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Enhancing Banana Drying Efficiency: A Phase Change Heat Storage System Utilizing Charcoal Briquettes

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ABSTRACT

This study aimed to enhance the efficiency of banana drying processes through the development and testing of a phase change heat storage system utilizing heat from charcoal briquettes. The system was designed and modeled using SolidWorks software, incorporating a parabolic dome and a heat storage unit made of SS400 steel. Temperature measurements were conducted within the dome and the heat storage system and efficiency testing was performed by comparing drying methods. Moisture content testing of market-dried bananas provided baseline data, with an average moisture content of 26.51% (w.b.). Drying experiments using a parabolic dome solar dryer demonstrated a reduction in banana moisture content from 70.18 to 25.53% (w.b.) after 4 days. Subsequently, testing with the phase change heat storage system revealed a further reduction in moisture content to 25.58% (w.b.) within 3 days of drying. The system-maintained temperatures inside the dome during nighttime, utilizing heat from charcoal briquettes to sustain drying processes. The results indicate that the phase change heat storage system significantly improves drying efficiency, with a 25% increase in production capacity compared to traditional solar drying methods. Implementation of this system offers a sustainable solution for banana processing, contributing to increased efficiency, reduced energy consumption, and enhanced product quality. This study underscores the potential of innovative drying technologies to address challenges in agricultural processing and promote sustainability within the industry.

Keywords: Banana drying, Phase change heat storage, Charcoal briquettes, Sustainable agriculture, Energy efficiency

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INTRODUCTION

The Musa ABB cv. 'Kluai Namwa Maliong' banana, belonging to the Musa genus, is commonly known as 'Kluai Namwa Maliong' banana. It is also known by various local names such as Kluai Namwa Sai Khao, Kluai Namwa Suan, Kluai Namwa Khao, and Kluai Namwa Ong. Generally, the 'Kluai Namwa Maliong' banana has a pseudo-stem that grows to about 3.5–4m in height. The pseudo-stem is green with reddish hues. The leaf sheaths are relatively narrow with slightly grooved midribs. The central veins of the leaves are green with pinkish hues. Each bunch typically contains around 9–16 hands, each having 16–18 fruits. The fruits are round, stout, with short peduncles. They are light green when unripe, turning to a fresh green when ripe. The ripe peel is thin, and yellowish, with a white to yellowish pulp. The flesh is creamy with a sweet taste and lacks seeds. Due to these characteristics, the 'Kluai Namwa Maliong' banana is popularly used in various food preparations, with dried bananas and banana chips being particularly renowned (Department of Agricultural Extension, 2020; Wongwaiwech et al., 2022).

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Dried bananas are a popular Thai snack made from ripe fruit that has been processed and dried (Janjai and Mahayothee, 2016). The production process typically begins with the harvesting of bananas after they have been fruiting for about 100-120 days. After harvesting, the bananas are separated into hands and allowed to ripen. Once ripe, they are peeled, removing all the fibers, and then arranged on drying racks in solar drying houses or parabolic domes. In the late afternoon of each day, the dried bananas are collected and brought out for further drying the next day, repeating the process for about 4-6 days (Chuewirot and Sundusdee, 1989; Thongpoon, 1997; Department of Agricultural Extension, 2020). Once they are ready, they become dried bananas and can be packaged for sale.

Drying is a process used to reduce the moisture content of products, which can be utilized for food preservation and agricultural produce (Leon et al., 2002; Jareanjit, 2012; Mofijur et al., 2019). A temperature range of 40-60°C is typically required for drying various products such as vegetables and fruits (Kant et al., 2016; Raponi et al., 2017; Mundpookier et al., 2023). Solar drying houses play a crucial role in the agricultural drying process, particularly in countries like Thailand, where solar energy potential is relatively high (Pruengam et al., 2019; Nabnean et al., 2020). However, solar drying facilities are limited to daytime operation only, which has led to research on thermal energy storage systems for moisture reduction during periods without sunlight. Phase Change Materials (PCMs) have been widely applied to reduce moisture or dry agricultural produce during periods without sunlight, helping maintain or control temperatures for longer durations (Malasai and Holasut, 2016). PCMs can store excess solar energy and release it when necessary, making them suitable for storing solar thermal energy (Devahastin and Pitaksuriyarat, 2006). Development and design of solar drying systems utilizing Paraffin wax as PCM have been explored to store excess solar energy during the day and release it when sunlight is insufficient or absent (Bal et al., 2010). Furthermore, biomass has been utilized in conjunction with solar drying systems due to its renewable energy properties. Biomass is commonly used as raw material for producing charcoal and charcoal briquettes (Tangmankongworakoon, 2014).

Charcoal briquettes are produced through a multi-step process starting with the carbonization of raw materials like wood or coconut shells in the absence of oxygen to eliminate volatile compounds and moisture. The carbonized material is then crushed, mixed with binders such as starch or clay, and compressed under high pressure into the desired shape, typically cylindrical or pillow-shaped briquettes. After pressing, the briquettes are dried to remove any remaining moisture, ensuring easier ignition and consistent burning. Charcoal briquettes can be used as fuel to provide heat efficiently in the drying process, making them suitable for reducing moisture content effectively. The raw materials for producing briquettes are not limited to wood or forestry residues but also include various agricultural residues found in Thailand such as corn cobs, sawdust, coconut husks, cassava peels, rice husks, sugarcane bagasse, and rice straw (Wirunphan et al., 2017). These agricultural residues can be transformed into briquettes, reducing agricultural waste and providing an environmentally friendly energy solution. Research has shown the feasibility of using biomass briquettes as an alternative energy source for solar drying systems, effectively reducing waste and environmental issues while promoting sustainability. Based on previous research studies, such as Chunkaew et al. (2018) a hot air blower has been developed using heat waste from a 200-liter incinerator for drying bananas, and the efficiency of the drying process has been studied. The main components of the drying machine include the drying chamber, air circulation system, and heat exchange pipes. The drying machine has been developed by designing the drying chamber on the 200-liter incinerator to reduce heat loss in the structure. Additionally, heat exchange pipes using copper tubes have been developed to increase heat for transfer to the air. Experiments were conducted at different temperatures, namely 60, 70, and 80°C, with a constant air inlet velocity of 1.8 meters per second. It was found that the temperature of 70°C is the most suitable temperature because the product exhibits vibrant color, high drying rates, and minimal energy consumption during the drying process. In another study, Pontecha (2020) also developed a solar-powered greenhouse dryer combined with a biomass stove for drying Nile tilapia. Comparative tests were conducted between solar energy alone and solar energy combined with the biomass stove. The tests with solar energy combined with the biomass stove were divided into two time periods: Period 1 from 8:00 AM to 6:00 PM and Period 2 from 6:00 PM to 4:00 AM. It was found that the solar-only dryer took only 2 days to dry. The environmental temperature averaged 35.0 and 28.3°C on Day 1 and Day 2, respectively. The internal temperature of the dryer averaged 42.4 and 36.6°C on Day 1 and Day 2, respectively. In contrast, the solar-powered dryer combined with the biomass stove took 20 hours to dry. The internal temperature of the dryer averaged 43.1°C, which was higher than the environmental temperature of 12.4°C. The moisture content of the dried Nile tilapia products in both formats complied with the standard for sun-dried fish products, which specifies a maximum moisture content of 65% by weight. From the results of the aforementioned research studies, it is found that there has been no research that developed a heat storage system using PCM in conjunction with charcoal briquettes. Therefore, this research aims to enhance the efficiency of the drying process by utilizing a phase change heat storage system, harnessing thermal energy from charcoal briquettes. This system aims to ensure a continuous drying process by storing heat during daylight hours and releasing it for drying when sunlight is not available (Holasut and Kumwachara, 2010). This approach can mitigate the limitations regarding drying duration and enable the continuous utilization of heat from the heat storage system (Sanchum, 2013). The innovation resulting from this research project can be effectively applied to community enterprise groups and banana processing entrepreneurs. This would lead to reduced energy consumption from fossil fuels and contribute to mitigating global warming. Additionally, it can reduce production costs for community enterprise groups and banana processing entrepreneurs, thus fostering self-reliance and sustainability within the community.

MATERIALS & METHODS

Designing a Phase Change Heat Storage System for Drying Banana Produce Using Heat from Charcoal Briquettes

A phase change heat storage system for banana drying utilizing heat from charcoal briquettes was designed and modeled using Solid Works software (Phasinam et al., 2024; Promjeen et al., 2024). Fig. 1–2 illustrates the system, which comprises a parabolic dome measuring 100cm wide, 120cm long, and with a radius of curvature of 50cm. Inside, it accommodates four trays for placing the banana products. The structural material is made of mild steel, while the dome's roof is constructed from clear polycarbonate sheets, 6mm thick, in a double-layered dome design (Raponi et al., 2017). The trays are stainless steel wire mesh trays, measuring 63cm wide and 93cm long. Solar panels are installed on the top of the dome to supply electricity to a 12-volt DC fan for air circulation and a temperature monitoring system inside the dome. The dome stands on wheels for easy mobility.

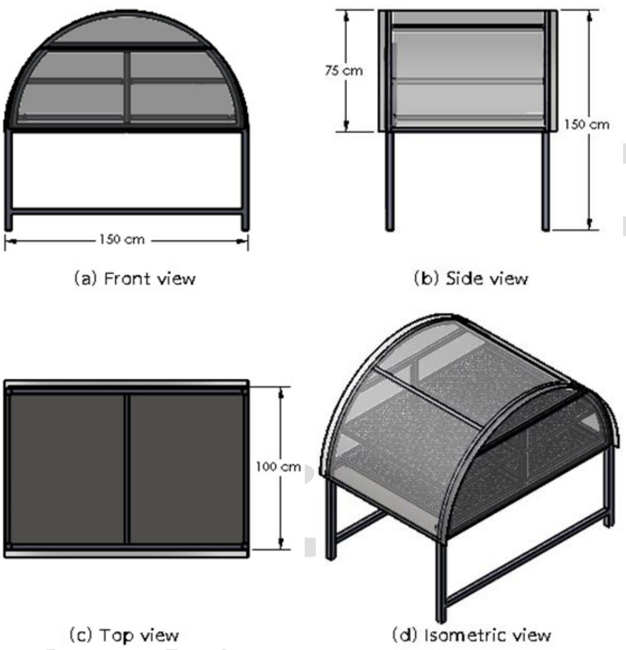

Fig. 1: Three-dimensional model of the parabolic dome.

The phase change heat storage system structure is fabricated from SS400 (Mild Steel) with dimensions of 25mm by 25mm. The structure has a width of 85cm and a length of 120cm. It is divided into two layers. The first layer consists of a tray containing paraffin wax to provide heat for reducing banana moisture during nighttime, while the second layer comprises a tray containing charcoal briquettes for transferring heat to the paraffin wax. The base of the phase change heat storage system structure is equipped with wheels for convenient mobility, as illustrated in Fig. 3.

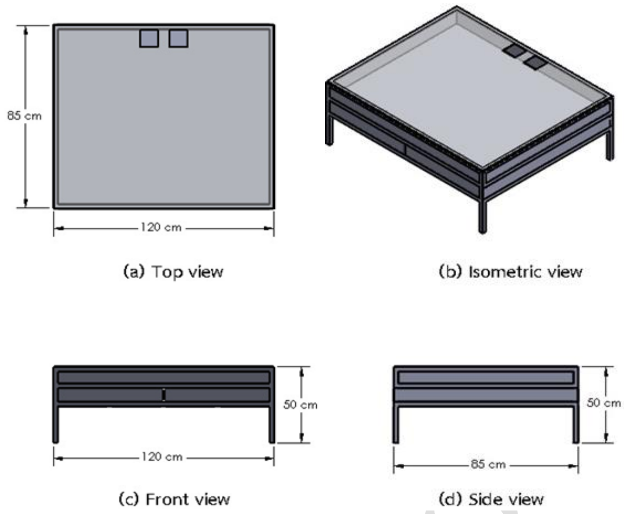

Fig. 2: Three-dimensional model of the phase change heat storage system.

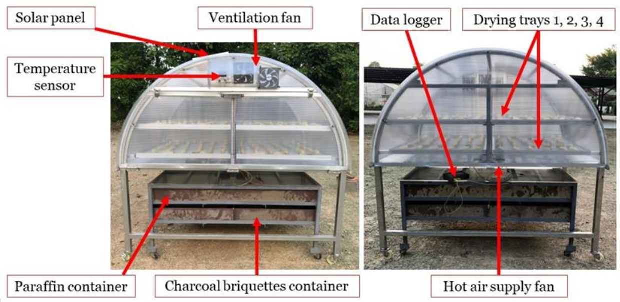

Fig. 3: Components of the parabolic dome and phase change heat storage system.

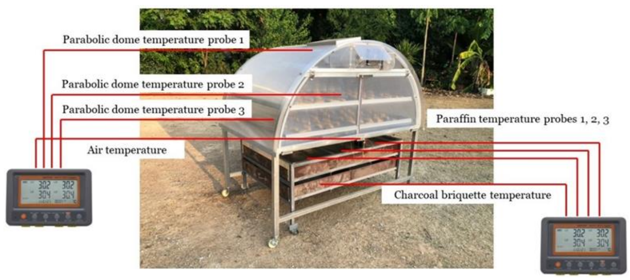

Fig. 4: Installation positions of temperature probes for measuring the temperature of the parabolic dome and phase change heat storage system.

Temperature measurements inside the parabolic dome and the phase change heat storage system were conducted by installing temperature probes at various positions. Four probe locations were distributed within the dome, as well as another four within the heat storage system, as depicted in Fig. 4. Subsequently, a data logger was installed to record temperature values every hour, and the collected temperature data were analyzed accordingly.

Efficiency Testing of a Phase Change Heat Storage System for Drying Banana Produce Using Heat from Charcoal Briquettes

Testing the efficiency of the phase change heat storage system for drying banana produce using heat from charcoal briquette will be conducted by comparing drying bananas in a parabolic dome solely utilizing solar heat against drying bananas in a parabolic dome powered by solar energy combined with a phase change heat storage system using heat from charcoal briquette. The testing procedure will proceed as follows:

Moisture Content Testing of Dried Bananas Obtained from the General Market

Testing to determine the moisture content of dried bananas obtained from typical market sources is conducted to provide baseline data for further experimentation. The testing process involves five steps as follows:

1) Randomly select 20 dried bananas from general market sources, weigh them, and record their initial weights.
2) Arrange the dried bananas on a stainless-steel tray and place them in a hot air oven set at 105±2°C for 24 hours (Gaewsondee et al., 2017; Nilnont and Phitakwinai, 2021), following the Association of Official Analytical Chemists standards (AOAC, 2000).
3) Remove the dried bananas from the drying chamber, weigh the bananas after drying, and record the results.
4) Repeat steps 1 to 3 for a total of three tests.
5) Analyze the experimental results to calculate the moisture content of the dried bananas.

Banana Drying Test Using a Parabolic Dome Solar Dryer

Testing the solar drying of bananas using only a parabolic dome solar dryer was conducted to provide data for comparison with banana drying using both a parabolic dome solar dryer and a phase change heat storage system. The procedure consisted of 5 steps as follows:

1) Prepare 120 ripe bananas by peeling and weighing them to record their initial weight.
2) Arrange the ripe bananas on 4 trays, with each tray containing 30 bananas, and then place them in the parabolic dome solar dryer. The drying process was conducted from 08:00 AM to 05:00 PM daily, during sunlight hours, as depicted in Fig. 5.
3) Randomly select 20 bananas from those dried in the parabolic dome solar dryer at 05:00 PM daily. Weigh them and then place them in a hot air oven set at 105±2°C for 24 hours (Gaewsondee et al., 2017; Nilnont and Phitakwinai, 2021), following the Association of Official Analytical Chemists standards (AOAC, 2000), to determine the moisture content of the bananas dried using only the parabolic dome solar dryer. The testing was stopped when the moisture content of the bananas matched that of the market-dried bananas.
4) Repeat steps 1 to 3 for a total of 3 test runs.
5) Analyze and evaluate the results obtained from the experiments.

Banana Drying Test Using a Phase Change Heat Storage System

Testing banana drying using a phase change heat storage system utilizing heat from charcoal briquettes involves the following 5 steps:

1) Prepare 120 ripe bananas by peeling and weighing them to record the initial weight of the ripe bananas.

Fig. 5: Arrangement of ripe bananas inside the parabolic dome solar dryer.

Fig. 6: Phase change heat storage system utilizing heat from charcoal briquette.

2) Arrange the ripe bananas on 4 trays, each containing 30 bananas, and then place them into the parabolic dome solar dryer. The drying process starts at 08:00 AM and continues until 08:00 AM the next day. Since there is no sunlight available after 5:00 PM, a phase change heat storage system using heat from charcoal briquettes is used to supplement the drying process, as shown in Fig. 6.
3) Randomly select 20 ripe bananas from the parabolic dome solar dryer at 08:00 AM each day, weigh them, and

then place them into a hot air oven at a temperature of 105±2°C for 24 hours (Gaewsondee et al., 2017; Nilnont and Phitakwinai, 2021), following the Association of Official Analytical Chemists standards (AOAC, 2000), to determine the moisture content of the bananas dried using the parabolic dome solar dryer combined with the phase change heat storage system using heat from charcoal briquettes. The testing continues until the moisture content of the dried bananas matches that of market-dried bananas, at which point the testing is terminated.

4) Repeat steps 1 to 3 for a total of 3 test runs.

5) Analyze and evaluate the results of the experiments.

RESULTS & DISCUSSION

Based on the efficiency testing of the phase change heat storage system for drying banana products using heat from charcoal briquettes, the following operational outcomes were observed:

The Moisture Content of Dried Bananas Obtained from the General Market

From the moisture content testing of dried bananas obtained from the general market by randomly sampling 20 dried banana samples, it was found that the average moisture content of market-dried bananas is 26.51% (w.b.), as shown in Fig. 7. This finding aligns with the research conducted by Borirak et al. (2021) which stated that the initial weight of the sample product averaged 49.24grams, and the final weight averaged 23.03 grams when drying bananas using a combined solar-energy drying cabinet. The final standard wet basis moisture content in the product was 28.40% (w.b.).

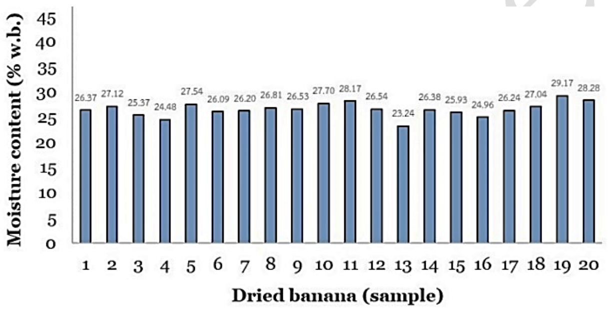

Fig. 7: The moisture content of dried bananas in the general market.

Drying Bananas with a Parabolic Dome Solar Dryer

From the test results of drying bananas with the parabolic dome solar dryer, it was observed that the air temperature ranged from 25 to 38°C. The maximum temperature occurred between 12:00 PM and 4:00 PM, with temperatures ranging from 35 to 38°C. When the parabolic dome received heat from sunlight, the average temperature inside reached 50.28°C, consistent with the research of Keawsuntia (2021), which stated that the daily air temperature ranged from approximately 30 to 38°C. The highest temperatures occurred between 12:00 PM and 2:00 PM, ranging from 35 to 38°C.

The initial moisture content of ripe bananas averaged 70.18% (w.b.). After drying for 4 days, the moisture content of the ripe bananas decreased to 25.53% (w.b.), as shown in Fig. 8. This is in line with the findings of Nabnean et al. (2020) who reported that the temperature inside the drying machine ranged from 33 to 58°C. This allowed the banana mass inside the dryer to effectively release moisture, reducing the moisture content from 73% (w.b.) to just 25% (w.b.) within 4 days. The moisture content of Namwa Maliong bananas ranged from 63.98% (w.b.) to 69.80% (w.b.) (Wongwaiwech et al., 2022) and Kreetachat et al. (2023) suggested that maintaining an appropriate moisture level and preserving the shape of the bananas requires drying temperatures above 50°C and drying times longer than 36 hours.

Drying Bananas Using a Phase Change Heat Storage System with Heat from Charcoal Briquettes

From the results of drying bananas using a phase change heat storage system with heat from charcoal briquettes, it was found that maintaining the temperature inside the parabolic dome from 6:00 PM to 10:00 PM can solely rely on the heat energy from the heat storage system. The charcoal briquettes used for heating the liquid paraffin can provide heat for 4 hours, from 6:00 PM to 10:00 PM. The maximum temperature of the charcoal briquettes averaged 275°C, gradually decreasing until the heat was depleted. The heat from the charcoal briquettes affects the liquefaction of the liquid paraffin, which has a temperature range of 50–75°C. Heat is transferred to the air in contact with the liquid paraffin in the form of latent heat, which is then used for drying the bananas. The average temperature of the air at the entrance of the parabolic dome from 6:00 PM to 10:00 PM is 45°C. Subsequently, the drying temperature inside the dome gradually decreases until it approaches the ambient temperature. This continuous decrease in temperature is due to the top surface of the liquid paraffin starting to solidify, acting as a heat insulator, resulting in reduced heat transfer between the liquid paraffin and the heat storage system (Fig. 9) (Kassanuk et al., 2017).

After examining the temperature inside the parabolic dome of the phase change heat storage system for drying banana produce using heat from charcoal briquettes, it was found that the air temperature ranged from approximately 25 to 40°C. The maximum air temperature occurred between 12:00 PM and 4:00 PM, with temperatures ranging from 35 to 40°C. When the parabolic dome received heat from sunlight, the maximum temperature inside the parabolic dome was between 12:00 PM and 4:00 PM, with an average temperature of 50°C. During periods without sunlight, from 6:00 PM to 10:00 PM, the parabolic dome received heat from the phase change heat storage system using heat from charcoal briquettes. The average temperature inside the parabolic dome during this time was 48°C for 4 hours. Regarding the moisture content of dried bananas tested using the phase change heat storage system for drying banana product using heat from charcoal briquettes, it was found that the initial moisture content of ripe bananas averaged 70% (w.b.). After drying for 3 days, the moisture content inside the ripe bananas decreased to 25.58% (w.b.).

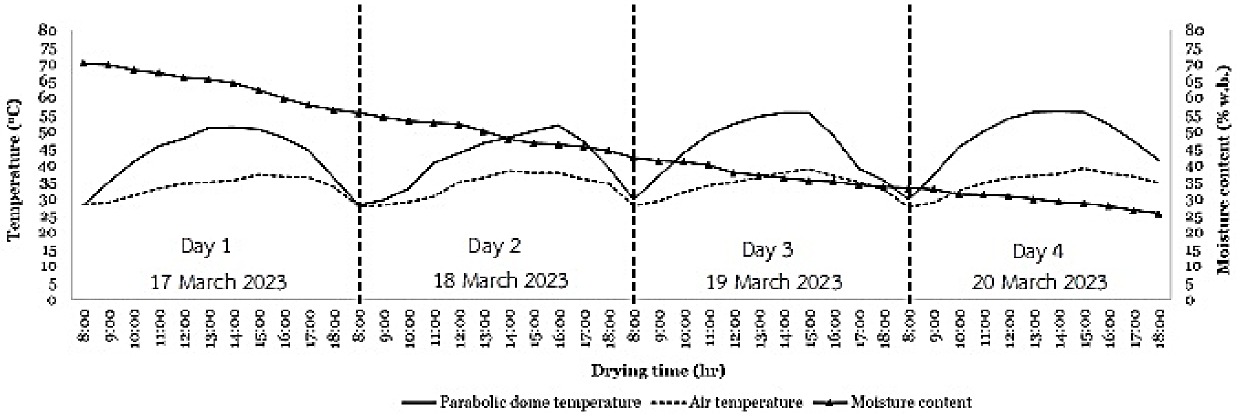

Fig. 8: Air temperature, parabolic dome temperature, and moisture content of bananas using parabolic dome solar dryer.

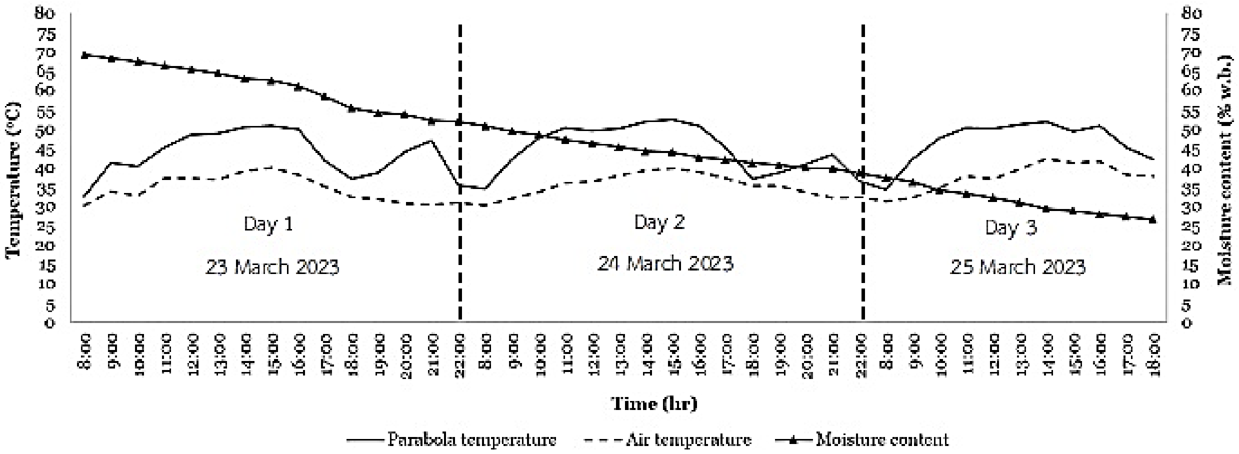

Fig. 9: Air temperature, parabolic dome temperature, and moisture content of bananas using a phase change heat storage system with heat from charcoal briquettes.

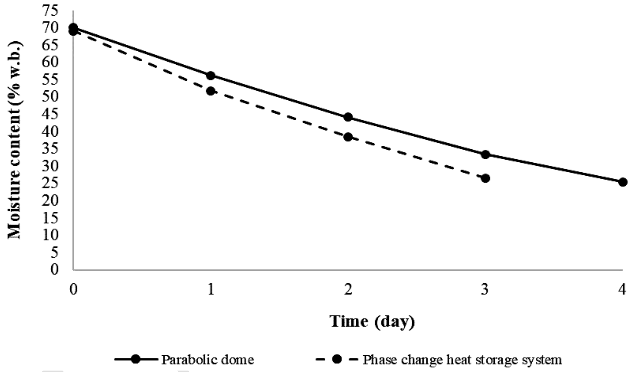

Fig. 10: The moisture content of the bananas during drying using the parabolic dome and the phase change heat storage system.

For the moisture content of ripe bananas tested between using the parabolic dome solar drying system and testing using the phase change heat storage system using heat from charcoal briquettes, it was found that drying bananas using the phase change heat storage system could reduce the moisture content of the bananas more effectively, resulting in a reduction of the drying time by 1 day compared to using only the parabolic dome solar drying system. Therefore, the reduced drying time allows for an increase in production capacity by 25%, as shown in Fig. 10. The dried banana products produced through drying with the phase change heat storage system are shown in Fig. 11.

Fig. 11: Dried bananas are produced utilizing the phase change heat storage system.

Conclusion

The phase change heat storage system for drying banana products using heat from charcoal briquettes is divided into two parts. Part 1 consists of a parabolic dome measuring 100cm wide, 120cm long, and with a curvature radius of 50cm. Inside the dome, there are four trays for placing the products, and solar panels are installed on the dome's roof to provide power to the ventilators and temperature sensors system. Part 2 is the phase change heat storage system made of SS400 steel, with dimensions of 85cm wide and 120cm long. The first layer is for containing paraffin, and the second layer is for containing charcoal briquettes. When drying bananas with the parabolic dome solar energy drying system, the maximum temperature inside the dome occurs between 12:00 PM and 4:00 PM, with an average temperature of 50.28°C. It can reduce the moisture content of ripe bananas from the standard wet content of 70.18 to 25.53% within 4 days. As for drying bananas using the phase change heat storage system fueled by charcoal briquettes, the peak temperature inside the parabolic dome typically occurs between 12:00 PM and 4:00 PM, reaching an average of 50°C. During periods lacking sunlight, from 6:00 PM to 10:00 PM, the average temperature inside the dome remains at 48°C. This method is also effective in reducing the moisture content of ripe bananas from the standard 70 to 25.58% within a 3-day timeframe. Implementing the phase change heat storage system with charcoal briquettes can consequently boost production capacity by 25%.

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Conflict of Interest

The authors declare no conflict of interest.

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