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Enhancing Oyster Mushroom Cultivation with Solar-Powered IoT and Machine Learning: Predicting Harvest Readiness

Gilda J. Taupa [1*], Mia V. Villarica [2], Albert A. Vinluan [3]
[1] Graduate Student, College of Information Technology, Central Bicol State University of Agriculture, Philippines
[2] Professor, College of Computer Studies, Laguna State Polytechnic University, Philippines
[3] Professor, College of Computing Studies, Isabela State University, Philippines
Email: [1] gilda.taupa@cbsua.edu.ph, [2] mia.villarica@lspu.edu.ph, [3] albert.a.vinluan@isu.edu.ph
ORCID ID: [1] 0009-0006-4200-6066, [2] 0000-0003-0952-4479, [3] 0009-0001-4570-1391
**Corresponding Author: Gilda J. Taupa*

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ABSTRACT

The cultivation of oyster mushrooms demands skillful control over environmental conditions and timely harvesting to optimize yield as well as quality. By using the IoT system, key growth parameters — temperature, humidity, air quality, and light intensity — are monitored. Simultaneously, a machine learning framework that uses Convolutional Neural Networks (CNNs) and object detection models analyze and capture patterns related to environmental factors that influence mushroom growth stages. This offers system integration with solar power to enhance sustainability and automates the environmental monitoring and control solutions thus reducing operation costs while keeping the quality of yield at a higher level. This novel study not only speeds up the growing process but also helps predict exactly when the crop is ready to harvest. Harvesting oyster mushrooms at the right time ensures they reach the best size and weight, leading to larger yields while preserving their taste, texture, and nutritional value for customer satisfaction. Accurate predictions of harvest readiness help farmers plan better to meet market demand and increase their profits. The result of this study used a machine learning model to predict if oyster mushrooms can be harvested. The trained model achieved 85% accuracy, with 97% precision and 82% recall, resulting in an F1 score of 89%. Cohen's Kappa analysis showed a strong match between the model's predictions and the farmer's judgment, with a Kappa value of 0.654 and a p-value of 0.000, meaning the model is reliable.

Keywords: oyster mushroom cultivation, solar-powered IoT, machine learning, harvest prediction, smart agriculture.

INTRODUCTION

In the Philippines, oyster mushroom farming continues to grow due to increasing consumer demand for more nutritious and organic food and the ease of mushroom cultivation [1]. However, predicting the right time to harvest remains a challenge for growers. Traditional methods of checking growth and knowing when to harvest depends on manual inspection, which is hard work, takes a lot of time, and can lead to mistakes [2].

These challenges can be addressed with the integration of technologies such as machine learning (ML) and the Internet of Things (IoT). IoT devices can continuously measure the temperature, humidity, light intensity, and air quality in the growing area. Real-time data can help farmers maintain the perfect growth environment for mushrooms. [3] In order to help farmers optimize yield while reducing waste, machine learning algorithms can predict the ideal time to harvest by looking at growth trends and environmental parameters. Comparably, [4] the adoption of solar-powered system will reduce or eliminate the need for utilizing traditional electrical sources, which decreases setup costs and enhances the environment—particularly in remote areas with limited access to electricity.

This study has the following objectives: First, was to develop a solar-powered IoT system and machine learning model to predict the harvest readiness of oyster mushrooms. The second was to evaluate the performance of the model along with accuracy, precision, recall/sensitivity, and F1 score using the confusion matrix. The third was to determine the

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reliability of the model by measuring its consistency with the assessment of mushroom farmers in harvest readiness of oyster mushrooms.

METHODOLOGY

The overall framework of this study exploits the integration of solar-powered IoT technology and machine learning, often referred as precision agriculture. A controlled setup was developed to monitor key growth parameters such as; temperature, humidity, air quality and light intensity. The real-time data collection enabled continuous tracking of the growing conditions. Then, a machine learning algorithm was employed to analyze the collected data and predict harvest readiness. By utilizing historical growth metrics, the models were trained, and the developed predictive framework could precisely determine the best time for harvesting. The uninterrupted operation of the monitoring system was driven by solar energy to guarantee sustainability and lower power consumption.

A. Experimental Setup

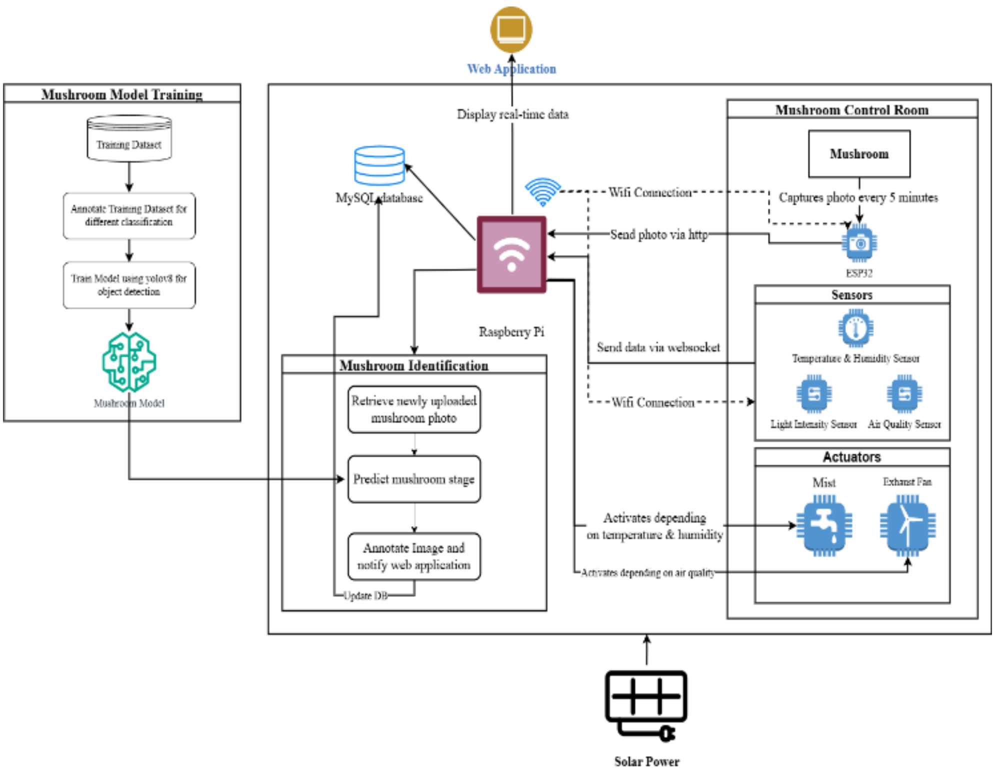

Figure 1. System Design

The IoT system for oyster mushroom cultivation, as shown in Figure 1, was designed and developed through various hardware components. The entire experimental setup was built in a 3 x 8 meters mushroom house. The Raspberry Pi serves as the central processing unit of the system, it is responsible for managing data from the sensors and at the same time controlling actuators. The ESP32-CAM that periodically captures images of the mushroom cultivation area, and Sensors (DHT11, light intensity and air quality) to monitor environmental conditions. In the system there are also Actuators, such as the misting system, exhaust fans, and lighting that maintain optimal temperature, humidity, air quality, and light intensity.

The system is capable of Image Processing and Growth Stage Detection inside the mushroom house. It will start with image acquisition wherein the ESP32-CAM captures images at regular intervals. These images are sent to the Raspberry Pi via REST API, where a pre-trained machine learning model analyzes the images. The model classifies mushrooms into three growth stages: Stage 1 (pinhead formation), Stage 2 is (button stage), and Stage 3 (mature mushrooms ready for harvest). The growth stage monitoring algorithm processes the images received from the

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ESP32-CAM and determines the current growth stage. If the oyster mushroom reach growth stage 3, the system triggers a harvest alert on the web application.

The entire system is powered by solar panels which captures the sunlight, battery storage for storing solar energy generated by the sun. The PV Panels selected for this system is monocrystalline, consisting of 6 panels, each has a dimension of 1.2m x 0.54m, with a capacity of 100 watts each, a total of 600 watts that is connected in parallel and placed strategically on the roof of the mushroom house. To maintain a continuous power supply, the system incorporates lithium-ion batteries with a capacity of 3.28 volts, 6500mAh. The system connection has 4 strings connected in series, each string has 11 batteries connected in parallel, a total capacity of 3.28-volt per battery equivalent to 71.5 Ah. The total capacity is equal to 13.12 volts. Additionally, the storage battery has its components called 100A Battery Management System (BMS) and 5A active balancer, where the discharged and charged of the batteries ensure its optimum performance, maintaining the safety and longevity of the batteries. On the other hand, the solar charge controller has a capacity of 40A, MPPT, 12-volts system.

The entire IoT system continuously collects data, which can be viewed in the web application for real-time monitoring. Automated control logic ensures that misting, ventilation and lighting are activated when predefined thresholds are exceeded, ensuring optimal conditions for mushroom growth without human intervention.

B. Data Collection

The data collection process in this study focused on gathering real-time environmental and growth data through solar-powered IoT sensors. Oyster mushroom fruit bags are arranged in the mushroom house, where temperature, humidity, air quality and light intensity are monitored. The researcher collected 8,900 images of oyster mushrooms using an ESP32 camera in a consistent background, angle and lighting. During the actual gathering of samples the mushroom fruit bags were arranged in quadrants. Each quadrant was divided into four sections, with fruit bag placed in each section. The ESP32 camera captures images every 5 minutes and stored them in the database.

C. Machine Learning Approach

This phase of the study focuses on model development. The YOLOv8 deep learning model was utilized in this research to precisely detect the stages of oyster mushroom growth. Designed for object detection, YOLOv8 can accurately identify and locate objects in images with high precision and in real time [16]. The collected datasets will be cleaned first to ensure consistency and quality, this is done by removing outliers, addressing missing values and normalizing numerical values. Then, the cleaned data will be divided into two subsets: 70% will be allocated for training the model and the remaining 30% will be used to test the dataset to evaluate the model's performance, see figure 2 for the model performance on mushroom dataset.

The confusion matrix is the evaluation metrics used to evaluate the performance of the model, including precision, accuracy, recall/sensitivity and F1 score, at the same time, determine its reliability by measuring its consistency in the assessment of the mushroom farmer on the readiness of the harvest of oyster mushrooms.

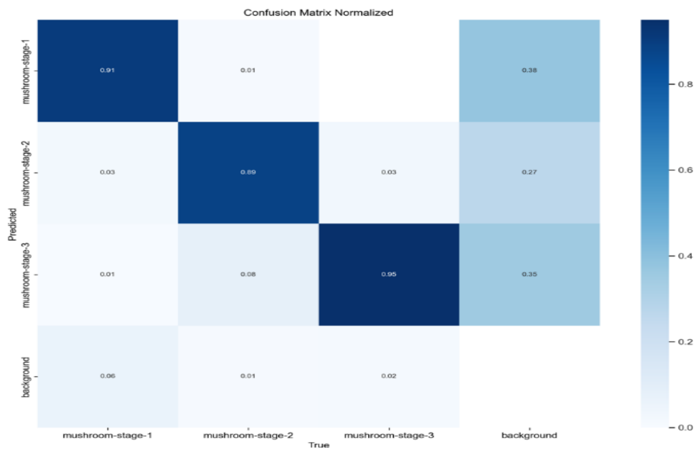

Figure 2. Normalized Confusion Matrix for Mushroom Stage Classification Model

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D. Solar-Powered System

The solar energy system for IoT devices in the oyster mushroom house is designed to provide sustainable and environmentally friendly energy. It consists of solar panels that capture sunlight and turn it into electricity. This electricity is stored in the LiFePo4 battery, which allows the system to continue working, even at night or on cloudy days. To reduce energy use, the system uses energy-efficient devices such as the WeMos Microcontroller, which can go into sleep mode when not collecting data. The PV panels were configured to produce enough energy to fulfill the daily power needs of the IoT devices and other electronics components. The entire IoT system consumes 94.57 watts of energy each day, the PV panels can generate an average of 600 watts daily, where the excess energy will be stored in the battery for later use. The entire generated power will last up to 5 days without harvesting from the sun.

E. Data Analysis

This study utilized developmental research and developed solar-powered IoT and Machine Learning that will predict the harvest readiness of oyster mushroom. There are 60 sample plants utilized in this study to evaluate the performance of a model along accuracy, precision, recall/sensitivity and F1 score using Confusion Matrix and determine its reliability by measuring its consistency to the assessment of mushroom farmer in harvest readiness of oyster mushroom. The collected data were analyzed using SPSS version 27 utilizing Cohen's Kappa as statistical treatment.

RESULTS AND DISCUSSIONS

In this section presented was the result of how solar-powered IoT and machine learning was utilized for environmental monitoring and harvest readiness prediction. The study intends to collect real-time data using the sensors from the growing environment and by using historical data the machine learning models can accurately predict when mushrooms are ready to be harvested. The following results shows how effective this method can be for farmers.

Solar-Powered IoT and Machine Learning for Predicting Harvest Readiness of Oyster Mushrooms

The result of this study proves that the use of solar-powered IoT and machine learning is effective to determine when oyster mushrooms should be harvested. The collection of data on environmental factors such as; temperature, humidity, air quality and light intensity are through sensors. Using historical data, a model is trained to know when is the right time to harvest. This project uses solar energy to lower power usage and cut on operational costs [6]. Prior research, such as that by [18] suggests that integrating IoT technology can significantly improve cultivation efficiency compared to traditional methods.

The integration of machine learning algorithms has improved the accuracy of the predictions compared to traditional methods, which often depend on manual inspection and can lead to errors. This advancement helps farmers reduce labor costs and reduce the time needed to determine when to harvest. Also, accurate predictions help keep the mushrooms in good condition, as harvesting at the right time ensures they have the best size, weight, and nutrition. Combining AI, ML and IoT holds significant potential in transforming agriculture through automation. Traditional methods will be replaced with precise cultivation techniques thereby enhancing crop yield to meet to meet the demands of a growing population [17]. Figure 3 shows the sample predictions of the mushroom stage classification model.

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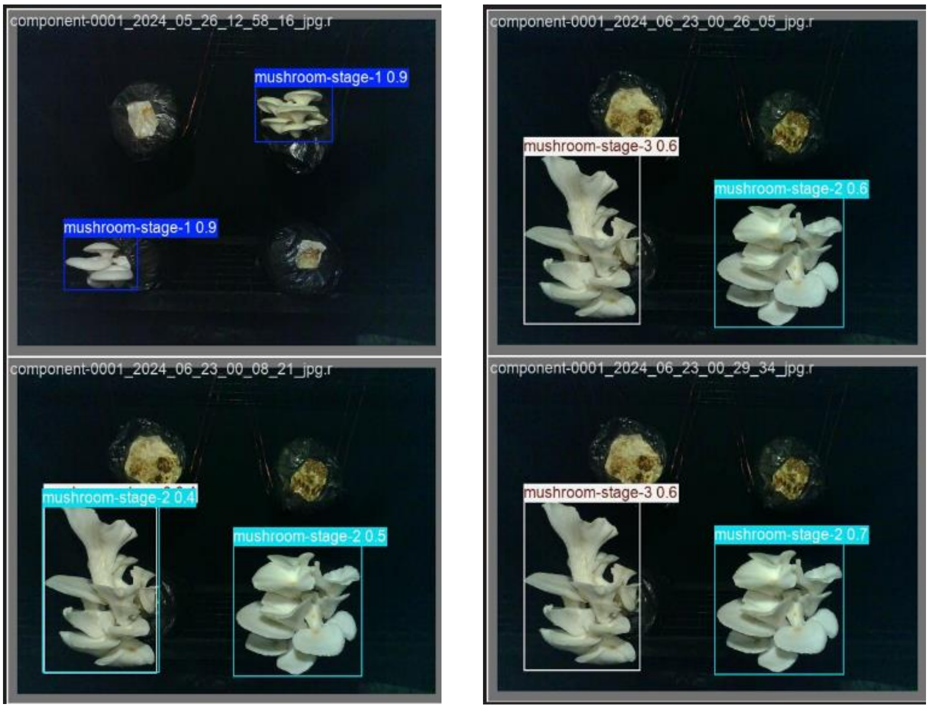

Figure 3. Model's ability to accurately identify and classify different stages of mushroom growth

Overall, the results of this study suggest a proper solution of growing oyster mushrooms, giving helpful insights to farmers who want to improve their harvests and meet market demand. Future work will focus on refining the model and exploring its use in different growing conditions.

Performance of the model along Accuracy, Precision, Recall/Sensitivity and F1 score using Confusion Matrix

This part tackled the performance of a model along accuracy, precision, recall/sensitivity and F1 score using Confusion Matrix. This area also shows where the model gets confused and the calculation of the accuracy of a classifier. Probabilistic approach to confusion matrices enhances evaluation key performance metrics such as accuracy, precision, recall, and F1 score. The method provides a clearer understanding of how the model works and how accurate its predictions are [19].

Table 1. Confusion Matrix of the Model

		Expected	
		Ready	**Not Ready**
Predicted	Ready	(TP) 37 (61%)	(FP) 1(2%)
	Not Ready	(FN) 8(13%)	(TN) 14(23%)

Table 1 shows the Confusion Matrix of the classified model. Data revealed that out of 60 sample plants, the machine detected 37(61%) true positive, 14 (23%) true negative, 8(13%) false negative and 1(2%) false positive. To further analyze the data, model performance is examined along accuracy, precision, recall/sensitivity and F1 score and the results are shown on the following table. Confusion matrices can be used to obtain performance metrics such as precision and recall that emphasizes the need for comprehensive evaluations beyond simple accuracy measures [20].

Table 2. Performance of the model along Accuracy, Precision, Recall/Sensitivity and F1 Score

Area for Model Performance	Computed Value
Accuracy	85%
Precision	97%

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Recall/Sensitivity	82%
F1 score	89%

Table 2 displays the performance of a model along accuracy, precision, recall/sensitivity and F1 score. As shown in the table, the 85% accuracy of the model provides a general overview of how often the classifier is correct. The precision of 97% indicates that the prediction of the model for the oyster mushroom to become ready for harvesting while it is not, is very low. Further, the 82% value for recall/sensitivity indicates that the prediction of the model for the oyster mushroom to become not ready for harvesting while it is ready, is very low. Lastly, the harmonic mean of precision and recall other known as F1 score resulted to 89% shows a balance between the precision and recall of the model. Precision, recall, and F1 score metrics was utilized in the study of [21] that further illustrates the capability of the algorithms in minimizing prediction errors.

Reliability of the Model

Table 3 shows the reliability of the model by measuring its consistency to the assessment of mushroom farmer in harvest readiness of oyster mushroom. Collected data were analyzed using SPSS version 27 utilizing Cohen's Kappa as statistical treatment.

Table 3. Reliability of the model using Cohen's Kappa

Cohen's Kappa (κ)	p-value	95% Confidence Interval	
		Upper	Lower
0.654	0.000	0.789	0.605

Legend:

Cohen's Kappa (k)	*Interpretation*
k < 0.20	Slight
0.21 ≥ k ≤ 0.40	Fair
0.41 ≥ k ≤ 0.60	Moderate
0.61 ≥ k ≤ 0.80	Substantial
k >0.80	Almost Perfect

Cohen's Kappa was run to determine if there was agreement between assessment of the machine and oyster mushroom farmer in term of harvest readiness of oyster mushroom. Data revealed that there was a substantial agreement between the two revealing a Cohen's Kappa and p-value of 0.654 0.000 respectively. These findings suggest that the reliability of the model is significantly higher from 0. In the study conducted by [22] showcases that Cohen's Kappa is effective when applied in agricultural technology research mostly in assessing the reliability of automated system against human expertise

CONCLUSION

This study concludes by proving the effectiveness of smart agriculture, the integration of solar-powered IoT technologies and machine learning models in enhancing oyster mushroom farming. The system increases the reliability of harvest timing by using Convolutional Neural Networks (CNNs) to predict growth stages and continuously observe the key environmental variables like temperature, humidity, air quality, and light intensity. Solar power energy assures sustainability, and automation guarantees better harvests and lowers operating costs [6]. The model's credibility as a predictor of harvest readiness is shown by its 85% accuracy, 97% precision, and 82% recall, as well as its impressive alignment with farmer feedback. This suggests that the model is effective in determining when the crops are ready to be harvested at the same time enhances the efficiency of mushroom cultivation [12]. For future works, improving the model's effectiveness by utilizing larger datasets and more advanced algorithms could result in even better predictions.

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