Design and implementation of smart farming prototype with renewable energy and IoT

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Article Info

Article history:

Received Dec 20, 2024
Revised Apr 7, 2025
Accepted Jul 2, 2025

Keywords:

Agricultural
Artificial intelligence
Farmer
Internet of things
Renewable energy
Smart farming
System usability scale

ABSTRACT

Indonesia faces food security challenges in several regions, and the adoption of advanced technologies such as artificial intelligence (AI), internet of thing (IoT), and renewable energy in the agricultural sector has not been optimal. This research aims to develop an integrated smart farming system, including monitoring, controlling, and prediction features based on renewable energy to support national food security, especially for chili plants. The method used in the research is an experiment, starting from analysis, design, manufacture, and testing. The result of the research is a smart farming prototype that has been tested with experts, partners and farmers. The results of expert testing obtained that the monitoring feature, in this case the accuracy is 4.36 out of 5 for all sensors, as well as the controlling and prediction features have met technical, functional, and practical needs. The results of the usability evaluation using the system usability scale (SUS) method involving partners and farmers obtained an average SUS score of 73.125. This result is categorized as an excellent rating and can be given a grade B and the acceptance range is high. So, from this study it can be concluded that the smart farming prototype can be used by chili farmers.

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1. INTRODUCTION

In 2022, Indonesia was ranked 63rd out of 113 countries in the Global Food Security Index [1]. In fact, Indonesia is an agricultural country whose economy depends on or is supported by the agricultural sector. In line with that, the Indonesian government has concerns about domestic food security [2], [3]. This is supported by the fact that in several regions there are still food shortages and malnutrition [4]. In addition, the presence of the industrial revolution affects the agricultural sector from upstream to downstream.

The industrial revolution 4.0 is based on an intelligent manufacturing system with a business model built by networks, computers, information technology, software and automation technology [5]-[9], as well as the current agricultural sector in the era of agriculture 5.0 [6], [10], [11]. Thus, agricultural yields that depend on weather conditions can be increased by utilizing intelligent manufacturing [12], [13]. For this reason, the development of smart farming is a solution to food security to increase the quantity and quality of agricultural production [14].

Smart farming has several important aspects such as: intelligent sensing, intelligent planning/analysis, and intelligent control [15]. Sensing data such as soil moisture, temperature, air humidity, rainfall, wind are connected to an intelligent control unit that is responsible for data storage and analysis. The results are then available to support farmer decisions [16]. The development of adaptive and optimal smart farming can be implemented by considering the initial situation, conditions and assets of agriculture.

Intelligent analysis in smart farming uses artificial intelligence (AI). This technique aims to make optimal decisions with various non-linear input parameters. In addition, a number of technologies act as enablers of smart farming including the internet of things (IoT), big data, robots, drones, and cloud computing [17], [18]. IoT technology can reduce costs and increase the scale of agriculture through the collection of sensor network data, spatial data from imaging sensors, and human observations recorded through smartphone applications [14]. In smart farming, power management using independent power source (solar panels) is needed in the entire system to ensure crop productivity [19].

This study will build an integrated farming system/smart farming with AI with monitoring, controlling and prediction features based on renewable energy using IoT for sustainable agriculture. This system will link the influence of environmental conditions such as soil moisture, temperature, rainfall, wind, including soil nutrients with plant factors, especially chili [19]. The selection of chili as the chosen planting object is due to the very high price fluctuations. In addition, chili plays an important role in the Indonesian economy and has a multiplier effect when there is a price spike [20].

The urgency of this research is as a solution to the vital problem of national food security along with the growth of the Indonesian population. This research will produce a system and implementation of smart farming in Indonesia which is equipped with a monitoring, controlling and prediction system using artificial neural network (ANN) in an integrated manner. Users can monitor and control the smart farming system. This research is an improvement on previous research, because previous smart farming research has not been integrated such as sensor network data acquisition [21]. Furthermore, in research [22] did not complete weather predictions, so in the development of a monitoring system for smart farming in this research it was improved by adding this. Moreover, the research improves research related to plants such as chili [23], [24] with a monitoring, controlling and prediction system from solar power based on IoT and AI.

The state of the art of this research includes new innovations related to the integration of advanced technology in managing agriculture holistically. The AI system uses machine learning algorithms to analyze data obtained from IoT sensors, providing timely monitoring, weather prediction and irrigation control. This technology not only increases production efficiency but also helps reduce excessive use of resources. In addition, the adaptively applied AI model is able to learn from past experiences, making it more effective and adaptable to changing agricultural conditions. Thus, this article implements and integrates the fields of AI, IoT, and renewable energy to create smart, efficient, and sustainable agricultural solutions.

2. METHOD

The components of the smart farming system are hardware and software, equipped with the IoT and AI. Figure 1 is a smart farming architecture designed to integrate IoT devices, renewable energy systems, and AI algorithms. The main components used include 7 sensors. These sensors are used to measure environmental parameters in real-time. The ESP32 microcontroller is used to process data from the sensor, while a 50 W solar panel and a 12 V/2.3 Ah storage battery are installed as the main power source. This system is equipped with an automatic water pump to control irrigation based on the results of soil moisture sensor data analysis (YL69). In addition, this system is also equipped with weather predictions, based on 4 values, namely: temperature, humidity, wind speed, and solar radiation.

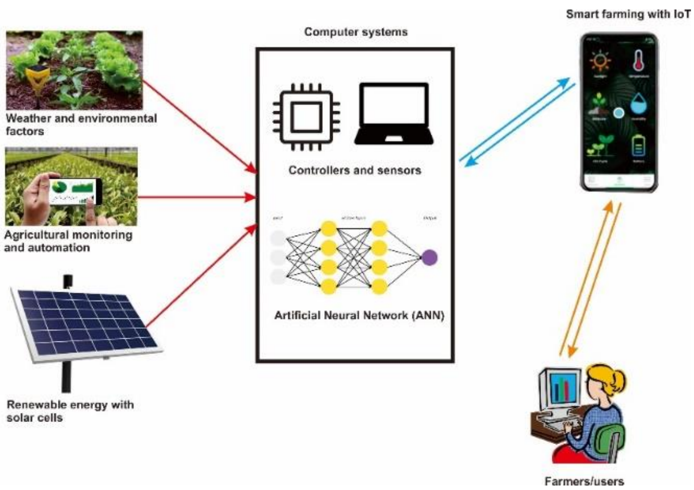


Figure 1. Smart farming architecture

This system uses solar panels connected to a solar charge controller to manage battery charging. The battery functions as an energy storage to ensure the system continues to operate for 24 hours, even though weather conditions are not supportive. Figure 2 is a schematic diagram of a renewable energy system. The components in Figure 2 include solar panels, solar charge, batteries, EPS32, relays, pumps and various sensors.

Figure 3 presents an integration design consisting of a portable pole and a mobile or web application. Figure 3(a) shows the design of the portable pole, while Figure 3(b) shows the display of the mobile/web application that supports the system. Based on Figure 4, the portable pole consists of: 1) a soil sensor is a sensor that can produce output data on soil moisture, soil temperature, soil pH; 2) the pole weight is made of iron with a square structure with a weight in the middle; 3) the support pole is made so that its height can be adjusted; 4) ESP32 Cam camera for monitoring land/gardens has a resolution of up to 1600x1200 pixels; 5) A toolbox consisting of ESP 32, WiFi, water pump, battery, DS 18B20 sensor, solar charger; 6) A 50 W solar cell is an independent energy source derived from sunlight; 7) A rainfall sensor functions to detect the amount of rainfall; 8) A wind sensor functions to detect and determine wind speed; 9) An LDR sensor functions as a solar radiation detector. Mobile/web application displays visualization data from camera (1) displays real-time garden/land conditions; irrigation status (2) displays irrigation history, watering status; sensor monitoring (3) displays smart agriculture sensor values; weather (4) displays today's weather and weather predictions.

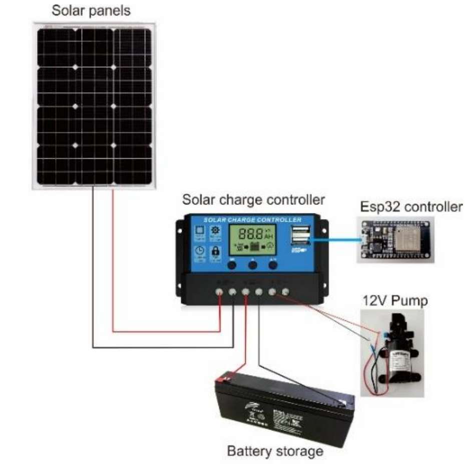
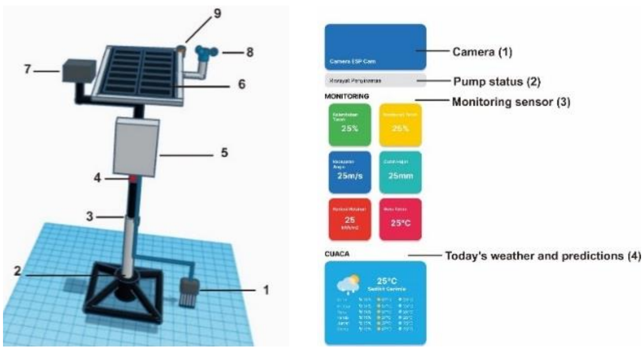


Figure 2. Schematic diagram of a renewable energy system



(a) (b)

Figure 3. System integration design, (a) prototype with portable pole and (b) web application

Figure 4 is a schematic diagram of the ANN for weather prediction. To build a prediction model, initial data can come from the BMKG dataset which contains historical information such as temperature, humidity, solar radiation, and wind speed. This data is used to train the ANN model because it is high quality and has wide coverage [25]. This dataset is pre-processed, including data cleaning, feature normalization, and dividing the dataset into training, validation, and testing data. The designed ANN model will have an input layer that matches the number of 4 features: temperature, humidity, solar radiation, and wind speed), several hidden layers and an output layer that produces the probability of whether rain will occur or not. After training is complete, this model is saved for use in the testing phase. In the testing phase, the trained model is tested with new data from sensors. This sensor data must be processed in such a way that it has the same format as BMKG data, including normalization using a consistent scale. Predictions are made directly on sensor data, and the results are compared with actual conditions to evaluate model performance.

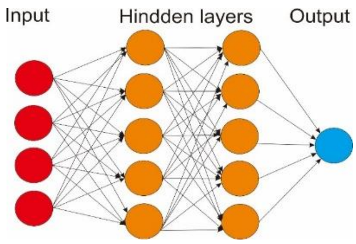


Figure 4. Schematic diagram of ANN for prediction

Smart farming system testing using usability evaluation involves experts and farmers as end-users as evaluators [26]. There are 3 experts and 1 practitioner in the smart farming prototype testing, including experts in electrical circuits or renewable energy, agricultural experts and AI experts and 1 practitioner, namely the IoT practitioner. The measurement instrument uses a scale from 1 to 5, scale 1 is very inaccurate, scale 2 is inaccurate, scale 3 is quite accurate, scale 4 is accurate and scale 5 is very accurate. The accuracy value of this sensor is important to ensure further analysis to be maximized [27].

Smart farming prototype user testing was conducted by partners and farmers in the Kismantoro area, Wonogiri. This testing involved 11 chili farmers and 1 partner, namely the owner of UD. Tani Tlaten. The testing instrument used the system usability scale (SUS), based on [26]. The SUS is a usability evaluation method that provides adequate results based on considerations of small sample. sizes, time, and costs. Table 1 explains that SUS has 10 questions and has 5 answer choices. Starting from strongly disagree, disagree, undecided, agree, and strongly agree.

Table 1. SUS instrument

No	Question	Scale
1	I think I want to use this system as often as possible	1 to 5
2	I feel this system is too complicated	1 to 5
3	I think this system is easy to use	1 to 5
4	I think I need technical support to be able to use this system	1 to 5
5	I think the functions in this system are well integrated	1 to 5
6	I think there are too many inconsistencies in this system	1 to 5
7	I think most people will learn to use this system very quickly	1 to 5
8	I find this system very difficult to use	1 to 5
9	I feel very confident using this system	1 to 5
10	I need to learn a lot before I can use this system	1 to 5

3. RESULTS AND DISCUSSION

Table 2 in APPENDIX is the components and functions used in building the smart farming prototype. For the wiring diagram of the components in Table 2, see Figure 5. Based on Figure 5, this smart farming prototype utilizes solar panels as the main energy source, where the energy produced is distributed through the solar charge controller (PWM) to charge the battery that functions as a power storage. An ESP32 microcontroller is used as a control center to read data from various sensors and process it. The connected sensors include an anemometer to measure wind speed, a rain sensor to detect the presence of rain, a temperature and humidity sensor (DHT22) to measure air conditions, and a soil moisture sensor to monitor water content in the soil. All data obtained from the sensor is displayed via an LCD display and then with IoT displayed on the website. In the cable connection, the red color indicates the positive path (VCC), while the black color is for the negative path (GND), with other cables adjusted to connect the input and output pins of each component. This system is designed to work automatically and independently by utilizing renewable energy from solar panels. making it an efficient solution for smart farming prototype needs.

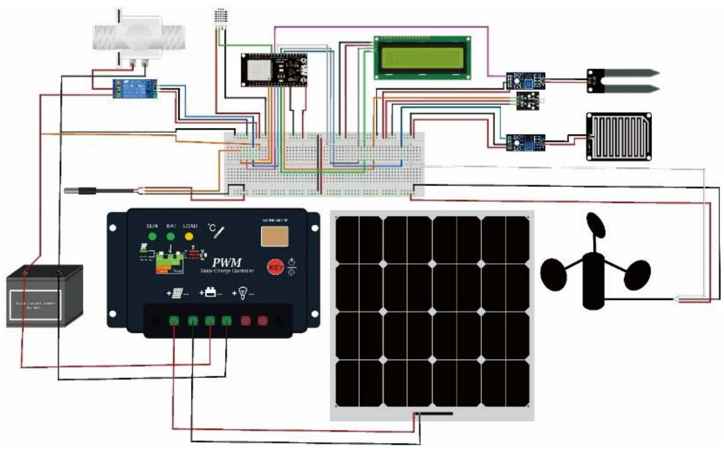


Figure 5. Wiring design

Figure 6 is a smart farming prototype. Based on Figure 6, the smart farming prototype consists of the following components: 1) soil sensor (temperature, humidity, and Ph); 2. Pole; 3. Chili; 4) Camera; 5) battery; 6) voltage indicator; 7) Pump; 8) solar charge; 9) LCD; 10) EPS32; 11) instruction board; 12) DHT 22 sensor; 13) Tool Box; 14) solar panel; 15) rain sensor; 16) LDR sensor; 17) wind speed sensor. The value of each sensor can be accessed via hppt://udb-smart-farm.vercel.app.

Figure 6. Smart farming prototype

Table 3 is the result of sensor performance observation. In sensor performance testing, experts compare the value of each sensor on the web with the measuring instrument at the test location. From the results, the average sensor performance, in that case its accuracy is 4.36 for all sensors, there are 7 seven sensors. This means that all sensors are accurate in their readings on the web compared to their comparative measuring instruments. From these results, experts can ensure that the smart farming prototype meets technical, functional, and practical needs according to the standards and expectations of experts in related fields [12], [18].

Table 3. Sensor performance test results

Field of expertise	Sensor performance testing						
	Soil moisture	Soil PH	Wind speed	Soil temperature	Sensor DHT22	Radiation	Rainfal l
IoT practitioner	3	3	4	5	4	4	4
Electrical circuit/renewable energy expert	5	5	5	5	5	5	5
AI expert	5	4	3	3	3	4	4
Agriculture expert	5	5	5	5	5	5	5
Average sensor performance	4.5	4.25	4.25	4.5	4.25	4.5	4.5

This smart farming prototype can control a pump with a voltage specification of 12 V DC and a pressure of 70 PSI based on a soil moisture sensor. Table 4 is the result of pump testing by experts based on soil moisture values. The test results from expert's state that all humidity conditions successfully control the pump according to the expected humidity value. The smart farming prototype system is considered successful if the pump functions according to the soil moisture value detected by the YL69 Sensor, so humidity monitoring is very important for optimal irrigation control [28], [29].

Table 4. Pump control test results

Field of expertise	Automatic pump control observation		
	Humidity condition < 30% (system expectation: pump on)	Humidity condition 30% - 70% (system expectation: pump off)	Humidity condition > 70% (system expectation: pump off)
IoT practitioner	Success	Success	Success
Electrical circuit expert/renewable energy	Success	Success	Success
AI expert	Success	Success	Success
Agriculture expert	Success	Success	Success

To build a prediction model, the initial data can come from the BMKG dataset containing historical information such as temperature, humidity, wind speed, solar radiation, and rainfall. This data is used to train the ANN model. The designed ANN model will have an input layer that matches the number of features (4 features: temperature, humidity, wind speed, and solar radiation), several hidden layers and an output layer that produces the probability of whether it is raining, cloudy or sunny. After training is complete, this model is saved for use in the testing phase. In the testing phase, the trained model is tested with new data from sensors. This sensor data must be processed in such a way that it has the same format as the BMKG data, including normalization using a consistent scale.

As explained above, testing the prediction model uses training data, namely public data from BMKG with a data period of January 5, 2023 - November 1, 2024, as many as 624 data records [30]. The test data uses data from a combination of public data and smart farming measurement sensors with a measurement period of 3 days. The data consists of 4 attributes, namely temperature (T), humidity (RH), wind speed (RR), solar radiation, and 1 label, namely rainfall (ff).

The modeling process uses cross validation to carry out model testing of 10 fold validation. The next process carried out is the training process, this process is carried out in the cross validation operator using a neural network algorithm, with this algorithm the data will be divided into 2, the first part is used as training data by 80% and the second part is used as testing data by 20%. The training process is carried out using neural network operators, training uses a 5 – 6 – 3 structure with 500 training cycles, learning rate 0.01 and momentum 0.1. The final stage of this process after training is testing the dataset using the neural net function which has been carried out on previous training data. This testing process measures performance using the main criterion of accuracy. Based on the prediction simulation using neural net, the accuracy value is 73.68%. Figure 7 is the prediction result using RapidMiner software. The prediction accuracy results are still within the acceptable range, but prediction accuracy results greater than 80% are expected [31]. In the future, to improve the accuracy level, a hybrid model can be used, combining ANN with other models such as long short-term memory (LSTM) [32].

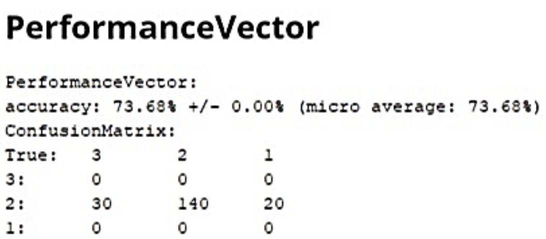


Figure 7. Prediction test results with RapidMiner

Table 5 explains that SUS has 10 questions and has 5 answer choices. Starting from strongly disagree, disagree, undecided, agree, and strongly agree. The score for each answer starts from 1 which is strongly disagree to 5 which is strongly agree. The calculation method in the SUS instrument is as follows [33], [34]: 1) the scale used is strongly disagree to strongly agree with a value of 1 to 5; 2) for odd-numbered statements, it is calculated by: the value of the user's response is reduced by the value of 1; 3) for even-numbered statements, it is calculated by: the value of 5 is reduced by the value of the user's response. Add up the response values that have been calculated in points 2 and 3 above, and multiply the result by the value of 2.5 which is the provision of the method. The results of this calculation will convert the value range to between 0-100. Table 4 is the result of the SUS instrument calculation.

Table 5. SUS instrument calculation results

Respondent	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Calculation results	Calculation results *2.5
R1	4	4	4	4	4	3	4	4	4	4	21	52.5
R2	4	4	4	4	4	4	4	4	4	4	20	50
R3	5	3	4	4	4	2	4	1	4	4	27	67.5
R4	5	1	5	3	5	2	5	1	5	3	35	87.5
R5	4	2	4	4	4	2	4	2	4	4	26	65
R6	5	1	5	4	5	2	4	2	4	2	32	80
R7	5	4	3	5	4	4	3	1	5	5	21	52.5
R8	4	1	4	2	5	1	5	1	4	2	35	87.5
R9	5	1	5	1	5	1	3	1	5	3	36	90
R10	4	3	3	3	5	1	3	1	4	2	29	72.5
R11	5	1	5	1	5	1	5	1	5	1	40	100
R12	4	3	3	3	5	1	4	2	4	2	29	72.5
Average SUS score												73.125

The results of the usability evaluation of the smart farming prototype using the SUS method have been successfully carried out by involving partners and chili farmers in Kismantoro, Wonogiri. The total respondents were 12, of which 83.33% were male and 16.67% were female with ages ranging from 26 to 62 years. From the calculation results, variations in scores were found among the respondents. The lowest score recorded was 52.5 while the highest score reached 100. Interestingly, some respondents gave a very positive assessment, indicating a high level of satisfaction with the usability of the smart farming prototype. After analyzing all the data, an average SUS score of 73.125 was obtained. Based on the SUS value, it is categorized that the excellent rating and can be grade B and the acceptable ranges are high [35], [36].

From this research, it can be concluded that the smart farming prototype can be used by chili farmers. However, the smart farming prototype has limitations, including the power of this system using solar panels so it is dependent on weather conditions but can be overcome with a battery with large power. So that weather prediction in this system is not only for monitoring chili plants but also for monitoring the power system of the smart farming prototype.

4. CONCLUSION

The implementation of an integrated smart farming system using AI, IoT, and renewable energy demonstrates significant potential for addressing Indonesia's food security challenges. The system's capability to monitor, control, and predict environmental conditions and plant growth, particularly for chili crops, provides a sustainable solution to enhance agricultural productivity and efficiency. Usability evaluations reveal an acceptable and promising system performance, with a high average SUS score of 73.125, highlighting the system's effectiveness and positive reception by end-users, including farmers and experts. This innovation supports sustainable agriculture, optimizes resources, and aligns with the goals of Agriculture 5.0. For that, agriculture 5.0 can be an inspiration for research and development. In this context, the application of smart farming strategies with IoT and AI has great potential to revolutionize chili cultivation, a staple crop in the Indonesian culinary landscape.

ACKNOWLEDGEMENTS

Acknowledgment to the Directorate of Vocational Higher Education, Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia for funding this research in accordance with the contract number of research and community service funding BOPTN vocational batch 3 fiscal year 2024 Number: 420/SPK/D.D4/PPK.01.APTV/VIII/2024

FUNDING INFORMATION

This research was funded by the Directorate of Academic and Vocational Higher Education, Ministry of Education, Culture, Research, and Technology, under Grant Number 420/SPK/D.D4/PPK.01.APTV/VIII/2024.

AUTHOR CONTRIBUTIONS STATEMENT

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Herliyani Hasanah	✓		✓	✓			✓		✓	✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this paper, entitled “Design and implementation of smart farming prototype with renewable energy and IoT”. All authors, Rudi Susanto, Wiji Lestari and Herliyani Hasanah have reviewed and approved the final version of the manuscript and have no financial or personal relationships that could inappropriately influence or bias the content of the paper.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study. Participants were informed about the research and voluntarily agreed to participate.

ETHICAL APPROVAL

The research related to human use has complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board.

DATA AVAILABILITY

The author states that the data supporting the findings of this study can be accessed through articles and public data sources owned by the BMKG, covering the time period from January 5, 2023, to November 1, 2024, at the following link: https://dataonline.bmkg.go.id/dataonline-home.

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APPENDIX

Table 2. Components and functions

No.	Component name	Number	Function	Image
1	ESP32 Dev Kit V4	1	IoT development platform that supports Wi-Fi connectivity and enables the integration of sensors, actuators, and data communications in a variety of smart applications with low power consumption.	
2	ESP32 Cam OV2640 + TTL	1	IoT module integrates a high-resolution camera with Wi-Fi connectivity, enabling image or video capture and wireless data transmission in applications such as remote monitoring.	
3	DS18B20 Waterproof Temperature	1	Waterproof temperature sensor that can measure temperature with high accuracy and transmit data digitally for a variety of applications, including environmental temperature monitoring.	
4	Photosensitive light LDR resistance sensor light module	1	Detects light intensity and converts it into an electrical signal that can be used in automation applications, such as lighting control.	
5	Arduino Anemometer Wind Speed Sensor	1	Measures wind speed and produces data that can be used in weather, automation, and environmental monitoring applications.	
6	Zhafira rainfall sensor ombrometer arduino tipping bucket rain-ASA	1	Measuring rainfall intensity and volume with a tipping bucket mechanism, producing data that can be used for weather monitoring and environmental analysis.	
7	Pompa DC 12V 70 PSI Sinleader Alat Siram Misting Sprayer Booster Pump	1	Sprayer or water pressure booster for irrigation applications, and spraying system.	
8	Soil Moisture Sensor and Sensor Module	1	Detects soil moisture levels and sends data to support irrigation automation and soil condition monitoring in smart farming applications.	
9	Soil Ph Sensor	1	Measuring the acidity or alkalinity of the soil, providing important data for soil fertility analysis and plant growth optimization.	
10	LCD Character 20x4 2004 5v green module +i2c module	1	Displays text information up to 4 lines with 20 characters per line efficiently, using I2C communication to save microcontroller pins.	
11	Electrical panel box 40 x 30 x 18 outdoor tonata / powder coated / hat	1	Protects equipment and control systems from external weather, dust, and physical damage outdoors.	
12	DHT22 Sensor	1	Measures air temperature and humidity with high accuracy, providing data that can be used in environmental monitoring applications.	
13	Solar Panel 50 Watt	1	Converts solar energy into electrical energy with a capacity of 50 watts, which can be used to charge batteries or power electronic devices in the smart farming prototype.	

Table 2. Components and functions (*Continue*…)

No.	Component name	Number	Function	Image
14	12 V Battery	1	Store electrical energy and provide a stable power source for various electronic devices and electrical systems.	
15	Solar charge	1	Converts solar energy into electricity and recharges batteries, ensuring a stable power supply for solar power systems or devices that rely on renewable energy.	
16	FRF Mifi / mini wifi / Bolt Slim Huawei E5372s modem	1	Provides wireless internet connection via 4G LTE network.	

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