

## Performance Evaluation of a Prototype Rotary Dryer for Granulated Palm Sugar Drying

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### ABSTRACT

*Granulated palm sugar requires efficient drying to meet industrial quality standards and accelerate production. This study aimed to evaluate the performance of a prototype rotary dryer in reducing moisture content to a maximum target of 2.5%. Tests were conducted at rotation speeds of  $23.83 \pm 0.1$  RPM and  $41.83 \pm 0.1$  RPM with drying durations of 1, 2, and 3 h using a 500-g batch capacity. All treatments were performed in triplicates, and successfully reduced moisture below the 2.5% target, meeting SNI 01-3743-2021 and the company's internal standards. The optimal condition, determined using the Simple Additive Weighting (SAW) method, was  $23.8 \pm 0.1$  RPM for 1 h, resulting in a final moisture of 2.4%, a product loss of 14.4%, and the lowest energy cost of IDR 821. Higher rotation speed increased the product loss to 55.07% due to centrifugal forces and uneven heat distribution. Sugar adhering to the cylinder walls highlighted the need for improved fin design and airflow. Future development should incorporate stable heating, expanded rotation speed (15–50 RPM) and temperature (60–80°C) variations, and automatic controls for small- to medium-scale food industry applications.*

## 1. INTRODUCTION

Granulated palm sugar is a processed product of palm sap, especially in the form of fine crystalline granules that are easily dissolved, the result of diversifying molded sugar with low moisture content, high practicality, and high shelf life (Kurniawan *et al.*, 2018). This sugar is often referred to as low-calorie sugar. In addition, palm sugar has a lower glycemic index of around 35, while granulated sugar has a glycemic index of 58 (Rimbawan & Siagian, 2004). This difference makes granulated palm sugar safer to consumer because it does not cause a drastic spike in blood sugar levels, making it more suitable for diabetics and individuals who maintain stable blood sugar levels. Its nutritional content includes carbohydrates, protein, calcium, and antioxidants (Fatriani & Yuniarti, 2019), and acts as a natural sweetener for non-sugarcane while reducing the import of refined sugar (Pratama *et al.*, 2015). Based on FAO (2023), global palm sugar production is growing by around 5% per year, with total production reaching 11.2 million tons in 2023. According to Navaityte *et al.* (2020), there is an increase in demand for granulated palm sugar in the international market, especially in North America, Europe, and the Asia Pacific. In fact, Bridges (1989) projects that global demand for this product can increase by 10–15% annually until 2029. To compete globally, granulated palm sugar must meet quality standards, especially moisture content, because the high moisture content makes the product easy to melt, sticky, and not durable (Pratama *et al.*, 2015). SNI 01-3743-2021 sets a maximum moisture content limit of 3%, but for premium quality, a target of 2.5% is required (BSN, 2021). At PT Daud, granulated palm sugar comes from the crushing of palm sugar with an initial moisture content of 4–5% which is dried up to 2.5%. Static drying takes 6–8 h, while rack dryers are more stable and hygienic than solar dryers, but still face uneven heat distribution that need for manual reversals, and result in non-uniform quality (Muhandri *et al.*, 2020). This is influenced by suboptimal drying operation conditions so that the final moisture content remains high (Meldayanoor *et al.*, 2019).

Previous studies have focused only on rack dryers, static dryers, or conventional hot air-based systems, and have not evaluated the use of small-scale rotary dryers with continuous mixing for granulated palm sugar products (Muhandri *et al.*, 2020). There has been no study assessing the performance of a rotary dryer based on a simple heat source such as a hair dryer, especially in reducing the moisture content to a premium standard of 2.5%. In addition, the effect of rotational speed and drying time on scattered loss, heating homogeneity, and energy efficiency has also not been systematically studied. Previous research also did not use multi-criteria approaches such as Simple Additive Weighting (SAW) to determine the optimal combination of operations. To address this gap, this study developed and tested a prototype of a small-scale rotary dryer with a hair dryer heat source that can produce even heat distribution without manual reversal. This study evaluates its performance in reducing the moisture content of granulated palm sugar from 4–5% to 2.5%, analyze the influence of operating parameters, and determines the best combination to shorten drying time and improve quality uniformity.

## 2. MATERIALS AND METHODS

### 2.1. Time and Place

This research was carried out from January to May 2024. Dryer testing and sampling were carried out in Bogor Regency, precisely at PT. Daud Teknik Maju Pratama, Agricultural Food Processing Engineering Laboratory, and Robotics and Control Instrumentation Laboratory, located in the Department of Mechanical and Biosystems Engineering, Faculty of Agricultural Technology, IPB University.

### 2.2. Tools and Materials

Main material used in this experiment was palm sugar. Important tools included (a) Rotary dryer machine (Figure 1), (b) Digital Tachometer, (c) Stopwatch, (d) Digital thermo-hygrometer, (e) Black digital thermometer (temperature), (f) Digital scale, (g) Analytical scale, (H) Oven, (h) Clamp meter, (i) Multitester.

Before the implementation of the research, it is necessary to make careful preparations, especially related to the readiness of the equipment for the preliminary research process and performance testing on the rotary dryer machine. In performance testing on rotary dryers, it is important to ensure the accuracy of each tool used to minimize the possibility of errors in data collection. In addition, it is also necessary to prepare all the necessary materials during the performance testing stage of the rotary dryer machine.

### 2.3. Stages of Data Collection

Data collection began with preparing materials and tools, as well as checking the rotary dryer and hair dryer machine. Hair dryer is practical, easy to control, stable, and produce a constant and directed flow of hot air. Observations were carried out on the dimensions of the engine components, the specifications of the drive motor, the transmission system,

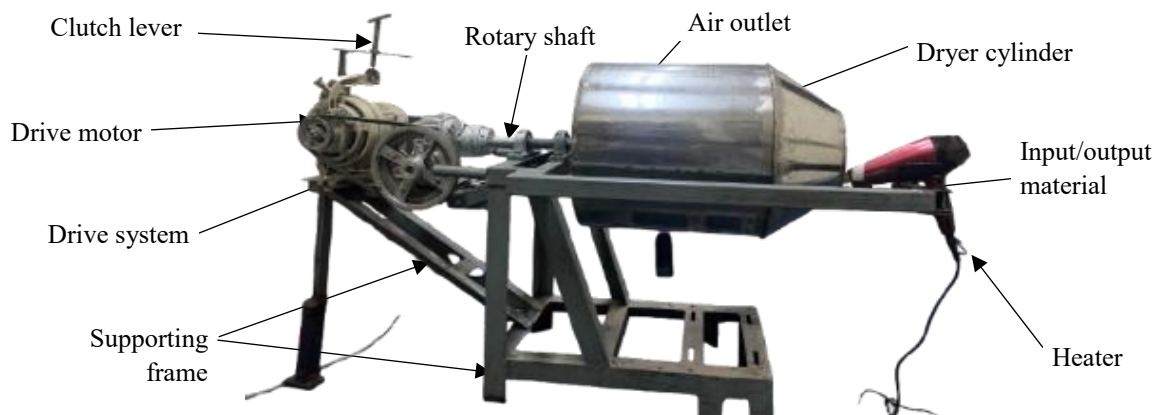


Figure 1. Components of rotary dryer machine to dry granulated palm sugar

the heating temperature, and the air speed of the hair dryer (70 °C, medium speed). The initial moisture content of the granulated palm sugar was measured using a 105 °C drying oven three times, with an average of 4.18% (wet base). This study used a factorial Complete Random Design (RAL) consisting of two main factors, namely the rotational speed and the drying time. The first factor, namely the rotational speed, consisted of two levels, namely 23.83±0.1 RPM and 41.83±0.1 RPM. The second factor, the drying time, consisted of three levels, namely 1, 2, and 3 h. Thus, there were 6 combinations of treatments tested in this study. Each combination of treatments was repeated three times to ensure data consistency and to calculate trial errors. The use of this factorial experimental design allowed the study to analyze the effect of the interaction between the rotation speed and drying time on the performance of the drying machine and the quality of the granulated palm sugar produced.

During the experiment, the control of the ambient temperature was carried out using a closed test chamber to avoid temperature and humidity variability caused by outside environmental conditions. This temperature control is very important because temperature and humidity can affect the drying rate and accuracy of material moisture content measurements. The temperature in the drying chamber was maintained by monitoring the air temperature using a digital thermo-hygrometer that provides real-time data on temperature and humidity. The setting of the air temperature at 70 °C was chosen because it is quite effective for drying the granulated palm sugar (Erwin & Meutia 2020). This temperature is able to dry material without damaging the nutritional components and maintaining the quality of the product, as well as according to the expected temperature in the drying process (Acimsard *et al.*, 2015).

Before being used in the experiment, all the measuring instruments used in the study, such as digital tachometers, thermo-hygrometers, and stopwatches, had undergone a calibration process to ensure the accuracy of the measurements. A digital tachometer, which is used to measure the rotational speed of a motor, is calibrated by comparing its measurement results with known speed standards and has an accuracy of up to ±0.1 RPM. Similarly, the thermo-hygrometer has been tested and calibrated to ensure accurate temperature and humidity measurements at the three main points in the drying chamber. The stopwatches used to record drying times were also tested for accuracy, with accuracy capabilities of up to 0.01 second, to ensure the reliability of data generated.

### 2.3.1. Optimum Holding Capacity of Drying Batches

The batch capacity in the drying process describes the amount of load, both in mass and volume, that can be handled by a machine in a single operational cycle. To determine this capacity, the first step is to calculate the volume of the main cylinder ( $V_s$ ) of the dryer, which is obtained through Equation (1):

$$V_s = (\pi \times r^2 \times t) - (3 \times V_\Delta) \tag{1}$$

where  $r$  is radius of cylindrical circle (m),  $t$  is cylinder length (m),  $V_\Delta$  is volume of fins in cylinder (m<sup>3</sup>).

Drying volume capacity ( $K_{VP}$ ) was calculated according to Equation (2) using assumption that optimal composition recommendations for the drying process is about 25% of the material and the remaining 75% left as space for air circulation (POA, 2022). While, optimum drying capacity based on mass ( $K_{TP}$ ) was calculated using Equation (2):

$$K_{VP} = 0.25 \times V_s \tag{2}$$

$$K_{TP} = \rho_t \times K_{VP} \tag{3}$$

### 2.3.2. Scattered Loss

Scattered loss ( $S_T$ ) is the percentage obtained from the comparison between the mass of the material lost due to scattering ( $m_{tc}$ ) divided by the mass of the raw material used ( $m_o$ ) (Rangkuti *et al.*, 2012). This loss was calculated as follows:

$$S_T = \frac{m_{tc}}{m_o} \times 100\% \tag{4}$$

### 2.3.3. Electric Energy Consumption and Cost

The energy requirements of a rotary dryer machine for drying granulated palm sugar was calculated based on the power ( $P$ ) required by the single-phase electric motor. In this system, the power ( $P$ ) of the electric motor was measured from voltage ( $V$ ) and current ( $I$ ) considering power factor ( $\phi$ ). The energy ( $W$ ) requirement was calculated from Equation (6).

$$P = V \times I \times \cos \varphi \tag{5}$$

$$W = P_{tot} \times t \tag{6}$$

where  $W$  is presented in kWh,  $P_{tot}$  is total power of electric motor (kW), and  $t$  is working time (h).

Finally, the electricity cost ( $T_{BL}$ ) was calculated by multiplying energy consumption with electricity tariff ( $T_L$ ) as detailed in Equation (7):

$$T_{BL} = W \times T_L \tag{7}$$

**2.3.4. Drying quality**

Drying quality refers to quality parameters that have been standardized for granulated palm sugar products. In this study, the parameters analyzed were the moisture content in the granulated palm sugar. The final stage of this analysis was comparing the initial and the final moisture content to evaluate the performance of the rotary dryer. The moisture content ( $K_a$ ) of the granulated palm sugar was measured using gravimetric method and was calculated using Equation (8):

$$K_a(\text{Wet Basis}) = \left[ \frac{M_{ga} - M_{gt}}{M_{ga}} \right] \times 100\% \tag{8}$$

where  $M_{ga}$  and  $M_{gt}$  is respectively mass of palm sugar sample (g) final granulated palm sugar (g).

**2.3.5. Total Solid Yield**

Total solid yield is an important indicator in the evaluation of drying results, which describes the content of solids that remain after the drying process has taken place. A high solid yield indicates a success in reducing moisture content without removing the main components from the material. The total solid yield was calculated by assuming that no scattered loss occurs during the drying process, as detailed in Equation (9):

$$\text{Total solid yield} = [m_o - (m_o \times (K_{A0} - K_{At}))] \tag{9}$$

where  $m_o$  is mass of initial granulated palm sugar (g),  $K_{At}$  is final moisture content of the material after drying (wet base),  $K_{A0}$  is initial moisture content of the material before drying (wet base).

**2.3.6. Simple Additive Weighting (SAW)**

The Simple Additive Weighting (SAW) method was used to determine the optimal treatment combination of several performance criteria of rotary dryers. SAW calculates the total score of each alternative (a combination of rotational speed and time) based on the normalization value and weight of each criterion. The SAW score for each alternative was calculated using Equation (10):

$$V_i = \sum w_j \times r_{ij} \tag{10}$$

where  $V_i$  is alternate end value  $i$  (combination of rotational speed and drying time),  $w_j$  is weight of the  $j^{\text{th}}$  criterion,  $r_{ij}$  is the normalization value of the  $i^{\text{th}}$  alternative to the  $j^{\text{th}}$  criterion, and  $n$  is total number of criteria.

The criteria used in this study included scattered loss (%), electricity cost (IDR), final moisture content (%), and total solids yield (g). The direction of the criteria is to get high total solid yield, while lowering the value of scattered lost, electricity cost, and final moisture content. For normalization, the values were grouped into two categories, namely: benefit (the bigger the better), using equation (11); and cost (the smaller the better), using equation (12):

$$r_{ij} = \frac{x_{ij}}{x_j(\text{max})} \tag{11}$$

$$r_{ij} = \frac{x_j(\text{min})}{x_{ij}} \tag{12}$$

The criteria weight was ordered according to the importance level of each criterion. The final score ( $V_i$ ) was calculated using the SAW formula (Equation 10). The alternative with the highest  $V_i$  value is selected to be the most optimal treatments.

## 2.4. Data Analysis

The experimental data were statistically analyzed for the mean, and standard deviation. Analysis of variance was performed to identify the influence of experimental factors on the drying results. In addition, to determine the most optimal treatment, further analysis was carried out using the Simple Additive Weighting (SAW) method. With SAW, the total value of each combination of rotational speed and drying time was calculated based on the weight and normalization value of the analyzed criteria, namely scattered loss, energy cost, final moisture content, and total solids. The highest SAW score indicates the most optimal combination of treatments to achieve the desired drying quality.

## 3. RESULTS AND DISCUSSION

### 3.1. Technical and Functional of Rotary Dryer Prototype

The machine used in this study is an innovation from a static drying system to a dynamic system with automatic stirring in a cylindrical drying chamber. The design of this rotary dryer machine uses the principles of conduction and convection in the drying process. Conduction occurs when hot air encounters the surface of the material, heating the material and causing water evaporation. Convection occurs when hot air moves through the material, bringing moisture out of the material. In addition, the turbulence generated by the rotation of the cylinder accelerates air circulation and increases evaporation efficiency, although at high speeds, turbulence also has the potential to cause material losses (scattered shrinkage) due to strong centrifugal forces.

This machine is an innovation from a static drying system to a dynamic system with automatic stirring in a cylindrical drying chamber. This rotary dryer machine has a horizontal cylindrical design with an indirect heating system using a hair dryer. The cylinder is equipped with three flights (lifting flights) to stir the material during rotation. The dimensions of the main tube (cylinder) are 40 cm in diameter and 40 cm long, resulting in an effective volume of 50,241.6 cm<sup>3</sup>. To ensure the material movement space and optimal hot air circulation during the drying process, a material filling fraction of 25% of the total net volume is used (POA, 2022). With this fraction, the volumetric capacity ( $K_{VP}$ ) of the machine is 12,560.4 cm<sup>3</sup>. The capacity of the material in the form of mass is calculated using the density of the granulated palm sugar material before drying. The results of the measurement of granulated palm sugar density can be seen in Table 1.

Table 1. Measurement results of density (g/cm<sup>3</sup>) of granulated palm sugar material

Repetition	Volume cm <sup>3</sup>	Density (g/cm <sup>3</sup> )	Average Density (g/cm <sup>3</sup> )
1	50	0.60	0.62±0.035
2	50	0.67	
3	50	0.67	
Average	50	0.65	
1	100	0.60	
2	100	0.57	
3	100	0.62	
Average	100	0.60	
1	150	0.65	
2	150	0.59	
3	150	0.61	
Average	150	0.62	

The calculation results showed that the rotary dryer machine had an optimum capacity of 7.8 kg per batch, assuming a filling of 25% of the cylinder volume, but the operational test found that the machine was only stable at a capacity of 500 g, so that the cylinder rotated constantly. The engine uses a single-phase electric motor with a mechanical clutch speed control system in the form of a lever at 23.83±0.1 RPM and 41.83±0.1 RPM, but without a torque reduction mechanism, so that performance is unstable when the load increases. Preliminary research shows that the machine is not ideal for drying granulated palm sugar directly from the moisture content of 14% and is more suitable as a second stage dryer to the moisture content of ≤ 2.5% without caramelization, so it requires an increase in motor power, a change of the transmission system to a gear reducer or gearhead motor, and an adjustment of hot air discharge to approach optimal capacity.

### 3.2. Scattered Loss

Scattered loss describes the percentage of material loss during the drying process, calculated based on the ratio between the mass of material lost and the initial mass of the raw material of 500 g. This calculation is important to know the extent of the efficiency of the tool in minimizing material losses (Sutejo *et al.*, 2023). A diagram of the relationship between the rotational speed of the cylinder and the drying time to the scattered loss of the rotary dryer machine is shown in Figure 2.

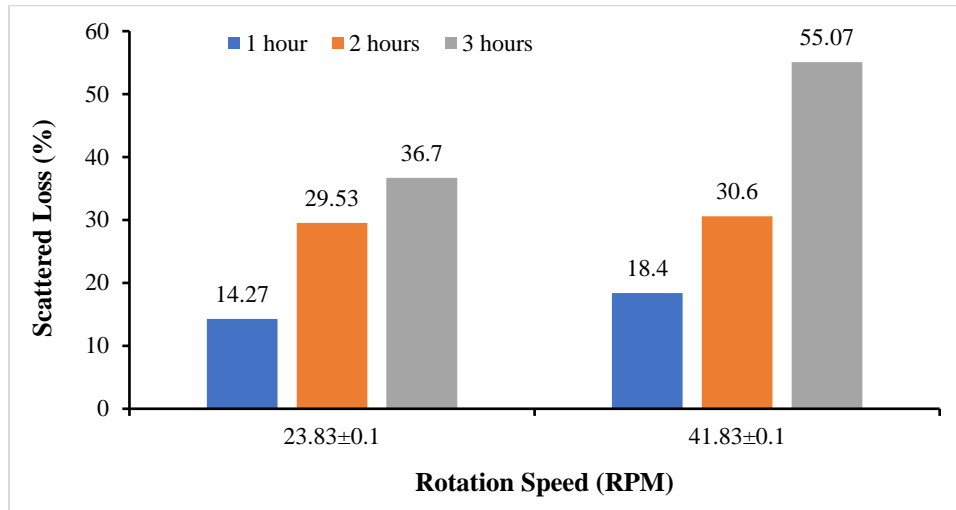


Figure 2. Effect of rotational speed (RPM) and drying time on the average of scattered loss

Based on the data obtained, it can be seen that the increase in drying time and the increase in rotation speed contribute to the increase in the value of scattered shrinkage. At a rotary speed of 23.83±0.1 RPM, the shrinkage value was recorded at 14.27% for a 1-hour batch, increasing to 29.53% for a 2-hour batch, and 36.70% for a 3-hour batch, while at a rotary speed of 41.83±0.1 RPM, the shrinkage values were 18.40% (1-hour batch), 30.60% (2-hour batch), and 55.07% (batch 2-hour), and 55.07% (batch) respectively 3 hours). This shows that the longer the drying time, the material loss tends to increase as the moisture content decreases, so that the material becomes lighter and easily carried by hot air or driven by drum rotation. At the same drying time, the scattered shrinkage value is always higher at a rotational speed of 41.83±0.1 RPM compared to a rotational speed of 23.83±0.1 RPM. For example, in a 3-hour time batch, the shrinkage reached 55.07% at high rotary speed compared to 36.70% at low rotary speed. This can be explained technically by the influence of an increasing centrifugal force as the drum rotation speed increases, which causes more material to be pushed towards the wall and out of the drying chamber if the holding or holding system is not optimal. The documentation of the shrinkage scattered after the drying process is shown in Figure 3.



Figure 3. Observation of scattered sugar loss after the drying process: (a) Upper frame, (b) Inlet, (c) Bottom frame

Based on visual documentation and direct observation, some materials are lost during drying due to suboptimal open design. Ants' sugar can be seen scattered on some of the main parts of the machine. Granulated palm sugar spatters can be seen in the area of the material intake gap at the front of the cylinder, the connection area between the

cylinder and the support frame, under the cylinder, and the working floor around the engine, and the steam exhaust hole at the rear of the cylinder. To overcome this, it is necessary to modify the design of the steam exhaust so that product particles are not wasted with water vapor.

The physical interpretation for this phenomenon is that at high speeds, the greater centrifugal force causes the material to be pushed more quickly towards the cylinder wall and out of the drying chamber, increasing the material loss. In addition, the high value of scattered shrinkage at  $41.83 \pm 0.1$  RPM also reflects the limitations of the prototype design and is one of the main sources of error in the experiment. Under extreme centrifugal force conditions, some of the granulated palm sugar not only escapes through the steam intake and discharge gaps but is also difficult to recollect thoroughly, so that the measured dispersed shrinkage mass is potentially slightly lower than the actual loss. This causes the calculated material efficiency to tend to be more optimistic than the actual field conditions, and needs to be improved in the development of the next machine design.

### 3.3. Engine Energy Requirements

The electrical power requirement is determined based on the results of voltage and current measurements conducted. In this test, the machine used is a rotary dryer machine with the components that make up the construction of this machine, namely a 1-phase electric motor and a hair dryer. Measurements were made at two variations of cylinder rotational speed, namely  $23.83 \pm 0.1$  RPM and  $41.83 \pm 0.1$  RPM, using 500 g of material. Power measurements are carried out using ampere pliers or clamp meters to determine the magnitude of the current from each cable without load and with load (Sutejo *et al.*, 2020). The results of the calculation of the electrical power required by the motor at rotational speeds of  $23.83 \pm 0.1$  RPM and  $41.83 \pm 0.1$  RPM, respectively, with a material weight of 500 g, can be seen in Table 2.

The time of use of the machine per one batch treatment is 1 hour, 2 hours, and 3 hours, with two variations of rotation speed, namely  $23.83 \pm 0.1$  RPM and  $41.83 \pm 0.1$  RPM, each of which has 3 repeats. Based on this data, it is known that the power needs for an electric motor for drying and sugar are for an electric motor with a rotational speed of  $23.83 \pm 0.1$

Table 2. Power requirements of the prototype of the rotary dryer of granulated palm sugar 500 g, optimum capacity

Tools	Voltage (V)	Electric Current (A)	Power (W)
Electric Motor ( $23.83 \pm 0.1$ RPM)	220	0.90	168.3
Electric Motor ( $41.83 \pm 0.1$ RPM)	220	0.97	181.4
Hair Dryer	220	2.00	400.0

RPM, which is 168.3 watts, and for a rotational speed of  $41.83 \pm 0.1$  RPM, which is 181.4 watts. Meanwhile, for the hair dryer, the power used is 400 watts. This is also in accordance with the product specifications listed. From the information on the power requirement, the electricity requirement, and the total cost per treatment for the operated material of 500 g, it can be seen in Table 3.

Table 3. Electricity cost requirements prototype rotary dryer machine optimum capacity 500 g

Speed and Spinning (RPM)	Time	Electric Motor Power (kW)	Hair Dryer Power (kW)	Electricity Requirement (kWh)	Electricity Tariff (Rp/kWh)	Total Electricity Cost (Rp)
$23.83 \pm 0.1$	1	0.1683	0.4	0.5683	1444.7	821
	2	0.1683	0.4	1.1366		1642
	3	0.1683	0.4	1.7049		2463
$41.83 \pm 0.1$	1	0.1813	0.4	0.5813	1444.7	840
	2	0.1813	0.4	1.1626		1680
	3	0.1813	0.4	1.7439		2519

The electricity tariff used as a reference refers to the B-2/TR group with a power of 6,600–200 kVA, amounting to Rp1,444.70 per kWh (May 2025). At a low speed of  $23.83 \pm 0.1$  RPM, electricity consumption was recorded at 0.5683 kWh (Rp821) for 1 hour, 1.1366 kWh (Rp1,642) for 2 hours, and 1.7049 kWh (Rp2,463) for 3 hours. At a high speed of  $41.83 \pm 0.1$  RPM, consumption was recorded at 0.5813 kWh (Rp840) for 1 hour, 1.1626 kWh (Rp1,680) for 2 hours, and 1.7439 kWh (Rp2,519) for 3 hours.

Thus, the total cost of electricity increases with the time of the engine and the speed of the motor's rotation. This is supported by Romadhon *et al.* (2020) that the duration of time and motor speed have a significant effect on energy consumption. The longer the operational time, the energy accumulation increases proportionately, so the efficiency of time and rotation speed needs to be considered to reduce electricity costs.

### 3.4. Temperature and Relative Humidity (RH) Profile of End of Drying

Based on the data obtained, the results of the study showed a clear influence of the variation in drying time and cylinder rotation speed on rotary dryers. The humidity and temperature profiles at the end of the drying process of granulated palm sugar materials can also be seen in Figure 4 and Figure 5. According to Van't Lan (2011), rotary dryers work on the principle of evaporation of water from materials through the difference in air humidity and temperature by utilizing hot air flow as well as cylindrical rotational movements to speed up the drying process.

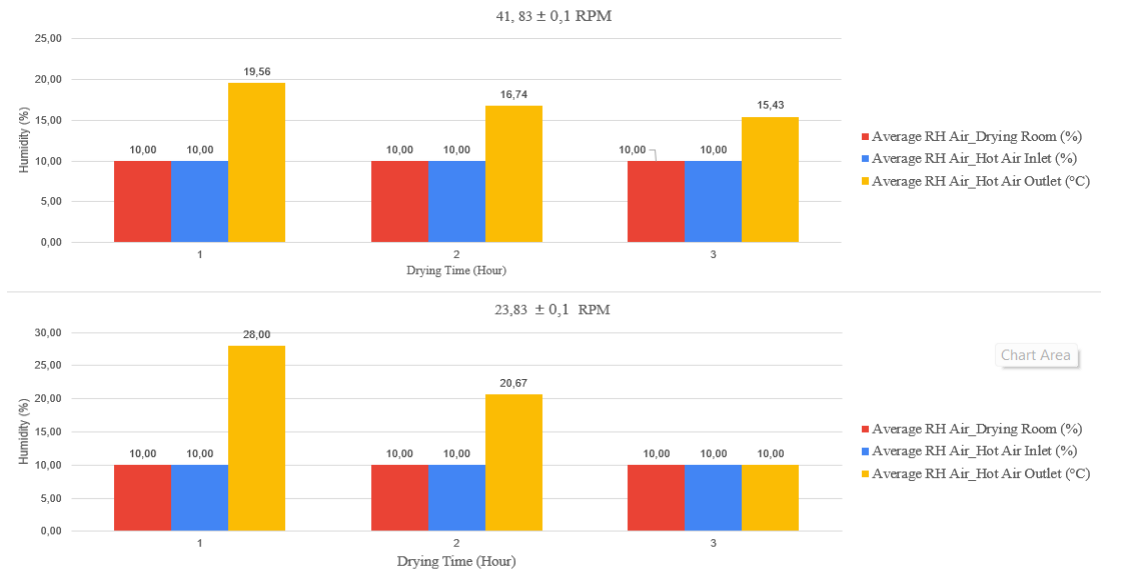


Figure 4. Air humidity profile at the end of the drying process

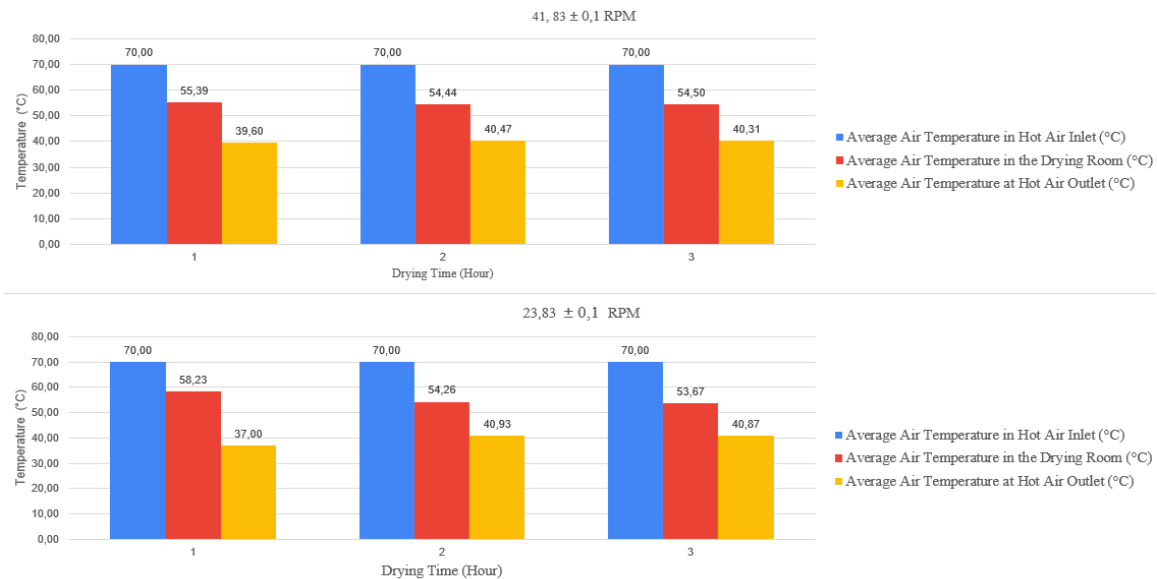


Figure 5. Air temperature profile at the end of the drying process

The results showed that the relative humidity (RH) in the material and the incoming air were stable at 10% throughout the treatment, indicating that the drying environment conditions were under control. Variations can be seen in the RH of the air out, where in the  $41.83 \pm 0.1$  RPM rotation, the value decreases from 19.56% (1 hour) to 15.43% (3 hours), while in the  $23.83 \pm 0.1$  RPM rotation, it decreases from 28% (1 hour) to 10% (3 hours). This shows that the longer the drying time, the lower the RH of the air coming out because the moisture content of the material is reduced. According to [Gómez-de la Cruz \*et al.\* \(2015\)](#), the increase in RH is due to water evaporation, but in this condition, the RH no longer increases because the water in the material has evaporated. At  $23.83 \pm 0.1$  RPM rotation for 3 hours, the same RH value on the material and outlet indicates drying is complete. The incoming air temperature is maintained at  $70.00$  °C as a source of heat energy, but it does not last until the end of the process because it is absorbed by materials to evaporate water. In addition, open ducts cause heat to be lost to the environment, according to the findings of [Has \*et al.\* \(2021\)](#) that large holes accelerate heat loss.

At low revs ( $23.83 \pm 0.1$  RPM), the inlet and exit temperature difference is quite large, which is  $33.00$  °C in 1-hour batch, then decreases to  $30.40$  °C (2 hours) and  $29.07$  °C (3 hours). This decrease indicates that the less moisture content of the material, the less heat is absorbed, so more heat escapes along with the exhaust air. In contrast, at high revs ( $41.83 \pm 0.1$  RPM), the output temperature is relatively stable in the range of  $39.60$ – $40.47$  °C with a difference of  $29$ – $30$  °C, indicating less efficient heat transfer due to the shorter shelf life of the material. This condition makes the heat not fully utilized for evaporation, so that the drying process is less than optimal. The results of the observation of the material attached to the cylinder wall and flights are shown in Figure 6.

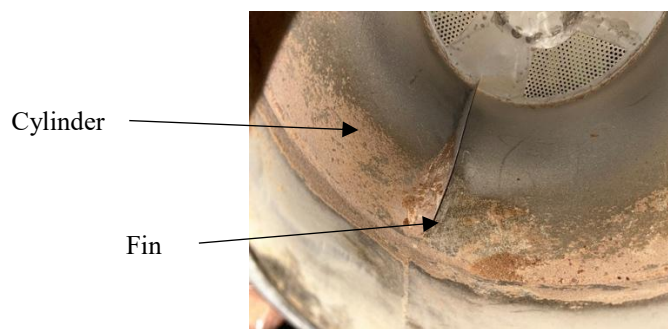


Figure 6. Granulated palm sugar attached to the wall of the cylinder and the fins

To overcome these problems, the selection of cylindrical materials can be considered for non-stick materials such as Teflon material or polytetrafluoroethylene material, which is a type of fluoropolymer plastic with properties that are non-sticky, heat-resistant, and resistant to chemicals. That way, the greater the temperature drop between the incoming air and the outgoing air, the more heat is absorbed and utilized by the material for the drying process. At low rotations, the temperature drop is greater and indicates an intensive heat absorption process. At high revs, the temperature drop is smaller and tends to be stable, which indicates that heat transfer does not take place optimally because the contact time between the material and the hot air is too short. Occurs so that the amount of evaporated water is higher and the drying speed is faster. The difference between the air temperature of the dryer and the temperature of the material triggers the transfer of steam that leaves the material ([Kurniawan \*et al.\*, 2020](#)).

### 3.5. Moisture Content Resulting from Drying

The testing of the quality of granulated palm sugar in this study refers to the quality of the moisture content of granulated palm sugar. Moisture content testing is carried out in accordance with SNI 01-2891- 1992 on how to test food and beverages ([BSN, 1992](#)). According to the granulated palm sugar moisture content quality standard (SNI) 01-3743-2021, which is good for sale in the international market, it has a moisture content of  $\leq 3\%$  ([BSN, 2021](#)). The initial moisture content measurement was carried out three times as a form of replication, and the average moisture content was obtained at around  $4.17 \pm 0.064\%$ . This value is still above the limit stipulated in SNI 01-3743-2021. Meanwhile, post-process moisture content measurements are carried out on each sample that has been dried, with

different time and rotation speed treatments. Visualization of the relationship between the moisture content of the material to the drying time, and rotational speed (RPM) with the target moisture content is shown in Figure 7.

Based on the comparison graph of the final moisture content to the drying time and rotary speed of the rotary dryer, the entire treatment lowered the moisture content to below 2.5%, stricter than SNI 01-3743-2021 of 3%. At 1 hour of drying, a speed of  $41.83 \pm 0.1$  RPM yielded 1.9% compared to 2.4% at  $23.83 \pm 0.1$  RPM, confirming that the high rotary speed improved the initial efficiency of drying (Effendy *et al.*, 2018; Raisa *et al.*, 2024), but at 3 hours the result was the same, which was 1.8%, in line with Geankoplis (2003), Sembada *et al.* (2020), and Sutejo *et al.* (2021), that bound water requires more energy and high temperatures and long durations significantly reduce water content. Rotary dryers of 1–3 hours (1.8–2.4%) are more efficient than conventional methods: natural 3.91% (Irundu *et al.* 2020), mechanical oven 2.72%, electric oven 2.97% (Meldayanoor *et al.*, 2019), LPG cylinder rack 8 h (Soolany *et al.*, 2023), because it uses a short time, low temperature, without gas, only using a hair dryer, so it is efficient, practical, economical, and worthy of being recommended as the main alternative for granulated palm sugar drying.

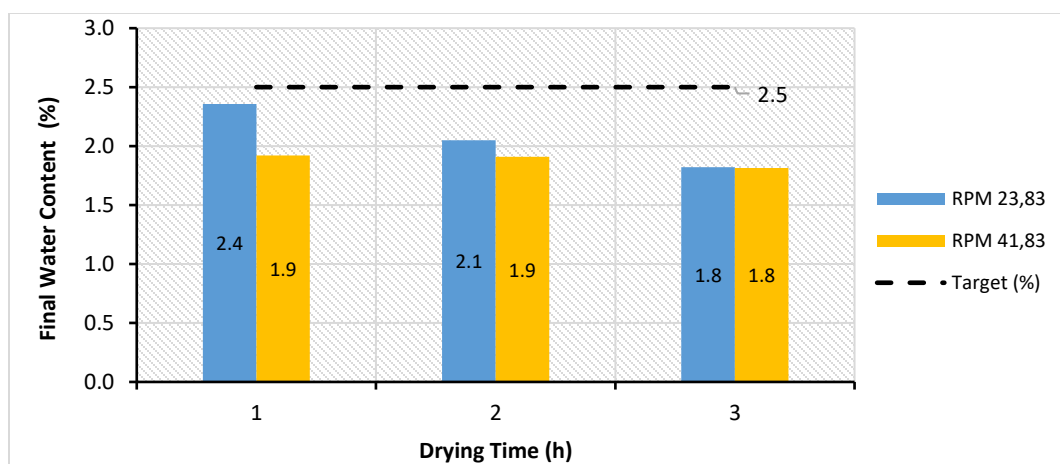


Figure 7. Visualization of the relationship between the moisture content of the material to the drying time, and the rotational speed (RPM) with the target moisture content

### 3.6. Total Solid Yield

In this study, tests were carried out on two variations of cylinder rotation speed, namely  $23.83 \pm 0.1$  RPM and  $41.83 \pm 0.1$  RPM, each for 3 hours of drying in stages (1 hour/batch). The results of the total solids measurement from each batch are presented in Table 4. The data shows that a rotational speed of  $23.83 \pm 0.1$  RPM results in higher total solids than  $41.83 \pm 0.1$  RPM, especially in the first and second hours. In the first hour, the highest total solids were recorded at 490.88 g, while a speed of  $41.83 \pm 0.1$  RPM yielded 488.70 g. This difference shows that the drying process at a speed of  $23.83 \pm 0.1$  RPM is more effective in reducing moisture content without removing solids. In the second batch, with a time of two hours, a similar pattern still continued, namely  $23.83 \pm 0.1$  RPM yielded 489.35 g, while  $41.83 \pm 0.1$  RPM remained 488.65 g. Only at the third hour, the two treatments showed very close results, namely 488.20 g for a rotational speed of  $23.83 \pm 0.1$  RPM and 488.17 g for a rotational speed of  $41.83 \pm 0.1$  RPM, which indicates that the drying process is starting to reach equilibrium, with a smaller change in moisture content.

Thus, if the total solids are used as the main benchmark, then it can be concluded that the speed of  $23.83 \pm 0.1$  RPM is superior in maintaining the mass of solids during drying. This rate results in a greater total value of solids in two-thirds of the process duration, making it more effective at maintaining material quality. Meanwhile, a speed of  $41.83 \pm 0.1$  RPM indicates stability, but is less than optimal in retaining solids in the early phase of the process. Therefore, in the context of drying materials with a high efficiency target against total solids, the use of a rotational speed of  $23.83 \pm 0.1$  RPM is more recommended. This is in line with the research of Romadhon *et al.* (2020), where the rotational speed and duration of the drying process play an important role in maintaining the stability of heat distribution in materials.

Table 4. Total solid yield from drying at different rotational speed and duration

Rotational Speed (RPM)	Time (h)	Total Solid Yield	
23.83±0.1	1	490.88 g	98.18 %
	2	489.35 g	97.87 %
	3	488.20 g	97.64 %
41.83±0.1	1	488.70 g	97.74 %
	2	488.65 g	97.73 %
	3	488.17 g	97.63 %

### 3.7. Determination of Optimum Drying Conditions

The determination of the optimal conditions for drying granulated palm sugar using a rotary dryer machine is carried out through a quantitative approach based on the Simple Additive Weighting (SAW) method. This method was chosen because of its good ability to solve multi-criteria decision-making problems, especially when there are trade-offs between criteria, such as product quality, energy efficiency, and process time (Biswas & Chaki, 2022). In this study, five evaluation criteria were used, namely final moisture content, scattered shrinkage, electricity cost, and total solids, with two main treatment variables, namely rotation speed and drying duration. The SAW process begins by normalizing the values on each criterion so that the scale is comparable, with the benefit approach (the bigger the better) using the Equation 11 and cost (the smaller the better) using the Equation 12.

After the normalization process, the value of each criterion is multiplied by the predetermined weight, i.e., scattered shrinkage 0.35; final moisture content 0.30; total solids 0.20; and electricity cost 0.15. This weighting is structured so that alternative assessments consider the balance between product quality and operational efficiency. The final value ( $V_i$ ) is then obtained from the sum of the results of multiplying the normalization value by the respective weight, thus allowing the determination of the most optimal treatment combination. A summary of the results of alternative rankings based on SAW scores can be seen in Table 5.

Table 5. Results of determining the optimal conditions of the SAW method

Alternatives	SAW Score	Rangkings
23.83±0.1 RPM - 1 hour	0.9250	1
41.83±0.1 RPM - 1 hour	0.9014	2
41.83±0.1 RPM - 2 hours	0.7198	3
23.83±0.1 RPM - 2 hours	0.7007	4
23.83±0.1 RPM - 3 hours	0.6850	5

Systematically, the results of the evaluation were separated between the performance aspects of the tool and the response of the material to the drying treatment. The performance of the appliance is represented by the cost of electricity, which relates to the energy efficiency and thermal performance of the appliance. Meanwhile, the quality of the material is evaluated through the final moisture content, scattered shrinkage, and total solids, which reflect the final quality of the product. The results of the SAW processing showed that the treatment with low speed (23.83±0.1 RPM) and a drying duration of 1 hour obtained the highest score of 0.9250, which means that it is the most optimal condition. This treatment is able to produce a final moisture content of 2.4%, a scattered shrinkage of only 14.27%, and the lowest electricity cost is Rp821, with 9.12 g/hour. Compared to other treatments, this condition shows the best balance between product quality and process efficiency.

Meanwhile, for other alternatives, such as high-speed use or longer durations, it produces some side effects. The use of high rotary speeds (41.83±0.1 RPM) over long periods of time tends to increase product shrinkage and energy costs. Therefore, alternative mechanisms such as increasing time or speed are not linear to better outcomes, and can actually have a negative impact if not designed in a balanced way.

### 3.8. Comparison with Previous Research

#### 3.8.1. Energy Efficiency

Comparisons with conventional methods should be made based on the energy consumption required to achieve the targeted moisture content, which is 2.5% or lower, as well as the required drying time. The rotary dryer in this study has a rotational speed of 23.83 RPM, which succeeded in reducing the moisture content of granulated palm sugar to 2.4% within 1 hour. The energy consumption used is 0.5683 kWh (IDR 821) for a batch of 500 g.

As for conventional drying, such as oven drying based on literature (Meldayanoor *et al.*, 2019), drying sugar with an oven takes about 6-8 hours to achieve a moisture content of 2.5%. The use of an electric oven at a temperature of 100°C records a higher energy consumption per batch, which can reach around 2.72 kWh for batches of similar mass, resulting in a higher cost (Rp3,935) per batch. Other studies with LPG rack dryers have resulted in drying times of up to 8 hours, and although it is more stable than solar drying, the energy used is higher, mainly due to the need for more LPG gas.

In terms of energy per kilogram of granulated palm sugar, rotary dryers show very significant advantages with lower energy consumption and much shorter drying times compared to both conventional methods. The comparison table can be seen in Table 6. It is clear that rotary dryers have great advantages in terms of energy efficiency and drying time compared to conventional drying methods.

Table 6. Comparison of drying energy efficiency

Drying Method	Drying Time (h)	Energy Consumption (kWh)	Energy Cost (IDR)	Final Moisture Content (%)
Rotary Dryer (23.83 RPM)	1	0.5683	821	2.4%
Rotary Dryer (41.83 RPM)	1	0.5813	840	1.9%
Electric Oven (100 °C)	6-8	2.72	3.935	2.5%
LPG Rack Dryer	8	1*	22.000	3.0%

\*) One bottle for 8 h operation time at a price of 22,000 IDR.

#### 3.8.2. Drying Time and Moisture Content

Rotary dryers (23.83 RPM) can lower the granulated palm sugar moisture content to 2.4% in 1 hour, which is more efficient compared to oven drying, which takes 6-8 hours to achieve similar moisture content. Even at high speeds (41.83 RPM), the engine can still produce the same moisture content (1.8%) in 3 hours. On the other hand, drying LPG racks under conventional conditions can take 8 hours, and even in some cases, drying cannot reach a moisture content below 3%. Table 6 also reveals a quantitative comparison of the drying time and moisture content achieved for each drying method. We can see that rotary dryers are much more efficient, not only in energy, but also in terms of time to reach quality standards (moisture content < 2.5%).

### 4. CONCLUSIONS AND SUGGESTIONS

The prototype rotary dryer type dryer machine has been successfully tested for its performance in reducing the moisture content of granulated palm sugar from 4.18% to below 2.5% according to SNI 01-3743-2021, with a time of 1-3 hours per batch, faster than the conventional method of 6-8 hours. The high rotary speed (41.83±0.1 RPM) resulted in large scattered shrinkage (18.4%) and uneven heat distribution, while the best combination was obtained at a speed of 23.83±0.1 RPM for 1 hour with a moisture content of 2.4%, scattered shrinkage of 14.4%, and the lowest energy cost (Rp821 per batch). However, the actual capacity of 500 g is only 6.4% of the theoretical capacity of 7 kg due to insufficient motor torque and less precise mechanical clutch design, as well as other quality parameters, such as ash content, reducing sugars, and caramelization potential at 70 °C, have not been studied. In addition, this study has an element of novelty through the application of the Simple Additive Weighting (SAW) method for the selection of the best combination of operations based on multi-criteria, namely final moisture content, scattered shrinkage, and energy cost simultaneously. The application of SAW to the analysis of food drying performance is still rare, as most previous studies have relied only on a single comparison between parameters or RSM-based optimization. The SAW

approach in this study provides a more objective, measurable, and holistic decision-making basis in determining the optimum operating conditions of small-scale rotary dryers.

To improve the quality of the research and development of this machine, several suggestions can be considered. It is necessary to vary the parameters more widely, including rotary speed of 15–50 RPM and variations in drying temperature (60, 70, and 80 °C) with a stable heat source such as a ceramic heater or blower. Product quality analysis must be more comprehensive by testing ash content, reducing sugars, water activity (Aw), and organoleptic characteristics. In terms of machine design, it is recommended to replace the hair dryer with a precision heating system, add real-time temperature and humidity sensors, modify the cylinder with non-stick materials such as Teflon, and add a cyclone separator. For production capacity, it is necessary to optimize the transmission system and drive motor to achieve a theoretical capacity of 7.8 kg per batch.

### AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
GR	✓	✓			✓	✓					✓		✓	✓
AS			✓	✓			✓	✓		✓		✓		
WH			✓	✓			✓	✓				✓		
ADP						✓			✓		✓		✓	

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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