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Drying banana slices using photovoltaic ventilation solar dryer

*Suherman, S., Hadiyanto, H., Asy-Syaqiq, M.A., Brastayudha, A.A. and Fahrudin, M.W.

Chemical Engineering Department Diponegoro University Jl. Prof. Soedharto, Tembalang, Semarang, 50239, Indonesia

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Abstract

The economic value of bananas is quite low due to the high volume of production and the short shelf life of the fruit. One of the popular methods of preserving agricultural produce is drying. The objectives of this research include determining the drying kinetics curve profile of banana slices and the drying rate using a solar dryer, analyzing the profile of incoming and outgoing air temperature, solar intensity, air humidity in the solar drying device, evaluating the performance of the solar dryer in terms of drying efficiency, as well as measuring the quality and comparing the solar-dried banana product with the open sun method. The temperature profile of the drying chamber remained relatively stable, throughout the drying process due to the addition of photovoltaic panel to generate electrical energy to run the D.C. fans and electrical heater. The fastest drying occurs in solar drying of photovoltaic ventilation with temperature of 60℃ with a drying time of 8 hrs and resulting in moisture content of 8.57%. The drying rate in solar instruments of photovoltaic ventilation at variable temperatures of 60℃, 50℃, 40℃ and open sun drying has an average drying rate of 0.0921 g/min, 0.0784 g/min, 0.0653 g/min, and 0.0529 g/min, respectively. The drying rate decreases as the drying time increases. The average efficiency of the dryer at 40°C, 50°C and 60°C, were 3.109%, 3.393% and 3.915%, respectively. For the quality analysis of the dried banana slice, the structure of dried banana slices with SEM analysis tends to be irregular and the surface was smooth. There were 20 compounds detected by GCMS method in dried banana slices, where there were five compounds that had the widest area or the largest presentation, namely 26.22% hexadecanoic acid, ethyl ester (CAS), 24.59% ethyl oleate, 5.47% silan, triethyl-fluoro-, 5.05% bis(2- ethylhexyl) ether and 4.83% ascorbaric acid (Vit-C).

1. Introduction

Indonesia is one of the producers of quite large fruit commodities, one of which is bananas. Banana is one of the important tropical fruits in the world (Pruengam *et al*., 2021). Banana is a herbal plant that has the widest distribution potential in Indonesia because it has a tropical climate so that bananas can grow in fields, gardens and in yards. Banana fruits provide quite high calories as well as rich in carbohydrates, vitamins B, B6 and C, minerals such as potassium, magnesium, iron, phosphorus and calcium (Afzal *et al*., 2022). Agricultural products have a fairly high water content (Susanto *et al*., 2023). Moisture content (MC) of agricultural products (fruits and vegetables) in the range of 80–85%, and both are consider unpreserved products (Kushwah *et al*., 2023). Therefore, fruits and vegetables need to be dried to increase storage capacity, reduce packaging requirements and minimize transport weight (Sagar and Suresh Kumar, 2010). Bananas have a fairly high water content, soft texture and deteriorate at high temperatures (Hassan *et al*., 2004). Therefore, bananas can be dried using solar heat, either by placing them directly in the sun's heat or by using a drier. Although open sun drying is a simple and effective method, but much of the heat generated from solar energy is wasted to the environment and resulting in a low drying efficiency (Pruengam *et al*., 2021). Furthermore, there are many disadvantages for the open sun traditional drying, a large free space, long drying time, many contaminants, and poor quality (Vengsungnle *et al*., 2020). Therefore, there is a need for a more efficient drying system, which is by using a solar dryer.

Research on drying bananas using solar dryers has been widely carried out. Mathematical modeling for

*Corresponding author.
Email: *suherman.mz@che.undip.ac.id*

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optimal design of a solar-assisted drying system for drying bananas was developed, and found the optimum values of the collector area and the recycle factor were found to be 26 m^2 and 90% (Smitabhindu *et al*., 2008). The bananas took 4 days to dry in the solar greenhouse dryer, whereas natural sun drying under similar circumstances required 5-6 days (Janjai *et al*., 2009). The Henderson and Pabis drying model is identified as the most appropriate for characterizing the solar drying patterns of plantain bananas (Koua *et al*., 2009). The temperature of the drying air plays a crucial and influential role in the banana drying process (Lingayat *et al*., 2017). The solar radiation received has a significant impact on the drying of bananas (Maia *et al*., 2017). The solar cabinet dryer with energy storage, operating in a multi-tray mixed mode, provides enhanced versatility for drying bananas (Arun *et al*., 2019). The Midilli and Kucuk model is deemed the most suitable model for solar thermal drying of bananas (Nasri, 2020). Assessing the performance and economic viability of a solar-biomass hybrid greenhouse dryer for the drying of banana slices was investigated (Kiburi *et al*., 2020). The solar-dried banana product achieved excellent quality in terms of flavor, color and texture (Nabnean and Nimnuan, 2020). A solar collector dryer with double-sided design was specifically developed for the purpose of drying banana slices (Pruengam *et al*., 2021). Refractance window drying of banana samples exhibited the highest nutrient retention within a shorter drying duration (Dadhaneeya *et al*., 2023). The investigation focused on utilizing response surface methodology to optimize the drying parameters of a hybrid indirect solar dryer for banana slices was conducted (Kushwah *et al*., 2023). In the case of drying bananas, the average thermal efficiencies achieved in the indirect solar dryer were measured to be 14.45% (El-Sebaey *et al*., 2023).

Drying bananas in Indonesia mostly still uses conventional methods, namely using sunlight, one of the problems in the drying process of sunlight is that products that are dried in an uncontrolled system result in discoloration, loss of taste, texture, and important micronutrients (Kiburi *et al.,* 2020). The method of open sun drying is considered less effective because it is very dependent on the weather (Suherman *et al*., 2021). Several research activities on the use of solar drying to dry agricultural products in Indonesia have been tested, such as Coffee Beans (Suherman et al., 2020), sugar-palm vermicelli (Suherman *et al*., 2020), cassava starch (Suherman *et al*., 2020), lime (Suherman *et al*., 2020), and ginger (Suherman *et al*., 2021).

Therefore, this study aims to analyze the profile of air temperature in and out, solar intensity, and air humidity in the solar dryer, obtain the profile of the banana drying kinetic curve and drying rate using a solar dryer, examine the performance of the photovoltaic ventilation solar dryer in terms of dryer efficiency, as well as take quality measurements and compare the products resulting from the drying of photovoltaic ventilation solar dryer and open sun drying (OSD).

2. Materials and methods

2.1 Materials

Banana fruits are bought at one of the markets in the Tembalang area, Central Java. The banana fruits are sliced to reach 100 g for each variable with a thickness of 4-5 mm. The initial moisture content of bananas was 52% measured by oven and calculated from the lost mass with a temperature of 105-110°C until a constant weight is obtained. Its determination based on the AOAC method by (Doymaz *et al*., 2006).

2.2 Experimental pr°Cedure

This research was conducted from 0900 to 1400 hrs under the sun was shining brightly and without raining. The experimental pr°Cedure for drying banana slices using a photovoltaic ventilation solar dryer can be seen in Figure 1. The experimental procedure was divided into three stages, namely preparation of raw material, drying process and product analysis.

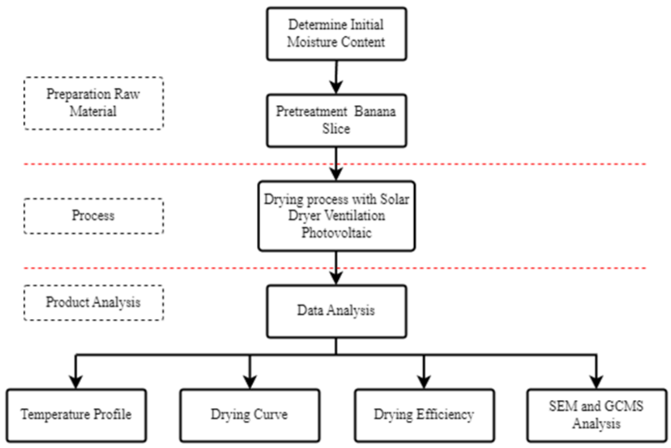

Figure 1. Scheme of research flow diagram.

During the process, temperature, relative humidity, solar intensity, and the mass of banana slices was measured once every 60-mins. The air temperature is measured by Krisbow KW0600561 digital temperature and relative humidity meter (accuracy ±0.1°C and ± 0.01%, respectively) and solar intensity measured by Bonad SM206 solar power meter (accuracy ±0.1 W/m^2). A Krisbow Electronic Kitchen Digital Scale 5 kg Slim Plate (accuracy ±0.1 g) was used to measure the weight of the banana slices.

During the experiment, banana slices were spread on the tray in the drying chamber. In the photovoltaic ventilation solar dryer, hot air flowed from behind of aluminum tray, which comes from the photovoltaic panel. Photovoltaic panel generated electrical energy to run the D.C. fans and electrical heater and thermal energy used in the collector box (Gupta *et al.*, 2023). Figure 2 shows the schematic of the photovoltaic ventilation solar dryer and Figure 3 show a photograph of the photovoltaic ventilation solar dryer. In photovoltaic ventilation solar dryers, the collector (glass film) is an absorber of solar heat and distributes it into the room. The collector can block some UV rays so they won't damage the dried material. Meanwhile, the exhaust fan will suck the air in the room along with the water vapor.

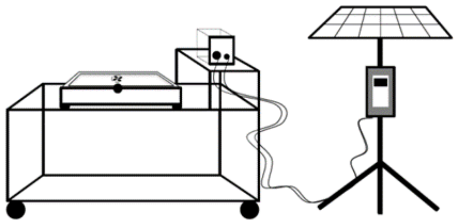

Figure 2. Scheme of photovoltaic ventilation solar dryer laboratory scale.

2.3 Drying process

The experiments were performed in the Laboratory of Chemical Engineering Department, Diponegoro University, Semarang, Indonesia. The two drying methods in this experiment were open sun drying (OSD) and photovoltaic ventilation solar dryer. For OSD method, 100 g of banana slices were spread on the aluminum tray and dried under the sky until the moisture content became lower than the standard limit, which is 12% w.b. The weight of the sample was measured once every 60 mins and record the ambient temperature, relative humidity, and solar intensity.

As for the photovoltaic ventilation solar dryer, the independent variable was the drying temperature (40°C, 50°C, and 60°C). To begin the experiment, 100 g of banana slices were prepared for each variable. The drying process was performed from 0900 to 1400 hrs until the moisture content was under 12% w.b. The temperature, relative humidity, solar intensity, and mass of banana slices were measured once every 60 mins. Air temperatures of the inlet dryer, dryer chamber and outlet dryer were also measured.

2.4 Data analysis

2.4.1 Initial moisture content

The banana slices' initial moisture content can be evaluated on a wet basis which is started in percent using gravimetric method and determine to the following equation (Hawa *et al.*, 2022):

$$\text{Initial moisture content (wet basis)} = \frac{M_i - M_d}{M_i} \times 100\%$$

Where M_i is the initial mass of sample (g) and M_d is the dried mass of sample (g).

2.4.2 Moisture content

Moisture content is usually expressed in percent of moisture present in the product. Moisture content of a product in the dryer can be given on the basis of total weight of the product to dried of the amount of solid weight present in the product. The moisture content on wet basis is given by the following equation (Nabnean and Nimnuan, 2020).

$$\text{MC (wet basis)} = \frac{M_W}{M_W + M_d} \times 100\%$$

Where MC represents of moisture content on a wet basis, M_W is the mass of moisture (g) and M_d is the mass of dry product (g).

2.4.3 Drying rate

Drying rate (Rd) is formed by a decrease of the water concentration during the time interval between two subsequent measurements divided by this time interval (Saravanan *et al.*, 2014):

$$Rd = \frac{M_i - M_d}{\Delta t}$$

Where Rd represents drying rate (g/min), M_i was the initial mass (g), and M_d was the mass after drying (g), and Δt was time interval (min).

2.4.4 Dryer efficiency

Dryer efficiency was the ratio of the energy required to remove moisture from a material to the total energy put into the solar drying chamber (Mugi and Chandramohan, 2021). It is calculated using:

$$\eta_d = \frac{m_W . L}{I . A_c . t}$$

Where η_d represents of dryer efficiency (%), L was the latent heat of vaporization of water (kJ/kg), I was solar intensity (W/m^2), A_C was the area of collector (m^2), and t was drying time (s).

2.4.5 Scanning electron microscope

Scanning electron microscopy (SEM) technology is an effective method for observing the microstructure change of samples during drying process, and then for revealing the effects of drying parameters on mass transfer and physical properties of samples. Scanning electron microscope analysis was performed on banana fruit to get images of the microstructures and chemical compounds present in banana slices under different drying conditions (Shi *et al.*, 2020).

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2.4.6 Gas chromatography mass spectrometry

Gas chromatography mass spectrometry (GCMS) is used to determine the chemical components present in the form of peek areas, which are the migration speeds of a compound in a certain period of time (Li *et al*., 2014). In this study, GCMS was used to find changes of aroma components in different drying methods, photovoltaic ventilation solar dryer and open sun drying.

3. Results and discussion

3.1 Analysis of weather condition and temperature profiles

Figures 4-6 show the variation of ambient temperature, relative humidity, and solar intensity during the drying of the banana slices using the photovoltaic ventilation solar dryer at 40°C, 50°C and 60°C, respectively. During the experiments, the weather condition was sunny and slightly cloudy. The relative humidity of ambient air decreased with increase in time due to increased solar radiation (Kiburi *et al*., 2020). The fluctuating sunlight intensity and temperature can be influenced by weather conditions and geographical position during measurement (Nabnean and Nimnuan, 2020; Murali *et al*., 2020).

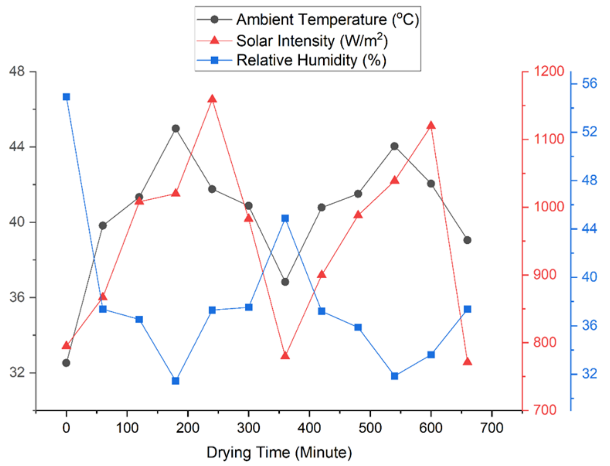

Figure 4. Average weather condition during photovoltaic ventilation solar dryer at 40°C.

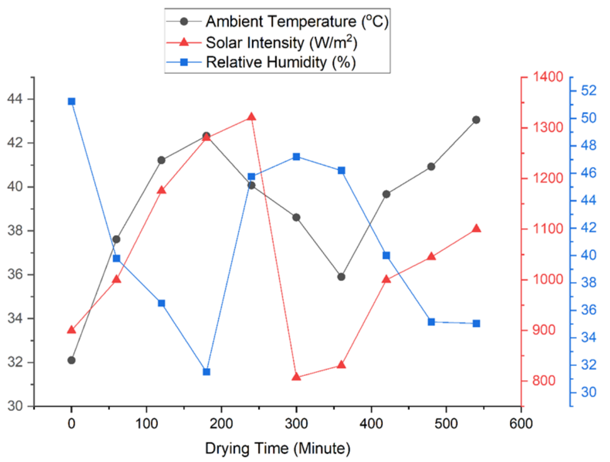

Figure 5. Average weather condition during photovoltaic ventilation solar dryer at 50°C.

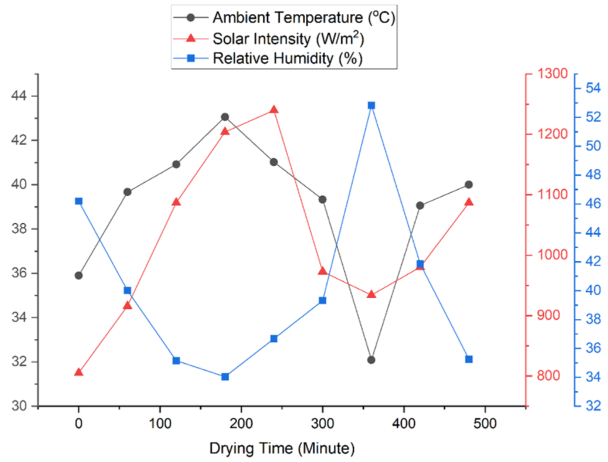

Figure 6. Average weather condition during photovoltaic ventilation solar dryer at 60°C.

Figure 7-9 show the variation of dryer temperature condition using the photovoltaic ventilation solar dryer at 40°C, 50°C and 60°C, respectively, representing the temperature at the drying chamber inlet, tray and outlet. The air enters the system at ambient temperature. The inlet and outlet temperatures are directly related to the incident of total solar radiation on the device (Maia *et al*., 2017). The temperature of the drying chamber remained relatively stable, throughout the drying process due to the addition of photovoltaic panel to generate

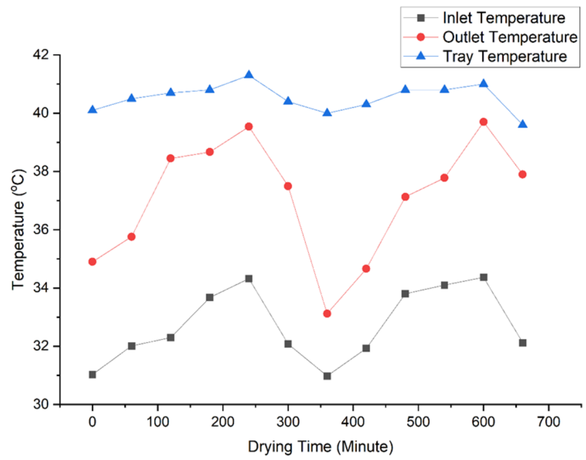

Figure 7. Temperature profiles during photovoltaic ventilation solar dryer at 40°C.

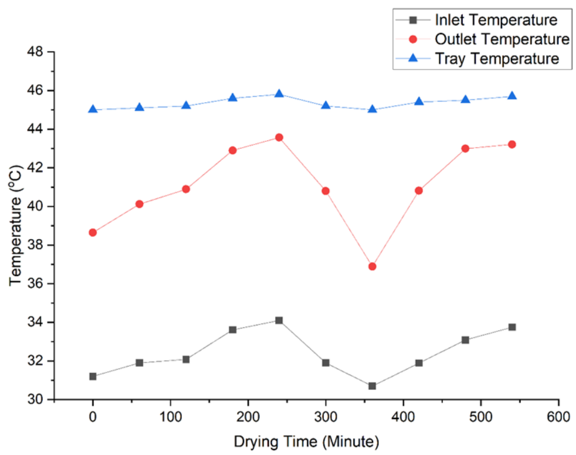

Figure 8. Temperature profiles during photovoltaic ventilation solar dryer at 50°C.

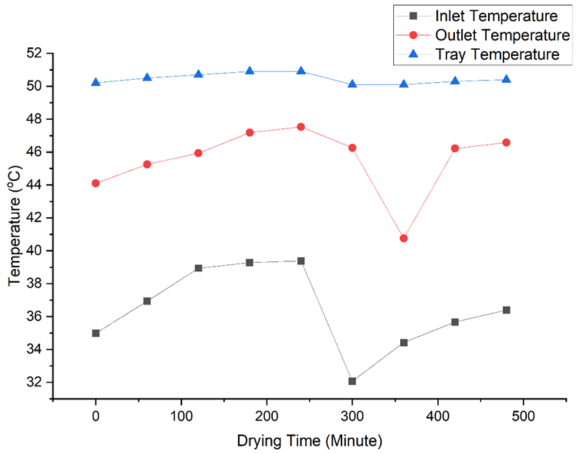

Figure 9. Temperature profiles during photovoltaic ventilation solar dryer at 60°C.

electrical energy to run the D.C. fans and electrical heater (Suherman *et al*., 2021). The drying at 60°C is considered to be the fastest because of the high temperature difference, indicating that a considerable amount of heat is required to evaporate the water from banana slices. The dryer temperature began to decrease at 1300 hrs onwards due to decreasing solar radiation. Contrary to the temperature profile, relative humidity profiles are shown to be increasing as drying continues (Suherman *et al*., 2021).

3.2 Analysis of moisture content and drying rate curve

The moisture content curve can be seen in Figure 10, where the final moisture content of banana slices dried using open sun drying method and photovoltaic ventilation solar dryer at 40°C, 50°C and 60°C was between 8.22–9.64% w.b from 52% on wet basis. It was noticed that the drying of banana slices was much faster at the initial drying time and thereafter gradually decreased with time. This is because the moisture content in the material decreases over time. Dry air will come into contact with the material, causing water diffusion from the material to the air. The movement of water from inside the material to the air is due to the heat energy provided from the air to the material and carried by the drying air (Momenzadeh *et al*., 2011). As time passes and the moisture content in the material decreases, the remaining water content is bound water within the material cells, resulting in a gradual reduction of the material's moisture content until it becomes constant. This bound water content is more difficult to remove as it is hygroscopically attached to the cell walls (Misha *et al*., 2013).

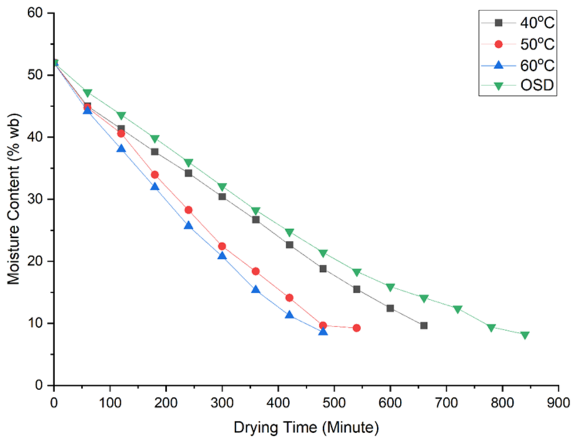

Figure 10. Moisture content curve.

The fastest drying occurs in the drying process using the photovoltaic ventilation solar dryer with a variable temperature of 60°C with a drying time of 8 hrs. This can be seen in Figure 11, where at a drying temperature of 60°C, the highest drying rate was 0.0921 g/min. Meanwhile, for the drying rate at drying temperatures of 40°C and 50°C, as well as open sun drying, were 0.0653 g/min, 0.0784 g/min, and 0.0529 g/min, respectively. The main factors that affect the drying rate are temperature and relative humidity, where the moisture content in the material will increase when the surrounding air is humid. In addition, the drying rate is also influenced by the drying temperature, where a lower drying temperature will slow down the drying rate (Ziegler *et al*., 2016). In essence, increasing the temperature enhances moisture evaporation since it increases the heat transfer between the banana slices and drying air; therefore, moisture removal from the banana slices increases (Alara *et al*., 2019).

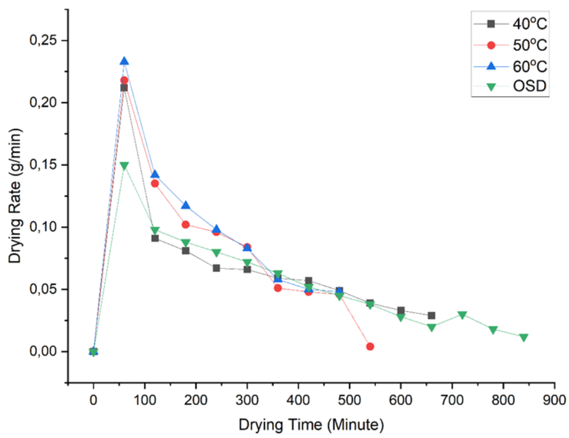

Figure 11. Drying rate curve.

3.3 Analysis of dryer efficiency

The relationship between the efficiency of photovoltaic ventilation solar dryer and drying time can be seen in Figure 12. The dryer efficiency was calculated as the energy utilized to evaporates the water content in the food with the total energy supplied to the dryer (Erick César *et al*., 2021). Based on the results, it can be seen that the efficiency of the photovoltaic ventilation solar dryer at 40°C, 50°C and 60°C were 1.5 - 10.06%, 0.137 - 8.95% and 1% - 10.39%, respectively. Dryer efficiency decreases rapidly during the first 60 min of drying, then decreases slowly until the drying ends. This is because at the early stage of drying, there is still water content on the material's surface, which is considered as free water and can easily evaporate (Misha *et al*., 2013). Furthermore, the fluctuations in the graph are due to differences in the solar intensity each day and similar observation was reported by Mugi *et al.* (2022). The Drying efficiency is strongly influenced by the solar intensity, the ambient air velocity, inlet air temperature, surface area of collector, and the glass material used in solar drying collectors (Suherman *et al*., 2020).

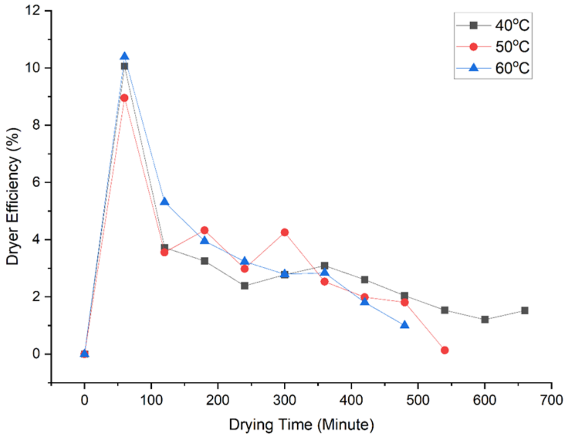

Figure 12. Dryer efficiency curve

Table 1 shows the average of dryer efficiency at 40°C, 50°C and 60°C, which are 3.109%, 3.393% and 3.915%, respectively. It can be seen that increasing drying temperature will increase the dryer efficiency. When the drying temperature increases, the dryer produces more energy, which can improve the heat and mass transfer of water from the inner part of the banana slices to the banana slices surface, resulting in rapid moisture uptake (Suherman *et al*., 2020). Based on the results, the drying efficiency in this experiment is still relatively low. This is due to the low capacity of the material being dried in the chamber, which results in a significant energy loss and reduces the efficiency of the drying equipment (Anum *et al*., 2017). Therefore, other than increasing the drying temperature, the drying efficiency can be enhanced by using a larger amount of banana slice, as there will be more water, which means more heat will be utilized for evaporation.

Table 1. The average drying efficiency of banana slices on various variables

Variable (°C)	Drying efficiency (%)
60	3.915
50	3.393
40	3.109

3.4 Scanning electron microscopy analysis

The analysis in this study aims to observe the morphological structure of dried banana slices. The SEM results can be seen in Figure 13 and 14 with 1000× and 5000× magnification, respectively. The structure of the dried banana slices tends to be irregular, but it has a smooth surface. The microstructure change is closely related to the moisture migration during the drying process. the relatively long dehydration period could provide enough time for the cell tissue of banana slices to contract and stick during the drying process, and then cause the compact and dense tissue structure of banana samples with few tiny micro-channels, which is not conducive to water diffusion and migration (Shi *et al*., 2020). Furthermore, the structures of samples dried at higher temperatures are more porous. As for surface properties, the stronger texture can be attributed to the crust layer formation on the surface of the dry material due to the migration of the solute, thus providing the dried materials with mechanical strength (Kamal *et al*., 2019). With the increase of drying temperature, the heating energy absorbed by water molecules leads to the enhancement of moisture mobility, turbulence, expansion and evaporation, causing the increase of micro -tunnels and reducing the shrinkage of organization structure, which is positive for moisture migration and the reduction of mass transfer resistance (Shi *et al*., 2020).

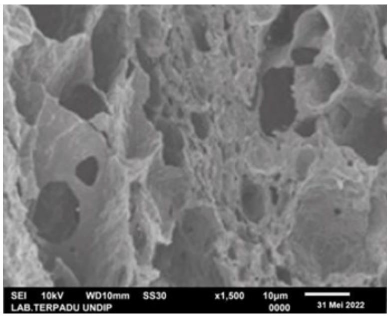

Figure 13. Morphology of banana slices with 1500× magnification

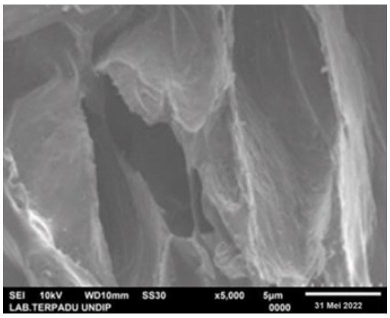

Figure 14. Morphology of banana slices with 5000× magnification

3.5 Gas chromatography mass spectrometry analysis

The drying temperature used in the chromatography gas mass spectrometry examination of banana samples from Banyumanik Market, Semarang, Central Java, was 60°C. The dominant group of chemical compounds contributing to banana flavour is the esters. Other significant groups are alcohols and carbonyl compounds

(Saha *et al*., 2018). The products not only undergo shrinkage and browning, but also lose their physiologically active ingredients and heat-sensitive nutrients (Zhao *et al*., 2023). The retention of aroma compounds depends on molecular weight, chemical group, polarity and relative volatility of compounds. The flavour of the fresh banana is adversely affected by storage and increasing storage temperature accelerated ripening, and that volatile composition at each stage varied with temperature (Saha *et al*., 2018). Not all substances found in GCMS are indicators of banana aroma. According to the test results, 20 chemical compounds were found in the banana sample with GCMS method.

The results of banana fruit components using GC-MS method shows the presence of several active compounds. From the generated chromatogram (Figure 15 and Table 2), the five compounds that have the largest area or presentation were 26.22% hexadecanoic acid, ethyl ester (CAS), 24.59% ethyl oleate, 5.47% silan, triethyl-fluoro-, 5.05% bis(2- ethylhexyl) ether, and 4.83% ascorbaric acid (Vit-C). The dominant peak in the GCMS results is hexadecanoic acid (ethyl ester), which has the ability to lower cholesterol in the blood (Tyagi and Agarwal, 2017). Hexadecanoic acid (ethyl ester) works to inhibit the enzyme cyclooxygenase (COX) II and produces selective anti-inflammatory action (Aparna *et al*., 2012). Hexadecanoic acid (ethyl ester) also has activity as an antioxidant (Shaaban *et al*., 2021).

4. Conclusion

The drying of banana slices using a photovoltaic solar dryer has been successfully implemented. The dryer has succeeded in drying banana slices from 52% to 8.57% within 8 hrs. The drying rate in the solar dryer is much higher compared to the open sun method. The efficiency of the dryer is still low at 3.5%, so it needs to be improved again. The results of scanning electron microscopy (SEM) analysis revealed that the structure of the dried banana slices tended to be irregular, while the surface remained smooth. Furthermore, gas chromatography-mass spectrometry (GCMS) identified twenty compounds in the dried banana slices. The novelty of this research is that the design of the new

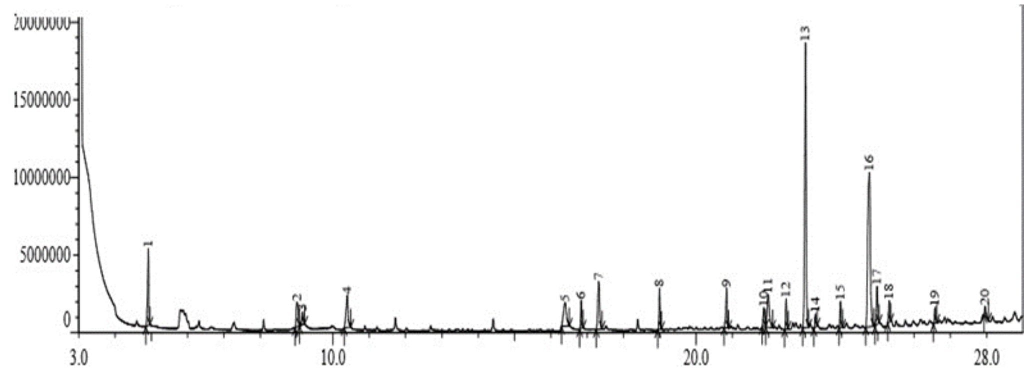

Figure 15. GCMS spectrum results of dried banana slices

Table 2. Aromatic compounds and dominant compounds detected by GCMS in dried banana slices

No	Percentage (%)	Compound
1	5.47	Silane, Triethyl-Fluoro-
2	3.02	Cyclotetrasiloxane, Octamethyl- (CAS)
3	1,00	Silane, Diethoxydiethyl-
4	4.11	1,2-Hexanediol (as)
5	4.31	Niacinamide
6	1.98	Cycloheptasiloxane, Tetradecamethyl-
7	5.05	Bis(2-Ethylhexyl) Ether
8	2.75	Hexadecamethylcyclooctasiloxane
9	3.05	Callium
10	1.75	1-Hexadecanol (Cas)
11	4.83	Ascorbaric Acid (Vit-C)
12	2.01	Eicosamethylcyclodecasiloxane
13	26.22	Hexadecanoic Acid, Ethyl Ester (CAS)
14	0.98	Isopropyl Palmitate
15	1.84	Hexadecamethyleyclooctasiloxane
16	24.59	Ethyl Oleate
17	3.23	Octadecanoic Acid, Ethyl Ester (CAS)
18	1.54	Cyclononasiloxane, Octadecamethyl-
19	1.12	Cyclononasiloxane
20	0.09	Tetracosamethylcyclododecasiloxane

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dryer has succeeded in drying banana slices quickly and with high product quality.

Conflict of interest

The authors declared no potential conflicts of interests with respect to the research, authorship and publication of this article.

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