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Smart Urban Farming 5.0: Integration of Vertical Farming Automation and Solar Panels for Maximum Energy Efficiency and Productivity in Major Cities in Indonesia

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ABSTRACT

This study explores the development of Smart Urban Farming 5.0 as an innovative solution to address energy efficiency and food security challenges in Indonesia's major urban centers. The research is driven by rapid urbanization, which limits agricultural land and increases the need for space- and energy-efficient farming systems. The main objective is to design and evaluate the integration of solar panels with automated vertical farming to enhance agricultural productivity while reducing reliance on conventional electricity sources. The methodology includes building an IoT- and AI-based automated farming prototype powered by solar energy, and testing its performance over three months by monitoring energy consumption, plant growth, and harvest quality. The results reveal a significant reduction in operational costs, a 62% decrease in traditional electricity usage, and a 28% increase in crop yields compared to conventional systems. While the system requires technical training, user feedback indicates high acceptance. Overall, Smart Urban Farming 5.0 proves to be a viable and effective approach for sustainable urban agriculture, contributing to clean energy and food-related Sustainable Development Goals (SDGs). This research opens pathways for future advancements in intelligent and environmentally friendly urban farming technologies.

Keywords: energy efficiency, solar panels, smart urban farming, vertical farming, and urban farming.

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1. Introduction

The supply of enough, sustainable, and healthful food is severely hampered by Indonesia's large cities' fast urbanization. Growing conventional agriculture in urban settings is hampered by a lack of green space, high energy costs, and the need for consistent fresh food. In this regard, Smart Urban Farming 5.0 stands out as a cutting-edge approach that combines automation of vertical farming with renewable energy, particularly solar panels, to increase agricultural production in large cities while enhancing energy efficiency. Growing crops in stages through vertical farming makes the most use of available space, which is crucial in crowded and land-constrained urban settings. Real-time environmental condition management is made possible by automation based on the Internet of Things (IoT) and artificial intelligence (AI), which boosts agricultural yields and resource efficiency. In addition to reducing reliance on costly and ecologically unfavorable conventional energy sources, the use of solar panels as a renewable energy source aids in the urban agricultural sector's attempts to lower carbon emissions [1,4].

The success of vertical and urban farming depends on the ecologically friendly management of water, fertilizers, and crop protection, as previous studies have demonstrated. It has been demonstrated that adding solar panels to vertical farming systems may save operating costs by as much as 50% while increasing crop yield, including that of vegetables and herbs, by utilizing energy-efficient controlled watering and lighting systems [2,5]. However, there is disagreement on the necessity of technical training for users of complicated automation systems, the high initial investment costs, and the space constraints in metropolitan settings. The secret to the technology's effective widespread adoption is tailoring it to the socioeconomic circumstances of the local area [3,6].

In addition to providing technological answers, Smart Urban Farming 5.0 has promise for advancing environmental sustainability and urban food security in the face of mounting urbanization challenges. This idea promotes the attainment of the Sustainable Development Goals (SDGs), particularly with regard to food and clean energy, and is consistent with the vision of contemporary agriculture, which places a high priority on resource efficiency and a decreased environmental effect [7]. Some experts contend that despite the technology's potential, social, economic, and technological obstacles still stand in the way of its broad adoption, such as cultural

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reluctance, a lack of funding, and the requirement for sufficient internet infrastructure. To tackle these challenges, government, academia, business, and communities must work together in a multidisciplinary manner [8].

The main objective of this research is to design and test a Smart Urban Farming 5.0 model that integrates vertical farming automation and solar panels to maximize energy efficiency and agricultural productivity in major cities in Indonesia. This research is expected to provide empirical evidence on the significant potential of integrating these technologies in improving urban food security, reducing conventional electricity consumption, and supporting environmentally friendly urban agriculture. Initial findings indicate that this system is able to significantly increase crop yields while reducing energy costs, opening up opportunities for the development of smarter and more sustainable urban agriculture in the future [9].

It is crucial to emphasize the wider function of urban farming in relation to food security and social sustainability in Indonesia's large cities, in addition to the technological advancements that have been discussed. Metropolitan farming has been shown to be a successful way to increase people's access to wholesome food while overcoming the constraints of agricultural land in metropolitan locations. By using vacant land in metropolitan locations near customers, urban farming can lower distribution costs, promote household food independence, and lessen reliance on food imports, according to studies. Additionally, by raising farmer earnings and generating new jobs, urban farming supports local economic empowerment.

Technology-wise, Smart Urban Farming 5.0, which combines solar panels, IoT, and AI, allows for more effective resource management, including automated watering and lighting that uses less energy and regulated air and fertilizer use smart farming technology may lower greenhouse gas emissions and improve resource use efficiency by up to 30%. Reliance on costly and environmentally harmful conventional energy is lessened with the usage of solar panels as a renewable energy source [10].

Significant obstacles still exist, though, mainly in the form of high upfront investment prices, urban space limits, and the requirement for technical training for users of sophisticated automation systems. Research emphasizes how crucial it is to modify the technology to fit local socioeconomic circumstances in order to ensure successful and long-lasting adoption. Additionally, the effective large-scale

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implementation of Smart Urban Farming 5.0 depends on interdisciplinary cooperation between communities, business, academia, and government.

Thus, the development of Smart Urban Farming 5.0 not only answers the technical challenges of energy efficiency and productivity, but also supports sustainable development goals related to food security, carbon emission reduction, and urban community empowerment. This research is expected to be an important foundation for the development of more holistic and sustainable urban farming policies and programs in the future [11].

2. Materials and Method

2.1. Research Design

In order to increase energy efficiency and productivity in tropical urban environments, this study designs and tests a Smart Urban Farming 5.0 system that combines solar panels and vertical farming automation using a Research and Development (R&D) approach using the ADDIE (Analysis, Design, Development, Implementation, Evaluation) model. In order for the research findings to be broadly applicable, the study's main goal is to create a system prototype that can be modified for use in different big cities without regard to local requirements.

2.2. Tools and Materials

Hardware:

- Vertical Automation System: A set of lightweight aluminum vertical plant racks equipped with a hydroponic Nutrient Film Technique (NFT) system and an automatic control system (ESP8266) based on a NodeMCU microcontroller that controls air circulation, full-spectrum LED lighting, and watering.
- Environmental sensors include the DHT22 (temperature and humidity) sensor, the DS18B20 soil temperature sensor, the light intensity sensor (photocell), the water pH sensor, the TDS (total dissolved solids) sensor for nutrient quality, and the ultrasonic water level sensor.
- Energy Source: A 300 Wp monocrystalline solar panel coupled with a 12V/100Ah lithium-ion battery storage system to supply lights and automation systems with constant power.

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Software:

- IoT Platform and Monitoring: Android and web-based applications using ThingsBoard for real-time monitoring and remote control.
- AI Algorithms: Long Short-Term Memory (LSTM) based machine learning models for irrigation and lighting requirement prediction based on historical sensor and weather data.

2.3. Methodology for Gathering Data

- Throughout the experiment, environmental data, including temperature, humidity, pH, TDS, and light intensity, was automatically gathered every ten minutes.
- Data on PV energy consumption and battery usage were continually tracked in order to analyze energy efficiency.
- Growth characteristics (plant height, number of leaves), yield (fresh weight), and quality (nutrient content) were used to gauge plant productivity.
- To assess social and technological elements, a survey on system satisfaction and ease of use was administered to prototype users.

2.4. Creation and Application Method

- Analysis: To ascertain the technological requirements and user demands of urban farming, a literature review and preliminary survey are conducted.
- System Design: CAD software and energy modeling were used for the mechanical design of the vertical rack, electronic circuit, and solar panel integration
- Software development: Python and Java are used to program microcontrollers and create Internet of Things-based monitoring apps.
- Field Trial: For three months, the prototype was put to the test in lab settings and cramped areas that mimic urban settings, with performance metrics recorded.
- In order to improve pesticide breakdown in the root zone, bioremediation approaches combine bioventing and biosparging procedures.

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2.5. Analysis of Data

- Descriptive and inferential statistics (ANOVA) were used to evaluate quantitative data in order to compare crop output and energy efficiency between the Smart Urban Farming 5.0 system with control without solar panels and automation.
- The ratio of energy usage efficiency (EUE) to operational cost reductions was calculated in order to undertake an energy performance study.
- To find limitations and opportunities for system improvement, content analysis techniques were applied to qualitative data from user surveys.

3. Result

3.1. System Performance and Data Description

A Smart Urban Farming 5.0 prototype that combines solar panels as a sustainable energy source with vertical farming automation was successfully created and tested by this study. During a three-month testing period, real-time data on plant growth characteristics, energy usage, and microenvironmental conditions were gathered. More than 120,000 temperature, humidity, nutritional pH, light intensity, and electricity use measurement points were included in the overall data collected. Based on sensor data, the automation system effectively controlled lighting, watering, and air circulation. An LSTM-based AI algorithm subsequently evaluated the data to forecast plant requirements.

3.2. Operational Cost Savings and Energy Efficiency

With an average energy conversion efficiency of 18.5%, it has been demonstrated that using solar panels as the primary energy source can supply steady electricity for the full vertical farming automation system. Compared to control systems without solar panels, typical networks' electricity usage has substantially cut by 62%. This indicates a great deal of promise for lowering carbon footprints and operating expenses in urban agriculture.

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Table 1. Comparison of Operating Costs and Energy Consumption

System	Energy Consumption (kWh/month)	Operational Cost (Rp/month)
Smart Urban Farming	48,3	350.000
Conventional System	127,1	920.000

3.3. Harvest Quality and Crop Productivity

The production of crops was greatly enhanced by the Smart Urban Farming 5.0 system. In comparison to the control, hydroponic vegetable plants grew 22% taller on average, and their fresh harvest yields rose by 28%. Using a portable spectrophotometer, the nutritional quality of the plants also revealed a rise in vitamin C and chlorophyll levels.

Table 2. Parameters of Plant Growth and Quality

Parameters	Smart Urban Farming 5.0	Control System
Plant Height (cm)	38.4 ± 2.1	31.5 ± 1.8
Harvest Weight (gram)	520 ± 35	405 ± 28
Vitamin C Content	45,2 ± 3,4	37,8 ± 2,9

3.4. Analysis of Statistics

In terms of energy consumption ($F(1, 10) = 45.67$; $p < .001$; partial $\eta^2 = .82$), crop productivity ($F(1, 10) = 38.54$; $p < .001$; partial $\eta^2 = .79$), and crop quality ($F(1, 10) = 27.89$; $p = .002$; partial $\eta^2 = .72$), a two-way ANOVA test revealed significant differences between the Smart Urban Farming 5.0 treatment and the control. The statistical significance of all differences was validated using the Tukey HSD post-hoc test.

3.5. Social Aspects and User Evaluation

According to a poll of thirty prototype users, the quality of harvest, time efficiency, and convenience of use were all well rated (average score of 4.5 out of 5). A number of respondents mentioned the necessity for further instruction on how to maintain the solar panels and use the automation system. This demonstrates how crucial technical support is to guaranteeing the long-term viability of technology adoption.

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4. Discussion

4.1. Analysis of the Results and Their Connection to Other Studies

According to the study's findings, the Smart Urban Farming 5.0 system's combination of solar panels and vertical farming automation greatly increases crop output and energy efficiency in urban settings. In the agricultural sector, where digital technologies like IoT, AI, and renewable energy play a significant role in resource optimization and environmental impact reduction, this finding aligns with the notion of smart farming 5.0, which has been developed as a symphony of the digital economy. The significance of sustainable and intelligent resource management to boost urban agriculture output. The study's findings of a 62% decrease in traditional electricity use and a 28% improvement in agricultural output support the idea that automation and solar panel utilization might help urban regions overcome their energy and land constraints [9].

Furthermore, despite the fact that it necessitates technical training, the high user satisfaction survey results show that the community accepts this technology. The results of Lovita et al. (2023) and other research that emphasize the significance of social and educational factors in the effective adoption of IoT and automation-based urban agricultural technologies are consistent with this [10]. According to the research of Mukhlis et al. (2023) and Riswandi et al. (2024), there is still a discussion over the expenses of early investments and the preparedness of digital infrastructure [11,12].

4.2. Wide-ranging Consequences of the Results

The results have wide-ranging effects for environmental sustainability and urban food security. The need for farming solutions that are energy and space efficient is growing as cities become more populated. The methodology provided by Smart Urban Farming 5.0 supports the sustainable development goals (SDGs) for clean energy and food by lowering carbon emissions while simultaneously increasing production. In addition to lessening the load on the city's electrical infrastructure, the decrease in traditional power usage also lowers operating expenses, which is especially important for big towns with limited resources.

From a technological standpoint, the use of artificial intelligence (AI) and sensors to autonomously control lighting and irrigation holds significant promise for

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enhancing water and fertilizer usage efficiency, a critical problem in urban agriculture. Agricultural systems become more energy independent and less reliant on fossil fuels when solar panels are used as a renewable energy source.

4.3. Difficulties and Conflicts

Notwithstanding the encouraging outcomes, issues and disagreements still need to be resolved. Numerous academics have pointed out that the high upfront costs and technical complexity of this technology can be significant obstacles to its broad adoption, particularly for urban farmers with low financial resources. According to the study's user survey, access to technical training and the preparedness of digital infrastructure are also essential for effective deployment. To get over these obstacles and guarantee the system's longevity, a multidisciplinary strategy and cooperation between the government, academics, business, and communities are required.

4.4. Prospects for Further Research

Future studies should focus on creating more flexible AI-based prediction models that integrate meteorological and microenvironmental data to optimize resource utilization in real-time. Enhancing accessibility and usability for urban farmers also requires the creation of user-friendly mobile applications. Furthermore, more thorough socioeconomic and environmental impact analyses are required to comprehend the long-term effects of implementing smart urban farming 5.0. Another key area of research is the creation of modular systems that can be tailored to various scales and local conditions, allowing this technology to be implemented in a variety of cities with distinct features. In smart urban agriculture, cooperation with the education and technical training sectors will boost human resource capacity and speed up technological transfer.

5. Conclusions

The Smart Urban Farming 5.0 system, which combines solar panels with vertical farming automation, is developed and tested critically and methodically in this project as a novel way to increase agricultural output and energy efficiency in Indonesia's largest cities. According to experimental data, as compared to traditional systems without automation and renewable energy, this system can considerably

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lower operating costs, boost hydroponic crop output by up to 28%, and cut conventional power use by up to 62%. Furthermore, the harvest's quality improved as well, demonstrating the two advantages of using this method. Although the complicated system requires technical expertise to use, user polls show a high degree of satisfaction.

By showing how digital technology and renewable energy may be integrated to overcome land and energy restrictions in urban locations, while also promoting food security and environmental sustainability, this study enhances scientific understanding in urban agriculture. Given the constraints of the investigation, which was carried out at a prototype scale and under constrained testing settings, these findings should be cautiously extrapolated.

The knowledge of how solar panels and vertical farming automation may be used to overcome the primary obstacles of urban farming in Indonesia's large cities high energy consumption and land scarcity is greatly expanded by this study. In addition to greatly increasing agricultural output, Smart Urban Farming 5.0 lessens reliance on costly traditional electricity that has an adverse effect on the environment by fusing IoT and AI technologies in an energy-efficient system. This aids in the pursuit of sustainable development objectives, particularly those pertaining to clean energy and food security.

The trial's scale, which is still a prototype, and its brief length are the study's limits. To guarantee the system's stability and adaptability in a range of urban settings, the results must be evaluated more extensively and over an extended period of time. For technology adoption to be successful and inclusive, additional focus must be placed on social and economic factors such user preparedness and upfront investment costs.

The creation of more adaptable modular models, a more thorough integration of environmental and meteorological data for more precise automated forecasts, and enhanced user education and training are some suggestions for more study. To determine the true impact of Smart Urban Farming 5.0 on enhancing urban populations' quality of life and environmental sustainability, a more comprehensive socioeconomic and environmental impact research is also required. Therefore, this study opens the door for a future transformation of urban agriculture that is more intelligent, effective, and sustainable.

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