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Article

Medicinal Plant Drying Using a Superabsorbent Polymer Dryer Incorporated with an Insulated Heater

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Keywords: superabsorbent polymer; dryer; heater; *Simplicia*; rhizomes



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1. Introduction

Simplicia is a natural ingredient used to manufacture medicinal products from medicinal plant materials that is subject to the drying process [1]. In Indonesia, the demand for herbal medicines produced from *Simplicia* has been increasing considerably due to the effectiveness of the herbal products in improving health conditions with relatively minimum side effects [2]. The *Simplicia* sold in the market should meet with the government regulations regarding the specifications of *Simplicia* products, especially the maximum allowable moisture content in *Simplicia* [3]. The moisture content in *Simplicia* determines the lifetime and durability of the products [4]. Hence, an effective drying technique that can reduce the moisture content in medicinal plant materials to produce *Simplicia* with less damage to the structure, composition, and biologically active components of the materials is required.

Numerous drying methods have been developed to produce *Simplicia* from fresh medicinal plant materials. Traditional open-sun drying is the most commonly used technique in rural areas because of its low cost, carried out by harnessing the energy from sunlight. However, this method still depends on the intensity of sun exposure and climatic conditions, which demands a large area to dry the materials and a long drying time [5]. Other drawbacks of open-sun drying include product contamination due to wind-blown dirt, dust, and debris, in addition to animal and human disturbances [6]. A solar dryer offers an alternative to replace direct sun drying, providing more even moisture removal and greater product hygiene [1]. The disadvantages of this technique comprise product overheating, limited drying capacity, and low product quality, which hinders its application on a large industrial scale [7]. Using an oven-drying method, a short drying time

and a more controlled operational temperature can be attained [8]. Nevertheless, this technique is less favorable in *Simplicia* drying due to its tendency to induce color changes and significantly reduce the quality of the materials [9]. Microwave-assisted drying can preserve bioactive substances in the medicinal plant materials with adequate dehydration efficiency. This technique can maintain the appearance and flavor of the fresh materials [10]. Unfortunately, the uneven heating, damage of material texture at a high drying rate, and increased equipment cost become the major issues in implementing this technique [11].

Superabsorbent polymers are hydrophilic polymers with the special ability to absorb and retain a considerable amount of water and moisture in their network structure without being dissolved [12]. These materials are widely employed in a number of fields, such as agriculture, building construction, medicine, and adhesives. In the agricultural field, superabsorbent polymers can significantly improve water efficiency, including water absorption and retention abilities [13]. Fang et al. (2018) have synthesized chitosan derivative graft acrylic acid superabsorbent polymers from amino ethyl chitosan and acrylic acid using radical polymerization [14]. The materials show good swelling ability, enhanced water evaporation rate, superior salt tolerance, and a high pH sensitivity. In cement and concrete research, the employment of superabsorbent polymers in the self-sealing of cracks in concrete has also been investigated. The superabsorbent polymers are able to re-swell and seal the cracks, which can considerably reduce the peak flow rate and total flow of concrete samples [15]. Superabsorbent polymers can also prevent autogenous shrinkage and enhance internal curing effects, which have no drawbacks to the compressive strength of cement paste [16]. Besides, bio-based superabsorbent polymers have been introduced by Draney et al. (2022), employing bio-based cross linker and backbone compounds to generate hydrogel materials that can absorb water into their matrix [17]. The chitosan and sodium alginate-based polymers verify that natural superabsorbent polymers are viable, with excellent water absorption and retention abilities.

Recently, our group has introduced a superabsorbent polymer dryer (Polydryer) to produce *Simplicia* from fresh medicinal plant samples. A superabsorbent polymer hydrogel (polygel) based on cassava starch and acrylic acid is utilized to reduce the relative humidity of the drying air, which can accelerate the drying rate [18]. The employment of the polygel is due to its excellent moisture-absorption properties with soft microstructures that tends to swell in the ambient air [19]. However, due to the low-temperature operation in the drying cabinet (27.4–35.2 °C), the drying process in the Polydryer requires 4–5 days to attain a moisture content of $\leq 12\%$ [18]. This relatively long drying time may not be beneficial for large-scale drying. Therefore, increasing the operating temperature in the drying cabinet is necessary to enhance the drying rate of the medicinal plant materials. From another study, a drying temperature below 60 °C tends to be an optimum condition for drying, with less material shrinkage, surface discoloration, and essential oil losses to the materials [20,21].

In this work, a superabsorbent polymer dryer was incorporated with an insulated gas-fueled heater to enhance the drying rate of medicinal plant drying in the Polydryer. The heater was connected with the polygel cabinet and the drying cabinet. The drying air entering the drying cabinet was controlled to give a temperature of not more than 60 °C. The medicinal plant materials investigated in this work included turmeric, ginger, greater galangal, Curcuma, and lesser galangal. The selection of turmeric, ginger, greater galangal, Curcuma, and lesser galangal was due to the availability of these medicinal plants in Indonesia [22–25]. In addition, their high contents of bioactive compounds also convinced us to use these medicinal plants as the samples in our study [26–29]. The drying profiles of the medicinal plant drying in the Polydryer with and without heater operation were acquired. The quality and microscopic structure of the *Simplicia* produced using the Polydryer with and without the employment of the heater were compared. The drying models of the medicinal plant materials in the Polydryer with the incorporation of the heater were proposed to study the drying kinetics of the materials. With a combination of low relative humidity due to the presence of the polygel and high temperature because of the heater operation, an enhanced drying rate of the medicinal plant samples was

highly expected. To the best of our knowledge, there are no studies reporting the drying of medicinal plant materials using the combination of both superabsorbent material and gas-fueled heater to attain an optimum drying condition inside the drying chamber.

2. Materials and Methods

2.1. Materials

Cassava starch was purchased from Budi Starch & Sweetener Ltd., Indonesia. Ammonium persulphate ($\geq 98\%$), acrylic acid (99%), sodium hydroxide (NaOH, $\geq 99\%$), and N,N-methylenebisacrylamide (MBA, $\geq 99\%$) were obtained from Merck. Sodium-bentonite powder (GTC4) was obtained from Mahesa Rekatama Ltd., Indonesia. Ginger (*Zingiber officinale*), turmeric (*Curcuma longa* Linn.), greater galangal (*Alpinia galanga*), Curcuma (*Curcuma xanthorrhiza*), and lesser galangal (*Kaempferia galangal*) were purchased from a local market (West Java, Indonesia). The acrylic acid was distilled and neutralized with 40% NaOH prior to the polygel synthesis. To eliminate the water, the ammonium persulphate was recrystallized. The moisture in the sodium-bentonite was evaporated at 95 °C and the dried sodium-bentonite was crushed using a mortar for 12.5 h before the experiments. Other chemicals were utilized as supplied by the manufacturers with no further purification. Distilled water was employed in the experiments.

2.2. Preparation of Polymer Hydrogel

Polygel was synthesized according to the reported methods [18,19,30]. A mixture of cassava starch and distilled water with a weight ratio of 1:20 was poured into a four-neck flask set up with a nitrogen line, a stirrer, and a thermometer. The temperature of the solution was increased to 90 °C for 30 min and decreased to 60–65 °C afterwards. Ammonium persulphate was added to the mixture. The ammonium persulphate worked as a chemical initiator. The concentration of ammonium persulphate was 0.5% (*w/w*). Here, the concentration stated in *w/w* indicated the weight ratio of the corresponding chemical to the total mass of the mixture. The mixture was then stirred for 15 min. Subsequently, the MBA, bentonite, and partially neutralized acrylic acid were poured into the four-neck flask. The concentration of MBA and bentonite was adjusted to 0.05 and 2% (*w/w*), respectively. The ratio of cassava starch to acrylic acid was controlled to 1:5 (*w/w*). The resultant suspension was slowly heated to reach a temperature of 70 °C to form a gel substance, which was the polygel. The substance was rinsed with distilled water and ethanol, and dried in an oven at 70 °C [19]. Low-temperature drying was required to retain the structure and morphology of the polymer materials [31]. The polygel produced was milled and sieved to obtain a uniform particle with a 20–80 mesh size range.

2.3. Design and Construction of Polydryer Incorporated with a Heater

The Polydryer was constructed by modifying the design of the previously reported Polydryer with a gas-fueled heater placed between the polygel cabinet and the drying cabinet, as shown in Figure 1.

Compared with our previous study, the incorporation of the heater in this study was aimed at enhancing the drying rate of medicinal plant materials in the Polydryer. The Polydryer was constructed with a 3-inch blower placed inside a wooden box, a wooden polygel cabinet with a size of 25 cm × 30 cm × 80 cm (length × width × height), a gas-fueled heater with a size of 57 cm × 43 cm × 60 cm (length × width × height), and a transparent cabinet made of an acrylic wall with a size of 25 cm × 30 cm × 80 cm (length × width × height). The polygel cabinet that was used to place the polygel was equipped with nine trays. The transparent drying cabinet that was employed to dry the medicinal plant materials was designed with three trays. A flexible pipe was utilized to connect each unit of the Polydryer. To prevent dust and other contamination, the inlet of the polygel cabinet and the outlet of the drying cabinet were covered with air filters. The gas-fueled heater was insulated with cotton tapes to prevent heat loss. Three hygrometers

that recorded temperature were positioned at the inlet of the blower, the inlet of the drying cabinet, and the outlet of the drying cabinet, respectively.

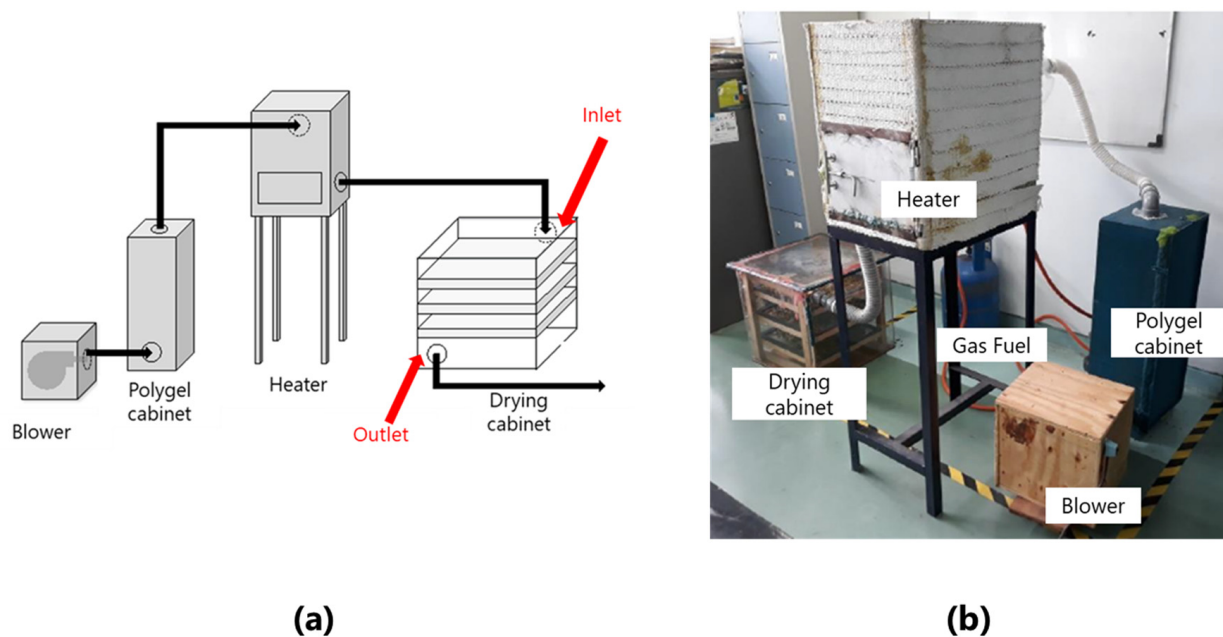


Figure 1. (a) Scheme and (b) photograph of Polydryer incorporated with a gas-fueled insulated heater.

2.4. Operation of Polydryer

In this study, the performance of the Polydryer with and without the operation of the heater in drying the medicinal plant materials into *Simplicia* was compared. The heater was not employed during the operation of the Polydryer without heater operation. Initially, fresh medicinal samples (turmeric, ginger, greater galangal, Curcuma, and lesser galangal) were cleaned with distilled water, peeled, and sliced into 3–4 mm thick blocks. As much as 2500 g of each sliced sample (turmeric, ginger, greater galangal, Curcuma, and lesser galangal) was placed in the trays inside the drying cabinet. Meanwhile, the prepared polygel was placed into the trays inside the polygel cabinet. The sample to polygel ratio was kept at 1:2 (w/w). After the cabinets were closed and no leak was spotted, the gas-fueled heater was switched on to reach a temperature of 60 °C. According to the literature, a drying temperature of less than 60 °C tends to be an optimum condition for accelerated drying, with less material shrinkage, surface discoloration, and essential oil losses to the materials [20,21]. The blower was subsequently operated to allow the drying air to enter the polygel cabinet. The drying airflow rate was adjusted to 108.3 m³/h. The relative humidity of the drying air was reduced in the polygel cabinet due to the moisture in the drying air being absorbed by the polygel. Afterwards, the drying air flowed into the heater to increase the temperature to 60 °C. The drying temperature was monitored using a thermocouple attached to the gas-fueled heater, which was then used as a reference to manually adjust the gas flow rate. The reason for using an airflow rate of 108.3 m³/h was due to an enhanced moisture rate, according to our previous study. We operated the Polydryer with different airflow rates of 28.5, 57.0, and 108.3 m³/h, and found that the removal of free water was accelerated with an enhanced drying time, though the effect of airflow rate was not significant during the removal of bound water. The temperature increase was aimed at enhancing the drying rate of the medicinal plant materials. The drying air subsequently entered the drying cabinet through the inlet located at the backside of the cabinet. The hygrometers were used to monitor the relative humidity and temperature at the inlet of the blower, and the inlet and outlet of the drying cabinet. Upon passing the drying cabinet, the drying air penetrated into the sliced samples and carried away the moisture in the samples. The drying air, rich with moisture, was then discharged to the environment through the

outlet of the drying cabinet. The drying process of the medicinal plant materials in the Polydryer was stopped when the moisture content in the dried samples reached $\leq 12\%$ or the sample deteriorated due to microbial decomposition.

2.5. Polygel Regeneration

The polygel could be regenerated to recover the moisture-absorption properties of the material prior to each experiment [19,30]. The wet and swollen polygel was taken out from the polygel cabinet and put in a heating tray. The tray was placed in the oven and dried at 50 °C. A drying time of around 20 min was sufficient to regenerate the polygel. The indicator that showed that the polygel was completely regenerated was when there was no significant change in mass observed during regeneration. After that, the polygel was placed back into the trays inside the polygel cabinet.

2.6. Acquisition of Drying Profiles

The relative humidity and temperature of the ambient air at the inlet of the blower and drying air at the inlet and outlet of the drying cabinet were recorded during the drying of the medicinal plant samples. The relative humidity and temperature changes during the drying process were used to generate the relative humidity and temperature profiles. The moisture content was measured at several points located in the inner parts of the samples using a moisture content meter, due to a higher moisture content in the inner part than in the outer part of the samples. In the Polydryer without heater operation, the moisture content was measured twice a day, with a time interval around 10–14 h. Meanwhile, in the Polydryer with heater operation, the moisture content was recorded at a time interval of 2–3 h because of the higher drying rate. The type of moisture content meter used in this study was a pin-type moisture meter. The initial moisture content of the samples was obtained using a gravimetric method by heating the samples at 105 °C for 5 h until a constant weight was attained. The experiments were performed with a minimum of two replications.

2.7. Product Characterization

The moisture content in the *Simplicia* was confirmed using the distillation technique to make sure that the dried material produced satisfied the maximum allowable moisture content in *Simplicia*. The color and physical appearance of the *Simplicia* produced via Polydryer with and without the heater were compared. The method used to compare the color and physical appearance of the *Simplicia* was through visual observation by some experts in the field of dried medicinal products. In addition, color analysis was also performed to measure the intensity of the RGB levels of each dried rhizome using ImageJ software [32]. This technique was used to confirm the color change induced by heat application in the Polydryer with the heater employment to support the visual observation. Five areas were taken for each dried sample and the average pixel count of the RGB levels for each dried sample was calculated. The scanning electron microscope (SEM) images of the *Simplicia* produced in the Polydryer with heater employment were acquired. The SEM images were taken on a JEOL-JSM-6510LV at an accelerating voltage of 5 kV. The ash content in the *Simplicia* was determined by grinding the *Simplicia* and pouring it into an ignited and tarred silicate crucible. The weight of the *Simplicia* product before and after the char ignition was used to calculate the ash content. The drying shrinkage of the *Simplicia* was determined by heating the ground *Simplicia* in a capped bottle. The use of the cap was aimed at evaporating all of the volatile matters in the sample by increasing pressure inside the bottle. The cap was subsequently opened inside a drying chamber and dried until a constant weight was attained [33]. The experiments were performed with a minimum of two replications.

2.8. Drying Model Fitting

The drying profiles of the rhizomes during drying in the Polydryer with the operation of the heater were converted into drying models by fitting using linear logarithmic equations of Lewis, Henderson and Pabis, and Page models as summarized in Table 1 [34–39]. Here, the moisture ratio (MR) and the drying coefficients (a) are dimensionless variables. The drying time (t) was stated on an hour basis (h). The unit of drying constant (k) in the Lewis and Henderson & Pabis Models was h^{-1} . Meanwhile, the unit of the k in the Page model depends on the calculated dimensionless empirical constant (n), h^{-n} . The drying models were plotted to investigate the drying kinetics of the medicinal plant drying. The model fittings were aimed at understanding the drying characteristics of the medicinal plant samples investigated in this study, so that the drying time could be estimated from the initial moisture content of the medicinal plant materials. The moisture ratio (MR) was determined using Equation (1).

$$MR = \frac{M - M_e}{M_o - M_e} \quad (1)$$

where M is the moisture content of a sample at a given time, M_e is the final moisture content after drying, and M_o is the initial moisture content in a fresh sample. In the mathematical equations shown in Table 1, the k and t represent the drying constant of the material and drying time, respectively. The best drying model was indicated by the highest R^2 value close to 1 obtained from the linear logarithmic equations.

Table 1. Thin-layer drying models employed to model medicinal plant drying in this work.

Model	Mathematical Equation	Linear Logarithmic Equation	Reference
Lewis	$MR = \exp(-kt)$	$\ln MR = -kt$	[34,39]
Henderson & Pabis	$MR = a \exp(-kt)$	$\ln MR = -kt + \ln(a)$	[35,36]
Page	$MR = \exp(-kt^n)$	$\ln(-\ln(MR)) = \ln(k) + n \ln(t)$	[37,38]

MR = moisture ratio, k = drying constant, t = drying time, a = drying coefficients, n = dimensionless empirical constant.

3. Results and Discussion

3.1. Temperature and Humidity Profiles in the Drying Cabinet

The Polydryer was operated using two different configurations: with and without the operation of the heater. In the Polydryer with heater operation, the heater was operated to give an inlet temperature of below 60 °C. The relative humidity profiles in the drying cabinet with and without the incorporation of the heater using sliced ginger as the samples are shown in Figure 2a,b.

The graphs indicate that relative humidity values at the inlet and outlet of the drying cabinet without the employment of the heater were higher than those with the heater. The enhanced inlet temperature of the drying cabinet due to the operation of the heater reduced the relative humidity in the drying cabinet [40]. The relative humidity at the inlet of the drying cabinet in the Polydryer without heater operation was lower than the relative humidity of the ambient air, which suggested that the presence of polygel material in the polygel cabinet also contributed to the moisture reduction (Figure 2a). With reduced relative humidity in the drying air prior to entering the heater, the heat load of the heater in the Polydryer with heater operation can be greatly reduced.

The relative humidity values at the outlet of the drying cabinet were higher than those recorded at the inlet. These showed that there were mass transfer phenomena between the drying air and the samples. Upon drying, the high moisture content in the samples was taken out by the drying air, resulting in the enhanced relative humidity values at the outlet of the drying cabinet [41]. The dry air penetrated into the samples, which facilitated efficient rhizome drying.

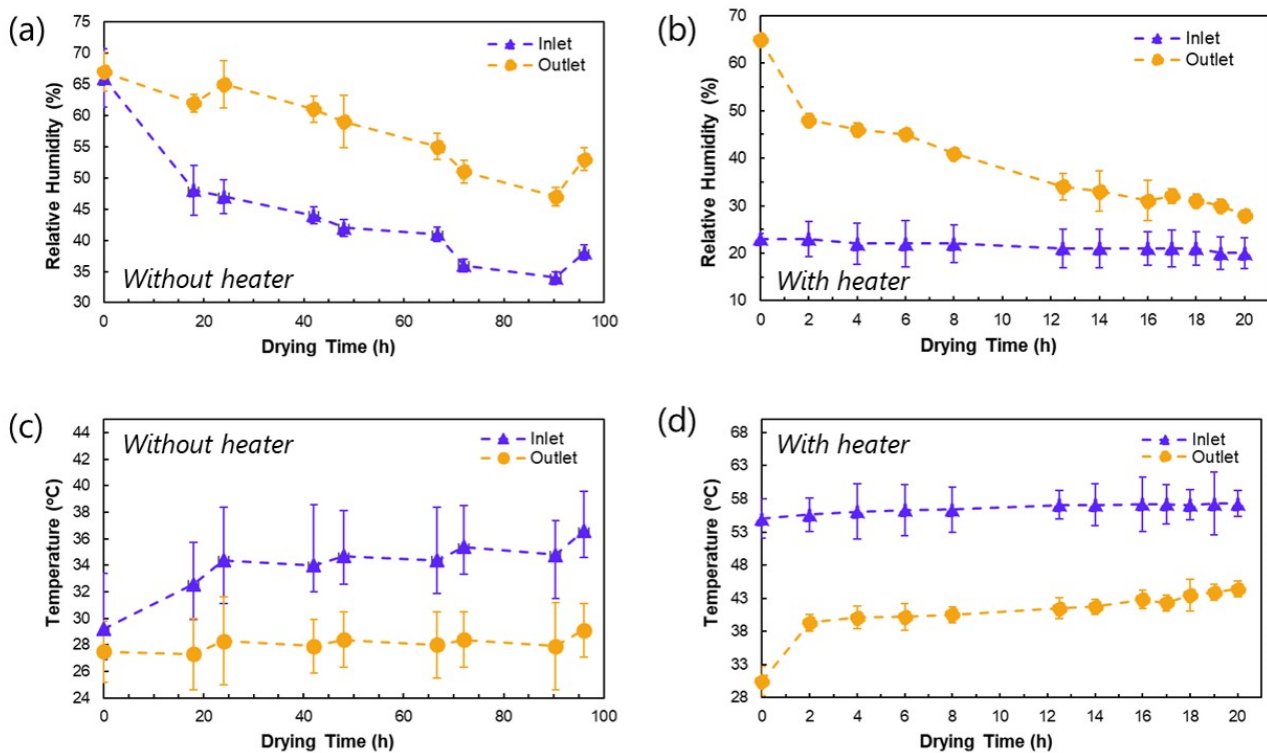


Figure 2. Relative humidity profiles in the drying cabinet of the Polydryer (a) without and (b) with the operation of a heater; and temperature profiles in the drying cabinet of the Polydryer (c) without and (d) with the operation of a heater using sliced ginger as the samples.

The temperatures at the inlet and outlet of the drying cabinet were monitored. The temperature profiles in the drying cabinet with and without the employment of the heater using sliced ginger as the samples are depicted in Figure 2c,d. The results showed that the temperatures recorded at the inlet and outlet of the drying cabinet in the Polydryer with the incorporation of the heater were above the temperature of the drying cabinet without the employment of the heater. This was likely due to the operation of the heater, which resulted in the rise of inlet temperature. The heater enhanced the temperature of the drying air to the desired drying temperature, resulting in water removal during drying [42]. In the Polydryer with the employment of the heater, the inlet temperature increased from 55 to 57.3 °C upon the drying process. In comparison, the inlet temperature in the drying cabinet rose from 29.2 to 36.6 °C in the Polydryer without heater operation. The temperature rise caused by the incorporation of the heater shortened the drying time of the sliced ginger samples from 96 to 20 h, reaching a final moisture content $\leq 12\%$. In another study on oven drying of bermuda grass (*Cynodon dactylon*) rhizomes, the drying time decreased from 32 to 18 h when the drying temperature increased from 30 to 50 °C. The high-driving force of heat transfer induced by higher temperatures is crucial in enhancing the drying rate of plant materials [43]. Using a mechanical dryer operated at temperatures of 50, 55, 60, and 65 °C, the drying time of ginger was 8, 8, 7, and 6 days, respectively. From the study, the optimum drying temperature was attained at 60 °C, with essential oil and oleoresin losses of 12.2% and 5.3%, respectively [21]. The rise of the inlet temperature in the Polydryer without the incorporation of the heater was expected due to less relative humidity as the Polydryer was further operated, making the dry air more prone to absorb energy from the environment. Dry air has a lower heat capacity than wet air, resulting in the higher tendency of the dry air to increase its temperature [44,45]. Moreover, the increase in the relative humidity inside the drying cabinet due to moisture diffusion also contributed to the rise of the inlet temperature of the drying cabinet [46].

The temperatures at the outlet of the drying cabinet in the Polydryer for both configurations with and without heater operation were lower than the inlet temperatures. This was expected due to some of the energy of the drying air being used to evaporate the moisture in the sliced ginger samples during the drying process. Moisture evaporation requires energy that can sharply reduce the drying air temperature [47]. Energy loss from the drying cabinet to the environment was unlikely to occur. This was due to the fact that the drying cabinet was made of acrylic glass, which is a type of heat-resistant material that has relatively low thermal conductivity [48].

The relative humidity profiles of the ambient air and the inlet and outlet of the drying cabinet in the Polydryer with heater operation are depicted in Figure 3.

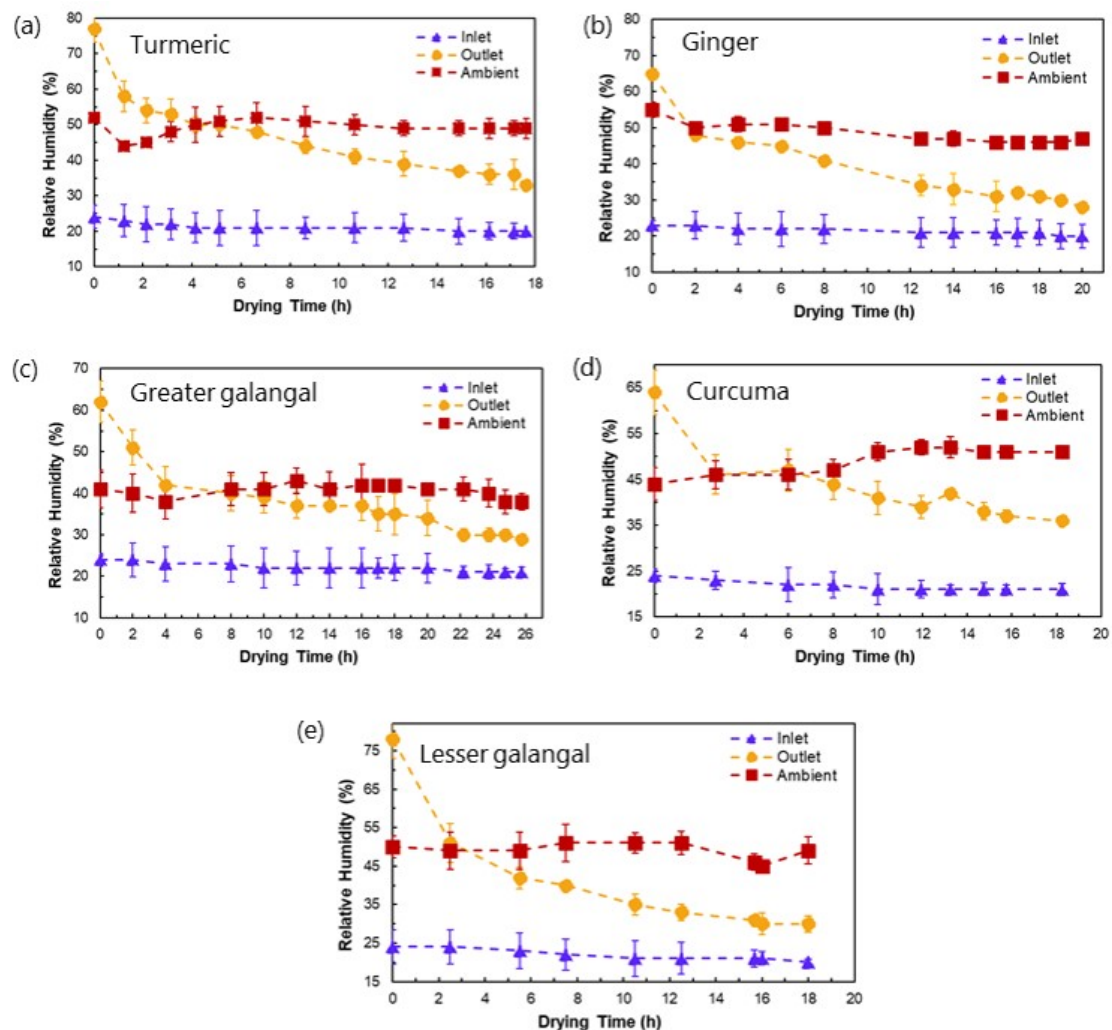


Figure 3. Relative humidity profiles of the ambient air and the drying cabinet in the Polydryer with the operation of a heater: (a) turmeric, (b) ginger, (c) greater galangal, (d) Curcuma, (e) lesser galangal.

The relative humidity changes during the drying process were measured for all rhizome samples. The graphs indicate that the trend of the relative humidity changes for all samples resembled one another. The relative humidity values of the ambient air and inlet of the drying cabinet tended to be constant, which indicated a stable drying condition in the Polydryer with the incorporation of the heater. In this configuration, the relative humidity value of the ambient air was in the range 41–55%. Upon entering the polygel cabinet and the heater, the relative humidity was reduced to 18–24%. The dry air subsequently entered the drying cabinet to dry the sliced rhizome samples. Compared with our previous studies on medicinal plant drying using a Polydryer without the employment of a heater,

the relative humidity obtained with heater operation was lower, implying a preferable drying condition [18]. The polygel material and the heater could simultaneously work in reducing moisture content in the drying air. The relative humidity recorded at the outlet of the drying cabinet was initially higher than the atmospheric air. This indicated that more moisture was released from the samples at the early stage of drying, resulting in the relative humidity increase at the outlet at the initial stage. The values varied slightly from one sample to another, implying different mass transfer mechanisms and initial moisture contents of each sample [49].

The temperature profiles of the ambient air and the inlet and outlet of the drying cabinet in the Polydryer with heater operation are shown in Figure 4.

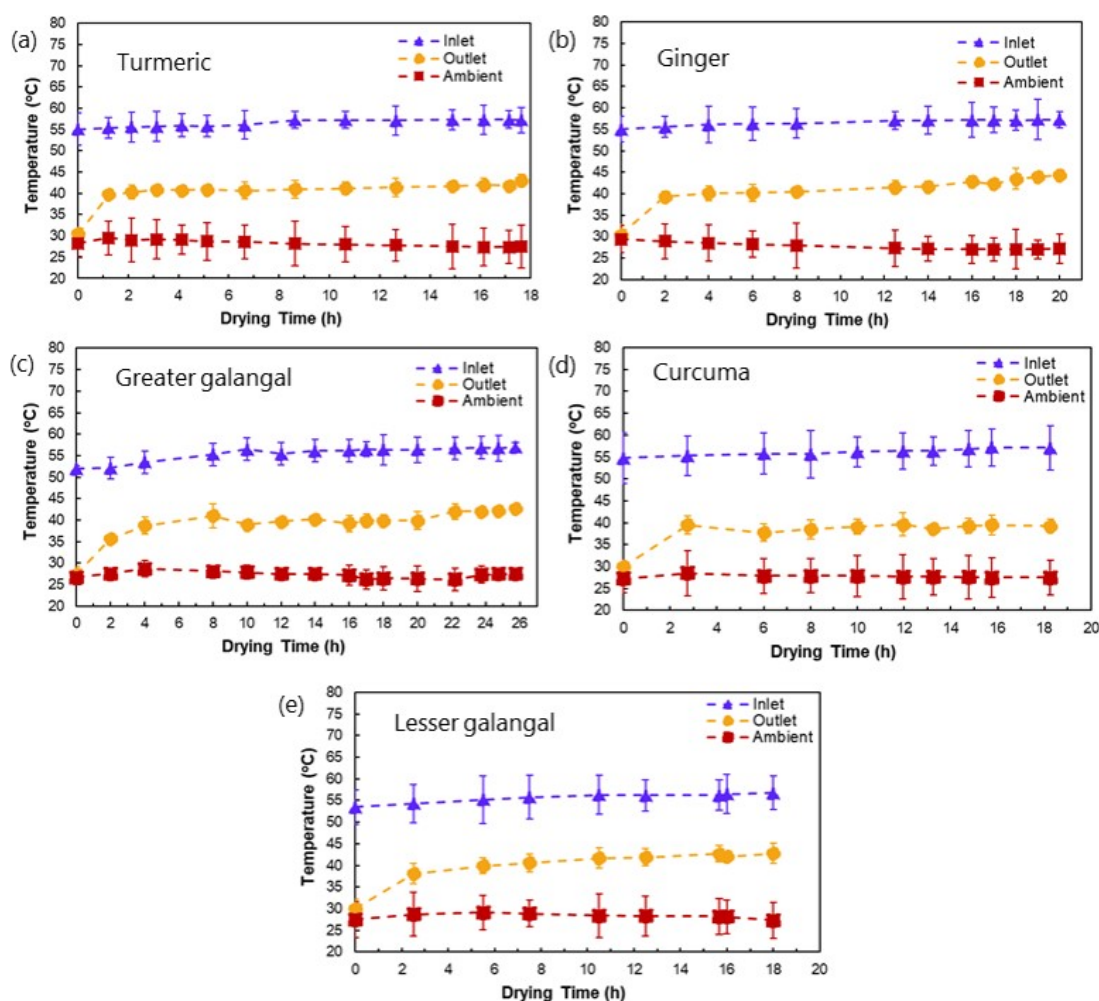


Figure 4. Temperature profiles of the ambient air and the drying cabinet in the Polydryer with the operation of a heater: (a) turmeric, (b) ginger, (c) greater galangal, (d) Curcuma, (e) lesser galangal.

The results showed that the temperature profiles of the ambient air and drying air at the inlet of the drying cabinet in the Polydryer with heater operation were steady, indicating a stable drying process. The ambient air temperature entering the polygel cabinet was in the range 26–29 °C. Upon passing the heater, the temperature significantly increased to 52–57 °C. Although the drying air temperature in the Polydryer with heater incorporation was higher than the temperature without the employment of the heater, the temperature range was lower than the permissible range for vegetable and fruit drying, to ensure that material degradation and bioactive compound decomposition was not triggered [50]. At a temperature higher than 60 °C, material shrinkage and surface discoloration may be observed [20]. During drying, the temperature at the outlet of the drying cabinet was

around 36–43 °C. The temperature reduction was expected due to some energy being used to evaporate the moisture in the rhizome samples [47].

3.2. Drying Profiles of Medicinal Plant Materials

The drying profiles of all rhizome samples were acquired using the Polydryer with and without heater operation (Figure 5).

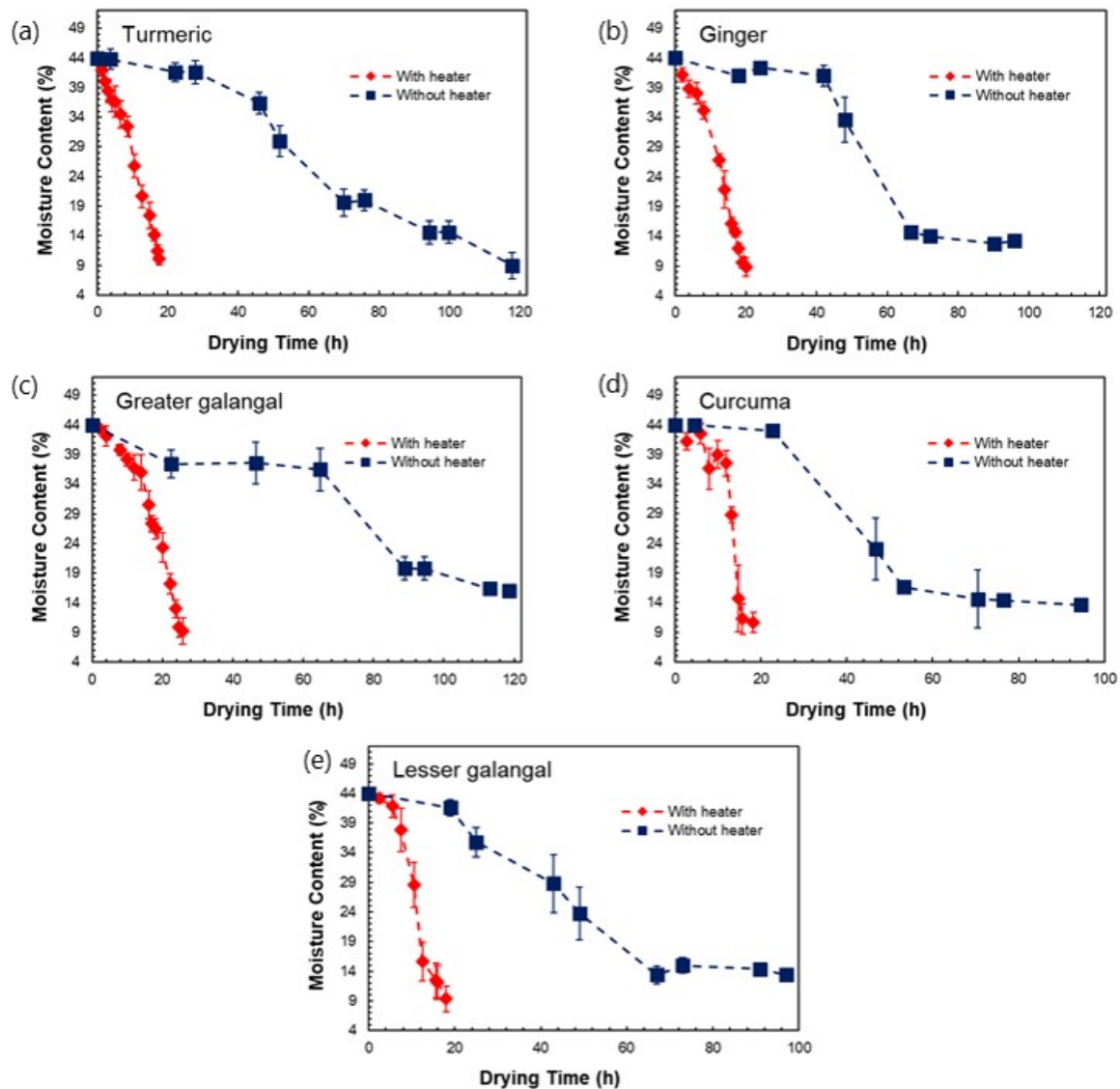


Figure 5. Drying profiles of medicinal plant samples in the Polydryer with and without the operation of a heater: (a) turmeric, (b) ginger, (c) greater galangal, (d) Curcuma, (e) lesser galangal.

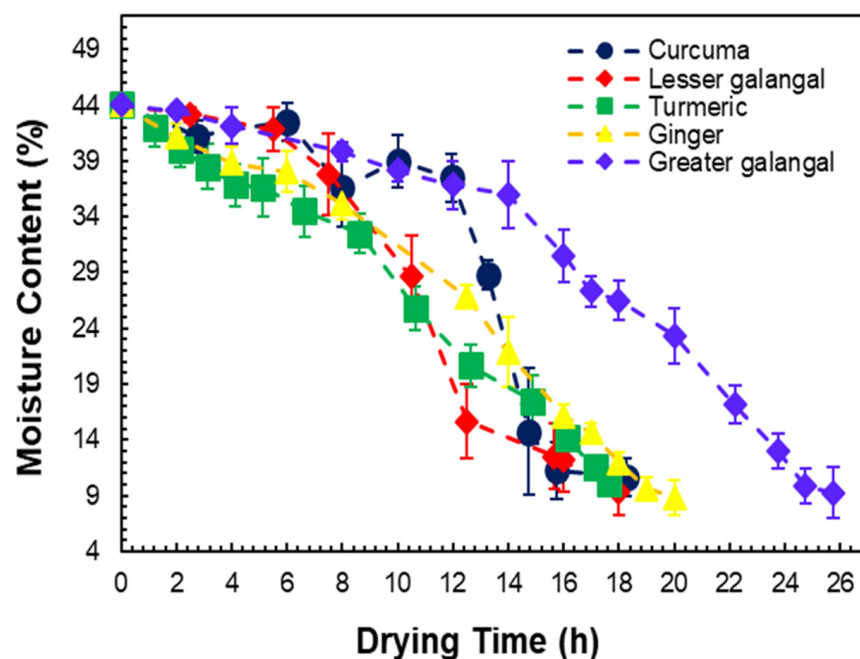
The graphs indicate that the employment of the heater greatly shortened the drying time of the samples. Rhizome drying in the Polydryer without heater operation required 95–119 h to attain a moisture content of 9.0–16.0%, as summarized in Table 2. Meanwhile, the Polydryer with the heater needed 18–26 h to reach a moisture content of 8.8–10.7%. The initial moisture content measured using the gravimetric method of all samples showed an initial moisture content of 73.2–89.2%, which caused a variation in drying time from one sample to another. A higher initial moisture content tended to prolong the drying time of the materials [51].

Table 2. Summary of drying time and moisture content in final products of different medicinal plant samples in the Polydryer with and without the operation of a heater.

No.	Material	Initial Moisture Content (%)	Final Moisture Content (%)		Drying Time (h)	
			without Heater	with Heater	without Heater	with Heater
1	Turmeric	83.1 ± 1.43	9.0 ± 2.10	10.2 ± 1.07	117 ± 1.00	18 ± 0.50
2	Ginger	83.2 ± 1.14	13.2 ± 1.17	8.8 ± 1.57	96 ± 0.50	20 ± 0.50
3	Greater galangal	89.2 ± 1.45	16.0 ± 0.63	9.3 ± 2.24	119 ± 1.00	25 ± 0.65
4	Curcuma	73.2 ± 1.50	13.6 ± 0.80	10.7 ± 1.70	95 ± 0.25	18 ± 0.40
5	Lesser galangal	75.2 ± 1.25	9.33 ± 2.13	9.3 ± 2.13	97 ± 0.30	18 ± 0.45

Our study showed that the drying time greatly reduced upon the operation of the heater up to five-fold. The high temperature (52–57 °C) and low humidity (18–24%) of the drying air were likely reasons for the shorter drying time. In another study on convective drying of turmeric, the drying time was reduced from 36 h to 23 h by increasing the drying temperature from 50 °C to 70 °C. The drying rate was enhanced with increasing drying temperature, resulting in a significant reduction of drying time [52]. Similarly, the drying time of ginger rhizomes decreased with increasing temperature under blanched and non-blanched conditions [53]. At higher temperatures, heat and mass transfer rates increased because more energy was supplied to the samples, which could shorten the drying time [54]. In accordance with a study conducted by Gan et al. (2017) on ginger and turmeric drying in a cabinet dryer, drying at a low relative humidity of 20% showed the most superior drying performance [55]. The treatment showed the highest amount of curcumin as the active compound in turmeric. Using a thin-layer dryer to dry galangal slices, the reduction of the relative humidity value of the drying air from 70% to 15% enhanced the drying rate. The low relative humidity enhanced the difference in water vapor pressure between the surface of the samples and the drying air, triggering more water vapor migrating out from the sample to the drying air [56].

The drying profiles of all rhizome samples dried using the Polydryer with the heater were combined and plotted in Figure 6.

**Figure 6.** Drying profiles of medicinal plant samples in the Polydryer with heater operation: turmeric, ginger, greater galangal, Curcuma, and lesser galangal.

The graph shows that all samples exhibited similar drying patterns. The greater galangal required a longer drying time due to its relatively higher initial moisture content. The differences in the drying profiles for each medicinal plant material were likely due to different free-water and bound-water contents in each medicinal sample material, which affected the kinetics of water-release rates. The final moisture content measured using the moisture content meter was verified using the distillation method, as summarized in Table 3. The results indicated that the moisture content of all samples obtained using the moisture content meter was close to the values measured using the distillation technique, indicating precise moisture-content measurements. From the results, the moisture content of the final products satisfied the maximum allowable moisture content in *Simplicia* [3].

Table 3. Summary of moisture content in final products of different medicinal plant samples dried in the Polydryer with a heater measured using a moisture content meter and distillation method.

No.	Material	Final Moisture Content Using Moisture Content Meter (%)	Final Moisture Content Using Distillation Method (%)	Maximum Moisture Content in <i>Simplicia</i> *
1	Ginger	8.8 ± 1.57	7.66 ± 0.58	≤10
2	Greater galangal	9.3 ± 2.24	7.32 ± 1.16	≤10
3	Curcuma	10.7 ± 1.70	7.98 ± 0.01	≤13
4	Lesser galangal	9.3 ± 2.13	11.3 ± 1.15	≤12

* The maximum moisture contents in *Simplicia* refer to the First Edition of Indonesian Herbal Pharmacopoeia by the Ministry of Health the Republic of Indonesia, 2009 [3].

In agreement with a study carried out by Sun et al. (2019), fresh ginger comprised three water components: free water, bound water, and immobilized water. The free water content was commonly the highest and showed a more favorable removal rate at the early stage of drying [8]. As the drying process continued, the evaporation rate of free water dropped and the evaporation rate of bound and immobilized water rose steadily [57]. The evaporation of free water rose with increasing power supplied to the material, and the immobilized water diffused to compensate for the water loss. The movement of immobilized water into bound water triggered a proportional increase of bound water [58].

In comparison with other drying techniques from the literature, the Polydryer operated with the heater requires a shorter drying time to dry medicinal plant materials. In the study on slice wild ginger drying using a greenhouse-effect solar dryer, drying wild ginger from an initial moisture content of 80% to a final moisture content of 8–11% needs 27.5 to 30 h of drying time. The drying process is performed at 47.2 °C in a rack-type greenhouse solar dryer for thin-layer drying [59]. Employing a solar tunnel dryer to dry ginger also reduces the moisture content of sliced ginger from 90.4% to 11.8% in 24 h (3 solar days). An average maximum temperature of 30 °C is observed at 9:00 AM, and 77 °C is recorded at 13:00 PM [60]. In the study of flow forced-convection solar dryers for Curcuma drying, the mixed-mode dryer requires 24 h of drying time, while the indirect-mode dryer takes 31 h to reach a final moisture content of 9.25%. The drying process is performed at 47.6 °C and 36.9 °C for the mixed-mode dryer and indirect-mode dryer, respectively [61]. The drying of turmeric in a natural circulation solar dryer requires 60.5 h and 66 h to reach a moisture content of 10%, investigated for water-boiled and steam-boiled turmeric, respectively. The average dryer temperature varies from 44 to 65 °C at an ambient temperature of 39–43 °C [62]. Based on the studies obtained from the literature, our Polydryer incorporated with the heater offers a promising option for medicinal plant drying that is efficient and implementable.

3.3. Drying Models of Medicinal Plant Materials

The drying data of all rhizome samples acquired using the Polydryer with heater operation were fitted using the linear logarithmic equations of Lewis, Henderson and Pabis, and Page models, as shown in Figure 7 [34,35,37].

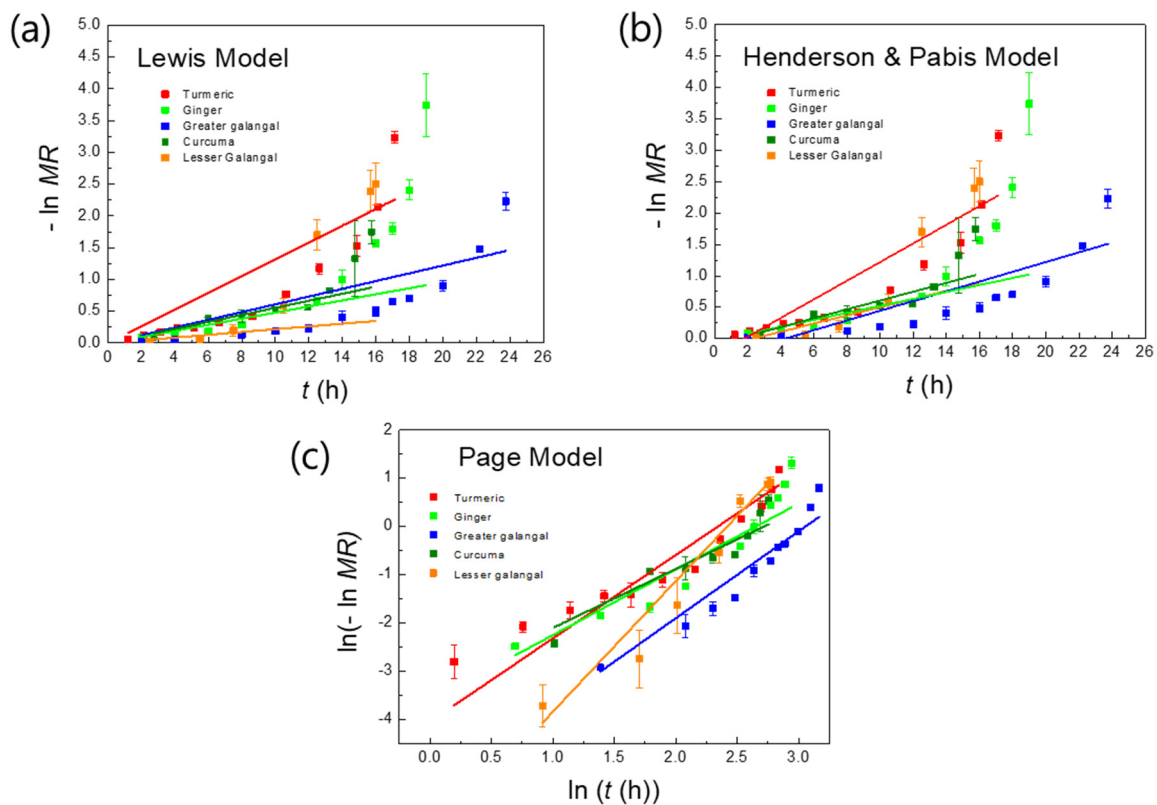


Figure 7. Drying data of medicinal plant materials in the Polydryer with heater operation fitted using linear logarithmic equations of (a) Lewis model, (b) Henderson and Pabis model, and (c) Page model.

By obtaining the most suitable drying model of medicinal plant samples investigated in this study and calculating each of the model parameters, the drying time of the medicinal plant materials can be easily predicted from the initial moisture content of the medicinal plant materials. Table 4 summarizes the results of experimental data fitting to the drying models listed in Table 1.

Table 4. Empirical constants of the drying models of medicinal plant drying in the Polydryer with heater operation calculated from Lewis, Henderson and Pabis, and Page models.

No.	Material	Lewis		Henderson & Pabis			Page		
		k	R ²	k	a	R ²	k	n	R ²
1	Turmeric	0.132	0.997	0.148	1.302	0.978	0.017	1.725	0.945
2	Ginger	0.048	0.872	0.056	1.035	0.797	0.027	1.361	0.963
3	Greater galangal	0.061	0.951	0.077	1.389	0.903	0.004	1.799	0.985
4	Curcuma	0.055	0.939	0.070	1.100	0.964	0.036	1.222	0.963
5	Lesser galangal	0.022	0.185	0.065	1.162	0.387	0.001	2.701	0.973

In these equations, molecular relative (*MR*), drying coefficients (*a*), and dimensionless empirical constant (*n*) have no units. The unit of the drying constant (*k*) in the Lewis and Henderson & Pabis Models is h⁻¹. Meanwhile, the unit of *k* in the Page model depends on the calculated dimensionless empirical constant (*n*), h^{-*n*}. The results showed that the medicinal plant drying using the Polydryer with the incorporation of the heater followed the Page model for ginger, greater galangal, Curcuma, and lesser galangal, indicated by the high R² values close to 1. Meanwhile, the turmeric was likely to follow the Lewis model, although the Page model also gave a high R² value. In general, the Lewis model demonstrated the lowest R² values because it tends to be biased and methodically undervalues early drying rates and overvalues later drying rates [63]. The Henderson and Pabis model

yielded R^2 values between the Lewis and Page models. This model is obtained from the first term of Fick's second law [64]. The R^2 value obtained using the Page model was the highest since it is a modification of the Lewis model that overcomes the shortcomings of the model [65].

Our results showed that the drying constants of the medicinal plant materials dried in the Polydryer were in the range $0.001\text{--}0.036\text{ h}^{-1}$, acquired using the Page model. In thin-layer drying, the drying constant is the combination of drying transport properties, including moisture diffusivity, density, specific heat, thermal conductivity, mass coefficients, and interface heat [66]. This parameter relies on the properties of the material and drying air. To optimize the value, the effect of air temperature, relative humidity, material size, and air velocity should also be involved [67]. A higher air temperature increases the moisture diffusivity, and low relative humidity of the drying air enhances the drying driving force [68]. There are two main periods during drying of porous structural materials: constant rate period and falling rate period [69]. In the drying of biological materials, the falling rate period is considered the dominant period in the drying process, characterized by effective moisture diffusion in the materials. The water transport mechanism is controlled by moisture diffusion [70]. According to the results obtained from this study, the constant period was expected to occur during the initial drying process (below 10–12 h), while the falling rate period was likely to happen after 10–12 h. Other materials from the literature that follow the Page drying model include sweet potato strips [71], red rice [72], saffron [73], spine gourd [74], and sweet lime peel [75].

3.4. Quality of Dried Medicinal Materials

The quality of the *Simplicia* products produced using the Polydryer with the heater operation were assessed and compared with the *Simplicia* products obtained using the Polydryer without heater operation, as presented in Figure 8.

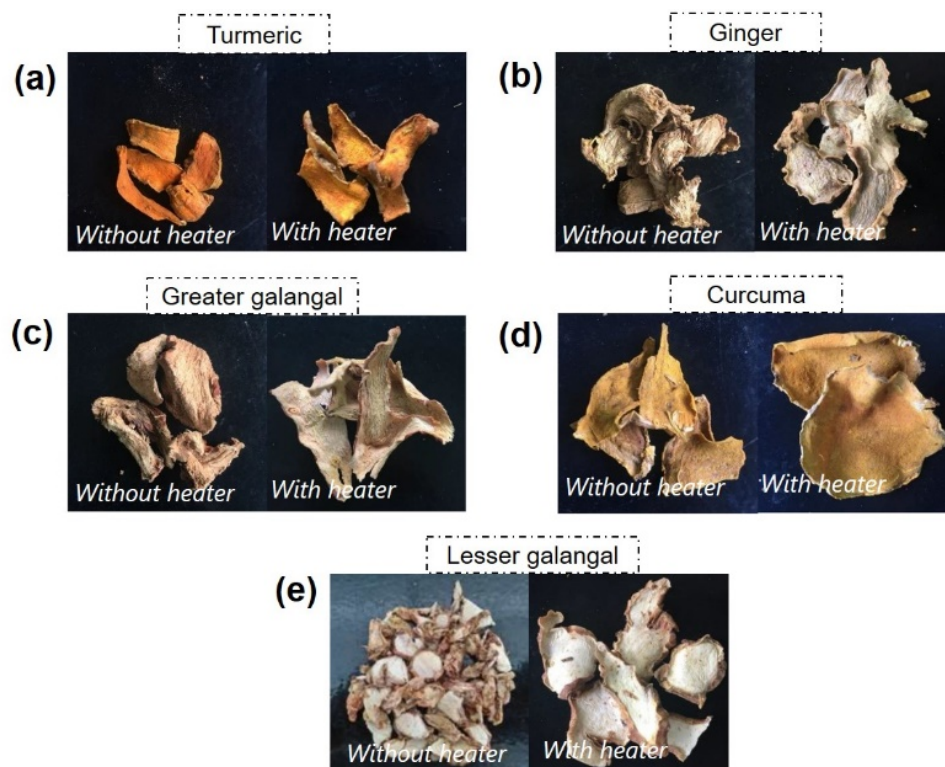


Figure 8. Dried medicinal plant samples produced in the Polydryer with and without heater operation: (a) turmeric, (b) ginger, (c) greater galangal, (d) Curcuma, (e) lesser galangal.

It can be seen that the color of the *Simplicia* products obtained in the Polydryer with the operation of heater was slightly lighter than the products processed without the employment of the heater. This was expected due to more heat applied into the materials that induced the color change [76]. The discoloration and browning of food materials are mainly triggered by various reactions, such as phenol polymerization, pigment destruction, and Maillard reaction of amino and hexoses components [77]. The application of heat may induce color change due to the degradation of thermo-labile pigments, resulting in the formation of dark compounds and a drop in luminosity of the material [78]. However, the color change observed in our study was not severe, and the quality of the *Simplicia* produced still outperformed that of the commercial *Simplicia*. Color analysis was also performed to measure the intensity of the RGB levels of each dried rhizome using ImageJ software (Figure 9) [32]. This technique was used to confirm the color change induced by heat application in the Polydryer with the heater employment to support the visual observation. Five areas were taken for each dried sample, and the average pixel count of the RGB levels for each dried sample was summarized (Table 5). Statistical analysis confirmed that the pixel counts of the products obtained using Polydryer with and without heater employment were not significantly different. Therefore, it was confirmed that, using both techniques, the quality of the products obtained were not significantly altered.

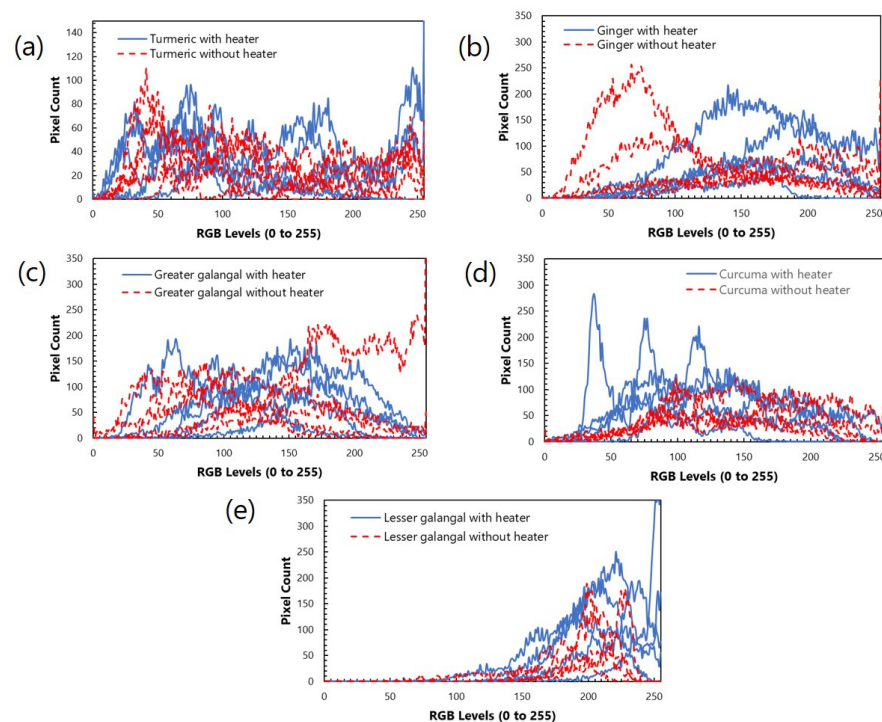


Figure 9. Intensity of the RGB level of each dried rhizome with and without heater employment analyzed using ImageJ software: (a) turmeric, (b) ginger, (c) greater galangal, (d) Curcuma, (e) lesser galangal [32].

Table 5. Summary of the average pixel counts of the RGB level of each dried rhizome with and without heater employment analyzed using ImageJ software [32].

No.	Material	Average Pixel Count	
		with Heater	without Heater
1	Turmeric	121.31	124.79
2	Ginger	161.43	141.09
3	Greater galangal	139.04	130.30
4	Curcuma	122.11	139.74
5	Lesser galangal	211.99	194.81

The ash content in the *Simplicia* products was analyzed and the results are shown in Table 6. The ash content in food substances indicates the mineral content in the materials. The variation of ash content may be caused by the type of biological products, soil variation, and maturity level of the ingredients [79]. Our results showed that the ash content in the dried greater galangal, Curcuma, and lesser galangal was close to the maximum allowable ash content in *Simplicia* [3]. Only ginger *Simplicia* exhibited high ash content, which was likely due to the high initial ash content of the fresh ginger samples. A similar amount of ash content in the dried ginger was also reported by Hasibuan et al. (2017) [80]. The ginger was dried using a combination of a solar energy–molecular sieve drying system. Overall, the drying of medicinal plant materials in the Polydryer was not likely to cause a rise in the ash content since the drying was performed in the drying cabinet and the drying air was filtered prior to entering the polygel cabinet.

Table 6. Summary of ash content in final products of different medicinal plant samples dried in the Polydryer with the operation of a heater.

No.	Material	Ash Content (%)	Maximum Ash Content in <i>Simplicia</i> (%) *
1	Ginger	6.49 ± 0.170	≤4.2
2	Greater galangal	4.04 ± 0.023	≤3.9
3	Curcuma	4.53 ± 0.044	≤4.8
4	Lesser galangal	4.29 ± 0.012	≤8.7

* The maximum ash contents in *Simplicia* refer to the First Edition of Indonesian Herbal Pharmacopoeia by the Ministry of Health the Republic of Indonesia [3].

The drying shrinkage of the *Simplicia* products obtained using the Polydryer incorporated with the heater is presented in Table 7. This parameter represents the amount of compounds in the materials that were lost during drying, not only the moisture content but also other volatile matters [81]. Characterization of the remaining essential oils and bioactive compounds in the dried samples as a result of the material shrinkage will be further investigated in our future work.

Table 7. Drying shrinkage in final products of different medicinal plant samples dried in the Polydryer with the operation of a heater.

No.	Material	Drying Shrinkage (%)
1	Ginger	12.35 ± 1.05
2	Greater galangal	18.71 ± 0.30
3	Curcuma	18.18 ± 0.97
4	Lesser galangal	16.73 ± 0.23

The *Simplicia* products obtained using the Polydryer incorporated with the heater were characterized using SEM to understand the morphology of the *Simplicia* products (Figure 10).

The SEM images showed that the structures of the dried medicinal plant materials generally comprised cellulosic walls and starch granules [82]. In the fresh materials, the starch granules were covered by the cellulosic walls, and the drying induced the break of cellulosic walls. From the SEM images acquired, the size of the starch granules was highly dependent on the type of the dried materials. Each dried material also had different shapes of starch granules: spherical/polyhedral, lenticular, or reniform [83]. Compared with our previous study on drying medicinal plant materials using the Polydryer without heater operation, the rupture of the cellulosic walls in our *Simplicia* obtained via the Polydryer with heater operation was not severe [18]. This indicated that the operation of the heater at a temperature below 60 °C was not likely to damage the structure of the material, and the amount of starch grains in the dried product was greatly maintained. In another study,

ginger drying performed at 60–80 °C was found to severely disrupt the cellulosic walls in the dried products [84].

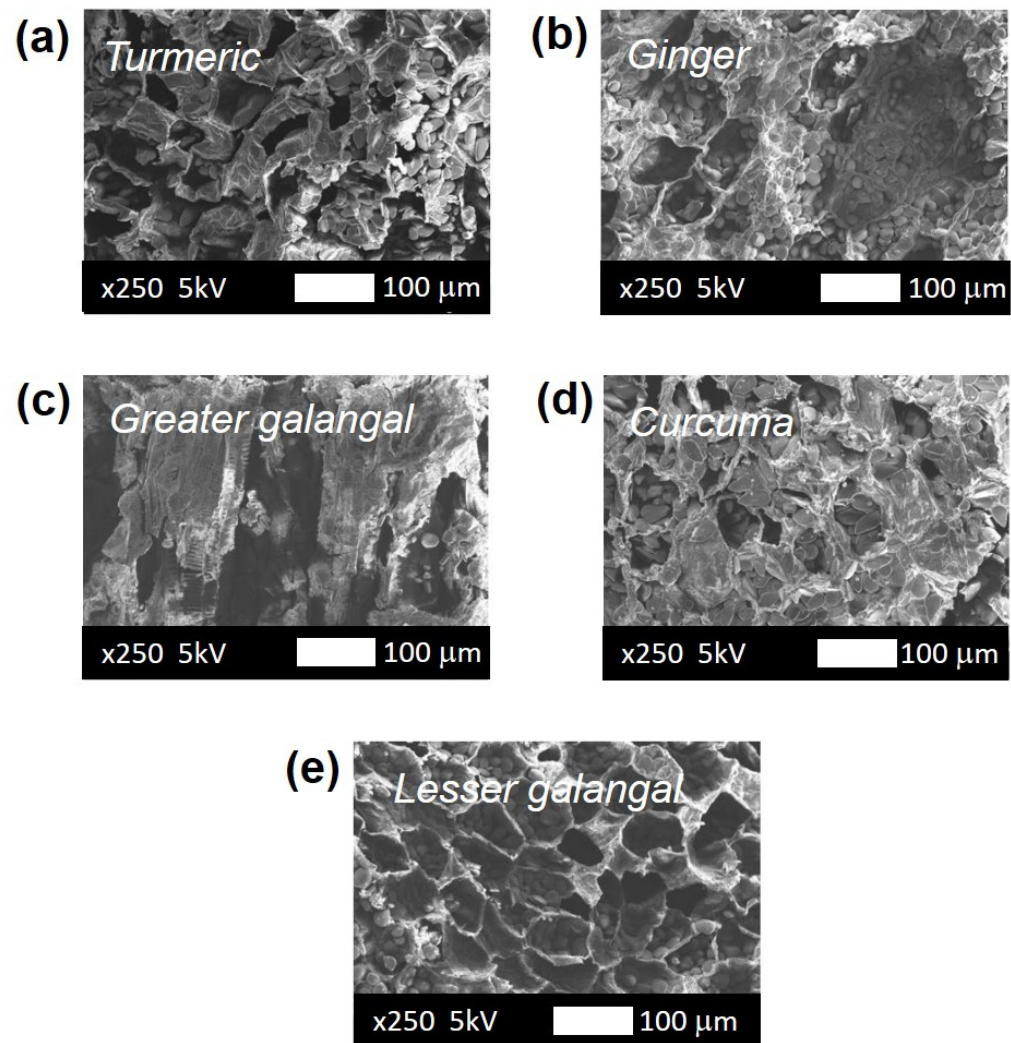


Figure 10. SEM images of Simplicia produced in the Polydryer with heater operation: (a) turmeric, (b) ginger, (c) greater galangal, (d) Curcuma, (e) lesser galangal.

3.5. Energy and Economic Aspect of Polydryers

In order to understand the advantages of incorporating the heater into the Polydryer, the energy and economic aspects of the Polydryer with and without the employment of a heater were compared. The energy consumptions of both dryers are summarized in Table 8. By considering the drying time for each material in the dryers, the power consumptions from the usage of gas fuel and electricity from the operation of the blower were calculated. The blower has a power requirement of 370 Watt, and 1 kg of gas fuel is assumed to be equal to 50 MJ [85]. It can be seen that the energy requirement for the Polydryer without heater operation was slightly lower than the one with a heater. However, since gas fuel is less expensive than electricity, the operation of the Polydryer with the employment of a heater was more economically favorable. The prices of gas fuel and electricity used in this study were 0.8 USD/kg and 0.09 USD/kWh, respectively [86,87]. According to the economic analysis provided in Table 8, it was found that the Polydryer with the operation of a heater was around 23.1% more cost-effective than the Polydryer without a heater operation, in terms of the total power cost.

Table 8. Energy consumption of Polydryer with and without the employment of a heater.

No.	Material	Gas Fuel Consumption (kg)		Electricity Consumption (kWh)		Total Power Consumption (kWh)		Total Power Cost (USD)	
		without Heater	with Heater	without Heater	with Heater	without Heater	with Heater	without Heater	with Heater
1	Turmeric	0	2.30	43.29	6.66	43.29	38.65	3.89	2.44
2	Ginger	0	2.56	35.52	7.40	35.52	42.95	3.19	2.71
3	Greater galangal	0	3.20	44.03	9.25	44.03	53.68	3.96	3.39
4	Curcuma	0	2.30	35.15	6.66	35.15	38.65	3.16	2.44
5	Lesser galangal	0	2.30	35.89	6.66	35.89	38.65	3.23	2.44

4. Conclusions

In this study, a superabsorbent polymer dryer was developed with the employment of a heater to enhance the drying rate of medicinal plant materials. The employment of the heater increased the temperature in the drying cabinet to not more than 60 °C. It also contributed to the moisture reduction in the drying air to reach a relative humidity of 20–25%. The presence of the polygel was found to reduce the heat load of the heater by decreasing the relative humidity of the air entering the heater. The results showed that the relative humidity and temperature at the inlet of the drying cabinet in the Polydryer with heater operation were in the range of 18–24% and 52–57 °C, respectively. The drying of the medicinal plant materials in the modified Polydryer required 18–26 h to attain a final moisture content of 8.8–10.7%. Conversely, the drying in the Polydryer without heater operation took 95–119 h to obtain a final moisture content of 9.0–16.0%. From the fitting of the drying data obtained from the experiments, the drying of medicinal plants in the Polydryer with the incorporation of the heater followed the Page model. The *Simplicia* products obtained using the Polydryer with heater operation showed a slightly lighter color than the *Simplicia* produced without the heater. Characterization using SEM showed that the use of heated drying air was not likely to damage the structure of the materials, which is composed of starch granules and cellulosic walls. Overall, the utilization of the heater in the design of Polydryer greatly enhanced the drying rate of medicinal plant materials by increasing the operating temperature and reducing the relative humidity value of the drying air. This drying machine is a promising and time-effective system that can be widely applied in food and drug industries. The Polydryer with the operation of a heater was found to be 23.1% more cost-effective than the Polydryer without a heater operation, in term of the total power cost consumed. Further investigation regarding the quality and the number of the bioactive compounds and essential oils in the dried products will be discussed in our future work.

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