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The Effect of Drying Methods on the Physicochemical Characteristics of Curly Red Chili (*Capsicum annuum* L.)

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ABSTRACT
Curly red chili has high nutritional content, which includes capsaicinoids, vitamin C, carotenoids, and antioxidant compounds. However, their high moisture content renders them perishable. During peak harvest seasons, prices for chili significantly decrease, while they tend to rise in colder months. Inefficient postharvest technologies contribute to substantial waste due to damage. Effective postharvest processing, such as drying, mitigates these challenges by reducing moisture content and extending shelf life. Various drying methods, including food dehydration, oven, vacuum frying, and freeze drying, have distinct advantages and disadvantages. Comparative studies have been conducted on these methods specifically for curly red chili. This study contributes to evaluating the effects of different drying methods on the color, moisture content, vitamin C content, and capsaicin concentration of curly red chili (Capsicum annuum L.) in order to determine the most effective method for preserving its nutritional and physicochemical qualities. The results indicate that the drying method significantly influences the physicochemical properties of curly red chili. Among the methods tested, freeze-drying emerged as the most effective, based on the color of 66.69 ± 2.25, moisture content of 3.81%, and vitamin C of 94.34 mg/100g. The optimal treatment yielded a spiciness level of 16504.71 SHU with a capsaicinoid content of 1100.32 mcg/g. Further research is needed to explore how moisture content affects capsaicin levels in curly red chili.

KEYWORDS
Capsaicin; Curly red chili; Drying; Freeze-drying; Vitamin C

1. INTRODUCTION

Indonesia, as an archipelagic country with abundant biodiversity, holds significant potential in the agricultural sector, particularly in chili (*Capsicum* spp.) production. Red chili is an essential component of Indonesian culinary culture and a high-value horticultural commodity. Based on data from the Food and Agriculture Organization, Indonesia ranks fourth as the largest chili-producing country in the world. In 2022, red chili production in Indonesia reached 1.48 million tons, showing a significant increase compared to the previous year [1], [2].

Curly red chili is one of the most widely consumed varieties due to its high nutritional content, such as capsaicinoids, vitamin C, carotenoids, and antioxidant compounds [3]. However, this commodity is highly perishable due to its high moisture content, which accelerates microbial growth and enzymatic degradation, leading to significant postharvest losses. Additionally, seasonal fluctuations in chili production create price instability, with oversupply and sharp price declines during harvest seasons, and scarcity with price spikes during off-seasons. The lack of effective and sustainable postharvest handling techniques exacerbates this issue, resulting in high levels of waste from spoilage and physical damage [4], [5].

Drying is an effective postharvest method for extending the shelf life of chili by reducing moisture content. However, the drying process can significantly affect nutritional quality and physical characteristics, such as color and texture. Therefore, pretreatment such as blanching is required to mitigate nutrient degradation and changes in the physicochemical characteristics of chili during drying [6], [7].

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Pretreatment techniques such as blanching are often applied. Blanching has been shown to inactivate enzymes responsible for spoilage and unwanted color changes, as well as to improve drying efficiency by facilitating moisture diffusion [8], [9]. Specifically, low-temperature long-time (LTST) blanching has been reported to maintain product quality during drying processes [10]. This method not only reduces enzymatic activity but also facilitates moisture removal by disrupting cellular structures, thereby improving drying efficiency [10], [11].

Several drying methods, such as oven drying, food dehydration drying, vacuum frying, and freeze-drying, are commonly used for preserving agricultural commodities [12]. Each technique offers specific advantages and limitations in terms of preserving nutritional content and physical characteristics. However, comprehensive comparative studies focusing on the effects of these drying methods on curly red chili remain limited in the literature.

Therefore, the present study aimed to investigate the effects of different drying methods on the color, moisture content, vitamin C content, and capsaicin concentration of curly red chili (*Capsicum annuum* L.). High-Performance Liquid Chromatography (HPLC) was employed to determine the capsaicin content in the most promising treatments. The findings of this study are expected to contribute to practical insights and scientific recommendations for the selection of optimal drying techniques to enhance postharvest quality, minimize nutritional losses, and improve the market value of curly red chili.

2. MATERIALS AND METHODS

2.1. Materials

The materials used in the study were curly red chili obtained from one trader in Citraland Market, Surabaya, East Java with medium size criteria following SNI Chili 4480:2016. The materials used for analysis consisted of methanol (EMSURE®, Merck KgaA, Germany), amylum indicator (Merck KgaA, Germany), iodine solution (EMSURE®, Merck KgaA, Germany), sodium thiosulfate (EMSURE®, Merck KgaA, Germany), potassium iodate (EMSURE®, Merck KgaA, Germany), sulfuric acid (FlukaTM, Honeywell, Germany), and distilled water.

2.2. Preparation of Curly Red Chili

Curly red chili samples were selected based on the Indonesian National Standard (SNI 4480:2016) for fresh chili, with medium-sized fruit as the selection criterion. Each fruit was free from physical damage, disease, and signs of spoilage. A total of 250 g of chili was used for each drying method. Prior to drying, all samples were subjected to a blanching pretreatment using a Thermomix (Vorwerk TM5, Germany) at 65 °C for 10 minutes. After blanching, the samples were evenly distributed and processed using four different drying methods. The drying experiments were conducted at the Food Processing Laboratory and the Food Chemistry and Biochemistry Laboratory, Department of Food Technology, Universitas Ciputra Surabaya. The drying process was performed with an oven at 60 °C for 14 hours, a food dehydrator at 70 °C for 10 hours, vacuum frying at 100 °C for 20 minutes, and freeze-drying at -50 °C for 24 hours.

2.3. Color Analysis

Color testing of samples was carried out with the CHN Spec CS-10 Colorimeter to determine the color value expressed in three units, namely L^*, a^*, and b^*. The L^* (lightness) value indicates the level of brightness, a^* (redness) indicates green color for negative values and red color for the opposite value, and b^* (yellowness) indicates blue color for negative values and yellow color for the opposite [13]. Each sample was analyzed in triplicate to ensure accuracy and reproducibility of the results.

2.4. Moisture Content Analysis

An analysis of the moisture content of the sample was carried out with a Shimadzu MOC63U moisture analyzer (Shimadzu, Japan). The chili samples were first crushed, and approximately 0.5 g of each sample was weighed and placed on an aluminium cup for analysis. Each sample was analyzed in triplicate to ensure accuracy and reproducibility of the results. The moisture content values were automatically recorded by the instrument [14].

2.5. Vitamin C Analysis

Vitamin C content testing was carried out using the iodometric titration method based on AOAC 967.22- 2005. The sample filtrate was pipetted as much as 5 mL and put into an erlenmeyer. Then, 1 mL of 10% H_2SO_4 solution and a few drops of 1% amylum indicator were added. Next, titrated with I_2 solution until blackish–red [15]. Each sample was analyzed in triplicate to ensure precision. Vitamin C calculations can be done using equation (1).

$$Vitamin\ C\ (mg/100g) = \frac{(Volume\ I_2 \times 0.88 \times dilution\ ratio) \times 100}{(sample\ weight)g} \quad (1)$$

2.6. Capsaicin Content Analysis

Capsaicin content was determined using the High-Performance Liquid Chromatography (HPLC) method, which is a validated procedure for the quantification of capsaicinoids in chili products and their extracts [15]. The analysis was performed by first extracting capsaicinoids from the dried chili samples using an organic solvent, typically acetonitrile or methanol. The extract was then filtered and injected into the HPLC system equipped with a C18 reversed-phase column. The mobile phase consisted of a mixture of acetonitrile and water, and the separation was carried out under isocratic conditions. Detection was performed using a UV detector at a wavelength of 280 nm. Capsaicin concentrations were determined by comparing the retention time and peak area with those of capsaicin standard solutions [16]. Each sample was analyzed in triplicate to ensure precision.

2.7. Research Design

This study used a Randomized Group Design, with four treatments and five replicates. Determination of the number of treatment replicates is based on the Federer method.

2.8. Data Analysis

The data results that have been obtained are then processed into statistical data with one-way analysis of variance (ANOVA, p=0.05) using the IBM SPSS (Statistical Product and Service Solution) Statistic 26 application. If the results obtained are significantly different, then further tests are carried out using the Duncan test. Data will be declared significant if the p-value is ≤ 0.05.

2.9. Determination of The Optimal Treatment Sample

The optimal treatment sample for curly red chili products was selected using the Simple Additive Weighting (SAW) method, following the approach of [17]. The determination criteria were based on physicochemical characteristics, including color, moisture content, and vitamin C content. The SAW analysis was performed using Microsoft Excel, with weighting assigned based on the average value of each parameter.

3. RESULTS AND DISCUSSION

3.1. Color

Based on color analysis, the L^*, a^*, b^* values were obtained, which is continued with further analysis, namely hue and chroma. The color evaluation uses L^* values to indicate brightness, a^* values to represent the red-green spectrum, and b^* values to indicate the blue-yellow spectrum. A positive a^* value indicates a red color, while a negative a^* value indicates a green color. Positive b^* values indicate yellow color and negative b^* values indicate blue color [18]. Based on the analysis results, there is no significant difference between oven (P1) and vacuum frying (P2). However, there is a significant difference between the two samples with a food dehydrator (P3) and freeze-drying (P4). Therefore, the effect of drying on color should be evaluated. Detailed color analysis data can be seen in Table 1.

The drying method influences color changes and brightness in curly red chili samples. According to Table 1, P4 exhibited the highest chroma value, indicating a brighter and more vivid color compared to other samples. This is due to the low degradation of color pigments in the sample. The freeze-drying mechanism with low temperature and vacuum pressure ensures that the pigments remain stable with minimal degradation. The low temperature inhibits polyphenol oxidase enzyme activity, which is responsible for browning [19]. Additionally, the sublimation process prevents maillard reactions since it bypasses the liquid phase, preserving the cell structure and trapping pigments within the sample matrix. Carotenoid and anthocyanin pigments are stable at low temperatures and vacuum pressure, minimizing oxidation and thermal degradation [20].

Table 1. Color of curly red chili pepper.

Sample	L^*	a^*	b^*	Chroma	Hue angle	Color Description		
						Name	Hue	Hex Code
P1	$51.46^{ab} \pm 0.39$	$26.11^{a} \pm 0.21$	$25.40^{a} \pm 0.61$	$36.54^{a} \pm 2.00$	$0.61^{a} \pm 0.20$	*Sepia*	*Brown*	#97563F
P2	$40.13^{a} \pm 0.65$	$24.63^{a} \pm 1.31$	$25.40^{a} \pm 1.19$	$35.60^{a} \pm 2.78$	$0.59^{a} \pm 0.35$	*Baker's Chocolate*	*Brown*	#692A13
P3	$49.19^{ab} \pm 0.51$	$28.37^{a} \pm 0.77$	$31.04^{b} \pm 1.95$	$42.31^{b} \pm 2.65$	$0.79^{ab} \pm 0.34$	*Alert Tan*	*Orange*	#93482C
P4	$57.22^{b} \pm 0.43$	$37.81^{b} \pm 0.45$	$54.66^{c} \pm 1.25$	$66.69^{c} \pm 2.25$	$1.23^{b} \pm 0.34$	*Tahiti Gold*	*Orange*	#DF772F

Notes: Data are presented as mean ± standard deviation. Different notations between treatments indicate significant differences between sample treatments ($p \leq 0.05$). Sample P1 (oven), sample P2 (vacuum frying), sample P3 (food dehydration), sample P4 (freeze-drying).

P1 and P2 statistical analysis indicated no significant difference, as evidenced by the same notation. Both treatments resulted in a brownish discoloration due to the degradation of color pigments, specifically, carotenoids and anthocyanins. The drying process was conducted at 60 °C to 70 °C for a prolonged duration, which facilitated pigment oxidation and browning reactions [21]. P2 was performed under vacuum conditions, utilizing oil as a heat transfer medium, which contributed to pigment degradation due to pigment solubility in oil [22]. The high drying temperature of 100 °C resulted in pigment degradation comparable to that observed in P1, where an oven was used at 60 °C. In P1, heat transfer occurred through air convection, providing more uniform heating despite requiring a longer processing time. This mechanism contributed to greater pigment stability [23], [24]. Conversely, P2 involves heat transfer via oil conduction, which generates higher thermal energy than air convection, leading to greater pigment degradation due to direct contact with oil [25]. Additionally, repeated oil usage accelerated the decline in color intensity as oxidation generated free radicals. Despite the shorter processing time, the high-temperature conditions in P2 induced thermal oxidation, reducing the intensity of the red color and leading to browning in curly red chili [26]. These factors collectively contributed to the lack of a significant difference between P1 and P2.

Statistical data analysis revealed that P3 exhibited a significant difference compared to P1, P2, and P4. This is attributed to the better preservation of color pigments, specifically carotenoids and anthocyanins, at lower temperatures. However, while P3 was effective in maintaining color intensity, it was not as effective as P4, as exposure to hot air still led to some degree of pigment degradation. The gradual water evaporation mechanism in P3 contributed to maintaining the color intensity of curly red chili, as the color pigments remained more stable. P3 also exhibited an orange color, which can be interpreted as the carotenoid pigments are better preserved compared to P1 and P2. This is due to the vacuum conditions used in the P3 drying process, which help reduce oxidation. However, some pigment degradation occurred due to high-temperature exposure and the use of oil as a heat transfer medium. The oil may have dissolved certain pigments, slightly reducing the overall color intensity [22].

3.2. Moisture Content

Chili has a high moisture content, which makes it highly perishable. To extend its shelf life, this study employed four different drying methods: oven, vacuum frying, food dehydration, and freeze-drying to reduce the moisture content of curly red chili. The results are summarized in Table 2.

The results of the variance test showed that the color in the three drying methods was not significantly different. It was known that the average moisture content obtained ranged from 3.81% to 4.15%. The results of the moisture content obtained meet the requirements of SNI 3389:2023 regarding dried chili, with a maximum moisture content limit of 11%. Based on Table 2, a significant difference was observed between treatments P1 and P2, P3, and P4. The highest moisture content was found in P1, and the lowest was found in P4. The P1 has a significant difference with other treatments; the highest water content is 4.88%. This is because air circulation and heat transfer are less effective, which causes water evaporation to be slower than in other treatments. The oven drying mechanism operates at high temperatures for an extended period but does so unevenly, causing some sample areas to retain more moisture. At the beginning of the drying process, there will be an increase in the drying rate due to the amount of water contained in the sample. However, as the process continues. The drying rate decreases due to the formation of a hardened outer layer on the chili's surface, which inhibits further moisture release. This phenomenon results in a relatively high final moisture content [27].

Table 2. Moisture content of curly red chili pepper.

Sample	Moisture content (%)
P1	$4.88^{b} \pm 0.42$
P2	$4.15^{a} \pm 0.41$
P3	$3.94^{a} \pm 0.41$
P4	$3.8^{a} \pm 0.42$

Notes: Data are presented as mean ± standard deviation. Different notations between treatments indicate significant differences between sample treatments ($p \leq 0.05$). Sample P1 (oven), sample P2 (vacuum frying), sample P3 (food dehydrator), sample P4 (freeze-drying).

P2 treatment conducted under vacuum pressure (-p=60 cmHg) obtained results that were not significantly different from P3 and P4. Vacuum frying uses oil and vacuum conditions to evaporate the moisture content of the sample without causing excessive nutrient degradation. The vacuum condition lowers the boiling point of water, facilitating faster moisture evaporation. Higher temperatures and lower vacuum pressures accelerate this process, as water evaporates more efficiently under reduced boiling point conditions. Additionally, oil has a higher thermal conductivity than air, allowing heat energy to be absorbed more rapidly by the sample, further enhancing drying efficiency [28].

The mechanism of P3 produces samples with efficient and uniform water evaporation. The drying rate of the dehydrator is faster compared to the oven due to its more stable temperature and air circulation. This facilitates the diffusion of water from the sample. Additionally, a stable temperature enhances heat transfer efficiency [29]. In P4, the drying process also demonstrates high efficiency in removing water from the material under low-temperature and vacuum conditions [20]. Additionally, the curly red chili was cut into three parts to accelerate the drying process. The freeze-drying rate tends to be slower compared to other drying methods. However, freeze-drying effectively removes moisture, including bound water, without damaging the structural integrity of the material.

The principle of freeze-drying is sublimation, where ice transforms directly into water vapor without passing through the liquid phase under low-pressure conditions. This low pressure enhances the efficiency of water vapor transfer from the material. Before the drying process, curly red chili is first frozen to form stable ice crystals, ensuring effective sublimation. The prolonged drying time in freeze-drying is due to the energy required to break molecular bonds in the ice phase, while the vacuum condition further slows down the rate of moisture removal [19], [20]. The efficiency of the drying mechanism enables maximum water evaporation, resulting in no significant differences among treatments P2, P3, and P4.

3.3. Vitamin C

One of the essential vitamins in chili is vitamin C, a water-soluble nutrient that is highly unstable at high temperatures [30]. Therefore, the drying process significantly affects the vitamin C in curly red chili. The results of the vitamin C content analysis are presented in Table 3.

Based on Table 3, the analysis results show that there are significant differences ($p \leq 0.05$) between treatments as evidenced by the different notations in each sample. Different drying machines have a significant effect on the stability of the vitamin C content of curly red chili. In addition to the drying method, vitamin C stability is influenced by factors such as temperature, pressure, heat transfer, and evaporation processes. The longer the chili processing process, the smaller the vitamin C content [31]. In this study, vitamin C analysis was conducted on powdered dried chili samples. The grinding process may further reduce vitamin C content, as smaller particles are more susceptible to oxidation when exposed to air. The finer the chili texture, the greater the potential loss of vitamin C. These factors contribute to the lower-than-expected vitamin C levels in dried curly red chili.

Table 3. Vitamin C content of curly red chili.

Sample	Vitamin C (mg/100g)
P1	$29.92^{a} \pm 1.02$
P2	$56.79^{c} \pm 1.57$
P3	$49.28^{b} \pm 1.17$
P4	$94.34^{d} \pm 1.40$

Notes: Data are presented as mean ± standard deviation. Different notations between treatments indicate significant differences between sample treatments ($p \leq 0.05$). Sample P1 (oven), sample P2 (vacuum frying), sample P3 (food dehydration), sample P4 (freeze-drying).

Among the treatments. P4 retained the highest vitamin C content at 94.34 mg/100g. The freeze-drying process effectively preserves vitamin C due to its reliance on sublimation, low temperatures, and vacuum pressure. These three factors prevent thermal degradation and oxidation of vitamin C so that the content is better maintained than in other drying machines [20]. In P2, despite using high temperature, it can still maintain vitamin C content better than P1 and P3. This is because vacuum conditions help reduce nutrient degradation. However, the use of oil as a heat transfer medium leads to some vitamin C degradation, resulting in lower retention than P4 [26].

The mechanism of the P3 drying machine is based on the principle of circulating hot air convection, so that the exposure to hot air is more even. Meanwhile, P1, with a high temperature and relatively longer time than P3, increases the rate of vitamin C oxidation. P1 mechanism heat transfer occurs by conduction, convection, and hot air radiation from the surface of the oven tray, causing faster loss of vitamin C. P1 has a lower relative humidity that can accelerate water evaporation. However, it can increase the oxidation of vitamin C. When the water content in chili is reduced a lot in a high-temperature environment, the oxidation of nutrients occurs faster. The higher the drying temperature used, the more sample nutrients are degraded [32], [33].

3.4. Capsaicin Content

Capsaicin content analysis was conducted only on the best-performing sample based on all evaluated parameters using the SAW method. Sample P4 was identified as the optimal treatment, as it had the lowest moisture content, which amounts to 3.81%, indicating a drier sample that meets the SNI 3389:2023 Dried Chili Quality Standard. Additionally, P4 exhibited superior hue, chroma, and vitamin C content, with amounts of 94.34 mg/100g compared to other treatments. Based on the analysis of this best-performing sample, capsaicin content and spiciness levels were further examined. As shown in Table 4, curly red chili treated with P4 contained 16504.71 Scoville Heat Units (SHU). According to SNI 4480:2016, the spiciness level of curly red chili in this study falls within the "mildly spicy" category, with a capsaicinoid content of 1100.32 mcg/g.

Capsaicin is a spicy compound in chili that gives a spicy taste sensation in the mouth. In addition, there are other compounds that also provide a spicy flavor, namely capsaicinoids. The compound is found in the white inner chili skin as a place to attach chili seeds and placenta [34]. The relatively low capsaicinoid content in this study can be attributed to the processing methods applied, including pretreatment blanching and grinding into powder. These processes can reduce the stability of capsaicinoids due to oxidation and enzymatic activity, particularly from peroxidase enzymes [35].

Table 4. Capsaicin content of curly red chili.

Parameters	Quantity
Spiciness level	16504.71 SHU
Total capsaicinoids	1100.32 mcg/g

Fresh curly red chili is around 30000–50000 SHU capsaicin content, which is influenced by the ripeness of the chili. As the chili matures, its capsaicin concentration increases, which is visually indicated by a deeper red color [16]. Moisture content also affects spiciness levels, where lower moisture content in fresh chilies corresponds to higher spiciness levels, while higher moisture content results in reduced pungency [36].

The capsaicinoid content with the P4 treatment was not fully retained due to several factors from the drying machine used. Although freeze-drying is highly effective in preserving nutrients, capsaicinoid retention in P4 was not entirely maintained due to sublimation effects during drying [37]. Capsaicinoids are concentrated in the placental tissue, making them susceptible to degradation as moisture evaporates. Additionally, the low-pressure conditions in freeze drying may contribute to the loss of these compounds. Further degradation may have occurred during the grinding process, which exposes the chili powder to oxidation [35], [37].

4. CONCLUSION

Drying methods using food dehydration, oven, vacuum frying, and freeze-drying significantly affect the physicochemical characteristics of curly red chili. This study shows that the drying method using freeze-drying obtained the best results from all parameters. Chili dried using this method had the best color retention and highest vitamin C content. Furthermore, P4 yielded a spiciness level of 16504.71 SHU with a capsaicinoid content of 1100.32 mcg/g, indicating that freeze-drying is an optimal method for preserving both nutritional quality and sensory attributes of curly red chili.

AUTHOR CONTRIBUTION

All author contributed equally to the main contributor to this paper. All authors read and approved the final paper. **Birgitta Allison Kesuma**: Writing (review & editing), writing (original draft), and formal analysis. **Ika Yohanna Pratiwi**: Investigation, writing (review & editing), supervision, and conceptualization. **Yohannes Somawiharja**: Writing (review & editing), writing (original draft), and investigation.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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