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Humidity Control for Gallus Gallus Domesticus and Sus Scrofa Meat Freshness Using Off-Grid Solar-Powered System

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Assessing the application of off-grid solar systems for meat preservation, this research examines their effects on *Gallus gallus domesticus* (chicken) and *Sus scrofa* (pork). Off-grid solar systems offer an alternative power source to conventional generators, helping to reduce high operating costs, CO_2 emissions, and fuel consumption. Maintaining optimal humidity is crucial for both meat quality and the effective operation of processing equipment. An off-grid solar system, including a battery and charge controller, was used to power a cooling system, regulate humidity, and manage CO_2 levels within safe ppm ranges. System performance was evaluated by monitoring CO_2 levels at 5-min intervals over 30 meat trials. Findings revealed that reducing humidity significantly lowered CO_2 levels for *Gallus gallus domesticus* (chicken) meat, with R^2 values of 0.83 when the cooling system was off and 0.91 when it was on. The relationship was weak for *Sus scrofa* (pork) meat, with R^2 values of 0.01 without the cooling system and 0.18 with it on. Exploring additional predictors or refining the Sus scrofa (pork) meat model may help reduce unexplained variance and enhance predictive accuracy. These results highlight the potential of off-grid solar systems to provide sustainable and cost-effective food storage solutions, especially in remote or underserved areas with limited traditional infrastructure.

1. Introduction

The Philippines is known as a tropical country because it lies near the equator. The country's average sunlight hour every year is 2,105 h. It has a great deal of solar energy potential. The average solar radiation ranges from 128 - 203 W/m^2, equivalent to around 4.5 - 5.5 kWh/m^2/d. Absorbing sun radiation throughout the year, the country has a significant potential for solar energy utilization. Solar energy replaces conventional electricity (Essam et al., 2022) in the drying process (Sanmartin et al., 2017), which is energy efficient and helps reduce environmental issues.

Concerns over the depletion of natural resources have heightened internationally in recent decades. Fossil fuel resources and the negative environmental, social, and economic consequences of their excessive use have motivated researchers to conduct in-depth investigations on renewable energy resources as potential alternatives. Solar energy, among these renewable energy sources, has the potential to supply a considerable portion of the world's energy needs for various reasons. It is pure, inexhaustible, and universally accessible (Chaibi et al., 2019).

In the past 50 y, meat consumption has doubled, and consumer demand continues climbing. Fresh meats, especially beef, play a crucial role in the food supply chain (Eom et al., 2014). To continue to provide consumers with fresh and high-quality products (Fletcher et al., 2018) while avoiding waste (Gull et al., 2021), meat processing plants must ensure high microbiological safety of commodities and processes quickly and efficiently (Santovito et al., 2021). Meat safety and quality, influenced by contaminating and autochthonous microflora, are critical for the meat industry because of the implications for public health and welfare (Yousefi et al., 2019).

Consumers want meat that is safe to eat, nutritious, and has a long shelf life. Concerns about microbial safety and quality among consumers and producers have led to the development of several analytical techniques (Biswas and Mandal, 2019).

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During manufacturing processes, microbial contamination of materials and food items is possible (PK, 2019). Changes in food's physical and chemical qualities result from technical processes (Perez de Vargas-Sansalvador et al., 2020). As a result of these changes, certain generic and specific microbial populations become prevalent in the product (Ma et al., 2018). The ability to evaluate the impacts of manufacturing (Escobedo et al., 2020), distribution, and storage systems on the microbiological safety and quality of food requires the identification of a microbe and knowledge of its growth response to environmental variables (Weston et al., 2021).

Controlling CO_2 inside food containers is crucial. According to Puligundla et al. (2012), it is essential to develop CO_2 sensors that can effectively monitor changes in gas concentration within food packaging, specially tailored for food packaging applications (Dodero et al., 2021). This need arises from contemporary society's requirement for innovative packaging solutions that offer enhanced functionality. Consequently, there is considerable research into CO_2 sensors that can be seamlessly integrated into food packaging to serve as freshness indicators and ensure the maintenance of food quality (Muller and Schmid, 2019).

Proper CO_2 levels are critical for preserving meat freshness and quality. Too much CO_2 can lead to meat spoilage, while too little can affect shelf life. A solar-based off-grid storage system can power ventilation to maintain ideal CO_2 concentrations, ensuring meat remains fresh for extended periods. Solar-based systems are renewable and sustainable, reducing reliance on fossil fuels and minimizing carbon emissions; this aligns with environmental goals while providing continuous energy to control CO_2 levels in storage facilities.

This study employs a self-powered solar power management system to monitor the real-time freshness of meat using temperature, humidity, and carbon dioxide sensors. Elevated levels of CO_2 in meat can accelerate microbial growth and spoilage. The researchers opted for an off-grid solar storage system to control humidity levels, directly impacting meat moisture content. High humidity increases meat moisture, promoting rapid bacterial growth, whereas low humidity reduces moisture, helping to preserve meat quality.

2. Methodology

A container powered by an off-grid solar system is designed to adjust to the right amount of humidity based on the conceptual design that has been determined. Once there is an amount of CO_2 in the container that is not acceptable for the meat to eat, this will give feedback to the system to start adjusting the humidity and temperature. The power circuit system comprises a photovoltaic (PV) solar panel and battery. A photovoltaic cell inside the solar panel converts sunlight into an electrical current. The effectiveness of a solar panel is determined by the size and quality of the solar cell, as well as the transparency of the protective cover. The red arrows in the figure represent how power flows on the entire system, while the blue arrows represent the data.

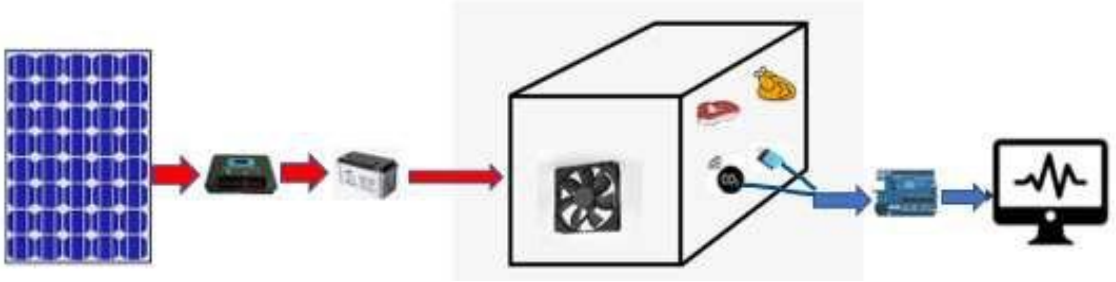

Figure 1 System Overview

Literature reports the optimal value of relative humidity for the meat is RH 70 % with a considerable range around it. The cooling system will only run if the sensor detects that the relative humidity (RH) is below and above 70 %. The cooling system will stop once the RH reaches 70 % inside the container. CO_2, temperature, and humidity are vital to this study. These sensors are connected to the microcontroller, as seen in Figure 1.

The system has MG-811, which is highly sensitive to CO_2 and less sensitive to low humidity and temperature dependency. The cooling system will be activated once it detects the amount of unsafe ppm to eat. The sensor is appropriate for the application system as it operates with low voltage and high detection zone of CO_2 from 0 ppm to 10×10^3 ppm.

The cooling system of the project is a DC fan that is 40 x 40 x 2.6 mm in size. The cooling system has Peltier, an effect-based thermoelectric cooling technique that is advantageous because it may cool an object without requiring any moving parts or other intricate machinery that separates the cooler from its surrounding environment. The equipment designed to benefit from this phenomenon is called Peltier elements, or thermo-electric coolers (TECs). By connecting them in series, simple Peltier elements can be built into more complex Peltier modules (also known as practical TECs) with more powerful cooling capabilities.

The DHT11 (Digital Humidity and Temperature) sensor module detects temperature and humidity in its surroundings, providing a calibrated digital output signal. Known for its compact size, low power consumption (3 V-5 V operating range), and capability for signal transmission up to 20 m, it is widely preferred for diverse applications. It features a temperature range of 0 °C to 50 °C and a humidity range of 20 % to 90 %, with an accuracy of ±1 °C for temperature and ±1 % for humidity.

2.1 Monitoring System

At the start of the experimentation, the initial parameters are examined. Next, the voltage is measured using the voltage sensor connected to an Arduino microcontroller. The Arduino board features four digital input channels, four digital output channels, six analog input channels, a 16 MHz quartz crystal oscillator, a Universal Serial Bus (USB) port, a power jack, an In-Circuit Serial Programming (ICSP) connector, and a reset button. The Arduino is utilized to transfer the sensor data to the computer.

2.2 Test Accuracy of the Temperature Sensor

This test was done to ensure the temperature sensor's accuracy in the experimental setup. The data gathered by the temperature sensor, DHT11 Sensor, was compared with a hand-held digital infrared thermometer. Both sensors were used simultaneously to test their accuracy. Keeping foods chilled at proper humidity is one of the best ways to prevent or slow the growth of bacteria.

2.3 Test Accuracy of the Humidity Sensor

To ensure the accuracy of the humidity sensor, the DHT11 sensor was compared with a digital hygrometer. Both sensors were used simultaneously to test their accuracy.

2.4 Test Accuracy of the Carbon Dioxide Sensor

The MG-811 sensor was compared with a digital CO_2 sensor and used simultaneously to test its accuracy. According to Lambert et al., the allowable amount of ppm that will change the quality of the meat and the growth of organisms in the presence of CO_2 levels can be seen in Table 1.

Table 1. Allowable ppm for pork and chicken meat freshness

Spoilage Organism	Parts Per Million (ppm)	Status
None	<600	No spoilage Organism Found
Brocothrix Ternosphacta	600	Harmful
Lactobacllus Viridiscens	1100	Harmful
Lactobacillus 173	1200	Harmful
Eschherichia Coli	2700	Harmful

2.5 Sizing of the Solar Panel and Battery

The solar panel and battery sizing are computed based on the required loads for the entire system. The solar panel has a size of 1.2 m × 0.54 m × 0.03 m and a 12.4 V battery as a power supply. The load includes a DC fan, thermoelectric cooler (Peltier), sensors, and the Arduino Uno. When solar energy stops producing solar power, the DC supply will begin to generate automatically.

The solar panel size needed to charge the battery was computed as follows: the total energy consumption is calculated based on the Power requirement (W) and the Operating hours (h) shown in Eq(1). At the same time, Days of Autonomy (Wh) or battery backup days were calculated as shown in Eq(2). Battery capacity (Ah) was computed using the formula Total Energy Consumption (Wh) divided by the Battery Voltage (V) as shown in Eq(3). The Solar Panel Size needed is calculated based on the energy produced by the panel during peak sun hours which is 4.5 h. The Energy required from the solar panel can be computed as Total Energy Consumption divided by Peak Sun Hours, as shown in Eq(4).

$$\text{Total Energy Consumption} = 60\ \text{W} * 8\ \text{h} = 480\ \text{Wh} \tag{1}$$

$$\text{Day(s) of Autonomy} = 1\ \text{d}\ ;\ 480\ \text{Wh} * 1\ \text{d} = 480\ \text{Wh} \tag{2}$$

$$\text{Battery Capacity} = 480\ \text{Wh}/12\ \text{V} = 40\ \text{Ah} \tag{3}$$

$$\text{Solar Panel Size} = 480\ \text{Wh}/4.5\ \text{Ah} = 106.67\ \text{W} \approx 120\ \text{W} \tag{4}$$

3. Results and Discussion

3.1 Experimentation Setup

The solar panel, battery, and cooling system are connected to a solar charge controller. Once the battery is fully charged, it will automatically cut the solar panel connection to avoid overcharging. Then, once the condition of the program is met, the cooling system will run. The storage box measures 0.38 m × 0.28 m × 0.15 m, and two sensors are 0.0254 m apart and 0.18 m – 0.20 m away from the cooling system. The DC fan with a Peltier measures 0.04 m × 0.04 m × 0.01 m.

3.2 Testing the Accuracy of Temperature Sensor

The DHT11 Sensor and the Digital Infrared Thermometer temperature readings were compared across 30 trials conducted inside a storage box. The DHT11 Sensor recorded an average temperature of 28.32 °C, while the Digital Infrared Thermometer recorded 28.26 °C. The percentage difference between the two devices was approximately 0.21 %, indicating highly consistent measurements. A two-tailed t-test produced a p-value of 0.03, below the critical value of 2.00, confirming no significant difference between the temperature measurements from the two devices.

3.3 Testing the Accuracy of Humidity Sensor

The DHT11 Sensor and Hygrometer were compared over 30 trials inside a storage box to assess their measurement accuracy. The average CO_2 readings were 386.77 ppm for the MG-811 Sensor and 385.67 ppm for the Digital CO_2 Sensor. The minimal percentage difference highlights the reliability and consistency of both sensors for CO_2 measurements, demonstrating their suitability for accurate environmental monitoring. A computed p-value of 0.71, below the critical value of 2.00, confirms no significant difference between the measurements taken by the DHT11 Sensor and the Digital Hygrometer for humidity.

3.4 Testing the Accuracy of the CO_2 Sensor

The MG-811 CO_2 Sensor was compared with a Digital CO_2 Sensor. The average CO_2 readings were 386.77 ppm for the MG-811 Sensor and 385.67 ppm for the Digital CO_2 Sensor. The negligible percentage difference between these readings highlights the reliability and consistency of both sensors for measuring CO_2 levels, making them well-suited for precise environmental monitoring. A two-tailed t-test yielded a p-value of 0.20, below the critical value of 2.00, indicating no significant difference between the measurements from the MG-811 Sensor and the Digital CO_2 Sensor.

3.5 Observation of humidity, temperature, and CO_2 in meat

For the experimentation to be considered accurate, all data was gathered at 5 min intervals, including humidity, temperature, and CO_2 levels. In the initial experiment, *Gallus gallus domesticus* (chicken) and *Sus scrofa* (pork) meat were defrosted and maintained at 28 °C, as measured by the DHT11 sensor before data collection began. The initial temperature of 28 °C serves as a baseline for evaluating subsequent changes in environmental factors. Figure 2 illustrates the results observed when the cooling system was turned off. To analyze the relationship between humidity and CO_2 levels using Python, the slope of the regression line and the Coefficient of Determination (R^2) were examined. As shown in Figure 2a, the slope of 1.91 indicates that for each one-unit increase in humidity, CO_2 levels are expected to rise by approximately 1.91 units. This suggests a positive correlation between humidity and CO_2 levels, with CO_2 increasing as humidity increases. An R^2 value of 0.83 demonstrates a strong fit for the linear regression model, indicating that changes in humidity can explain 83 % of the variability in CO_2 levels. This high R^2 value confirms a robust linear relationship between the two variables. The observed relationship between humidity and carbon dioxide levels highlights moisture's impact on gas production within the storage environment, potentially influencing food preservation conditions. In Figure 2b, the slope of -0.35 suggests that for each one-unit increase in the predictor variable (humidity), the CO_2 level is expected to decrease by approximately 0.35 units. This negative slope indicates an inverse relationship between humidity and CO_2 levels, with CO_2 levels increasing as humidity decreases. The very low R^2 value of 0.01 reveals that the model accounts for only a minimal portion of the variability in CO_2 levels. This indicates that other variables or interactions should be explored to better explain the variability in CO_2 levels (Stock and Watson, 2019).

For the second experiment, *Gallus gallus domesticus* (chicken) and *Sus scrofa* (pork) meat were tested with the cooling system operational, utilizing a Peltier element to lower temperatures. In Figure 3a, the slope of 10.26 indicates that for each one-unit increase in the independent variable (humidity), CO_2 levels are expected to rise by approximately 10.26 units. This positive slope suggests a strong positive relationship between humidity and CO_2 levels. The R^2 value of 0.91 means that about 90.73 % of the variability in CO_2 levels is explained by changes in humidity. This high R^2 value indicates that humidity strongly predicts CO_2 levels, capturing most of the variation in the dependent variable. In Figure 3b, the positive slope of 4.13 indicates a direct relationship between the independent variable and CO_2 levels. The R^2 value of 0.18 suggests that the model does not effectively explain the variability in CO_2 levels. This low R^2 value implies that additional variables or factors may be needed to better account for the variation in CO_2 levels.

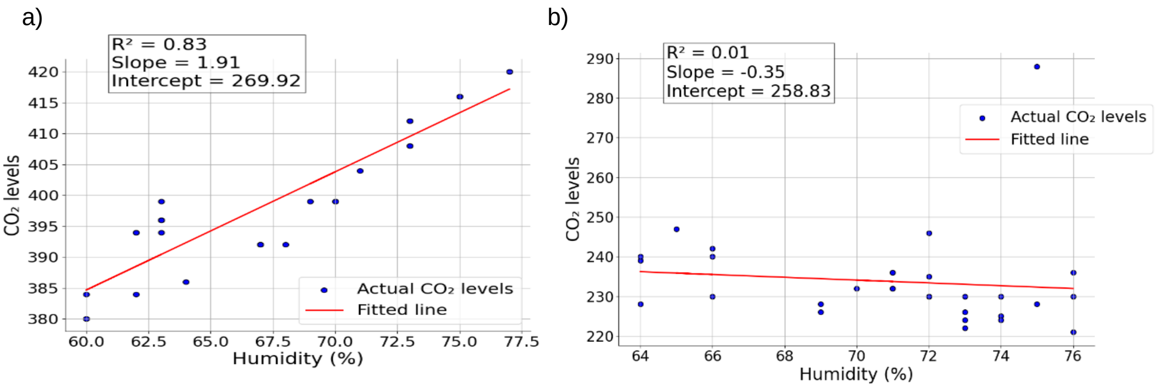

Figure 2: (a) Gallus gallus domesticus (Chicken) meat at 28 °C with the cooling system turned off and (b) Sus scrofa (Pork) Meat at 28 °C with the cooling system turned off

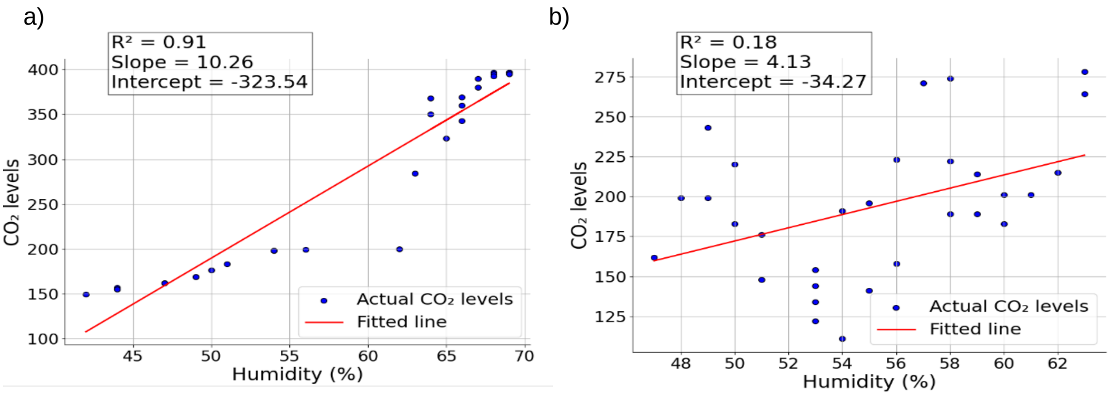

Figure 3: (a) Gallus gallus domesticus (Chicken) meat at 15 °C and at 14 °C with the cooling system turned on and (b) Sus scrofa (Pork) Meat at 15 °C and at 14 °C with the cooling system turned on

3.6 Statistical Analysis

A descriptive analysis of the summary reading for the temperature, relative humidity, and CO_2 of the *Sus scrofa* (pork) and *Gallus gallus domesticus* (chicken) meat was gathered, and the statistics of each of the thirty trials were conducted with the cooling system turned on. It includes information on the measurements, mean, standard deviation, sample variance, median, minimum, maximum, and range. A further statistical component-specifically standard error is examined. Skewness and Kurtosis have also been computed to measure the data's symmetry or asymmetry. The skewness values for the *Gallus gallus domesticus* (chicken) meat's temperature, humidity, and CO_2 levels were -0.58, -0.45, and -0.05. The kurtosis values for these variables were -1.78 for temperature, -1.49 for humidity, and -1.94 for CO_2. The skewness values for *Sus scrofa* (pork) meat's temperature, humidity, and CO_2 were -2.81, 0.01, and 0.20. The corresponding kurtosis values for these variables were 6.31 for temperature, -0.99 for humidity, and -0.43 for CO_2. For the *Sus scrofa* (pork) meat, the data shows that the amount of CO_2 fluctuates. To verify and support the normality of the data, Hair et al. (2018) said that to demonstrate a normal univariate distribution, values for asymmetry (skewness) and Kurtosis between -2 and +2; -7 and +7 are considered acceptable.

4. Conclusion

30 trials were conducted for the *Gallus gallus domesticus* (chicken) meat and 30 trials for the *Sus scrofa* (pork) meat, initially set at 28 °C. Analysis revealed a strong positive correlation between humidity and CO_2 levels in chicken meat, with a regression slope of 1.91 and an R^2 value of 0.83, indicating that 83 % of the variability in

CO_2 levels can be explained by humidity. This suggests that higher humidity significantly increases CO_2 levels in chicken meat. For pork meat, the relationship with humidity was less clear. With the cooling system off, the slope was -0.35 and the R^2 value was 0.01, indicating a minimal impact of humidity on CO_2 levels and suggesting that other factors may be influencing CO_2 variability. Additional factors to consider include other gases such as methane (CH_4), ammonia (NH_3), and sulfur dioxide (SO_2), which can affect meat quality. Also important is the pH level of the meat, as it influences microbial growth and spoilage. When the cooling system was operational, the analysis showed a positive slope of 4.13 for pork meat, but the R^2 value of 0.18 suggested that humidity only partially explains CO_2 variability, with other variables likely contributing to the observed CO_2 levels. Descriptive statistics and skewness/kurtosis analysis revealed relatively normal distributions for chicken meat, while pork meat showed more variability and deviations from normal distribution in CO_2 levels. The meat samples from both types remained safe to eat after 2 h at room temperature, with CO_2 levels well below the spoilage threshold of 600 ppm. These findings emphasize the need for advanced humidity control in meat processing. Future research should focus on innovative sensors and feedback systems for different meats to optimize humidity regulation, extend shelf life, and improve food safety by studying humidity's impact on microbial growth and enzymatic activities.

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