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Original Article

Effect of the moisture adsorbents on shallot bulb drying

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Abstract

Ingredient deterioration, extended drying times, and inefficient energy use are still issues with current shallot bulb drying. As a result, it is suggested that air dehumidification using solid adsorbents increase the driving force in shallot drying. Zeolite and silica, which were used in this study as moisture adsorbents, increased the mass transfer of water from shallot to air. Dehumidification was used to dry about 25 kg of fresh shallots for 4 hours at temperatures of 30 °C, 40 °C, and 50 °C, with an average air velocity of 7.8 m/s. Results indicated that using adsorbents throughout the drying process could speed up the reduction of moisture content. In addition, Page's model predicted accurately the rate of shallot bulb drying for any variable. The total phenolic compounds (TPC) decreased at higher drying temperature and longer drying time. The addition of zeolite can keep the TPC high. Meanwhile, the thermal energy efficiency rose at higher temperatures. Response surface methodology (RSM) determined that air dehumidified by zeolite at a drying temperature of 50 °C produced the best of shallot drying results.

Keywords: Shallot bulbs, Adsorbent drying, Total phenolic, Mathematical modeling

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Introduction

In Central and Southeast Asia, shallot (*Allium cepa* L.) is widely distributed. Shallot has a variety of chemical and nutritional components including potassium, fiber, vitamin C, phenolic content, flavonoids, and other antioxidants (Djaeni and Arifin, 2017). Shallot bulbs are frequently used as a flavoring in many recipes in different countries, both fresh and dried. In addition, shallot bulbs can also be used as medicine for cataracts, blood pressure, anemia, cardiovascular disease, and thrombolysis (Bamba et al., 2020; Gouda and Nidoni, 2014). Freshly harvested shallots contain an average moisture level of roughly 85% w.b. After being harvested, the outer layer of shallot still has higher free moisture that can encourage germination and increase micro bacteria activities. Therefore, the moisture in the outer layer of shallot bulbs must be kept low to prevent spoilage and maintain the freshness of the inner layer of shallot bulbs.

Currently, reducing moisture from other food and agricultural products, with efficient time and energy, low operating costs, and resulting high ingredient retention is still an important issue in the drying process (Djaeni et al., 2021). The physical and chemical properties of food products are also considered in the selection of drying techniques, including sun drying, vacuum drying, freeze drying, and convective drying. A woven bamboo net was added to the shallot bulb sun drying to avoid contaminations from insects, birds, and dust (S Lestari et al., 2019). Despite that, the moisture loss was greater when the product was dried on the field. A study compared the drying process of open sun drying and solar convection drying (Befikadu et al., 2018). When open sun drying required 20 hours to dry onion slices, the proposed solar convection drying only needed half of its time. However, the onion quality has not been examined. Increasing the drying rate also could be achieved by increasing the drying temperature in a hot-air drying process (Sehrawat and Nema, 2018). In this dryer type, raising the temperature by 10 °C reduced the drying time by nearly 40%. The drying time was shortened due to a larger moisture diffusivity (Bhong and Kale, 2020). The moisture diffusivity influenced the energy needed to evaporate water vapor from red onion slices. Nevertheless, hot-air temperatures (upper 60 °C) caused a significant change in the physical and chemical qualities of onion. Several studies applied other methods to overcome this issue, including a vacuum freeze dryer, microwave freeze dryer, and low-pressure superheated steam dryer (LPSSD) (Sehrawat and Nema, 2018; Wang et al., 2018). These dryers are widely known for their capability to keep the products' quality, such as color, rehydration ratio, and total phenolic compounds (TPC). However, their energy consumption and cost are higher than hot-air drying, so the process can be less feasible.

One of the developments in the drying method is adsorption drying (Djaeni et al., 2020; Djaeni and Arifin, 2017) where moisture content in air as the drying medium was reduced by adsorptive materials (Sasongko et al., 2020). The type of adsorbent is important to air dehumidification with the adsorption system. Although solid and liquid desiccant can be used as the adsorbent, the solid desiccant is more common, and adsorbents such as silica gel and zeolite have been widely used (Batukray, 2019). Drying with adsorbent improves the driving force for drying, reduces energy consumption, and preserves the product quality (Djaeni and Perdanianti, 2019). Based on previous studies, drying using several adsorbents such as silica gel and zeolite was possible to reduce the drying time (Djaeni and Perdanianti, 2019; A'yuni et al., 2022). This drying technique showed positive results for seaweed (Pradana et al., 2019), paddy rice (Utari et al., 2018), corn (Abasi et al., 2017), and mint leaves (Kannan et al., 2021). The goal of this study was to investigate the effect of drying condition and moisture adsorbents on energy efficiency, moisture removal, and TPC.

Material and Methods

Materials

Fresh shallot (*Allium cepa* L.) bulbs were harvested from Sukomoro, Nganjuk, East Java (7°36′03.9″S 111°55′50.6″E), in September (dry season). Adsorbents (silica and zeolite) and ethanol (96%) were purchased at CV. Indrasari, Semarang, Central Java. Charcoal fuel was purchased from a charcoal agent in Semarang. UV-vis spectrophotometer (UV1700; Shimadzu Corporation, Kyoto, Japan) was employed for the analysis of total phenolics in shallots.

Sample preparation

The drying sample was 25 kg of shallot (*Allium cepa* L.) bulbs with moisture content of 84%–86% (w.b). The moisture content was analyzed by thermogravimetric method using electric oven (Memmert UN110, Schwabach, Germany). The shallot bulbs were put in a box dryer (capacity of 1 ton) and then dried at 30 °C, 40 °C, and 50 °C with the respective treatments without adsorbent (control) and with 10 kg of adsorbent (silica or zeolite).

Drying procedure

Figure-1 showed the shallot (*Allium cepa* L.) bulb drying process using a box dryer. The experiment was begun by placing 25 kg of shallot bulbs into a box dryer. Zeolite was in contact with the surrounding air as the drying medium. The air was then heated up to 40 °C and used for shallot drying. The moisture in onion was checked every 10 minutes using the thermogravimetric method for 4 hours. Meanwhile, the total phenolic compounds (TPC) was analyzed every 60 minutes. The procedures were repeated at 30 °C and 50 °C. In the next step, the silica was also used for substituting zeolite in the same operational temperatures.

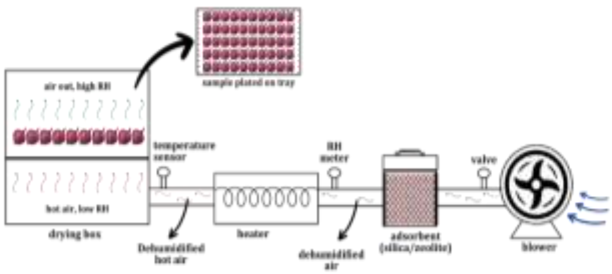

Figure-1. Schematic of shallot bulb drying using box dryer with the adsorbent method

Mathematical modelling

The assumption of this study was the reduction in water content only happens in the outer layers of shallot (*Allium cepa* L.) bulbs, so the drying process can be described using a thin layer mathematical model as depicted in Table-1 (Ademiluyi and Abowei, 2013). Mathematical models predict and simulate how the drying process occurs. Thin layer drying models are frequently employed for constructing drying systems, enhancing drying processes, and fully explaining drying behavior. The quality of the materials being dried, the drying conditions, and the drying method are factors that have a great influence on the drying process, and all of these can be described by kinetic models or drying mathematical models (Onwude et al., 2016).

Table-1. Mathematical model used

Model	Equation	
Newton	$MR = \exp(-kt)$	(1)
Page	$MR = \exp(-kt^n)$	(2)
Modified Page	$MR = \exp(-kt)^n$	(3)
Henderson and Pabis	$MR = a\exp(-kt)$	(4)

The constant values in the model (*k*, *a*, and *n*) were derived using nonlinear regression analysis-based Levenberg–Marquardt algorithm. The results of these model constants were then used to analyze the predicted moisture ratio. Moisture ratio, *MR*, was determined from Equation 5:

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (5)$$

where M_t is the moisture content at observed time *t* (dry basis), M_e is the equilibrium moisture content (dry basis), *t* is observed time (minute), and M_i is the initial moisture content (dry basis). Furthermore, to find out whether the models can be accurate and acceptable, statistical analysis was carried out, such as sum of square error (SSE) (Eq. 6), the root mean squared error (RMSE) (Eq. 7), and coefficient of determination (R^2) (Eq. 8) (Mahayothee et al., 2020). The best model was selected based on the lowest RMSE, the lowest SSE, and the highest coefficient of determination (R^2) (Sahoo et al., 2012):

$$SSE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre.i} - MR_{exp.i}\right)^2 \quad (6)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre.i} - MR_{exp.i}\right)^2} \quad (7)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - \overline{MR}_{exp}\right)^2} \quad (8)$$

$$X^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-k} \quad (9)$$

where $MR_{exp.i}$ and $MR_{pre.i}$, respectively, are the experimental and anticipated moisture ratios; *N* is the number of observational data (triplicate); and *k* is the drying constant value (s^{-1}).

Total phenolic compounds (TPC) in shallot

Determination of the total phenolic content of shallot (*Allium cepa L.*) extract according to Mustafa et al. (2010) and Ghafoor et al. (2019) with several modification, was determined using the spectrophotometer method at a wavelength of 600 – 800 nm and using the Folin-Ciocalteau (FC) reagent. This test was carried out by dissolving 10 grams of sample in 5 mL of aquabidest using a sonicator for 15 minutes. The residue then homogenized with aquabidest to produce a solution. The solution (300 µL) was mixed with 1.5 mL of Folin Ciocalteau reagent and kept for 3 minutes. Then, sodium carbonate solution was added (1.2 mL at a concentration of 7.5%) and homogenized. This mixture was incubated at a range of operating time at room temperature, and the absorbance was measured at the maximum wavelength obtained.

Thermal efficiency

Thermal efficiency is the amount of heat consumed by a product divided by heat supplied, as expressed using the following equation (A'yuni et al., 2022):

$$\eta = \frac{M_t(MR_{in} - MR_{out})\lambda}{FCp(T_{in} - T_{out})} \times 100\% \quad (10)$$

where η is the thermal efficiency (%); M_t denotes the mass of dry shallot at a certain time (kg); MR_i and MR_f are the initial and final of moisture ratio, respectively, λ is the latent heat vaporization at various temperatures of 30 °C, 40 °C, and 50 °C (kJ/kg); *F* is the mass flow of air (kg/s); *Cp* is the specific heat of air (kJ/kg°C); and T_{in} and T_{out} are the inlet and outlet temperatures of the drying chamber, respectively.

Table-2. Factor level of independent variables of shallot bulb drying

Run	Drying time X_1 , (min)	Temperature X_2, (°C)
1	150	40
2	150	40
3	60	30
4	60	50
5	277.28	40
6	22.72	40
7	240	50
8	240	30
9	150	40
10	150	25.86
11	150	40
12	150	54.14
13	150	40

Experimental design

Response surface methodology (RSM) was utilized in the experimental design of this study. The impact of independent variables, time (X_1) and temperature (X_2), as given in
, on dependent parameters (responses), which are moisture content (Y_1) and TPC (Y_2), was studied using the central composite design (CCD). These two responses can be expressed as follows:

$$Y = A_0 + A_0X_1 + A_2X_2 + A_{12}X_1X_2 + A_1X_1^2 + A_{22}X_2^2 \quad (11)$$

where *Y* represents the response variable (thermal efficiency, %); A_0 constant parameter; A_1 and A_2 are linear parameters; A_{12} as interaction effect; and A_{11} and A_{22} are the square effects. The CCD identified the optimum variables to find the ideal response.

Statistical analysis

The drying process optimization using RSM and the statistical analysis were evaluated by Minitab Statistical Software trial version (Minitab LLC., USA) and Microsoft excel (Microsoft Corp., USA). The statistical significance of the drying factors was tested using two-way analysis of variance (ANOVA) with the confidence level, *p-value*. The significance of the study was indicated by *p-value* $\leq$ 0.05. In order to fulfill the statistical analysis, all the data of this experiment were collected in triplicates.

Results and Discussion

Effect of adsorbent on moisture reduction

This study observed the effect of temperature and type of adsorbent on the moisture content reduction. The drying curves of shallot bulbs using adsorbent by silica gel and zeolite at various temperatures were displayed in Figure-2. For all cases, the moisture reduction of shallot bulbs after drying with adsorbent was faster than that of without it. It means that the drying procedure using an adsorbent accelerated the drying rate (Djaeni et al., 2021). The drying process using an adsorbent reduced absolute humidity and relative humidity of air so that it enhanced the driving force for mass transfer from shallot surface to the air (Djaeni et al., 2018; A'yuni et al., 2022; Zhao et al., 2021).

In this instance, three drying models (Page's model, Newton's model, and Henderson–Pabi's model) were assessed (Table 3–6). Result showed that the Page's model has the highest average R^2 value with the lowest RMSE and SSE values compared to the other two models.

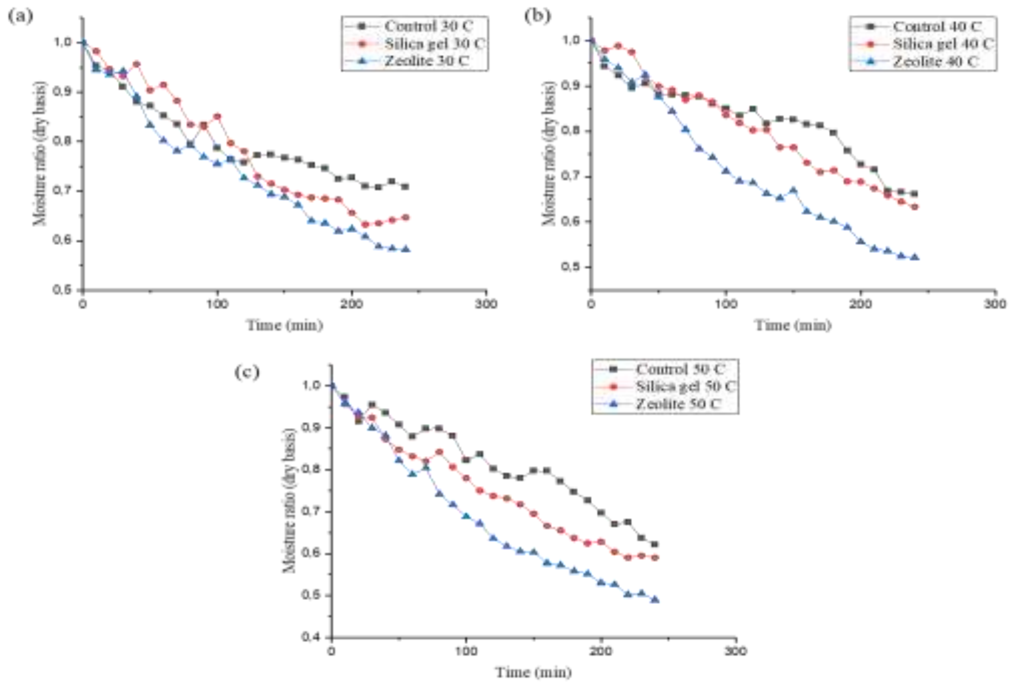

Figure-2. Drying curve of shallot bulbs using silica gel, zeolite, and control at temperatures of (a) 30 °C, (b) 40 °C, and (c) 50 °C

Table-3. The value of a statistical parameter to the Page's model at various drying temperatures

Treatments	T (°C)	*k*	*n*	SSE	RMSE	R^2	X^2	*EF*
Control	30	0.0152	0.577	0.005	0.071	0.970	0.0002	0.970
	40	0.0036	0.837	0.021	0.108	0.893	0.0008	0.888
	50	0.0012	1.071	0.012	0.041	0.959	0.0005	0.958
Silica gel	30	0.0020	1.005	0.011	0.041	0.975	0.0004	0.971
	40	0.0013	1.069	0.003	0.003	0.990	0.0001	0.991
	50	0.0050	0.858	0.004	0.014	0.989	0.0002	0.990
Zeolite	30	0.0072	0.794	0.006	0.010	0.984	0.0002	1.000
	40	0.0043	0.923	0.007	0.016	0.987	0.0003	1.000
	50	0.0067	0.862	0.006	0.017	0.990	0.0002	1.000

Table-4. The value of a statistical parameter to the modified Page's model at various drying temperatures

Treatments	T (°C)	*k*	SSE	RMSE	R^2	X^2	*EF*
Control	30	0.0000071	0.035	0.187	0.914	0.0014	0.791
	40	0.0000063	0.023	0.151	0.904	0.0009	0.876
	50	0.0000070	0.012	0.110	0.959	0.0005	0.956
Silica gel	30	0.0000083	0.011	0.060	0.971	0.0004	0.971
	40	0.0000075	0.004	0.060	0.990	0.0001	0.989
	50	0.0000097	0.008	0.089	0.988	0.0003	0.979
Zeolite	30	0.0000101	0.015	0.124	0.977	0.0006	0.959
	40	0.0000117	0.009	0.092	0.986	0.0003	0.984
	50	0.0000133	0.012	0.111	0.985	0.0005	0.979

Table-5. The value of a statistical parameter to the Newton's model at various drying temperatures

Treatments	T (^oC)	*k*	SSE	RMSE	R^2	X^2	*EF*
Control	30	0.0018	0.035	0.187	0.914	0.0014	0.791
	40	0.0016	0.023	0.151	0.904	0.0009	0.876
	50	0.0017	0.012	0.110	0.956	0.0005	0.956
Silica gel	30	0.0021	0.011	0.104	0.971	0.0004	0.971
	40	0.0019	0.004	0.060	0.990	0.0001	0.989
	50	0.0024	0.008	0.089	0.988	0.0003	0.979
Zeolite	30	0.0025	0.015	0.124	0.977	0.0006	0.959
	40	0.0029	0.009	0.092	0.986	0.0003	0.984
	50	0.0033	0.012	0.111	0.985	0.0005	0.979

Table-6. The value of a statistical parameter to the Henderson–Pabi's model at various drying temperatures

Treatments	T (^oC)	*k*	*a*	SSE	RMSE	R^2	X^2	*EF*
Control	30	0.0014	0.941	0.015	0.124	0.908	0.0006	0.908
	40	0.0014	0.969	0.017	0.131	0.906	0.0007	0.906
	50	0.0017	0.998	0.012	0.110	0.956	0.0005	0.956
Silica gel	30	0.0021	1.004	0.011	0.103	0.971	0.0004	0.971
	40	0.0019	1.009	0.003	0.056	0.990	0.0001	0.990
	50	0.0023	0.975	0.005	0.068	0.988	0.0002	0.988
Zeolite	30	0.0023	0.966	0.009	0.097	0.975	0.0004	0.975
	40	0.0029	0.990	0.008	0.089	0.985	0.0003	0.985
	50	0.0032	0.978	0.010	0.100	0.983	0.0004	0.983

The analysis of the drying model was first performed by linearizing the models' equations. The predicted moisture ratio was then used to connect the drying models and the experimental results. The constant values, R^2, RMSE, and SSE, were calculated using nonlinear regression analysis by examining the trendlines on each model graph and fitting curves. The values of R^2 which are close to 1 and the values of X^2, RMSE, and SSE which are close to 0 were used to determine the value of the agreement between experimental and predictive data. Table 3–6 depicted the findings of the statistical parameters analysis of each model. The results of the four models show that the Page model has the highest R^2 value and the lowest X^2 value. This suggests that the Page model is the most suitable model in describing the drying characteristics of shallots based on the resulting constant values.

Thermal efficiency

Thermal efficiency was calculated using Equation 10, as presented in Figure-3. It can be seen that with zeolite, the energy efficiency increased by around 20% and 10% higher than that of drying without adsorbent and with zeolite, respectively. Adsorbent improved the driving force of drying and reduced the drying time. Then, a shorter drying time lowered the heat use of the drying process. Moreover, the high energy efficiency is also caused by the increase in drying temperature (A'yuni et al., 2022). This result is consistent with the hypothesis that rising temperatures will increase the vapor pressure of water, causing faster evaporation of water (Liu et al., 2018).

Table-7. Two-way ANOVA for the effect of treatments and temperature on the energy efficiency

Source of Variation	*SS*	*df*	*MS*	*F*	*p-value*	*F crit*
Treatments	407.81	2	203.91	111.78	0.00	6.94
Temperature	81.61	2	40.80	22.37	0.01	6.94
Error	7.30	4	1.82			
Total	496.72	8				

The highest thermal efficiency of this experiment was about 71.5% at air temperature of 50 °C and still comparable to the highest thermal efficiency found in the hybrid microwave-hot-air dryer at 60 °C (Maftoonazad et al., 2020) and a gas fired hot-air dryer at 70 °C (El-Mesery and Mwithiga, 2012). According to this comparison, shallot bulbs drying using a box dryer with dehumidification was able to produce an efficient process even at a low temperature. Table-7 showed a two-way ANOVA of the heat efficiency. The analysis showed that treatments and temperatures impacted substantially the energy efficiency (*p-value* < 0.05).

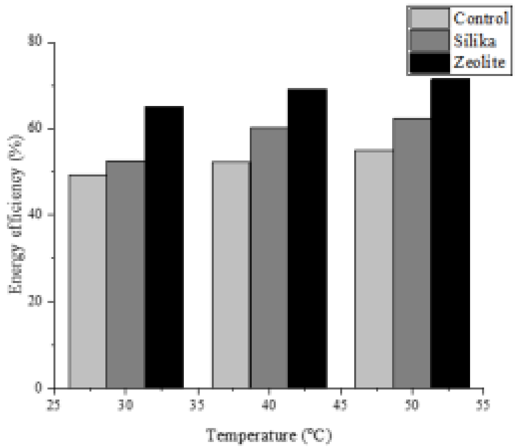

Figure-3. Energy efficiency of shallot bulb drying using box dryer

Total phenolic compounds (TPC)

Total phenolic compounds (TPC) in each treatment showed fluctuating values that was relatively decreased (Figure-4).

The input hot-air deteriorated TPC with increasing temperature and drying time. This is in accordance with a statement that phenolic is one of the bioactive compounds that are sensitive to heat (Podsedek, 2007). Previous study stated that increasing the temperature impacted on the total phenolics reduction (Arslan and Özcan, 2010). Compared with the drying without adsorbent, TPC retention with adsorbent was higher. For instance, using zeolite and silica at 50 °C, the TPC retention was 67.2% and 76.9%, respectively. However, without adsorbent, the TPC retention was about 42.0%. Hence, because of a high influence of temperature on TPC, the drying process with adsorbent is considerably more effective.

The degradation of TPC during drying was mainly due to the action of enzymes such as polyphenol oxidase (PPO) and peroxidase (POD) (McSweeney and Seetharaman, 2015). Several studies demonstrated that high temperature drying provided good control of enzyme activity leading to the best TPC retention. Meanwhile, drying at a lower temperature took more time to complete the operation, which increased the level of phenolic degradation (Nguyen et al., 2022; Samoticha et al., 2016). Comparatively, in onion drying, lowering the relative humidity increased the driving force of drying at either low or medium temperature so that the drying time was reduced and total phenolic component breakdown was minimized (Sasongko et al., 2020).

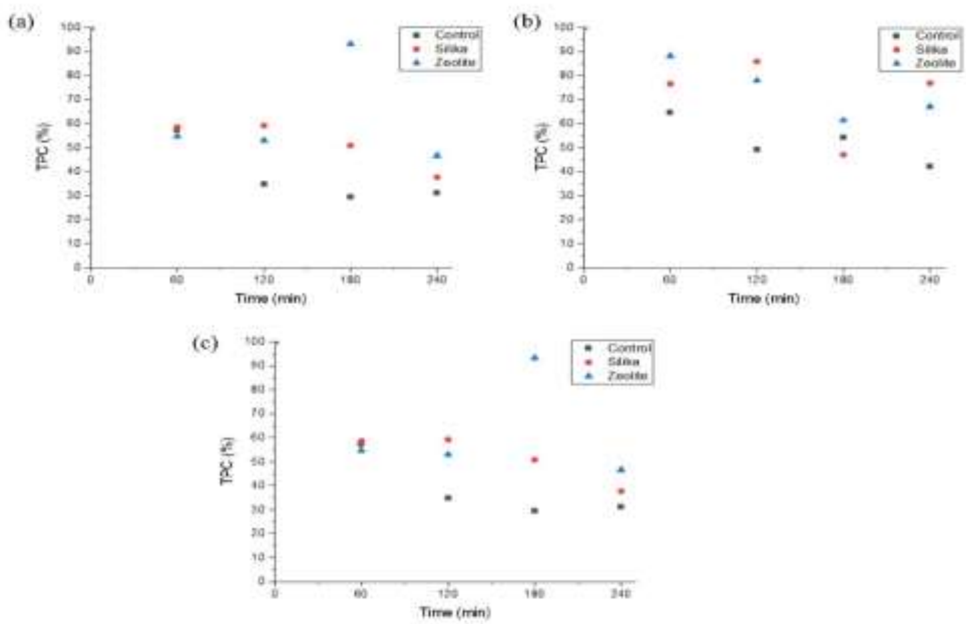

Figure-4. Total phenolic compounds (TPC) retention of shallot bulb drying at various temperatures: 30 °C (a), 40 °C (b), and 50 °C (c)

Response surface methodology (RSM)

The effect of two independent variables on bulbs drying was analyzed using CCD. The RSM of the moisture content and TPC were in Table-8. Based on the regression, drying time and temperature affected significantly the moisture content and TPC in shallot bulbs both in the control treatment, with silica, and zeolite (*p-value* < 0.05). The response surface correlations for each significant value were presented in Figure-5. It is shown that the lowest moisture content was at the longest drying time and highest temperature. For TPC retention, the lowest values were found when the temperature is low and the drying time is long. At a longer drying time, the compounds' degradation occurred longer even at a lower temperature. However, research discovered that there is no significant impact of different temperatures (60 °C and 70 °C) on TPC (Roman et al., 2020). Using RSM, the highest TPC retention of drying with zeolite was 88.3% at 50 °C and 60 min. Meanwhile with silica, the highest TPC retention was 84.8% at 54 °C and 150 min. Compared to previous study, this result is still higher than the hot-air dryer (74%) and vacuum dryer (84%) and lower than LPPSD (89%) (Sehrawat and Nema, 2018).

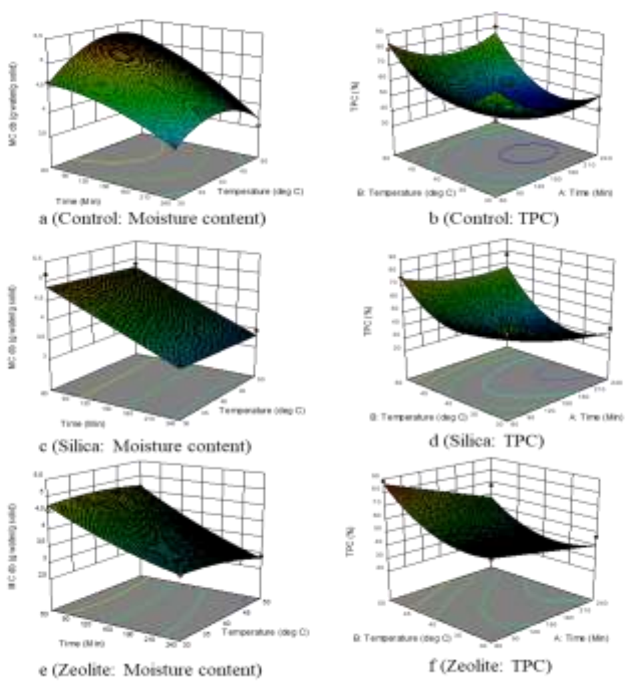

Figure-5. Response surface relation between drying time (min) and temperature (°C)

Table-8. Response surface models for shallot bulb drying

Output variables	Treatment	Model	*p-value*	(R^2)
Moisture content (gr water/gr solid)	Control	$-2.79936 + 0.00746095x_1 + 0.36906x_2 - 0.000189694x_1x_2 - 0.00002024x_1^2 - 0.00412494x_2^2$	< 0.0001	0.9786
	Silica	$7.43036 - 0.013378x_1 - 0.087981x_2 + 0.0000283056x_1x_2 + 0.0000141836x_1^2 + 0.000982125x_2^2$	< 0.0001	0.9641
	Zeolite	$3.56330 - 0.00823508x_1 - 0.095618x_2 + 0.000136111x_1x_2 + 0.0000159954x_1^2 + 0.00113187x_2^2$	< 0.0001	0.9912
Total phenolic compounds retention (%)	Control	$380.48640 - 0.68102x_1 - 15.04299x_2 + 0.00420661x_1x_2 + 0.00142487x_1^2 + 0.19163x_2^2$	0.0091	0.8466
	Silica	$389.00459 - 0.54664x_1 - 16.34955x_2 + 0.00590072x_1x_2 + 0.000677204x_1^2 + 0.20685x_2^2$	0.0003	0.9449
	Zeolite	$191.35372 + 0.019608x_1 - 7.96206x_2 - 0.00363542x_1x_2 + 0.00000707408x_1^2 + 0.12109x_2^2$	0.0010	0.9197

*x_1 = drying time; x_2 = temperature

Conclusion

Adsorption drying at 30, 40, and 50 °C with silica gel and zeolite adsorbents have been carried out for onion. Compared to the control treatment (onion drying without adsorbent), the addition of silica gel and zeolite as moisture adsorbers can improve the drying performances in term of onion quality and thermal efficiency. As a result, the adsorption dryer can reduce drying time, enhance thermal efficiency up to 71.5%. In addition, the total phenolic content (TPC) retention can be kept high especially at lower drying temperatures. Mathematical models have been also developed to represent the kinetics of drying onions. Here, the moisture reduction during the drying can be well illustrated by Page's model.

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Contribution of Authors

Nissa MC: Performed the experiment, analyzed and interpreted data and prepared the manuscript
A'yuni DQ: Analyzed and interpreted data and prepared the manuscript
Sasongko SB: Assisted in model development, data interpretation, as well as edited the manuscript
Prasetyaningrum A: Assisted in data analysis and interpretation and edited the manuscript
Djaeni M: Performed equipment design, experimental set up, and prepared the manuscript
Hii CL: Assisted in data interpretation and edited the manuscript

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