3 How efficient is the contribution of this development model in strengthening national food security through diversification of nutritious food sources?

Methods

This study employs an integrative qualitative and quantitative approach, in accordance with the research objective of developing a smart farming model for Spirulina cultivation (Takona, 2024). The study was conducted at a cultivation site in Kulon Progo, Special Region of Yogyakarta, Indonesia, in collaboration with PT Munda Green Energy, which has benefited from mentoring by local academic partners in Yogyakarta. The research was conducted over four months, from November 2024 to February 2025.

The research was structured into three key phases: Preparation, Implementation, and Monitoring & Evaluation. This design facilitated iterative refinement of the smart farming model based on empirical data and stakeholder feedback.

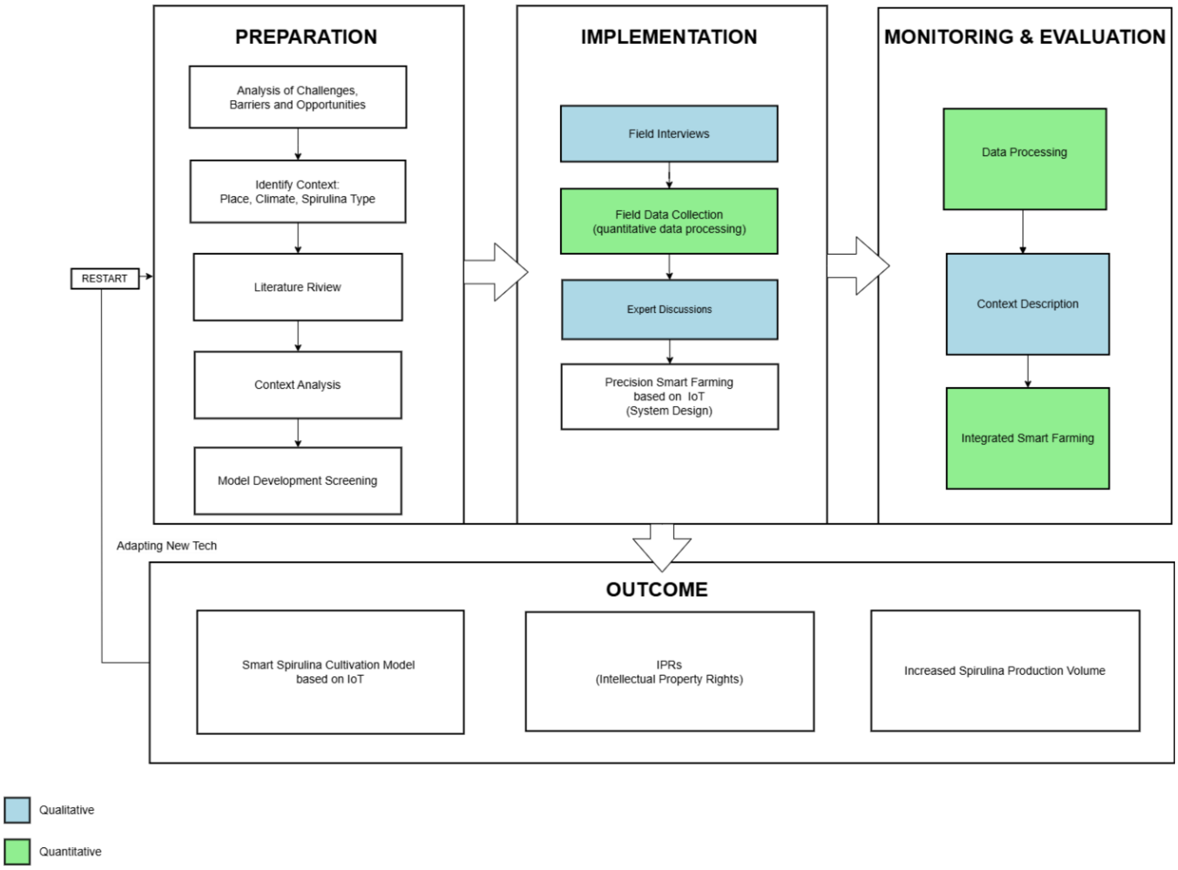

Figure 1
Research Framework for IoT-based Smart Spirulina Farming Model Development

All methodological steps were designed to align with the research objective of developing a sustainable, scalable smart farming model for Spirulina. The combined use of qualitative and quantitative methods ensures a robust and replicable research process. Results from this evaluation were used to validate the feasibility and scalability of the proposed smart Spirulina farming model.

Results and Discussions

The implementation of the IoT-based smart farming system for Spirulina cultivation produced substantial improvements in cultivation efficiency, operational sustainability, and labor productivity compared to conventional methods.

1. General Overview of the Research

This study developed an Integrated Smart Farming (ISF) model for Spirulina cultivation, consisting of three key stages: (1) IoT-based system design and prototyping; (2) Laboratory-scale optimization; (3) Semi-commercial field testing in collaboration with PT Munda Green Energy, Yogyakarta.

2. Implementation of the Smart Farming

Microalgae cultivation can be managed in a smarter and more sustainable manner, delivering significant benefits to the biotechnology industry, environmental sustainability, as well as the food and energy sectors. This is illustrated in the following figure:

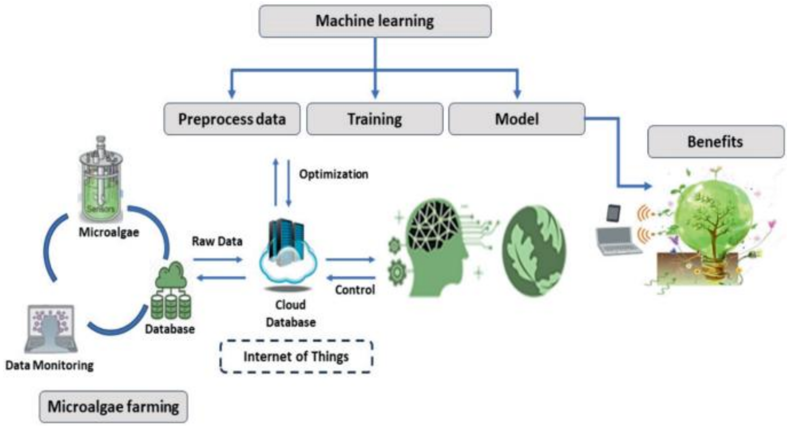

Figure 2
Process of Integrated Smart Farming Model
Source: (Buckner et al., 2016)

Workflow Based on Modified Spirulina Cultivation Process Adapted to Local Needs and Context :

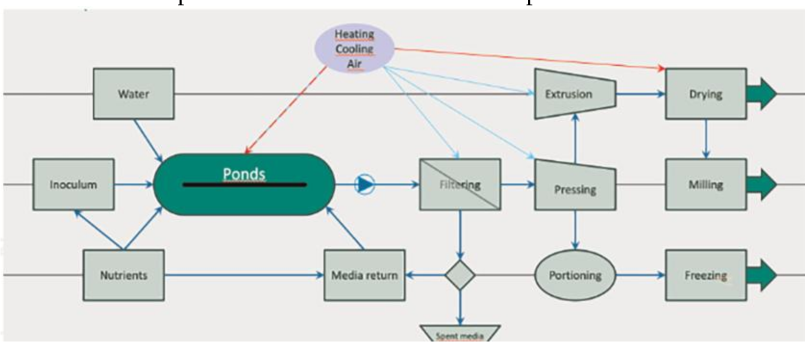

Figure 3
Workflow of Spirulina Cultivation Process
Source**:** (Buckner et al., 2016)

The Spirulina production workflow begins with the preparation of the growth medium (water and nutrients), followed by cultivation in ponds or bioreactors under tightly controlled IoT-based management of temperature, pH, and nutrient levels. After harvesting, the Spirulina biomass is separated, cooled, and processed through drying or freezing techniques to preserve nutritional quality. The final product, in dried or frozen form, is suitable for use as a high-nutrition supplement or food ingredient. The complete cultivation-to-product process is illustrated in Figure below:

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Figure 4
Spirulina Cultivation Process to Final Product

3. Comparison of Smart Farming and Conventional Methods

The comparative analysis between smart farming and conventional Spirulina cultivation is presented in :

Table 1 Comparison of Spirulina Cultivation: Smart Farming vs. Conventional Methods

Aspect	Smart Farming Spirulina	Conventional Spirulina Farming
Water Quality Monitoring	Real-time IoT sensor monitoring (pH, temperature, oxygen)	Manual monitoring with basic tools
Nutrient and Fertilizer Usage	Data-driven optimal dosing to minimize waste	Often suboptimal, prone to nutrient waste
Production Efficiency	High efficiency via automation and environment control	Lower efficiency, dependent on farmer experience
Spirulina Growth Rate	Faster due to continuous optimal conditions	Slower due to inconsistent manual control
Operational Costs	Lower long-term costs due to resource savings	Higher costs due to inefficient resource use
Environmental Impact	Environmentally friendly due to controlled inputs	Potential pollution due to unmanaged waste
Risk Management	Early problem detection via automated monitoring	Reactive problem management
Technology Utilization	IoT, AI, big data	Minimal technology use, labor-intensive

Source: Data Processing Result, 2025

4. Biomass Growth Rate and Cultivation Efficiency

The application of IoT-based smart farming resulted in a significant improvement in Spirulina biomass:

Table 2 Biomass Growth Rate Comparison

Parameter	Conventional Method	Smart Farming (IoT)	Increase (%)	Source
Biomass Growth Rate (g/L/day)	0.45	0.56	24.8%	Laboratory Test
Biomass Growth Rate (g/L/day)	0.48	0.60	25.0%	Buckner et al. (2016)
Average Increase	-	-	24.9%	Combined Average

Source: (Data Processing Result, 2025; Buckner et al., 2016)

The optimized parameters achieved in the integrated smart farming system are summarized in :

Table 3 Optimal Parameters in Integrated Smart Farming for Spirulina

Factor	Optimal Range / Description
Temperature	25–35°C optimal, min. 15°C, >40°C causes oxidative stress
Water pH	9.5–11.0 alkaline; >10.5 to reduce contamination
Light Intensity	300–500 µmol photon/m²/s; shading to avoid photoinhibition
Nutrient Availability	Balanced C, N, P; phosphorus limitation enhances β-glucan
Salinity	~4–5.5 g Na^+/L; affects protein and lipid content
Water Quality	Sterile, heavy metal-free, pathogen-free; smart irrigation used
Aeration and Oxygen	Requires stripping to prevent O_2 accumulation
Harvest Timing	Morning; higher protein and amino acid content
EPS and FFA Impact	Excessive levels inhibit growth
Light Quality	Red-filtered light enhances protein and phycocyanin content

Source: Data Processing Result, 2025

5. Spirulina Production Efficiency

Efficiency gains from implementing the smart farming system are presented in:

Table 4 Spirulina Production Efficiency Outcomes

Parameter	Smart Farming	Conventional	Increase (%)
Biomass Growth Rate (g/L/day)	0.78	0.58	34.5%
Protein Content (%)	67.2%	60.8%	10.5%
Water Use Efficiency (%)	92%	78%	14%
Operational Cost Reduction	-20%	-	-

Source: Data Processing Result, 2025

6. Environmental Aspects of the Smart Farming System

The smart farming system demonstrated several environmental benefits:

- 25% reduction in carbon emissions through the use of energy-efficient LED lighting and renewable energy sources.
- Minimized nutrient waste through precision-controlled nutrient dosing.
- Up to 40% water savings through Recirculating Aquaculture System (RAS) integration.

These outcomes align with global sustainability goals and national food security initiatives.

The implementation of the Integrated Smart Farming model significantly enhanced Spirulina production by improving biomass growth, protein content, resource efficiency, and environmental sustainability. These results support Indonesia's blue-green economy and contribute to national food security through sustainable innovation in agricultural practices.

7. Evaluation of Model Development Outcomes

The comprehensive evaluation of the integrated smart farming model for Spirulina cultivation reveals notable advancements across multiple performance dimensions.

Table 5 Evaluation of Model Development Outcomes

Aspect	Outcome Summary
Productivity	Biomass growth increased by 34.5%; faster production cycle.

Nutritional Quality	Protein content improved by 10.5%; higher nutritional value.
Resource Efficiency	Water use efficiency improved by 14%; significant water savings.
Cost Efficiency	Operational costs reduced by 20%; long-term economic benefits.
Environmental Control	Precise control of temperature, pH, light; consistent product quality; 25% reduction in carbon footprint.
Sustainability	Minimized nutrient and energy waste; improved circular resource use.
Technical Feasibility	Technically and economically viable.
Scalability	Suitable model for sustainable Spirulina-based agroindustry development in Indonesia.

Source: Data Processing Result, 2025

This evaluation confirms that the smart farming model not only enhances operational efficiency but also contributes significantly to national food security and aligns with Indonesia's blue-green economy agenda. The model demonstrates scalability and adaptability, offering a promising pathway for wider adoption across diverse agricultural contexts.

Conclusion

Based on the research results and analyses conducted, several important conclusions are drawn:

1. Development of an Integrated Smart Farming Model for Spirulina Cultivation:
   The smart farming model using IoT and machine learning significantly enhances Spirulina cultivation efficiency and productivity. Real-time monitoring and control of temperature, pH, and light intensity resulted in biomass growth rates up to 34.5% higher compared to conventional methods. Automated nutrient delivery and aeration systems reduced resource wastage, improved water use efficiency by 14%, and lowered operational costs by up to 20%. Therefore, this model provides a sustainable and economically viable solution for Spirulina cultivation.
2. Challenges and Opportunities for Smart Farming Implementation in Indonesia:
   Implementing smart farming in Indonesia faces challenges such as high initial costs, limited technical knowledge among farmers, and restricted technology access. Nevertheless, significant opportunities exist due to Spirulina's potential as an alternative nutrient-rich food source capable of addressing malnutrition and food insecurity. Government support through food security programs and community empowerment could accelerate the adoption of this technology.
3. Contribution of the Smart Farming Model to National Food Security:
   The smart farming model developed contributes significantly to strengthening national food security through diversification of high-nutrient food sources, particularly Spirulina, which contains up to 67.2% protein. Additionally, Spirulina cultivation via smart farming practices is environmentally friendly, reducing carbon footprints by up to 25% and minimizing nutrient waste, thus supporting agricultural ecosystem sustainability.

Managerial Implications

The development of the Integrated Smart Farming model provides several managerial insights for stakeholders in the Spirulina industry and the broader agri-biotechnology sector:

- For Industry Practitioners: The model offers a proven framework for enhancing production efficiency, reducing operational costs, and achieving consistent product quality. Adoption of IoT and AI technologies can enable producers to meet growing market demand for high-quality Spirulina-based products.
- For Policy Makers: The findings support the formulation of policies that encourage the adoption of smart farming technologies in microalgae cultivation, contributing to national food security strategies and sustainable agricultural development.
- For Research and Innovation: The success of the ISF model highlights the importance of cross-disciplinary collaboration between biotechnology, agricultural engineering, and information technology sectors to drive innovation in sustainable food production systems.

Recommendations

To further advance the implementation and scalability of smart Spirulina farming in Indonesia and beyond, the following recommendations are proposed:

- Broader Dissemination and Training: Capacity-building initiatives should be developed to train local farmers and SMEs in the operation and maintenance of IoT-based Spirulina cultivation systems.
- Policy Support and Incentives: Government agencies should consider providing incentives, such as subsidies or tax breaks, to facilitate the adoption of smart farming technologies in the microalgae industry.
- Future Research Directions: Further research is recommended to explore the integration of renewable energy sources with the ISF model, as well as to investigate the potential of machine learning for predictive yield optimization across diverse climatic conditions.

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