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Development of an Integrated Smart Agrivoltaic System for Real-Time Monitoring and Automated Control in Spinach and Mustard Green Cultivation: A Case Study in Salatiga, Indonesia

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Abstract: This research develops an agrivoltaic farming system to improve land use by combining solar energy generation with agricultural practices. This system uses solar panels to provide green energy and also protects plants from extreme heat, reduces water evaporation and increases crop yields. Design of monitoring and control tools using Arduino Mega integrating soil moisture, temperature and water pH sensors to ensure optimal agricultural conditions. The results of this research show that the solar panel configuration produces an average voltage of 49.68 V and the monitoring system displays data effectively, and the soil moisture control system achieves an error rate of 2.24% for spinach plants and 2.60% for green mustard plants. Additionally, an error rate of 0.38% was recorded for temperature measurements.

Keywords: agrivoltaic; renewable energy; solar panel; spinach; green mustrad

Abstrak: Penelitian ini mengembangkan sistem pertanian agrivoltaik untuk meningkatkan pemanfaatan lahan dengan menggabungkan pembangkitan energi surya dengan praktik pertanian. Sistem ini menggunakan panel surya untuk menyediakan energi hijau dan juga melindungi tanaman dari panas ekstrem, mengurangi penguapan air, serta meningkatkan hasil panen. Perancangan alat monitoring dan kontrol menggunakan Arduino Mega mengintegrasikan sensor kelembaban tanah, suhu, dan pH air untuk menjamin kondisi pertanian yang optimal. Hasil penelitian ini menunjukkan bahwa konfigurasi panel surya menghasilkan tegangan rata-rata mencapai 49.68 V serta sistem pemantauan menampilkan data secara efektif, dan sistem pengontrol kelembaban tanah mencapai tingkat kesalahan sebesar 2.24% untuk tanaman bayam dan 2.60% untuk tanaman sawi hijau. Selain itu, tingkat kesalahan sebesar 0.38% tercatat untuk pengukuran suhu.

Kata kunci: agrivoltaik; energi terbarukan; solar panel; bayam; sawi hijau

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1. Introduction

Climate change, rapid population expansion, and rising energy and food consumption pose unprecedented challenges to the global community[1], [2]. These interrelated constraints are especially important in emerging nations such as Indonesia, where increased urbanization and agricultural growth frequently struggle for land use. As the world's population is expected to reach 9.7 billion by 2050, food demand is expected to climb by more than 50%[3], while energy demands will rise simultaneously, putting extra strain on finite natural resources[4].

Indonesia, a country with tremendous agricultural potential and a strong commitment to sustainability, has set ambitious national targets to attain 23% renewable energy in the energy mix by 2025 and improve domestic food security through smart and efficient agriculture techniques[5]. However, the combined difficulties of climate or weather variability and competing land uses endanger that goal. Extreme weather events, irregular rainfall, and rising temperatures directly impact crop yields and water availability, making it difficult to supply food needs while developing sustainable, renewable energy infrastructure.

One interesting answer to these interrelated problems is agrivoltaic systems, which combine the production of solar photovoltaic (PV) energy with the cultivation of crops on the same land. This dual land use technique increases land use efficiency and reduces microclimate stress on plants through partial shading while generating clean electricity [6], [7].

In its development, the adoption of Internet of Things (IoT) technology can expand the possibilities for intelligent agrivoltaic systems to be used by the general public [8], [9]. This development enables real-time monitoring of environmental variables and automatic regulation of plant growth parameters, maximising energy output and plant productivity.

2. Literature Review

Several recent studies have looked into smart farming systems, which combine sensors, controls, and wireless connectivity to allow for data-driven agricultural decision making. However, many existing technologies are either too expensive or inflexible for small-scale and rural installations, especially in Indonesia [10], [11], [12].

To fill these gaps, this study describes the creation of an Integrated Smart Agrivoltaic System prototype for growing spinach (Spinacia oleracea) and mustard greens (Brassica juncea), two popular and nutritionally significant plants. An Arduino microcontroller connects to environmental sensors that measure soil moisture, temperature, humidity, and light intensity. Real-time sensor data is used to automatically activate irrigation and shade devices, resulting in ideal growing conditions.

The prototype is powered by solar panels, illustrating the viability of off-grid, sustainable farming using clean energy[13], [14]. This combination of smart control and renewable energy seeks to reduce water and energy usage while preserving agricultural output, providing a solution that aligns with Indonesia's renewable energy and food security objectives. This study adds to the growing field of precision agrivoltaics by presenting a cost-effective model for climate-resilient, resource-efficient food and energy production. It is a step toward empowering local farmers with readily available technologies that address national sustainability goals in the face of environmental and socioeconomic obstacles[15], [16].

3. Method

3.1. Site Selection

The experimental site is located in the open area of the Faculty of Electronics and Computer Engineering, situated at coordinates 7°19'05"S, 110°30'03"E. This location was selected due to its consistent exposure to adequate solar irradiance, which is suitable for the optimal growth of mustard greens and spinach, as well as for the effective operation of photovoltaic (PV) panels. Additionally, the ambient temperature at the site remains within a moderate range, reducing the risk of thermal stress on both crops and system components. These environmental conditions make the site appropriate for testing the integrated agrivoltaic system.

Figure 1. Site Selection for Study in Salatiga

3.2. Agrivoltaic System Design

The prototype of the smart agrivoltaic system is constructed on an open field and consists of two primary planting plots which can be seen in Figure 2. It consists solar PV (1), solar PV controller (2), agrivoltaic farm area (3), controller and monitoring box (4), and non-agrivoltaic farm area (5). The agrivoltaic farm area, measuring 200 cm by 170 cm, is located beneath a tilted solar panel array mounted on a four-legged metal frame. This solar panel provides both electrical energy for the system and partial shading for the crops, simulating agrivoltaic conditions[17]. Mounted beneath the solar panel is an enclosure that houses key electrical components, including the solar charge controller, battery, and microcontroller. Adjacent to the shaded plot is a table positioned at a height of 150 cm, on which the central control system is placed for easy monitoring and data access. A non-agrivoltaic farm area, located to the right and left fully exposed to sunlight. This arrangement allows for the observation of growth differences in spinach and mustard greens under varying light intensities, while simultaneously assessing the performance of the integrated monitoring and automation system powered by two 100 WP solar panels[18], [19].

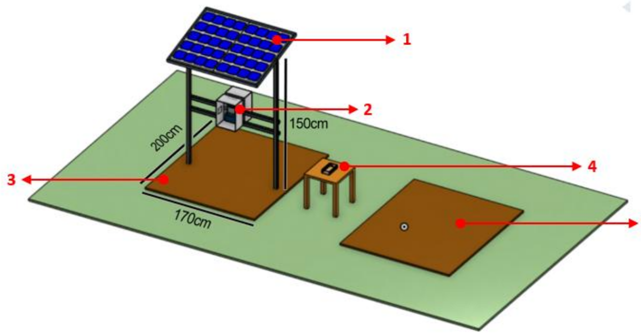

Figure 2. Agrivoltaic System Design

The solar panel will receive sunlight and convert it into direct current (DC). After the solar panel converts sunlight into direct electric current, the electric current will flow to the SCC. It will regulate the current and voltage according to the needs of the battery (battery). The battery will supply power to turn on the monitoring system and controlling system. The system of solar panels can be seen in Figure 3.

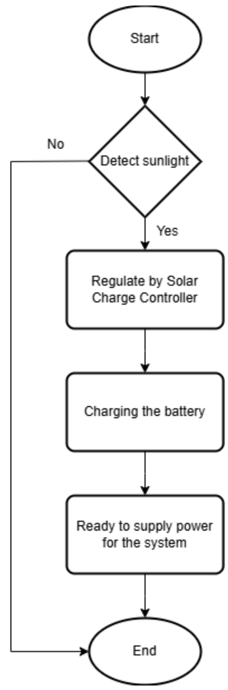

Figure 3. Solar panel system

The monitoring system will consist of 3 sensors: pH meter to measure pH levels, Soil Moisture Hygrometer Humidity sensor to measure soil moisture, and DHT-22 to measure temperature. The LCD will display data from the three sensors. If the value obtained from the three sensors does not reach the desired value, the controlling system consisting of a pump containing water will water the farm until the soil is moist enough, for fertilization is carried out within a period of 2 times a week. The monitoring and controlling system will be operated by Arduino Mega. The box diagram of this system is shown in Figure 4 and the flowchart of the monitoring and controlling system is shown in Figure 5.

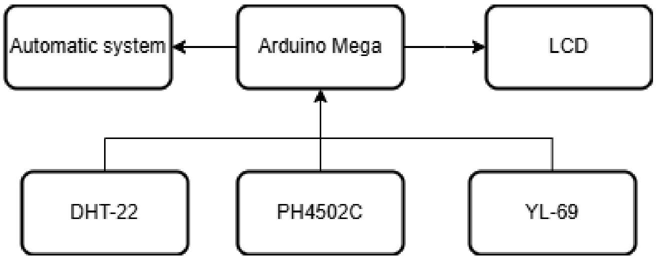

Figure 4. Agrivoltaic Controlling System

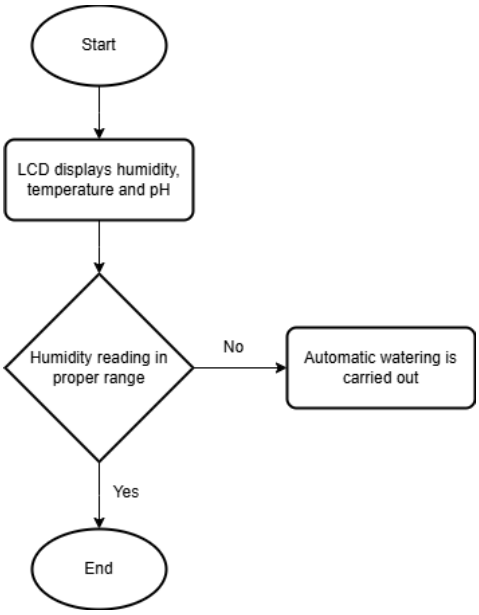

Figure 5. Agrivoltaic Monitoring System

4. Results and Discussion

Solar panels with a capacity of 100 WP are installed in series to increase the output voltage according to system needs, while keeping the output current consistent. The solar panels are connected to the Solar Charge Controller to ensure that the solar panels operate at maximum power point. The Solar Charge Controller is also connected to an inverter which is connected to a battery to store power. This system is placed in a container in the form of an unused PC case which can be seen in Fig. 6

Figure 6. Solar Panel Electrical Box Installation

The developed monitoring and control system was implemented using a network of environmental and soil sensors to ensure accurate data acquisition across different agricultural conditions which can be seen in Fig.7. A total of twelve YL-69 soil moisture sensors were scattered uniformly, with one sensor allocated to each plant, allowing for exact monitoring of each plant water content and great spatial precision when controlling irrigation. Furthermore, two DHT-22 temperature and humidity sensors were strategically placed to monitor and compare microclimatic changes between the agrivoltaic and non-agrivoltaic plots. This configuration allowed for a quantitative study of the effect of solar panel shading on ambient temperature and relative humidity in the production area. Furthermore, a PH4502C pH sensor was included into the irrigation system to continuously test and maintain the ideal pH.

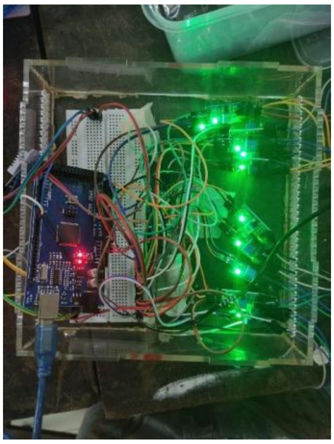

Figure 7. Monitoring and Controlling System Installation for Agrivoltaics

4.1 . Soil moisture testing

Soil moisture data were collected over 14 days can be seen in the Table 1 to Table 4. It is to compare the accuracy and consistency of the sensor-based monitoring system to manual observations. This investigation aimed to confirm the YL-69 sensors' ability to detect soil moisture reliably under different environmental circumstances in an agrivoltaic configuration.

Tabel 1. Soil Moisture Testing for Spinach in Agrivoltaiv System

Time (Day)	Plant 1		Plant 2		Plant 3		Error rates (%)
	Sensor	Manual	Sensor	Manual	Sensor	Manual	
1	703	679	698	678	713	690	3.27
2	730	711	740	720	716	692	2.97
3	726	707	718	698	717	698	2.76
4	736	716	748	730	743	726	2.53
5	735	712	726	708	698	767	-1.07
6	723	705	720	703	727	704	2.75
7	703	680	719	699	731	715	2.83
8	726	709	742	718	698	780	-1.59
9	733	714	718	700	711	688	2.86
10	736	717	723	705	695	675	2.72
11	739	718	737	717	748	728	2.82
12	727	708	698	678	733	719	2.53
13	723	703	721	701	705	685	2.87
14	706	687	707	683	709	688	3.11
Average	724.71	704.71	722.50	702.71	717.43	711.07	2.24

The table above shows that the soil moisture values recorded by the sensors closely match the manual reading trends, thus indicating the reliability of the automatic monitoring system. Minor variances were seen at specific points, such as on days 5, 8, and 11, which could be attributed to changes in hot daily weather conditions that changed the soil evaporation rate and moisture retention. Throughout the observation period, soil moisture measurements fluctuated between 680 and 780, indicating that the YL-69 sensor continued to provide reliable readings despite changing environmental conditions. These findings support the accuracy of sensor-based monitoring systems in real-time soil moisture measurements and their suitability for automatic irrigation control in agrivoltaic applications.

Soil moisture data for mustard plants was collected over 14 days to evaluate the efficacy of the sensor-based monitoring system compared with manual readings. This assessment aims to ensure the consistency and reliability of the YL-69 sensor in detecting fluctuations in soil moisture in various environmental conditions, especially weather in agrivoltaic systems.

Tabel 2. Soil Moisture Testing for Mustard Green in Agrivoltaic System

Time (Day)	Plant 1		Plant 2		Plant 3		Error rates (%)
	Sensor	Manual	Sensor	Manual	Sensor	Manual	
1	739	716	719	702	743	721	2.90
2	723	703	741	723	712	683	3.19
3	717	698	740	718	741	723	2.76
4	760	739	704	683	722	702	2.92
5	729	707	739	718	737	715	3.04
6	720	696	733	714	748	727	3.00
7	738	713	707	684	726	708	3.14
8	737	718	721	703	756	736	2.64
9	729	711	732	713	730	710	2.67
10	738	718	708	789	724	703	-1.50
11	730	708	723	702	707	685	3.10
12	736	716	715	694	724	706	2.79
13	727	708	731	711	724	704	2.78
14	723	701	727	707	713	694	2.90
Average	731.86	710.86	724.29	711.50	729.07	708.36	2.60

The test results show that the sensor readings almost match the manual measurements, which shows the reliable performance of the YL-69 soil moisture sensor in detecting real-time fluctuations in soil moisture. Minor differences occurred on some days, especially on day 10, which were caused by daily weather variations, including temperature, humidity, and sunlight intensity, which influence the rate of soil evaporation. Soil moisture readings fluctuated between approximately 680 and 780, with both results showing comparable trends and stability over the test period. The overall results demonstrate the precision and reliability of the sensor-based monitoring system, strengthening its efficacy in soil moisture management and automatic irrigation control in the context of agrivoltaic systems.

Tabel 3. Soil Moisture Testing for Spinach in Non-Agrivoltaic System

Time (Day)	Plant 1		Plant 2		Plant 3		Error rates (%)
	Sensor	Manual	Sensor	Manual	Sensor	Manual	
1	663	639	658	638	673	650	3.48
2	690	671	700	680	676	652	3.15
3	686	667	678	658	677	658	2.93
4	696	676	708	690	703	686	2.68
5	735	712	726	708	698	676	3.01
6	683	665	680	663	687	664	2.91
7	663	640	679	659	691	675	3.00
8	686	669	702	678	658	640	2.96
9	693	674	678	660	671	648	3.03
10	696	677	683	665	655	635	2.89
11	699	678	697	677	708	688	2.99
12	687	668	658	638	693	679	2.68
13	683	663	681	661	665	645	3.05
14	666	647	667	643	669	648	3.30
Average	687.57	667.57	685.36	665.57	680.29	660.29	3.00

Tabel 4. Soil Moisture Testing for Mustard Green in Non-Agrivoltaic System

Time (Day)	Plant 1		Plant 2		Plant 3		Error rates (%)
	Sensor	Manual	Sensor	Manual	Sensor	Manual	
1	699	676	679	662	703	681	3.07
2	683	663	701	683	672	653	2.85
3	677	658	700	678	701	683	2.92
4	720	699	664	643	682	662	3.10
5	729	707	739	718	737	715	3.04
6	680	656	696	674	708	687	3.33
7	698	673	667	644	686	668	3.33
8	697	678	681	663	716	696	2.80
9	689	671	692	673	690	670	2.83
10	698	678	668	649	684	663	3.01
11	690	668	683	662	667	645	3.29
12	696	676	675	654	684	666	2.96
13	687	668	691	671	684	664	2.95
14	683	662	687	667	673	654	3.03
Average	694.71	673.79	687.36	667.21	691.93	671.93	3.04

The trial results showed that soil moisture levels in agrivoltaic farming systems were consistently better than those in non-agrivoltaic systems during the testing period. This difference is caused by the presence of solar panels, which provide partial shade protection, thereby reducing direct solar radiation to plants and the soil and limiting the air evaporation rate from the soil surface. Assessment of measurement precision shows that the error detection rate of soil moisture in agrivoltaic farming systems is 2.24% and 2.60%. However, in non-agrivoltaic systems, the error rate increases slightly, namely 3.00% for spinach and 3.04% for mustard greens. The results show that the sensor-based monitoring system exhibits high measurement precision in both environments, with a slight increase in consistency in the agrivoltaic configuration due to the more stable microclimate state. The findings affirm that the incorporation of solar panels enhances renewable energy production while simultaneously significantly impacting soil moisture retention and irrigation efficiency in agricultural contexts.

4.2 Temperatur Testing

The results of testing conducted on systems that use agrivoltaics and those that do not show that the DHT-22 sensor and the thermometer do not produce the same results that can be seen in the image below. The average temperature reading from the thermometer was 25.77 degrees Celsius, whereas the average temperature reading from the DHT-22 sensor was 25.92 degrees Celsius, when testing the agrivoltaics system. Then, an average total error value of 0.38% was recorded. For the non-agrivoltaics system with a thermometer and the DHT-22 sensor, with the former yielding an average value of 26.43°C and the latter 26.38°C. The temperature in the non-agrivoltaics farming system is higher than in the agrivoltaics farming system, according to the test results. This occurs because the agrivoltaics farming system is shielded from the sun's rays, resulting in a cooler environment.

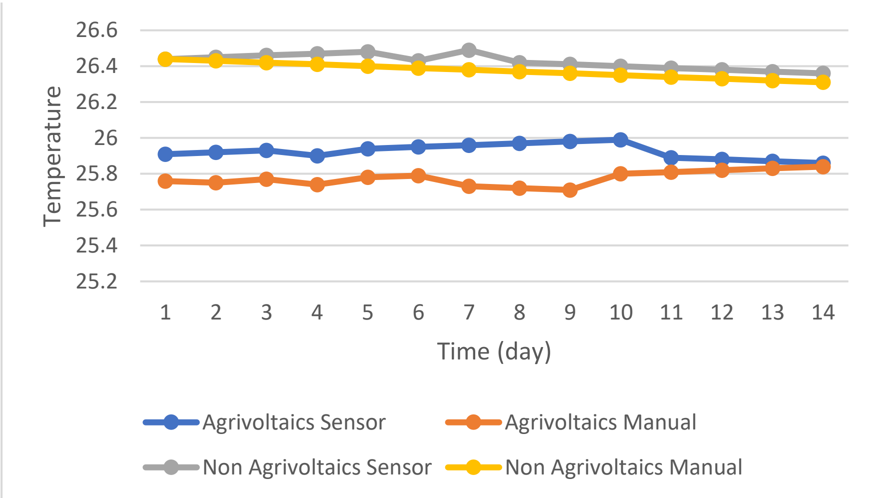

Figure 8. Temperature Testing of Agrivoltaics and Non-Agrivoltaics Systems

4.3 pH Testing

To assess the precision of the water quality monitoring component of the system, pH measurements were performed utilizing both the PH4502C sensor and a normal laboratory pH meter as a benchmark. This comparison sought to assess the accuracy and dependability of the PH4502C sensor in quantifying the pH level of irrigation water utilized in agrivoltaic and non-agrivoltaic systems.

Tabel 5. Water pH Testing

Time (day)	Sensor	Manual	Error rate (%)
1	7.28	7.3	0.27
2	7.06	6.96	1.42
3	7.2	7.2	0
4	7.49	7.48	0.13
5	7.47	7.47	0
6	7.42	7.41	0.13
7	7.32	7.3	0.27
8	7.05	7	0.71
9	7.36	7.33	0.41
10	6.99	7.03	0.57
11	7.01	6.99	0.29
12	7.04	7.05	0.14
13	7.03	7.08	0.71
14	7.04	7.22	2.49
Average	7.19	7.2	0.54

From Table 5, water quality testing for the irrigation system revealed a little discrepancy between the findings from the PH4502C sensor and those from a calibrated laboratory pH meter. The PH4502C sensor measured an average pH of 7.19, and the manual pH meter showed an average of 7.20. The calculated average error rate of 0.54% indicates that the PH4502C sensor produces good and stable measurements, which is in agreement with the reference instrument. The measurement data validates that the sensor can consistently monitor irrigation water pH levels in the neutral range, which is important for optimal nutrient absorption and healthy plant growth.

4.4 Solar Panel Testing

At this stage, the performance of the solar panel system configuration used in the agrivoltaic system is tested, specifically by monitoring the output voltage in various weather conditions and solar radiation. The results can be seen in Table 6.

Tabel 6. Solar PV Testing

Time (day)	Solar PV outut voltage (V)
1	49.11
2	47.98
3	50.91
4	50.52
5	49.71
6	51.44
7	48.96
8	47.13
9	48.43
10	51.37
11	48.76
12	49.25
13	50.04
14	51.88
Average	49.68

The solar panel performance tests produced an average output voltage of 49.68 V, indicating that the photovoltaic (PV) module configuration functions within the expected range under field conditions. The displayed output voltage varied during the observation period, primarily due to erratic weather conditions in Salatiga. Such changes are characteristic of real-world outdoor testing, where cloud-covered weather, air humidity, and sunlight intensity affect solar panels' voltage and current attributes. Despite these fluctuations, the system maintains stability and responsiveness using MPPT, and the results demonstrate its capacity to adapt to varying external conditions while ensuring consistent energy generation performance.

5. Conclusion

The agrivoltaic system for spinach and mustard greens was successfully designed and demonstrated reliable performance in the Salatiga area. The solar panel configuration produces sufficient voltage to charge the battery, with an average output of 49.68 V, thus ensuring a stable power supply for system functionality. The monitoring system can efficiently show environmental indicators such as soil moisture, air temperature and water pH for crop irrigation management.

Test data shows that the average soil moisture value for spinach plants cultivated using an agrivoltaic system is 721.55, different from 684.4 in a non-agrivoltaic system. The average soil moisture of mustard plants is 728.4 in agrivoltaic conditions and 691.33 in non-agrivoltaic conditions. Both results show that the partial shading impact of solar panels helps maintain soil moisture by reducing direct sunlight exposure to soil and plants. The average temperature in the agrivoltaic system is 25.92°C, slightly lower than the temperature in the non-agrivoltaic system, which is 26.43°C. The temperature difference indicates that the agrivoltaic system creates a more stable microclimate with lower temperature conditions, thereby improving plant growth conditions with sufficient exposure to sunlight. Evaluation of the water quality monitoring system showed that the PH4502C sensor demonstrated a good level of accuracy, producing an average value of 7.19 and an error rate of 0.54%. These results verify that the sensor can reliably measure irrigation water pH levels.

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