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Development of a freeze-drying prototype with embedded technology to enhance value and extend the shelf life of asparagus for agricultural communities

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Abstract

This study aims to develop and evaluate a freeze-dryer prototype to enhance the value and extend the shelf life of asparagus for agricultural communities. The research focuses on optimizing drying efficiency, energy consumption, and economic feasibility. The prototype was designed with a PLC-based control system featuring PID temperature regulation and real-time data transmission. The drying process was analyzed in terms of moisture reduction, drying rate, energy consumption, and operational stability. Experiments were conducted to assess performance across different production capacities. The freeze-dryer effectively reduces asparagus moisture content by 91.9 ± 0.3%, achieving a final moisture level of 8.1 ± 0.3%, which complies with dried food standards. The average drying rate is 0.00275 ± 0.00001 kg/hour. The system maintains an ice condenser temperature of -40 °C (±0.4 °C) and drying pressures between 0.90 and 0.95 mbar. Energy consumption analysis indicates that 51.9% of total energy is used during the primary drying stage. Increasing production capacity from 150 to 2000 grams significantly lowers energy consumption per unit, from 4,575 to 390 kWh/kg. Stability tests confirm continuous operation for 50 hours with an average power factor of 0.84 and voltage stability (%CV = 0.23). The developed prototype demonstrates high efficiency, operational stability, and cost-effectiveness. Economic analysis reveals economies of scale, with processing costs decreasing to 1,740 baht/kg at a 2000-gram capacity, though electricity remains a significant cost factor. This freeze-drying technology provides an effective solution for asparagus preservation, offering a viable approach for agricultural communities to enhance product value, reduce post-harvest losses, and improve economic returns.

Keywords: Efficiency, Embedded systems, Freeze-drying, Organic asparagus, Programmable logic controller.

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1. Introduction

In the central region of Thailand, a group of farmers engages in asparagus cultivation for commercial purposes [1-5]. This community, Ban Tha Pluak Sung, located in Tha Din Dam Subdistrict, Chai Badan District, Lopburi Province, Thailand, has adopted organic farming practices emphasizing sustainable agricultural methods (as shown in Figure 1). The primary crop cultivated is organic asparagus, which accounts for 99% of the community's total agricultural exports, covering an area of 55.4 rai. In addition, 5 rai are allocated for other organic vegetables sold in local markets. The average production capacity of fresh asparagus is approximately 1,500 kilograms per week, enabling the farming group to export up to 48,000 kilograms annually, generating a total revenue of 4,320,000 THB per year (at an average price of 90 THB per kilogram) [6].

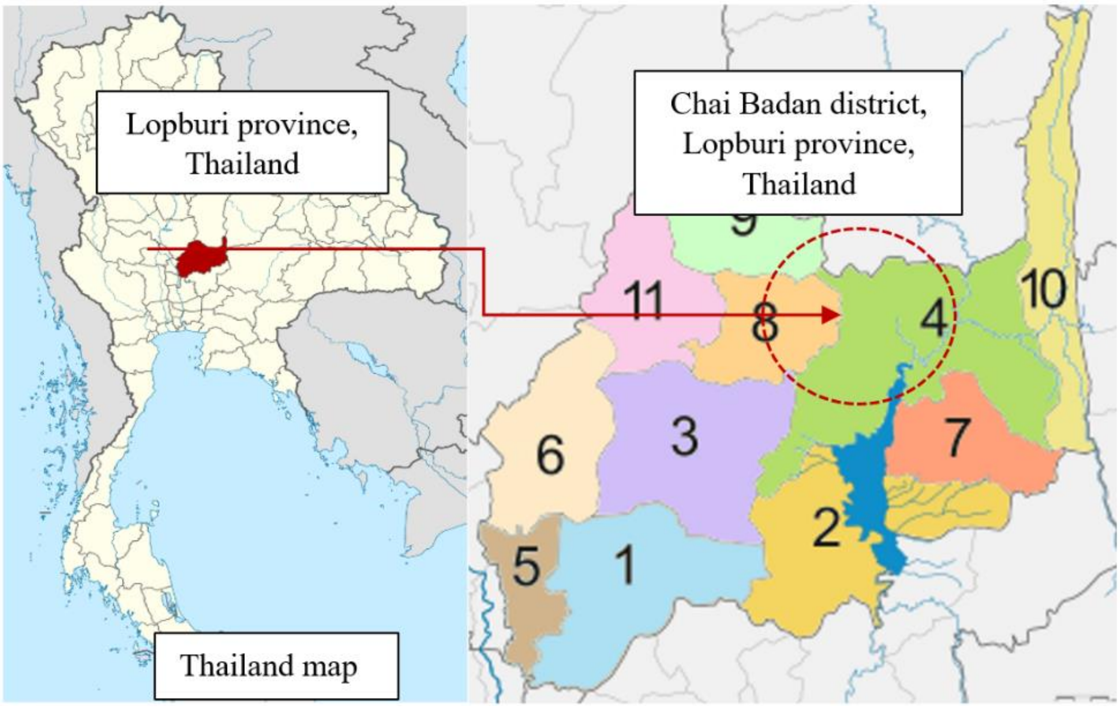


Figure 1.
Chai Badan District, Lopburi Province, Thailand [7].

The primary challenge faced by farmers in producing fresh asparagus lies in its perishable nature, necessitating daily harvesting. Maintaining product freshness requires temperature control during transportation, which significantly increases production and logistics costs. Furthermore, transportation disruptions, such as those caused by the COVID-19 pandemic, border closures, natural disasters, or logistical interruptions, often prevent asparagus from promptly reaching consumers or export markets [8-12]. This results in spoilage, a tarnished product reputation, increased production costs, and reduced income for the community's households. To address these challenges, the farming group seeks solutions to extend the shelf life of asparagus and manage the daily harvest more effectively to prevent market oversupply. Moreover, the group aims to broaden the consumer base by developing value-added products through processing technologies. These innovations would enhance product diversity, maintain nutritional value, and boost the overall economic value of asparagus. Figure 2 illustrates organic asparagus.

Freeze-drying is a widely utilized preservation technique for food, pharmaceuticals, and biological products due to its superior ability to maintain product quality compared to other drying methods. This process involves freezing the material into a solid state, followed by reducing system pressure to sublimate the water content directly in a vacuum environment. Freeze-drying is a commonly used process to reduce the weight of agricultural products while enhancing their stability for long-term storage. This process is highly beneficial for farmers, as it helps preserve the quality and extend the shelf life of agricultural products [13-19].

Figure 2.
Organic asparagus.

Freeze drying occurs in three main phases. The first step is the Freezing Phase: This is the most critical phase. Various methods can be used, including a freezer, a chilled bath (shell freezer), or a shelf in the freeze dryer. The material is cooled below its triple point to ensure sublimation instead of melting, preserving its physical form. Rapid freezing is often necessary to prevent large ice crystals from damaging cell walls in biological materials. The Primary Drying (Sublimation) Phase: In this phase, the pressure is lowered, and heat is applied to the material, causing the water to sublimate. The vacuum helps speed up sublimation, and a cold condenser provides a surface for the water vapor to condense and solidify. Around 95% of the water is removed during this stage, and the Secondary Drying (Adsorption) Phase: This final phase removes ionically bound water molecules. By raising the temperature higher than in the primary drying phase, the bonds between the material and water molecules are broken. The material retains a porous structure after freeze drying is complete. Once the process is finished, the vacuum is broken with an inert gas before sealing the material [20].

The need for this research arises from several challenges in the freeze-drying of asparagus. While freeze-drying effectively extends shelf life, commercially available machines are often expensive and have high energy consumption, leading to increased production costs for businesses. Additionally, most existing machines lack an integrated monitoring system, making it difficult for operators to optimize efficiency and manage product quality effectively. These limitations highlight the need for a more cost-effective, energy-efficient, and intelligent freeze-drying system, which served as the motivation for this study.

This research aims to apply electrical engineering and technology to address the aforementioned issues for the benefit of farmers and their communities. By developing technology that extends the shelf life of asparagus and addresses seasonal overproduction, the project seeks to attract new consumer groups through processed products that retain nutritional value while increasing asparagus's economic value. The research ultimately aims to improve the livelihoods of farmers and community members by reducing production costs and increasing income in alignment with the sufficiency economy philosophy. Thus, the objective of this study is to develop a prototype freeze-drying machine utilizing embedded systems technology. The research will involve designing and constructing a system capable of efficiently controlling the freeze-drying process. The performance of the prototype will be evaluated to ensure its practical applicability and alignment with user requirements.

2. Literature Review

This research focuses on the development of a freeze-drying prototype with embedded technology to enhance value and extend the shelf life of asparagus for agricultural communities. The researcher has searched for related studies, which can be summarized in Table 1.

Table 1.
Summary of relevant research.

References	Short Summary
Osiripun [21]	This study focuses on the development of freeze-dried peeled Long-Kong fruit by optimizing the pre-treatment process with calcium chloride and sucrose immersion to enhance product quality and consumer acceptance. The findings suggest that a 1% calcium chloride solution enhances the surface tension of the fruit, while immersion in a 30 °Brix sucrose solution for 24 hours effectively reduces moisture content. The sensory evaluation confirmed the highest consumer preference for this treatment. The final product meets nutritional and safety standards, with a shelf life of at least 24 weeks in aluminum foil bags and PET cans.
Munder, et al. [22]	The study developed innovative methods to measure sorption and drying data for high oleic sunflower seeds. Using a system of microbalances and a precise laboratory dryer, data on sorption (temperature 25–50°C, water activity 0.10–0.95) and drying (temperature 30–90°C, air humidity 0.010–0.020 kg·kg−1) were collected. A drying model was created and validated with high accuracy (R^2 = 0.99, MAPE = 8.3%), and an analytical solution for predicting diffusion coefficients was also developed (R^2 = 0.976, MAPE = 6.33%). The water vapor pressure deficit approach simplifies the integration of parameters into agro-industrial applications with embedded microcontrollers.
Bhatta, et al. [23]	The review discusses the benefits and challenges of vacuum freeze-drying for biological materials, highlighting its ability to preserve the structure, shape, and nutritional content of products with minimal volume reduction. This technique has been widely used for various biological materials such as meats, dairy, and pharmaceuticals. Despite its high energy consumption compared to conventional drying methods, freeze-drying has gained popularity in the food industry, particularly for plant-based foods. The demand for natural and organic products has led to increased applications of freeze-drying in fruits, vegetables, and beverages. The review covers recent advancements, challenges (such as high sugar or lipid content), and quality considerations for freeze-dried plant-based foods.

3. Methodology

The research objectives are to develop a prototype freeze-drying machine utilizing embedded technology and to test and evaluate the freeze-drying machine for processing asparagus, focusing on agricultural products from a farmer's case study in Ban Tha Pluak Sung Community, Tha Din Dam Subdistrict, Chai Badan District, Lopburi Province. The development of a freeze-drying prototype with embedded technology aims to enhance value and extend the shelf life of asparagus for agricultural communities. This development features a monitoring system that can send data to users in real-time via the cloud system. In addition, the freeze-drying machine is designed to use less energy than the freeze-drying machines currently available in the market.

To achieve the objectives, the research was conducted in four main stages:

- Research design
- Design and construction
- Testing and evaluation process
- The data analysis

3.1. Research Design

This study is experimental research aimed at developing and testing the performance of a freeze-drying machine for processing organic asparagus for a community enterprise. The scope of the research is shown in Table 2.

Table 2.
The scope of the research.

Scope of design and development	Scope of Experimentation
- Design of freeze dryer controlled by a PLC system. - Set production capacity not exceeding 2.5 kg per cycle. - Control temperature in the range of -20°C to 45°C. - Control vacuum pressure in the range of 0.05 to 1.0 mbar.	- Tested with export-grade organic asparagus - Performed five replications per experimental condition - Experimental duration was 48 to 52 hours per cycle - Controlled the environment to remain constant throughout the experiment

3.2. Freeze-Drying Design and Prototype

3.2.1. Freeze-Drying Design

The main components of the developed freeze-drying system consist of: 1. A temperature and pressure measurement system with high-precision sensors, 2. A control and monitoring system via PLC, 3. A vacuum system controlled by an automatic pump and valve, 4. A vapor compression cooling system using a compressor, 5. A stainless steel cylindrical freeze-drying chamber, and 6. An online electricity consumption tracking system via ESP32 and PZEM-004T, as shown in Figure 3.

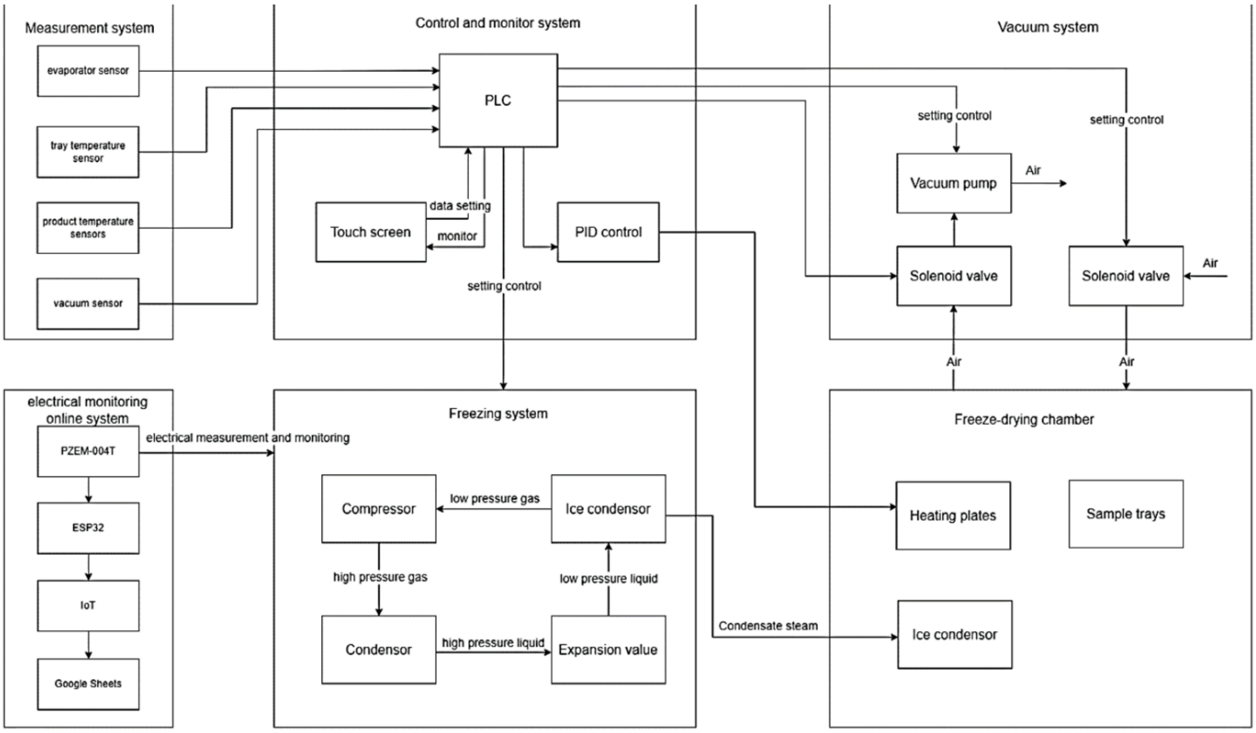
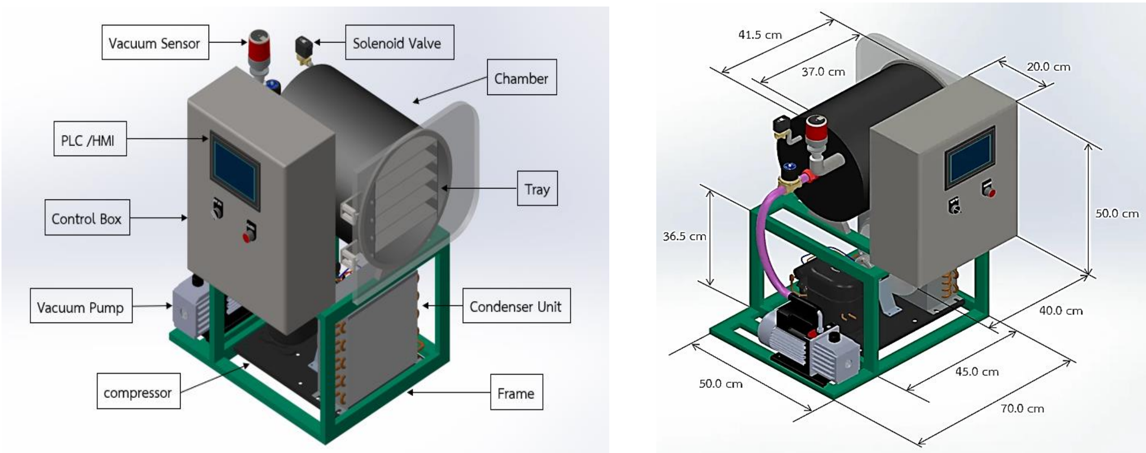


Figure 3.
Freeze-drying system component diagram.

The layout of the main components of the freeze-drying machine includes a vacuum pressure sensor, a vacuum control valve, a freeze-drying chamber, product trays, a Programmable Logic Controller (PLC) with a Human-Machine Interface (HMI) touchscreen, an electrical control box, a vacuum pump, a compressor, a refrigerant condenser unit, and a supporting frame. The design emphasizes an arrangement that facilitates ease of operation and maintenance, as illustrated in Figure 4 (a). Figure 4 (b) shows a 3D model with the overall dimensions of the freeze-drying machine. The machine measures 70.0 cm in width, 50.0 cm in length, and 50.0 cm in height. The cylindrical drying chamber has a diameter of 35.0 cm and a length of 37.0 cm, insulated with a 4.5 cm thick layer. The design prioritizes compactness to ensure ease of mobility and efficient space utilization.



(a) (b)

Figure 4.
(a) Freeze drying system component diagram (b) 3D Model and Dimensions of the Freeze-Drying Machine.

3.2.2. Freeze-Drying Prototype

The mechanical system installation includes the following steps: (a) Fabricating the drying chamber using grade 304 stainless steel and installing fiberglass insulation to prevent thermal loss. (b) Installing the refrigeration system, charging it with R404A refrigerant, and conducting leak tests on the system. (c) Installing the vacuum pump, solenoid valve, and pressure sensor, and integrating them with the automated control system, as shown in Figure 5.

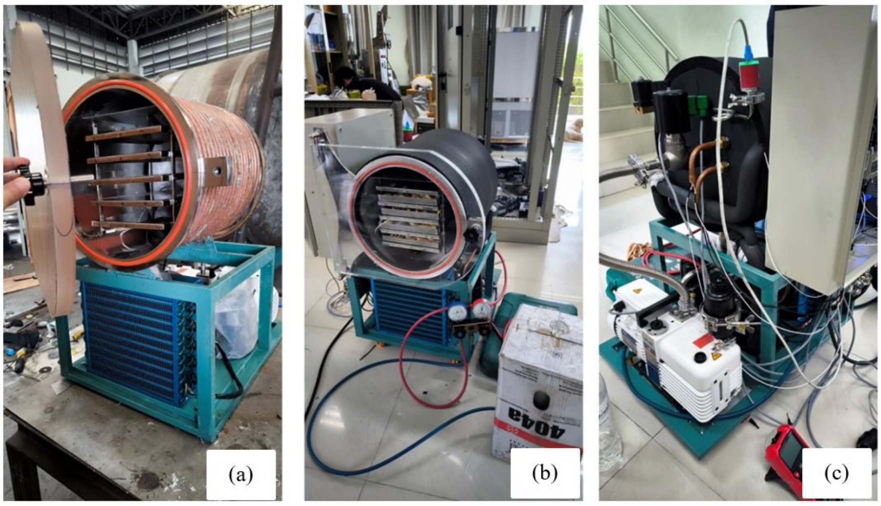


Figure 5.
Mechanical installation of freeze-drying.

The electrical and control system installation includes the following steps: (a) Installing the temperature control system using an electric heater and a Solid State Relay (SSR). (b) Installing a PLC and a touchscreen HMI within a control cabinet equipped with a protection system. (c) Setting up a data logging system using an ESP32 microcontroller and a PZEM-004T power measurement module, with cloud integration via Google Sheets, as illustrated in Figure 6.

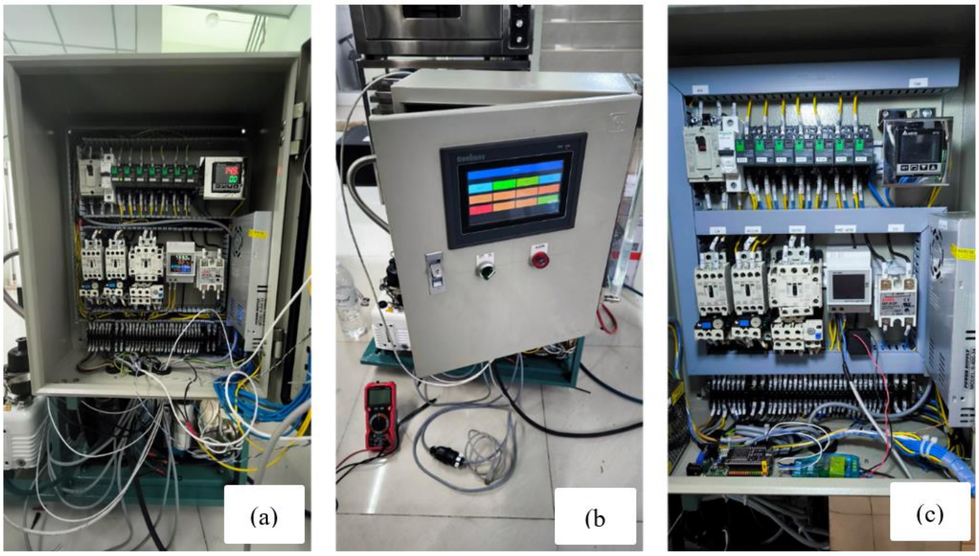


Figure 6.
Electrical and control system installation for freeze-drying.

3.2.3. Machine Operation Procedures

The operation of the developed freeze-drying machine consists of the following: a temperature control system utilizing PID to regulate temperature during each stage of operation, automatic control of the compressor and vacuum pump, and the workflow of the entire system is illustrated in Figure 7, with three main operational stages detailed as follows:

3.2.3.1. Freezing Stage

Temperature is maintained at -20°C for six hours.
The compressor operates continuously to maintain the required temperature.
2. Primary Drying
Temperature is controlled between -25°C and 45°C.
Vacuum pressure is maintained at 0.1 to 1.0 mbar.
Duration: 20 to 25 hours.
The PID system ensures precise heating control.
3. Secondary Drying
Temperature is maintained at 45 °C.
Vacuum pressure is maintained at 0.05–0.1 mbar.
Duration: 27 hours.
The dryness of the product is monitored periodically.

3.2.3.2. Stage Highlights

Freezing Stage: Freezing the water in the cells to form small ice crystals preserves cell structure and reduces product shrinkage.

Primary Drying: Under vacuum pressure below 1.0 mbar, the ice sublimates directly into vapor. Gradual temperature increases prevent ice melting and maintain product structure.

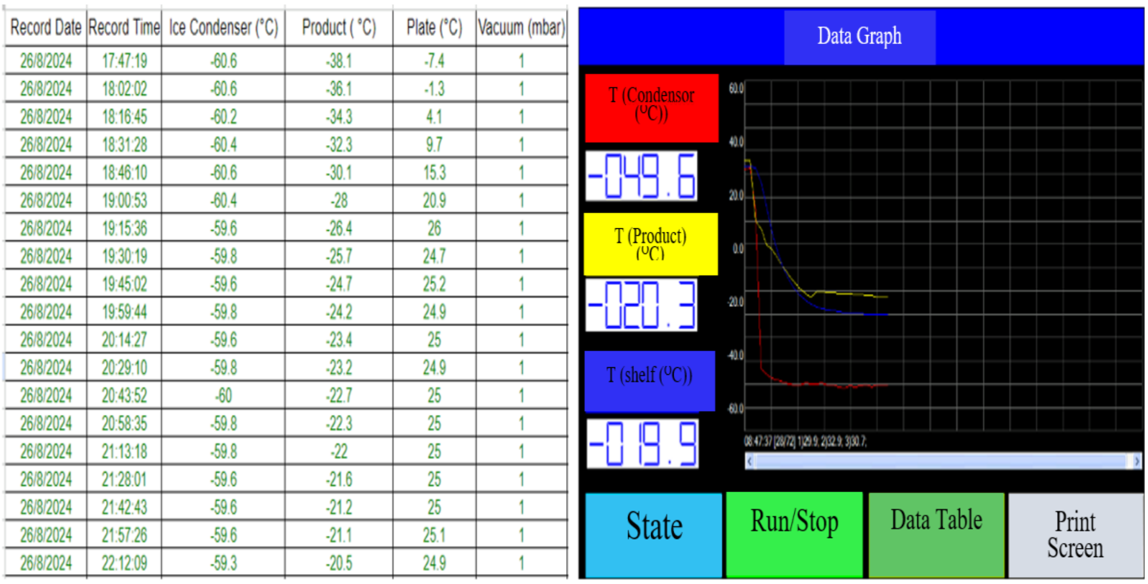
Secondary Drying: The temperature and pressure at this stage remove bound moisture, reducing final moisture content to below 10% according to standards. This process ensures sensitive nutrients remain intact.

The control of all three stages is managed via PID through a PLC system, ensuring stability in temperature and pressure. This contributes to maintaining product quality and optimizing energy efficiency.

Figure 7.
Freeze-drying machine working process flow diagram.

3.2.3.3. Data collection

The data logging system using a Programmable Logic Controller (PLC) includes Real-Time Data Display: Temperature and pressure data are presented in tabular format with numerical values updated in real time. Graphical Representation: The system provides graphs showing changes in temperature and pressure over time. Data Recording Interval: Data is logged every 5 minutes throughout the entire drying process. The data logging system using a PLC displays information via a touchscreen interface, as shown in Figure 8. Figure 9 illustrates the energy monitoring and data logging system, which includes: Connection Setup: Integration between the ESP32 microcontroller and the PZEM-004T energy measurement module. Data Logging: Recording of voltage, current, power, and cumulative energy consumption into Google Sheets. Graphical Visualization: Line graphs for analyzing energy usage trends.



Record Date	Record Time	Ice Condenser (°C)	Product (°C)	Plate (°C)	Vacuum (mbar)
26/8/2024	17:47:19	-60.6	-38.1	-7.4	1
26/8/2024	18:02:02	-60.6	-36.1	-1.3	1
26/8/2024	18:16:45	-60.2	-34.3	4.1	1
26/8/2024	18:31:28	-60.4	-32.3	9.7	1
26/8/2024	18:46:10	-60.6	-30.1	15.3	1
26/8/2024	19:00:53	-60.4	-28	20.9	1
26/8/2024	19:15:36	-59.6	-26.4	26	1
26/8/2024	19:30:19	-59.8	-25.7	24.7	1
26/8/2024	19:45:02	-59.6	-24.7	25.2	1
26/8/2024	19:59:44	-59.8	-24.2	24.9	1
26/8/2024	20:14:27	-59.6	-23.4	25	1
26/8/2024	20:29:10	-59.8	-23.2	24.9	1
26/8/2024	20:43:52	-60	-22.7	25	1
26/8/2024	20:58:35	-59.8	-22.3	25	1
26/8/2024	21:13:18	-59.8	-22	25	1
26/8/2024	21:28:01	-59.6	-21.6	25	1
26/8/2024	21:42:43	-59.6	-21.2	25	1
26/8/2024	21:57:26	-59.6	-21.1	25.1	1
26/8/2024	22:12:09	-59.3	-20.5	24.9	1

Figure 8.
The data-logging system using a PLC displays information through a touchscreen interface.

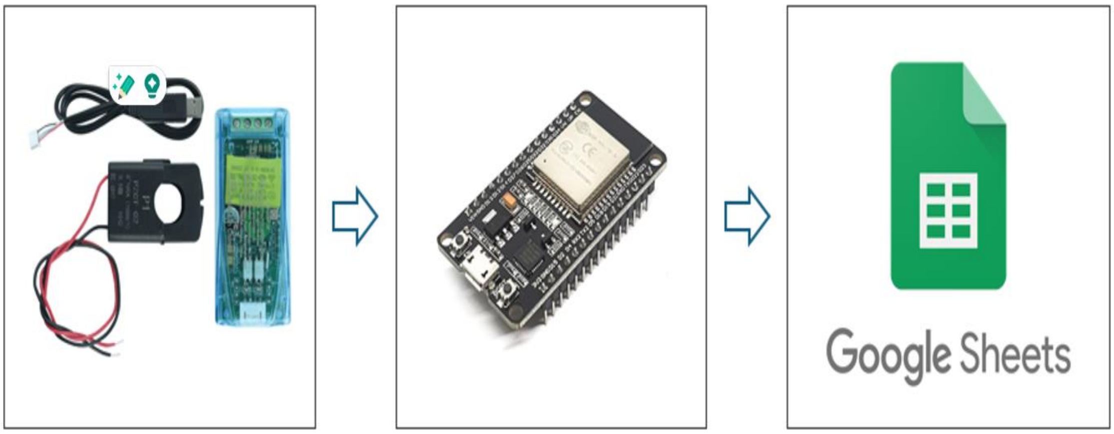


Figure 9.
The data logging system using a PLC displays information through a touchscreen interface.

The operation of the online electrical data recording system consists of three main components: Data Reading from PZEM-004T – This module measures electrical parameters, including voltage, current, power, energy, frequency, and power factor. Wi-Fi Connectivity and Data Processing – The system connects to Wi-Fi for processing and organizing the collected data. Data Transmission to Google Sheets – The processed data is sent to Google Sheets using the HTTP protocol. The system operates continuously, recording data at 5-minute intervals. The workflow diagram of the online electrical data recording system is shown in Figure 10.

Figure 11 illustrates the graph generated by the real-time electrical parameter monitoring and recording system via Google Sheets. The graph displays voltage, current, power, and cumulative energy data, which are recorded every five minutes throughout the drying process.

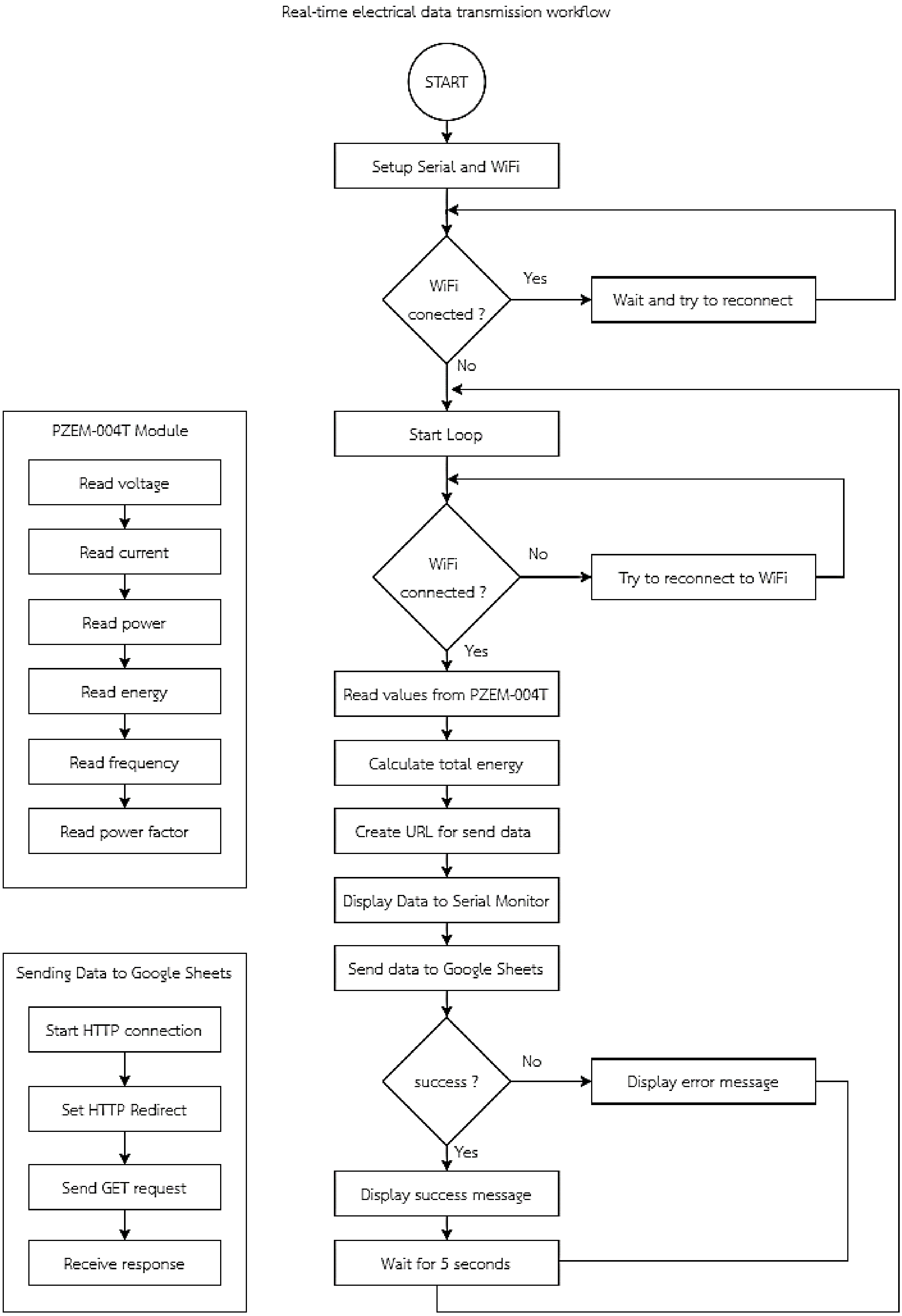


Figure 10.
The workflow diagram of the online electrical data recording system.

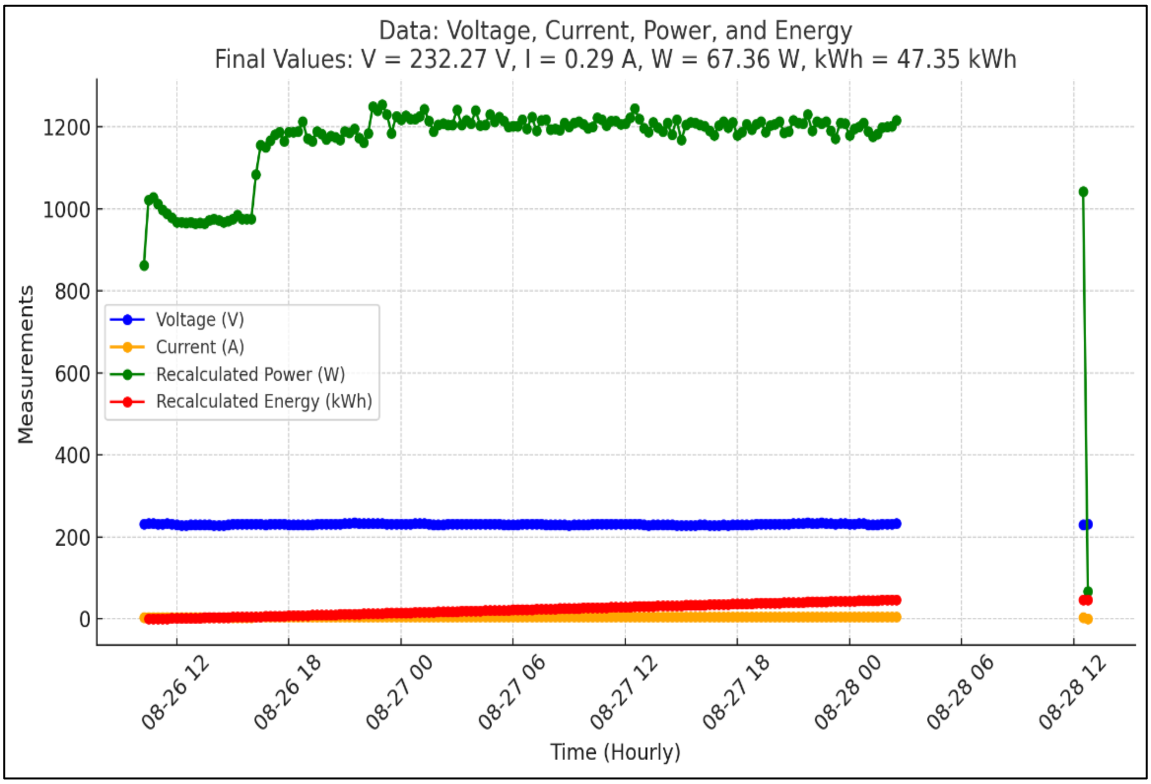


Figure 11.
An example of real-time electrical data recording is displayed through a cloud-based system.

3.3. Testing and Evaluation Process

The preparation steps for asparagus in the experiment include trimming—cutting the asparagus to a length of 20 centimeters; weighing—measuring 150 grams of asparagus per experimental batch; and arranging—placing the asparagus evenly on a tray for drying, ensuring uniform distribution for efficient drying. The experimental process is illustrated in Figure 12.

Figure 12.
The steps for preparing materials for the experiment.

The configuration of the system via the Human-Machine Interface (HMI) includes setting the temperature, pressure, and duration for each operational step, along with a real-time system status display. This is illustrated in Figure 13.

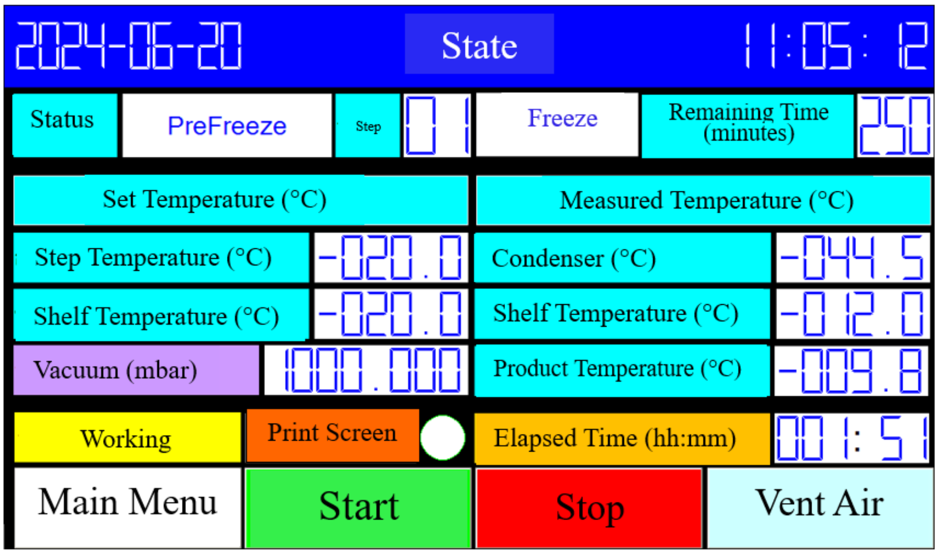


Figure 13.
Operational control parameter settings.

3.4. The Data Analysis

The data analysis in this research is divided into three aspects: Energy Efficiency Analysis – Evaluating the system's energy usage and efficiency; Drying Performance Analysis – Assessing the effectiveness of the drying process; and Control Accuracy Analysis – Measuring the precision of the control mechanisms. Details are provided as follows.

Energy efficiency analysis involves examining the electrical energy consumed during each phase of operation, using the data recorded by the PZEM-004T module, which includes:

- Calculation of electrical energy consumption [24]

  The general equation for calculating electrical energy is:

$$E = P \times t \tag{1}$$

Where: E is the electrical energy consumed (in watt-hours, Wh).
P is Power (in watts, W), which can be obtained from the data recorded by the PZEM-004T
t is the Time the system operates (in hours, h)

This involves evaluating how efficiently electrical energy is used during operation. Energy efficiency can be calculated using the following Equation 2 [25]:

$$\eta = \frac{E}{m} \tag{2}$$

Where: η is Energy efficiency (in kWh per kilogram, kWh/kg)
E is Electrical energy consumed (in kWh)
m is the Mass of the dried product (in kg)

- Drying Performance Analysis

  Moisture Content Reduction Calculation (MC) can be calculated using the following Equation 3 [26]:

$$MC = \frac{m_i - m_f}{m_i} \times 100 \tag{3}$$

Where: MC is Moisture content reduction (%)
m_i is Initial weight (kg)
m_f is Final weight (kg)

Drying Rate Calculation (DR) can be calculated using the following Equation 4 [27]:

$$DR = \frac{m_w}{t} \tag{4}$$

Where: DR is Drying rate (kg/h)
m_w is the Amount of water evaporated (kg)
t is Drying time (hours)

- Control Accuracy Analysis [28]

Temperature Control Analysis

Acceptable maximum deviation: ±2°C

Standard deviation of temperature
Time to reach a stable state
Pressure Control Analysis
Acceptable maximum deviation: ±0.05 mbar
Analysis of vacuum system stability
Evaluation of pressure level maintenance efficiency

These three aspects of analysis will utilize data recorded from the automatic control system and the measurements taken throughout the drying process to assess the overall performance of the developed freeze-drying machine.

4. Result and Discussion

This study aims to evaluate the performance of a developed freeze dryer for processing organic asparagus. A total of eight experiments were conducted, each using 150 grams of fresh asparagus as the raw material and a drying duration of 50 hours per cycle. The research findings are presented in five key sections, prioritized by significance: drying performance, process control, energy consumption analysis, electrical system stability, and economic feasibility analysis.

4.1. Drying Performance

4.1.1. Moisture Reduction

The analysis of moisture reduction efficiency for asparagus processed using the freeze dryer is presented in Table 3. Key parameters considered include initial weight, final weight, and percentage of moisture reduction.

Table 3.
Moisture reduction results of asparagus (n=8).

Parameter	Mean ± SD	Range	%CV
Initial weight (kg)	0.150 ± 0.000	0.150–0.150	0.00
Final weight (kg)	0.012 ± 0.001	0.011–0.013	8.33
Weight reduction (%)	91.9 ± 0.3	91.3–92.0	0.33
Final moisture (%)	8.1 ± 0.3	8.0–8.7	3.70

The results in Table 3 demonstrate that the freeze dryer effectively and consistently reduces the moisture content of asparagus. The process achieved an average weight reduction of 91.9 ± 0.3%, while maintaining the final moisture content at 8.1 ± 0.3%, meeting the standard for dried food products, which specifies a moisture content below 10%. Furthermore, the low coefficient of variation (%CV) indicates the stability and uniformity of the drying process.

4.1.2. Drying Rate

The average drying rate, calculated as the amount of water evaporated per unit of time, was 0.00275 ± 0.00001 kg/h. The variation in the drying rate throughout the process is illustrated in Figure 14.

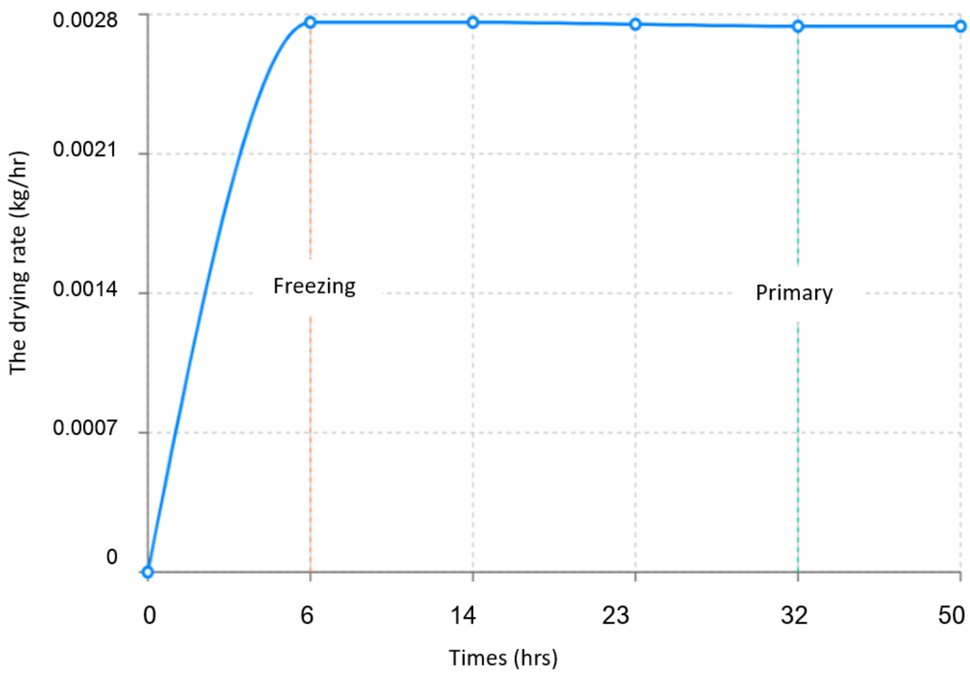


Figure 14.
Graph of Drying Rate versus Time

Figure 14 shows the variation in drying rate over a 50-hour period. The x-axis represents the drying time (hours), while the y-axis represents the drying rate (kg/h). The graph indicates that the drying rate reaches its peak during the initial phase of primary drying, as this stage involves the sublimation of ice from the product at its maximum rate. Subsequently, the drying rate gradually decreases during the secondary drying phase, aligning with the freeze-drying theory, which states that the sublimation of ice is most significant at the beginning and diminishes as the remaining moisture content in the product decreases.

4.2. Process Control

4.2.1. Temperature and Pressure Control

The temperature and pressure control during each stage of the drying process was managed using a PLC system, divided into three main stages: Freezing, Primary Drying, and Secondary Drying. The control parameters and their results are summarized in Table 4.

Table 4.
Temperature and pressure control parameters at each stage (n=8).

Stage	Time (h)	Ice Condenser (°C)	Product (°C)	Pressure (mbar)
Freezing	0–6	-40/-42.5 ± 0.3	-20/-20.1 ± 0.5	Not Active
Primary (Initial)	6–14	-40/-43.5 ± 0.4	-20/-20.0 ± 0.4	0.92 ± 0.05
Primary (Middle)	14–23	-40/-43.2 ± 0.4	25/25.2 ± 0.3	0.90 ± 0.05
Primary (Final)	23–32	-40/-42.8 ± 0.4	45/45.0 ± 0.3	0.92 ± 0.05
Secondary	32–50	-40/-41.2 ± 0.4	45/45.0 ± 0.3	0.95 ± 0.03

The experimental results in Table 4 indicate that the control system accurately maintained the temperature of both the ice condenser and the product, with minimal standard deviation throughout the process. The ice condenser temperature was consistently controlled at approximately -40°C, effectively capturing sublimated water vapor. Meanwhile, the product temperature was adjusted according to each stage of the process, starting at -20°C during the freezing stage and gradually increasing to 45°C during the secondary drying stage.

Additionally, the system demonstrated stable pressure control during the primary and secondary drying stages, maintaining pressure levels within the range of 0.90–0.95 mbar, further highlighting its reliability and effectiveness in ensuring optimal drying conditions.

The variations in temperature and pressure throughout the 50-hour freeze-drying process are illustrated in a graph. The x-axis represents the operation time (hours), the left y-axis represents temperature (°C), and the right y-axis represents pressure (mbar).

- The blue line indicates the temperature of the ice condenser.
- The red line represents the product's temperature.
- The green line indicates the pressure levels.

The graph clearly delineates the three distinct operational stages: Freezing, Primary Drying, and Secondary Drying. The control system demonstrates precise and stable regulation of temperature and pressure throughout the process. The smooth transitions in product temperature during stage changes highlight the efficiency of the PID control implemented in the PLC system.

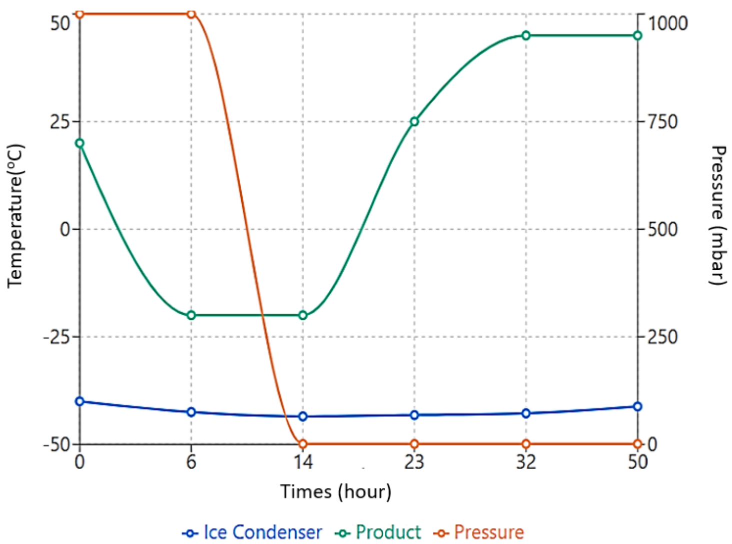


Figure 15.
Temperature and pressure variations during the freeze-drying process.

The Ice Condenser temperature was consistently maintained at approximately -40°C, while the product temperature exhibited a controlled increase from -20°C during the freezing stage to 45°C during the secondary drying stage. The pressure remained within the optimal range of 0.90–0.95 mbar during the drying stages, ensuring effective sublimation and drying efficiency. The temperature and pressure variations during the freeze-drying process are shown in Figure 15.

4.3. Energy Consumption Analysis

4.3.1. Data Logging Using PZEM-004T and ESP32

The energy measurement and logging system utilized the PZEM-004T module in conjunction with the ESP32 microcontroller to collect real-time electrical parameters. The recorded data is summarized in Table 5.

Table 5.
Electrical parameter measurements at each stage of operation (n=8)

Stage	Voltage (V)	Current (A)	Power (W)	Power Factor (PF)
Freezing	230.08 ± 0.56	4.84 ± 0.19	1117.39 ± 17.50	0.85 ± 0.02
Primary	229.78 ± 0.46	5.04 ± 0.23	1165.59 ± 19.61	0.84 ± 0.04
Secondary	229.85 ± 0.58	5.04 ± 0.23	1122.38 ± 19.71	0.84 ± 0.03

From Table 5, it can be observed that the system demonstrates high electrical stability, with the voltage remaining constant between 229.78 and 230.08 V throughout the operation. The highest current was recorded during the primary drying stage (5.04 A), which corresponds to the increased energy usage during this phase for the sublimation of ice from the product. The power factor values (0.84 to 0.85) indicate good energy efficiency, reflecting the system's optimal use of electrical power.

The comparison of electrical parameter values throughout the process, with the horizontal axis representing time (hours), the left vertical axis representing voltage (V) and current (A), and the right vertical axis representing the power factor. From the graph, it can be seen that the relationship between current and power increases during the primary drying period, while voltage and power factor remain stable throughout the process. The graph showing the comparison of electrical parameter values during each working period is shown in Figure 16.

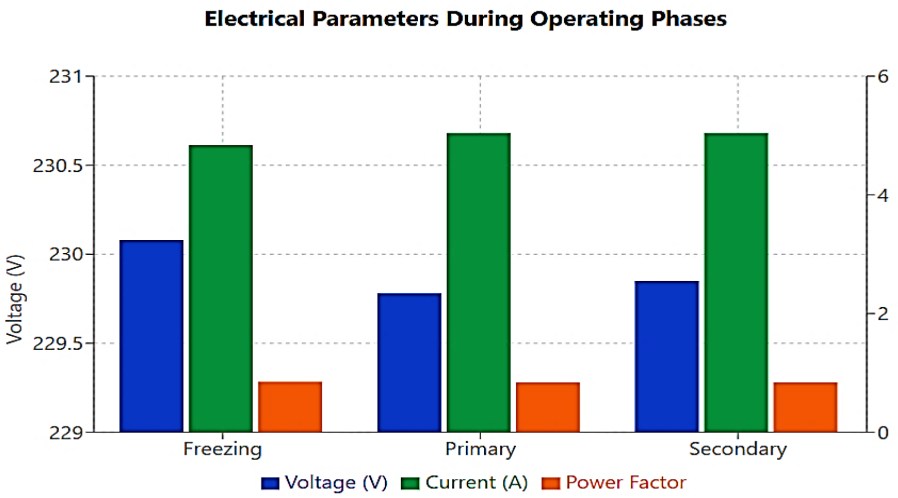


Figure 16.
Comparison of electrical parameters throughout the freeze-drying process.

4.3.2. Energy Consumption in Each Stage

The analysis of energy consumption in each stage of the freeze-drying process is presented below.

Table 6.
Energy consumption in each stage of the drying process (n=8).

Stage	Time (hrs)	Power (W) ± SD	Energy (kWh) ± SD	Proportion (%)
Freezing	6	1,103.3 ± 9.9	12.8 ± 0.3	23.3
Primary Drying	26	1,141.6 ± 18.5	28.5 ± 0.4	51.9
Secondary Drying	18	1,107.4 ± 24.1	13.6 ± 0.2	24.8
Total	50	1,117.4 ± 17.5	54.9 ± 0.6	100.0

From the analysis in Table 6, it is evident that the Primary Drying stage consumed the most energy, accounting for 51.9% of the total energy usage. This is due to the high energy required for the sublimation of ice from the product during this phase. The total energy consumption per production cycle was 54.9 ± 0.6 kWh. The consistency of energy usage is reflected in the low standard deviation values for each stage of the process, indicating stable and efficient energy consumption throughout the drying operation.

Figure 17 presents the proportion of energy consumption in each stage of the drying process in a pie chart. It shows that the primary drying stage consumes the highest amount of energy (51.9%), followed by the secondary drying stage (24.8%) and the freezing stage (23.3%). The high energy consumption in the primary drying stage corresponds to the increased heat energy required for the sublimation of ice from the product.

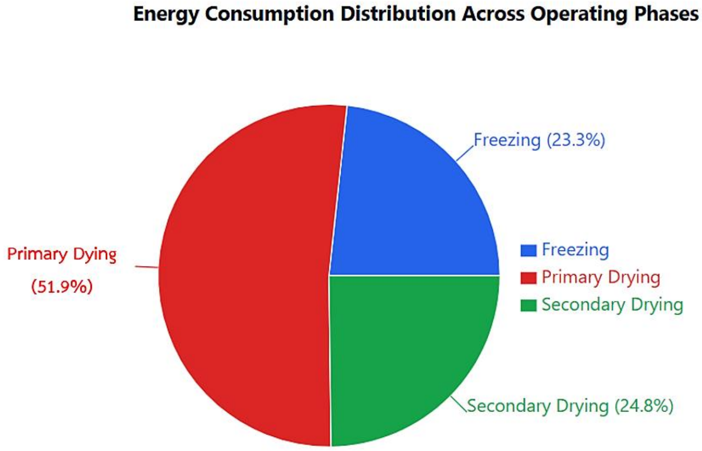


Figure 17.
Energy consumption proportion in each stage of the freeze-drying process.

4.3.3. Energy Efficiency at Different Production Capacities

An analysis of energy efficiency at different production capacities was conducted by experimenting with raw material quantities of 150, 500, 1,000, and 2,000 grams per cycle. The results are shown in Table 7.

Table 7.
Energy efficiency index at different production capacities (n=3).

Raw material quantity (g)	Energy per Cycle (kWh)	Energy per product (kWh/kg)	Electricity cost per kilogram (THB/kg)
150	54.9 ± 0.6	4,575 ± 67	18,300 ± 268
500	56.8 ± 0.7	1,420 ± 35	5,680 ± 140
1000	58.9 ± 0.8	736 ± 28	2,944 ± 112
2000	62.4 ± 0.9	390 ± 22	1,560 ± 88

Note: Calculated at an electricity rate of 4 THB/kWh [29].

From the analysis in Table 7, it is evident that increasing production capacity leads to a significant improvement in energy efficiency. Although energy consumption per cycle increases slightly from 54.9 kWh at 150g to 62.4 kWh at 2000g, the energy used per kilogram of product decreases drastically from 4,575 kWh/kg to just 390 kWh/kg when production capacity is increased to 2000g per cycle. This demonstrates a clear economy of scale effect.

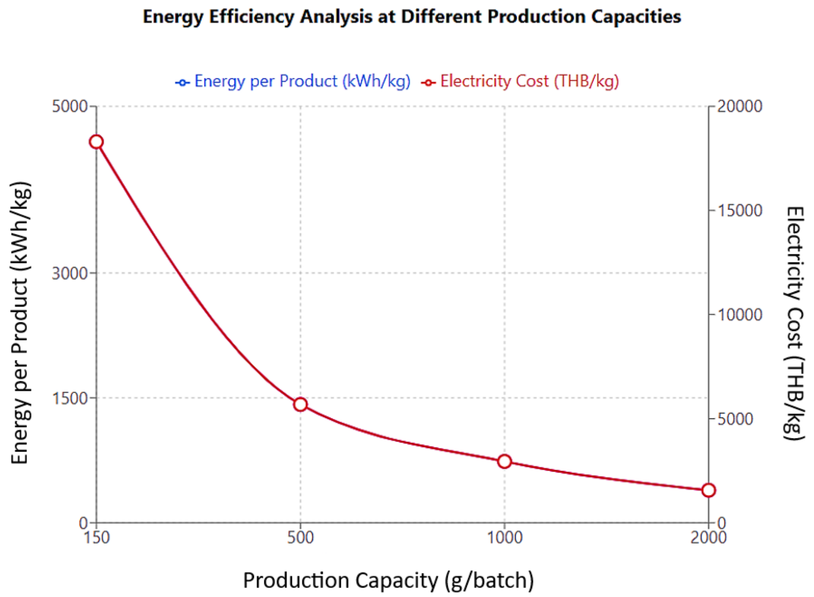


Figure 18.
Energy efficiency at different production capacities.

Figure 18 illustrates the relationship between production capacity and energy efficiency. The x-axis represents the quantity of raw materials (g), while the y-axis indicates the energy used per kilogram of product (kWh/kg). The graph demonstrates an exponential decrease in energy consumption per unit of product as production capacity increases. The rate of decrease is steeper at lower production capacities and gradually levels off as production increases.

4.4. Electrical System Stability

An analysis of the electrical system's stability during continuous operation for 50 hours is shown in Table 8.

Table 8.
Electrical system stability during continuous operation for 50 Hours (n=8).

Parameter	Mean	Standard deviation	%CV	Min.-Max.
Voltage (V)	229.8	±0.52	0.23	231.2-228.4
Current (A)	4.97	±0.22	4.43	5.28-4.66
Power Factor	0.84	±0.03	3.57	0.87-0.81

The analysis in Table 8 shows that the system maintains high stability, particularly in the voltage parameter, with a low coefficient of variation (%CV) of 0.23, indicating consistent voltage throughout operation. The current varies according to the load but remains within acceptable limits (%CV = 4.43). The average power factor of 0.84 reflects the system's efficient energy usage.

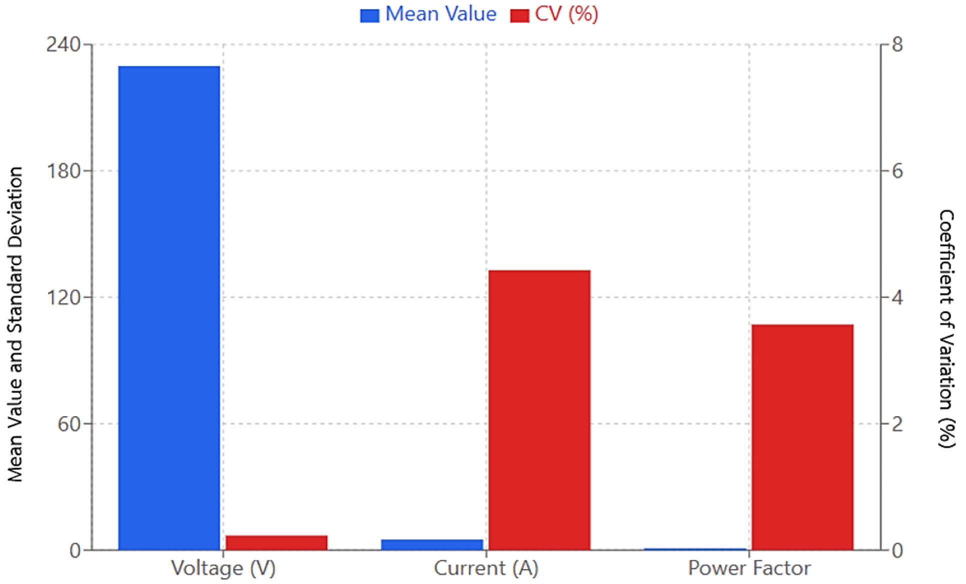


Figure 19.
Comparison of electrical parameters during operation.

Figure 19 shows the comparison of electrical parameters during operation. The x-axis represents the operating time (hours), the left y-axis shows the voltage and current, and the right y-axis shows the power factor. The graph illustrates that the system is able to maintain the stability of the electrical parameters effectively throughout the 50-hour operational period.

4.5. Economic Analysis

An analysis of the operating costs at different production capacities is shown in Table 9.

Table 9.
Operating cost analysis at different production capacities.

Item	150g/Cycle	500g/Cycle	1000g/Cycle	2000g/Cycle
Electricity Cost (THB/kg)	18,300	5,680	2,944	1,560
Labor Cost (THB/kg)	1,200	400	220	120
Maintenance Cost (THB/kg)	500	180	100	60
Total Cost (THB/kg)	20,000	6,260	3,264	1,740

From the cost analysis in Table 9, it is evident that increasing the production capacity significantly reduces the cost per unit of the product. At a production capacity of 2000g per cycle, the total cost per kilogram is the lowest at 1,740 THB, compared to 20,000 THB at 150g per cycle, which represents a reduction of 91.3%. Electricity costs remain the primary cost driver, accounting for approximately 90% of the total cost at all production capacities.

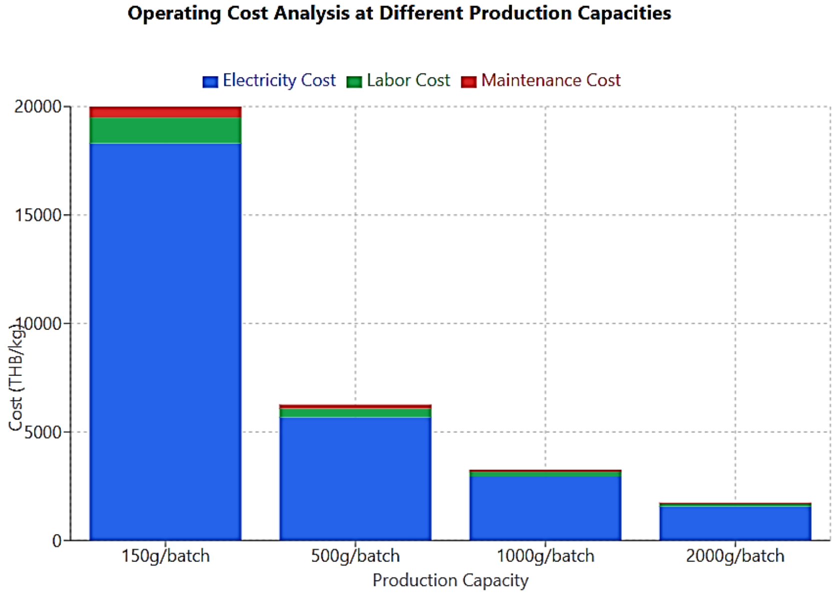


Figure 20.
Operating cost analysis at different production capacities.
Note: Calculations were made at an electricity rate of 4 THB per kWh.

Figure 20 presents a stacked bar chart comparing the operating costs at different production capacities, including electricity costs (blue), labor costs (green), and maintenance costs (red) for 150g, 500g, 1000g, and 2000g per cycle. The graph clearly shows a significant reduction in total cost per kilogram as production capacity increases, from 20,000 THB/kg at 150g per cycle to just 1,740 THB/kg at 2000g per cycle (a 91.3% decrease). Electricity costs remain the dominant expense, accounting for about 90% of the total cost at all production capacities.

5. Conclusion

The experiments and performance analysis of the developed freeze-drying machine yielded the following results in each aspect:

Drying Performance: The machine efficiently and consistently reduced moisture content, achieving a weight reduction of 91.9 ± 0.3%, with a final moisture content of 8.1 ± 0.3%, meeting the standards for dried food products. The average drying rate was 0.00275 ± 0.00001 kg/h. The PLC-based control system accurately controlled both temperature and pressure. The ice condenser temperature was maintained at -40°C (standard deviation ±0.4°C), and product temperature was regulated as required during each operation phase. Pressure during the primary and secondary drying stages was stable, ranging from 0.90 to 0.95 mbar. The PZEM-004T and ESP32 data logging system showed that the primary drying stage consumed the most energy, accounting for 51.9% of total energy usage. Increasing the production capacity from 150g to 2000g significantly reduced energy consumption per product, from 4,575 kWh/kg to 390 kWh/kg. The system demonstrated high stability during 50 hours of continuous operation, with an average power factor of 0.84. Voltage stability was high (%CV = 0.23), and current fluctuated appropriately according to the load. The cost analysis revealed clear economies of scale, with a production capacity of 2000g per cycle showing the lowest cost per kilogram at 1,740 THB, a reduction of 91.3% compared to production at 150g per cycle.

Recommendations for future work: To improve the control system and increase drying efficiency, an intelligent control system (AI or machine learning) can be used to adjust the temperature and pressure to suit the characteristics of the product in each cycle. Additionally, analyzing the impact of proactive control can enhance the stability of pressure and temperature during the drying process. It is also recommended to increase the efficiency of using energy from alternative energy sources, such as solar power or energy storage systems, to reduce energy costs. Furthermore, analyzing the use of heat energy recycling systems in the drying process can minimize energy loss. By addressing these future research areas, the freeze-drying system can achieve greater performance, lower production costs, and higher competitiveness in the food preservation industry.

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