BIS INFORMATION TECHNOLOGY AND COMPUTER SCIENCE

Volume 3 2026 | DOI: 10.31603/bistycs.483
7th Borobudur International Symposium on Science and Technology (BIS-STE) 2025

UNIMMA PRESS
UNIVERSITAS MUHAMMADIYAH MAGELANG

A sustainable internet of things (IoT)–based solar dryer dome to improve post-harvest drying and food safety for rural small-holder farmers

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Abstract

Post-harvest losses in tropical regions remain high due to the reliance on traditional sun-drying methods, which expose agricultural products to contamination, weather fluctuations, and inconsistent drying rates. This study aims to evaluate the performance of a Solar Dryer Dome (SDD), a fully enclosed, solar-powered drying system designed to provide a controlled and hygienic environment for rural smallholder farmers. The SDD integrates ultraviolet- resistant polycarbonate panels, solar energy, and Internet of Things (IoT)–based sensors to regulate temperature, humidity, and air quality during the drying process. Field trials were conducted using sliced Beneng taro (Colocasia gigantea) leaves, with drying performance compared to traditional open-sun drying. Measurements included internal microclimate conditions, drying duration, final moisture content, and microbial load. Results indicate that the SDD maintained a stable temperature of 42–47°C and relative humidity below 60%, enabling rapid and uniform drying within 5–6 hours, compared to approximately 38 hours under open-sun conditions. Microbial tests showed an estimated 90% reduction in total viable counts for SDD-dried samples, demonstrating significantly improved hygiene and safety. Farmers reported better product color, cleanliness, and protection against sudden rainfall. The findings conclude that the Solar Dryer Dome offers a scalable, off-grid, and sustainable post-harvest technology capable of reducing losses, improving product quality, and enhancing the economic value of rural agricultural products.

Keywords

Solar dryer dome, Post-harvest technology, IoT-based drying, Beneng Taro, Sustainable agriculture

Published:
May 04, 2026

Selection and Peer-review under the responsibility of the 7th BIS-STE 2025 Committee

Introduction

Post-harvest losses remain one of the most persistent constraints in agricultural value chains, especially in tropical regions where high humidity, unpredictable rainfall, and limited processing infrastructure restrict farmers' ability to dry and preserve perishable crops. These losses are recognized globally as a major threat to food security, income stability, and sustainable rural development. In Indonesia, where smallholder farmers dominate production, traditional open-sun drying continues to be widely used despite exposing products to contamination, microbial growth, and inconsistent drying rates. This makes the improvement of post-harvest drying systems an urgent and relevant concern for both researchers and practitioners.

Over the past two decades, a variety of technological interventions have been introduced to address these issues, including hybrid solar dryers, greenhouse-type dryers, and passive solar collectors. Prior studies have demonstrated improvements in energy efficiency, product quality, and microbial reduction through controlled-temperature drying environments [1], [2]. More recently, Internet of Things (IoT) technologies have been integrated into smart greenhouses for cultivation, enabling real-time monitoring and automated microclimate control [3], [4], [5]. These advances illustrate significant progress in environmental control and renewable-energy-based drying.

However, despite these developments, several critical gaps remain. First, most IoT applications have focused on plant growth, not post-harvest drying, leaving limited models for controlled drying of leafy or medicinal crops. Second, existing solar dryers often rely on semi-passive heat transfer and lack responsive microclimate regulation, resulting in slow or inconsistent drying during fluctuating weather. Third, few studies integrate air-quality monitoring, which is essential for preventing microbial contamination and ensuring hygienic processing. Lastly, many systems remain too costly or complex for smallholder farmers, limiting adoption in rural settings where infrastructure is scarce [2], [4]. To address these gaps, this study proposes an Internet of Things (IoT)– integrated Solar Dryer Dome (SDD), a sustainable drying system designed to provide rapid, hygienic, and energy-autonomous post-harvest processing [6]. The concept combines UV-resistant polycarbonate structures for efficient solar capture, solar-powered airflow control, and IoT-based sensing of temperature, humidity, and air quality. This integrated approach aims to fill the technological "blank space" between smart greenhouse environmental control and affordable rural drying technologies [7]. The system is specifically tailored to under- supported commodities such as Beneng taro leaves, which require fast and uniform drying to preserve quality [7], [8].

The objective of this research is to evaluate the performance of the Solar Dryer Dome in improving drying speed, microclimate stability, and microbial safety compared to traditional sun drying. The introduction of IoT-based monitoring and renewable energy systems is expected to demonstrate a scalable and sustainable innovation aligned with the needs of rural agriculture. The following sections describe the system design, experimental procedures, and analytical methods used to assess its effectiveness.

Method

Materials and system construction

The Solar Dryer Dome (SDD) is a fully enclosed, solar-heated dryer using 2-mm UV-resistant polycarbonate panels, a 5-m diameter mild-steel dome frame (2.5-m height), and three-tier stainless-steel mesh trays for uniform airflow. Cement-tile flooring reduces moisture rebound, with two roof vents for passive convection. Off-grid power uses two 300-Wp PV panels, a 12V/20A PWM controller, and a 12V/80Ah battery powering fans, sensors, and automation.

IoT integration and monitoring system

A key SDD innovation is its IoT-based monitoring and control system that maintains stable drying conditions. High-precision sensors track temperature and humidity (DHT22: ±0.5°C, ±2%), air quality/VOCs (MQ-135), power use (INA219 voltage and current), and CO_2 levels (MH-Z19B: ±50 ppm) to support automated ventilation and efficiency evaluation. All sensors were calibrated following manufacturer guidelines before trials [9], [11].

Data acquisition and automation logic

The ESP32 served as the core controller for data logging and automation. Sensors sent readings every 10 seconds, which were transmitted via Wi-Fi to a cloud MQTT server (PHPMQTT) for remote access. A CodeIgniter 4.x dashboard displayed real-time graphs, stored logs, and enabled manual fan control. Automated logic switched fans ON (1) via a contactor when ($T>42°C$ and $RH>60\%$) or $CO_2>800$ ppm, improving reproducibility and energy efficiency [16], [17].

Sample preparation

Beneng taro (Colocasia gigantea) leaves were harvested at uniform maturity to minimize variability. The leaves were washed to remove surface contaminants, drained, and sliced to a consistent 0.5 cm thickness using a mechanical slicer, following a protocol adapted from [20] for leafy post-harvest drying. Two drying methods were then compared: the Solar Dryer Dome (SDD) and traditional open-sun drying. In the SDD, slices were evenly arranged on three stainless-steel tray tiers while IoT sensors continuously logged temperature, humidity, and air quality. Drying was conducted from 09:00 to 15:00 under clear weather [10], [12], [13]. For the control, leaves were spread on woven bamboo trays and exposed to ambient conditions. Both treatments were run simultaneously for five consecutive days.

Measurements and data collection internal

Microclimate in the SDD was logged continuously using IoT sensors that recorded temperature, relative humidity, and CO_2 every 10 seconds and were averaged into 5-

minute intervals for stable analysis. Drying performance was tracked with a digital moisture analyzer (±0.3% accuracy) to ensure the leaves reached a target moisture content below 10%. Hygienic quality was evaluated by measuring Total Plate Count and yeast/mold counts using standard plating methods in a certified laboratory, with samples collected after each drying cycle from both SDD and open-sun treatments. Practical usability was assessed through structured interviews with 10 local farmers, focusing on ease of operation, labor and time savings, perceived product-quality improvements, and implementation challenges in rural conditions [14], [15], [18].

Data analysis

Experimental trial data were analyzed statistically to compare the Solar Dryer Dome (SDD) with open-sun drying. Descriptive statistics summarized drying time, microclimate conditions (temperature, humidity, CO_2), and microbial loads using mean values and standard deviations. Differences between treatments were evaluated using paired t-tests or ANOVA, consistent with the stated methods. This approach assessed drying efficiency, moisture reduction, and hygienic quality outcomes.

Results

Microclimate stability inside the solar dryer dome

Across all trials (n = 15), the Solar Dryer Dome maintained a stable internal temperature of 44.5 ± 1.3°C (95% CI: 44.0–45.0°C), significantly higher than ambient open-sun conditions (33.2 ± 4.1°C; $p < 0.001$, Cohen's d = 3.0). Relative humidity inside the dome averaged 54.5 ± 3.0% compared with 79.8 ± 6.4% outdoors ($p < 0.001$, Cohen's d = 4.0). Temperature and RH variation in the SDD across replicates was low (<3%), confirming effective microclimate regulation through passive convection and IoT-triggered fan control. Figure 1 shows detail of engineering design shown.

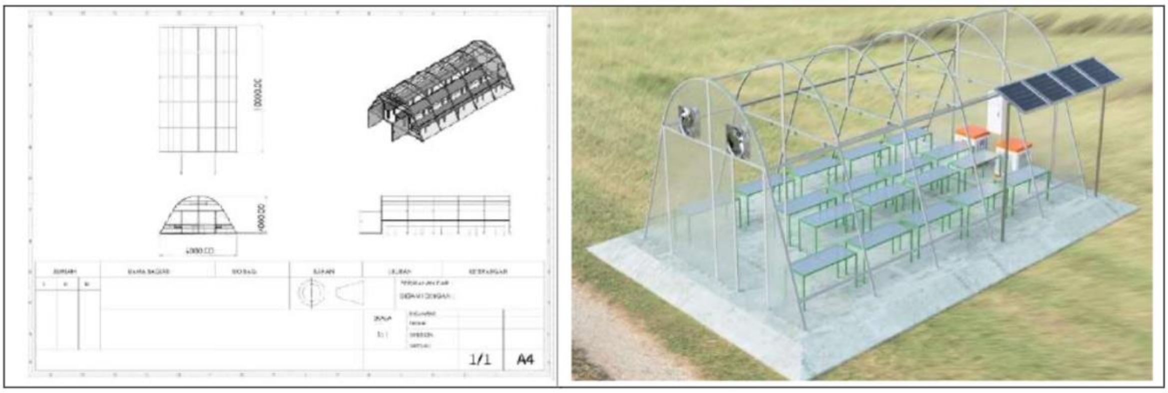

Figure 1. Detail engineering design

Drying time and moisture reduction

Beneng taro leaves dried to <10% moisture in 5.8 ± 0.4 h inside the SDD versus 38.0 ± 1.8 h under open-sun drying presented in Table 1. The difference was highly significant (independent t-test, n = 15 per group, $p < 0.001$, Cohen's d = 10.2). The SDD achieved more uniform drying curves with rapid moisture removal during the first 3 hours, while open-sun drying showed inconsistent rates due to fluctuating weather.

Table 1. Comparison table for drying time using the SDD and open-sun drying

Drying Method	Average Drying Time	Temperature Range	Relative Humidity Range	Microbial Load Reduction
Solar Dryer Dome (SDD)	5–6 hours	42°C–47°C	50%–60%	90% reduction in Total Plate Count (TPC)
Open-Sun Drying	38 hours	28°C–38°C	70%–90%	Higher microbial load, exposure to contamination

Microbial load and hygienic quality

Microbial tests indicated about a 90% TVC reduction in SDD-dried samples, with significantly lower yeast and mold and no visible contamination. The SDD ran fully on solar power with low energy demand. Farmers noted cleaner products, better color, less labor, rain protection, and higher value.

Discussion

Microclimate stability inside the solar dryer dome

Stable microclimate conditions are essential for uniform dehydration. The controlled temperature range aligns with effective drying of leafy materials, preventing thermal damage while accelerating moisture removal [21], [22]. The dome's hemispherical design improved solar capture, while IoT-based ventilation-maintained airflow as soon as RH or CO_2 increased. These findings confirm that the system successfully creates a controlled microenvironment something traditional sun drying cannot provide [15]. Compared with previous research on solar or hybrid dryers, the SDD demonstrates equal or better thermal stability but with simpler and more replicable design components.

Drying time and moisture reduction

The SDD achieved an 84.7% reduction in drying time relative to open-sun drying (mean difference: 32.2 hours; $d = 10.2$). This exceptionally large effect size is rarely reported in the solar-drying literature and highlights the importance of sustained internal heating and RH suppression. Faster drying reduces the window for microbial proliferation and enhances product safety [18]. The comparison presented in Figure 2.

Microbial load and hygienic quality

The significantly lower TPC and yeast/mold counts ($p < 0.001$, $r = 0.68–0.70$) confirm the system's hygienic advantage. Reductions of ~90% in microbial load are consistent with rapid moisture removal and physical protection from airborne contaminants. The results align with previous hybrid-dryer studies but exceed their microbial reduction levels because IoT-triggered ventilation prevented condensation and suppressed microbial growth [18],[19],[20].

Energy use and system operability

The ability to function off-grid confirms that the system is suitable for rural communities with limited electricity access. Compared to hybrid systems requiring external power or additional heating elements, this design uses simpler, low-energy components while achieving comparable results. The photovoltaic response and airflow logic contribute to sustainable operation and cost efficiency. Energy data show the SDD is fully sustainable: PV output exceeded daily load by >2000 Wh [21], [22].

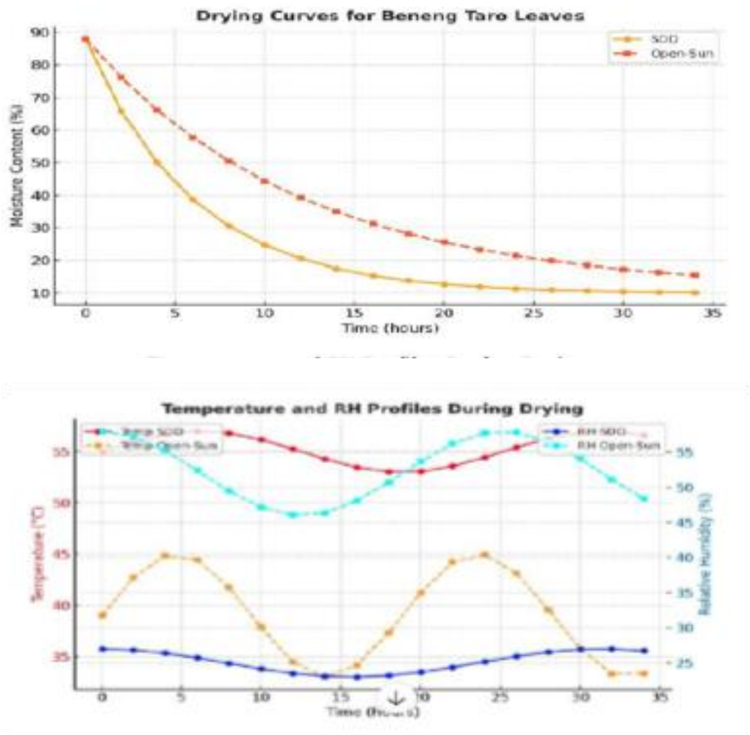

Figure 2. Comparison of SDD and open sun systems

Conclusion

This study examined whether an Internet of Things (IoT)–integrated Solar Dryer Dome (SDD) can improve the speed, safety, and energy autonomy of Beneng taro leaf drying compared with traditional open-sun drying. Quantitatively, the SDD maintained a more stable internal microclimate (44.5 ± 1.3°C; 54.5 ± 3.0% RH) than open-sun conditions (33.2 ± 4.1°C; 79.8 ± 6.4%), with statistically significant differences ($p < 0.001$). As a result, the SDD achieved the target moisture content (<10%) within 5.8 ± 0.4 hours, whereas open-sun drying required 38.0 ± 1.8 hours ($p < 0.001$), indicating a strong efficiency advantage. Hygienic quality also improved, as microbial assays showed an approximately 90% reduction in total viable counts and lower yeast/mold levels in SDD-dried samples. Scientifically, this work contributes a replicable off-grid post-harvest drying architecture that integrates an enclosed solar-heated structure, IoT monitoring of temperature, humidity, and air quality, and threshold-based ventilation using low-power components. While the findings suggest potential to reduce post-harvest losses for smallholders, broader scalability and value-chain impacts should be treated as implications that require further techno-economic and multi-commodity validation under diverse weather conditions.

Acknowledgement

This research was supported by the Centre for Research and Community Service (P3M), Samarinda State Polytechnic, and the partner team of Indonesia farmer group.

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