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Kinetic Study on the Physicochemical of Ulam Raja (*Cosmos caudatus*) Leaves Powder

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Ulam raja (*Cosmos caudatus*) is a popular medicinal herb due to its high content of bioactive compounds. However, the leaves must be dried prior to use to extend the shelf life of *C. caudatus* leaf powder. The main objective of this study was to determine the effects of different oven drying times and temperatures on the physicochemical properties and antioxidant activity of *C. caudatus* leaf powder. The leaves were dried at 60 °C, 80 °C, and 100 °C, and the moisture reduction kinetics were modelled using zero-, first-, and second-order reaction equations to determine the drying rate constants. Proximate analysis was conducted and the aqueous leaf extracts were prepared for antioxidant evaluation, including total phenolic content via the Folin–Ciocalteu assay and radical scavenging activity using the DPPH assay. Color (L, a, b*) were also measured to assess extract quality. The second-order kinetic model was identified as the most suitable for describing the drying rate of *C. caudatus* leaves. Both nutrient and phenolic contents were significantly reduced at higher drying temperatures (80 °C to 100 °C), as excessive heat compromised leaf quality. While higher drying temperatures shortened drying time, 60 °C yielded the highest activation energy (25.508 kJ/mol) without compromising energy consumption, drying efficiency, or nutritional quality.

Keywords: *Cosmos caudatus*; drying; kinetic model; moisture content

I. INTRODUCTION

Cosmos caudatus, known as ulam raja in Malaysia and kenikir in Indonesia, belongs to the Asteraceae family. It is native to Latin America but has been naturalised across tropical regions of Southeast Asia. The plant is characterised by soft, pungent leaves and a distinctive flavour, making it a culinary staple in salads and fresh side dishes in the region (Hui *et al.*, 2017). Interest in *C. caudatus* has surged due to its high content of bioactive compounds (Seyedreihani *et al.*, 2017), particularly flavonoids, phenolics, and vitamins, which have garnered attention for both nutritional and medicinal applications and potential medicinal properties including suppressing atherosclerosis (Moshawih *et al.*, 2017), obesity (Rahman *et al.*, 2017) and diabetic (Firdaus *et al.*, 2021). In addition, this plant also has been reported to contain several active compounds such as quercetin -3-O-rutinoside, rutin, quercitrin and vitexin which contribute to the antioxidant capacity (Rafi *et al.*, 2023).

Drying is one of the most preferred post-harvest techniques for extending the shelf-life of the plant material, enhancing their suitability for processing, storage, marketing, and value addition. The primary purpose of drying is to remove moisture by evaporating water from biomaterials, thereby reducing water activity to levels that inhibit microbial growth, extend shelf life, and preserve quality (Li *et al.*, 2019). Some biochemical reactions are prevented or slowed down, changes in sensory properties and losses in some volatile compounds (Hamrouni-Sellami *et al.*, 2013). Several drying techniques have been introduced such as oven drying, microwave drying, fluidised bed method and solar energy. In particular, oven drying is

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an attractive method due its cost-effective, shorter time and low energy consumption.

In a previous study on oven drying, while a high oven temperature increased the drying rate and decreased drying time, it can cause the dried product to exhibit thermal breakdown, hence decreasing its quality (Alara *et al*., 2019). In addition, to the product's bulk density and its ability to rehydrate, when a product is dried or exposed to high heat for an excessively long time, the flavour, colour, and nutrients of the product suffer (Diaz *et al*., 2003). The drying process had a substantial impact on the proximate composition of dried vegetables (Emelike & Akusu, 2020). Thus, concluding from the effects of drying that if the temperature at which it is dried is increased, the nutraceutical properties will be reduced (López-Vidaña *et al*., 2017).

Research indicates that drying spearmint at elevated temperatures causes loss of volatile compounds and antioxidants, impacting its therapeutic value (Diäaz-Maroto *et al*., 2003). High-temperature drying can reduce catechin content and antioxidant capacity, which are key nutraceutical components in tea (Salee *et al*., 2024).

While previous studies have explored the nutritional and antioxidant properties of *C. caudatus*, limited research has focused on the kinetic modelling of moisture reduction during drying and its impact on physicochemical and antioxidant properties of the leaf powder. This study addresses the gap by examining the effects of drying temperature and ions on moisture kinetics and quality attributed of *C. caudatus* leaf powder.

II. MATERIALS AND METHOD

A. Materials

C. caudatus was harvested from Kuala Kurau, Perak, Malaysia at the mature stage of leaf development. All reagents and solvents were of analytical grade, unless otherwise specified and used without further purification.

B. Experimental Procedure

C. caudatus leaflet was individually separated from the stem by hand and 100 g were weighed and spread uniformly over stainless-steel trays and exposed to the set experimental temperature. Samples were dried using three different temperatures: 60 ℃, 80 ℃, and 100 ℃ in an oven dryer (Incubator Memmert BE 500, Germany). The leaves were dried by using an oven drying method until it reached a constant moisture content. Approximately, 1 g of dried leaves were taken out of the oven for every 30 minutes to evaluate the moisture content using the moisture analyser (A & D MX-50, Mettler Toledo, Malaysia). Leaves were considered dry once they reached a constant weight. The dried leaves were then ground into powder using dry food blender (Philips 600 W, Malaysia) and kept in vacuum seal bag prior to analysis (Yang *et al*., 2017).

C. Powder Preparation

C. caudatus powder was extracted by adding 14 g of the dried powder to 100 mL of deionised water for extraction (Seyedreihani *et al*., 2017). The mixture was incubated in a water bath at 85 ℃ for 30 minutes with occasional shaking. Ulam raja extract was obtained by filtering the aqueous mixture through a filter paper (Whatman, No. 1 Wycombe, UK) to remove the liquid extract from the solid particles in the mixture. There was no information on particle size after grinding because it was not critical for the aqueous extraction (Seyedreihani *et al*., 2017).

D. Kinetic Modelling

C. caudatus leaves were packaged in different conditions after drying in **hot-air oven velocity of 1 m/s** at various temperature (60, 80 and 100 °C) with the relative air humidity at 27±2 °C. The decrement of moisture content of leaves during drying was calculated by using the standard equation for zero, first and second-order reactions and reductions rate constants were determined by fitting equation experimental data.

$$[M] = [M]_0 - kt \quad \text{(Eq. 1)}$$

$$\ln[M] = \ln[M]_0 - kt \quad \text{(Eq. 2)}$$

$$1/([M]) = 1/[M]_0 + kt \quad \text{(Eq. 3)}$$

Where M is the moisture content at any given drying time, $[M]_0$ are initial values of moisture content and k is rate constants.

E. Proximate Analysis

The proximate parameters (crude protein, fat, fibre, ash, moisture) content of the leaves of *C. caudatus* were determined according to the Association of Official Analytical Chemists (AOAC) method moisture (930.04), protein (984.13), fibre (962.09), ash (930.04) and moisture (930.04). The total carbohydrate is calculated by subtracting the sum of the weights of moisture, protein, ash, and fibre (13). The formula is:

$$Carbohydrate\ (\%) = 100 - (\%Moisture + \%Crude\ Protein + \%Lipids + \%Ash + \%Crude\ Fibre) \quad \text{(Eq. 4)}$$

F. Preparation of C. Caudatus Extract

The leaf extract for antioxidants analyses was prepared based on the method (Seyedreihani *et al.*, 2017). Briefly, 14 g of dried powder was added to 100 mL deionised water for extraction. The mixture of leaf extract and water was incubated in a water bath at 85 °C for 30 minutes with shaking. Then, the mixture was filtered through a filter paper (Whatmann, No. 1). The supernatant was collected for subsequent analysis.

G. Physicochemical Properties of C. caudatus Extract

1. Determination of Phenolic Content

The total phenolic content (TPC) of the extract was determined using Folin-Ciocalteau assay method (Seyedreihani *et al.*, 2014). A sample of 350 uL was added to 2.5 ml of Folin-Ciocalteu phenol reagent. After 4 minutes, 2 mL of sodium carbonate was mixed and then incubated at room temperature (27 °C) for 2 hours. The absorbance was measured at 765 nm. The standard curve was expressed in mg of gallic acid equivalent (GAE) per gram of plant material.

2. Determination of Radical Scavenging Activity

DPPH assay was carried out based on the method by Seyedreihani *et al.* (2014) with slight modification. Briefly, 1 mL of the sample was added to 3 mL of methanolic 0.1 mM DPPH solution. The mixture was incubated in the dark for 30 min and then measured at 517 nm with methanol as blank and DPPH solution as a negative control. The results were expressed as % inhibition based on the formula:

$$\%DPPH\ Inhibition = \frac{Abs\ control - Abs\ sample}{Abs\ control} 100 \quad \text{(Eq. 5)}$$

3. Colour

The samples colour characteristics (L*, a* and b*) were measured with a colorimeter (Minolta CM-3500d, Osaka, Japan). L* denotes the lightness coefficient, which ranges from 0 to 100 (black to white), a* stands for redness (- to +; green to red) and b* stands for yellowness (- to +; blue to red) values.

H. Statistical Analysis

All experiments were performed in triplicate and the data are presented as mean ± standard deviation. The data were subjected to statistical analysis of variance using SPSS 25.0 for Windows (SPSS Inc., Chicago, IL, USA). Statistical differences were determined by one-way analysis of variance (ANOVA) with Tukey's post hoc test and the least significant differences ($p<0.05$) were conducted to identify significance level.

III. RESULT AND DISCUSSION

A. Kinetic Model

In this study, drying kinematics of *C. caudatus* has been an analysed and depicted in Figure 1. For all temperature, moisture content constantly decreases as drying time increases. The drying rate is not constant, as the process started, drying action was quick at first, but then drying slowed down due to higher energy requirements to remove confined water. The least drying time recorded by 60 °C while temperatures of 100 °C produced the shortest drying times.

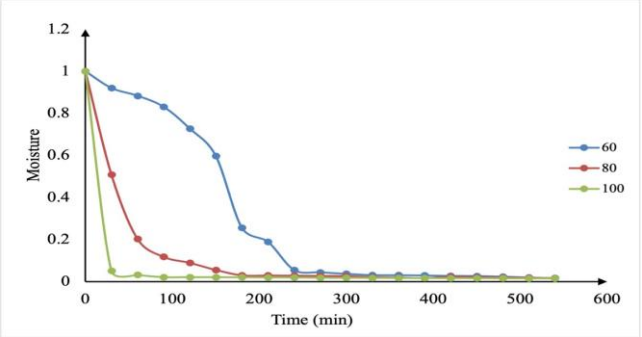

Figure 1. Moisture against time at different drying temperatures

There are two drying periods are shown in Figure 1, falling and constant rate drying. Initially, the process entered a falling rate which water was lost rapidly from the outer leaf layers to the surface, resulting in a rapid drying rate (Özbek & Dadali, 2007). Moreover, there was a constant drying time, the amount of water on the leaves surface dropped, resulting in a pressure difference between the surface and inside the leaves (Li *et al.*, 2022). Therefore, the moisture in the inner region will evaporate and shifted to the outer surface during drying (Thongcharoenpipat *et al.*, 2023). During falling stage, the drying rate continuously falls because the effect of lower concentration on reducing diffusivity is significantly greater than the effect of increasing temperature (Gutoff & Cohen, 2016).

When drying at 60 °C, it took a longer time to achieve a sufficient amount of heat to initiate the evaporation of moisture from the surface of the leaves. Thus, the falling rate period is longer until 240 minutes before it reached the constant drying period. Meanwhile, for 80 °C and 100 °C the falling rate period is at 180 minutes and 90 minutes, respectively. When the temperature was increasing, the heat generation, the vaporisation gradient within the food and rate of water evaporation were increasing. Therefore, moisture content was rapidly to achieve equilibrium and decreasing the drying time (Alara *et al.*, 2019; Nguyen *et al.*, 2019). Therefore, it increases the drying rate. The process entered a falling rate when the drying rate starts to decrease and wetted spots in the surface continually diminish until the surface of leaves is no longer saturated and dried (Mbegbu *et al.*, 2021). While during the falling rate stage, the drying rate continuously falls because the effect of lower concentration on reducing diffusivity is significantly greater than the effect of increasing temperature on increasing diffusivity (Gutoff & Cohen, 2016).

The data of the drying of *C. caudatus* leaves were adjusted to a zero-order, first-order and second -order kinetic reaction model as a function of temperature and time. The generation of a linear form of the reaction rate equation, followed by regression analysis on the transform Additionally, the reaction rate constant (k0, k1, k2) and coefficient of determination (R^2) were determined and shown in Table 1. All calculations were made for all three models in order to determine the best kinetic reaction model. As shown, the second-order kinetic model R^2 was between 0.72-0.92 which was greater than zero-order (0.17-0.77) and first-order (0.35-0.90) kinetic model. k0, k1, k2 of zero to-order, first-order and second-order kinetics varies from -0.0473 to -0.1709, -0.0033 to -0.0089 and 0.0009 to 0.0013 min^{-1}, respectively.

Therefore, the different drying temperature of *C. caudatus* can be reasonably explained by the second-order kinetic reaction model. In order to accurately simulate and optimise drying processes, moisture diffusivity must be considered during the first falling rate stage for high moisture content matrices, while vapor diffusion is second falling rate stage of drying (Chen *et al.*, 2013; Hassini *et al.*, 2007). Based on Figure 2, the moisture diffusivity (D_{eff}) were obtained by plotting the graph of Ln [MR] versus the drying time in order to compute the effectiveness moisture diffusivity and determine the value of the slope (D_{eff}).

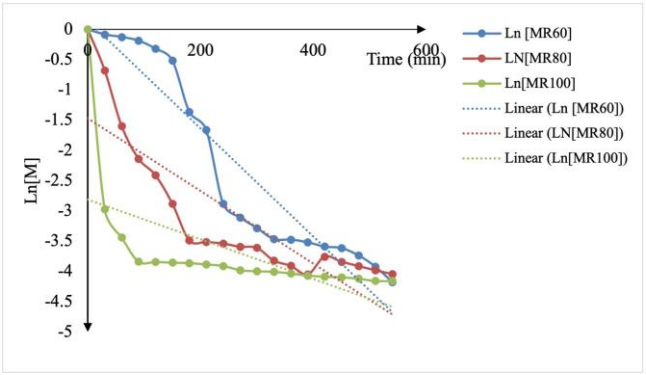

Figure 2. Relationship between Ln [MR] and times at 60 ℃, 80 ℃, and 100 ℃

Fick's second rule describes the moisture transfer phenomenon in biological material during drying. The concept of effective moisture diffusivity (D_{eff}) encompasses multiple simultaneous transport phenomena, including

capillary action, molecular diffusion, liquid and vapor diffusion, thermal diffusion, and surface diffusion. Several factors can influence (D_{eff}) such as temperature, initial moisture content, material thickness, porosity, density, and interactions between water and biopolymers like lipids, proteins, and starches (Izadi *et al.*, 2020).

The effective moisture diffusivity (D_{eff}) at various temperature were determined and reported in Table 2. The effective moisture diffusion of leaves was calculated to be within the range of 3.58 x 10-9 to 1.33 x 10-9 m^2/s across the tested temperatures. Contrary, The D_{eff} value obtained from this study showed a a significant decrement pattern when rising temperature increased due to enhanced molecular mobility. These findings were inconsistent with previous findings by Latiff *et al.* (2020), where D_{eff} increased with temperature and activation energy (E_a) was reported 39.35 kJ/mol.

Several scientifically plausible may be attributed for this inconsistency. Firstly, differences in drying methodology (e.g., type of dryer, airflow control, sample load), sample thickness, or the precision of moisture content determination may contribute to variations in D*eff*. However, temperature-induced structural changes (e.g., case hardening or shrinkage, or surface layer formation) ca significantly hinder moisture migration at elevated temperatures. Physical alterations can reduce the internal porosity and restrict vapor flow pathways, thereby resulting in lower D_{eff} values despite higher thermal energy input.

Thus, while Latiff *et al.*'s findings align with classical drying theory, the findings of this study highlight the critical role of microstructural changes that may dominate the drying behaviour of *C. caudatus* under certain thermal conditions. These results emphasise the importance of considering both thermodynamic and structural factors when interpreting moisture diffusion behaviour in plant materials.

Table 1. Kinetic parameters for the moisture content of dried ulam raja at 60 ℃, 80 ℃, and 100 °C

Temperature (℃)	**Reaction Kinetics**					
	0th order		**1st order**		**2nd order**	
	R^2	$k\ (min^{-1})$	R^2	$k\ (min^{-1})$	R^2	$k\ (min^{-1})$
60	0.7724	-0.1709	0.8996	-0.0089	0.9176	0.0013
80	0.3809	-0.0772	0.7218	-0.006	0.8987	0.0012
100	0.1684	-0.0473	0.3487	-0.0033	0.7194	0.0009

Table 2. The value of D_{eff} at different drying temperatures and activation energy (E_a) for the drying process

Temperature (℃)	$D_{eff} \times 10^{-9}\ (m^2/s)$	**E_a (kJ/mol)**
60	3.58	25.51
80	2.41	-
100	1.33	-

Figure 3 depicts the linear relationship between Ln D_{eff} with 1/T was used to calculate activation energy (E_a) for drying of *C. caudatus* leaves (R^2= 0.9775). The term "activation energy" refer to the amount of energy needed by a molecule to initiate a chemical reaction. Low activation energy means that the dried item will lose its moisture quickly and easily (Kokasih *et al.*, 2020). The E_a values of dried *C. caudatus* obtained is 25.5 kJ/mol which is in line with the wide range of 12.7-110 kJ/mol reported for fruits and vegetables (Wang *et al.*, 2018). The higher the sample's initial moisture content, the greater the amount of energy that must be expended throughout the drying process; hence, the activation energy must also be increased (Haq *et al.*, 2018).

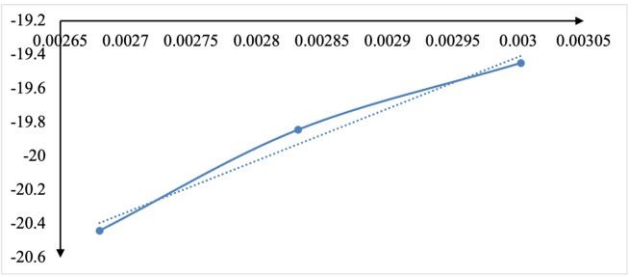

Figure 3. Effective diffusivity and reciprocal absolute temperature

B. Proximate Analysis

The proximate composition of *C. caudatus* leaves differed significantly ($p<0.05$) between each drying temperature as shown in Table 3. Fresh sample had the highest moisture content (86.28%), followed by 60 °C (8.84%), 80 °C (0.46%) and 100 °C (0.44). During drying, a simultaneous heat and mass transfer process occurs, resulting in the elimination of moisture from the heated material (Adeboye *et al.*, 2020). The acceptable moisture percentage for dried vegetables is less than 10% which unfavourable conditions for the growth of microorganisms and boosting the shelf-life stability (FAO, 2005).

Table 3. Proximate composition of fresh and dried ulam raja powder at 60 °C, 80 °C, and 100 °C

Sample	Fresh	Urp 60 $\mathcal{C}$	Urp 80 $\mathcal{C}$	Urp 100 $\mathcal{C}$
Protein	$\mathbf{2.63 \pm 0.14^{c}}$	$\mathbf{2.23 \pm 0.18^{c}}$	$\mathbf{1.44 \pm 0.20^{b}}$	$\mathbf{0.85 \pm 0.18^{a}}$
Moisture	$\mathbf{86.28 \pm 0.20^{d}}$	$\mathbf{8.84 \pm 0.78^{c}}$	$\mathbf{4.31 \pm 0.52^{a}}$	$\mathbf{4.80 \pm 0.10^{b}}$
Fat	$\mathbf{1.71 \pm 0.10^{b}}$	$\mathbf{0.61 \pm 0.40^{a}}$	$\mathbf{0.99 \pm 0.59^{ab}}$	$\mathbf{1.44 \pm 0.32^{ab}}$
Ash	$\mathbf{0.99 \pm 0.90^{a}}$	$\mathbf{7.23 \pm 0.28^{b}}$	$\mathbf{8.05 \pm 0.26^{b}}$	$\mathbf{7.82 \pm 0.74^{b}}$
Fiber	$\mathbf{5.05 \pm 0.20^{c}}$	$\mathbf{1.48 \pm 0.22^{a}}$	$\mathbf{3.69 \pm 0.40^{b}}$	$\mathbf{1.62 \pm 0.32^{a}}$
Carbohydrate	$\mathbf{2.91 \pm 1.13^{a}}$	$\mathbf{79.62 \pm 0.24^{b}}$	$\mathbf{81.53 \pm 0.78^{c}}$	$\mathbf{83.36 \pm 0.29^{c}}$

At 60 °C, the drying process may be too mild to fully break down the plant cell walls, leading to incomplete release or detection of fibre components (Lewicki, 2006). At 80 °C, the temperature may be optimal for breaking down cell walls and releasing insoluble fibre components without degrading them, resulting in a higher measurable fibre content (Vega-Gálvez *et al.*, 2009). At 100 °C, thermal degradation of fibre components (especially hemicellulose and pectin) may occur, leading to a reduction in fibre content (Ratti, 2001).

Fresh leaves had the highest protein content with 2.63%. compared to dried leaves. Furthermore, protein content was significantly reduced ($p<0.05$) when the drying temperature increased. Drying at 100 °C had the lowest protein content with 0.85% followed by 80 °C and 60 °C at 1.44% and 2.23%, respectively. The observed reduction in protein content in dried samples could be linked to the amount of drying heat applied (Timm *et al*., 2020). High temperatures cause protein degradation probably because of lipid oxidation, where oxygen reacts with unsaturated fatty acids, producing free radicals that destroy fat-soluble vitamins and decrease the nutritional value of proteins (Catorze *et al*., 2022). Fresh sample had the highest fat content (1.71%) compared to the dried samples ranging from 0.81 to 1.44%. The decrease in fat content of dried samples could be associated with the oxidation reaction during drying (Perera, 2005). In lipid oxidation, oxygen reacts with unsaturated fatty acids resulting in rancid and unpleasant flavours (Bonazzi & Dumoulin, 2011).

C. *Total Phenolic Content (TPC)*

Table 4 depicts the effects of drying procedures on the TPC of dried *C. caudatus* leaves. As shown, the total phenolic content of dried leaves ranged from 0.44 – 0.95 mg GAE/g compared to fresh (0.95 mg GAE/g). Drying considerably ($p<0.05$) decreased the phenolic content of leaves of all drying temperatures. Table IV showed that the total phenolic content of fresh is the highest at 0.9 mg GAE/g, followed by URP 60 °C, 80 °C and 100 °C with 0.65%, 0.46% and 0.44%, respectively. Drying of betel leaves at higher temperature led to thermal decomposition of phenolic components in leaves due to the activation of oxidative enzymes such as polyphenoloxidase and peroxidase during the drying process (Pin *et al*., 2009; Gümüşay *et al*., 2015). Moreover, prolonged the drying time, caused the polyphenols turn to thermolabile, which resulting in the loss of flavonoids and tannins (Vashisth *et al*., 2011).

Table 4. Total phenolic content (TPC) of fresh and dried ulam raja powder at 60 ℃, 80 ℃, and 100 ℃

Sample	Fresh	Urp 60 ℃	Urp 80 ℃	Urp 100 ℃
TPC (MG GAE/G)	0.95 ± 0.06^{c}	0.65 ± 0.01^{b}	0.46 ± 0.03^{a}	0.44 ± 0.08^{a}

D. Radical Scavenging Activity

Antioxidants (phenolic compounds) quench the free radicals and provide protection against structural damage and dysfunction of organism cells, which can cause harmful health effects such as cancer and cardiovascular diseases (Danowska - Oziewicz *et al*., 2020). The radical scavenging is simple and efficient method to determine the ability of plant materials to scavenge free radicals which mainly influenced by the OH group position (Nahar *et al*., 2022). From Table V, the fresh leaves exhibited the greatest scavenging activity at 87.30%, which attributed to the contribution of phenolic compound (Khodja *et al*., 2020). Meanwhile, the antioxidant activity reduced dramatically ($p<0.05$) with increasing temperature from 60 to 100 °C at 6.43% to 76.50%. This may be because the antioxidant compounds were heat-sensitive which could diminish when subjected to high drying temperatures (Rocha *et al*., 2011; Chong & Lim, 2012).

E. Colour

Colour plays a major role in the acceptability of the food products (Azza *et al*., 2011). Three chromatic coordinates, L*, a* and b*, representing lightness/darkness, redness-greenness, and yellowness-blueness, respectively, are used to measure the colour variations in a food product.

According to Table 5, the lightness (L*) value of fresh *C. caudatus* possesses the highest value with 42.92 followed by URP 60, 80 and 100 ℃ with 41.31%, 41.35%, and 40.11%, respectively. The decreasing in lightness means that the sample become darker after being heated by different temperature due to the formation of other chlorophyll derivatives, such as chlorophyllides or transformation of none or less coloured precursor of green colour to a more visible green colour. Besides that, decreased of lightness of dried leaves may resulted from non-enzymatic reaction and

clarity characteristics of gelatinised starch which causes the polyphenol peroxidase (POD) inactivation leading to pigment browning (Pimpaporn *et al.*, 2007).

Table 5. Colour (L*, a*, and b*) value of fresh and dried Ulam Raja powder at 60 ℃, 80 ℃, and 100 ℃

Sample	Fresh	Urp 60℃	Urp 80℃	Urp 100℃
L*	42.92 ± 0.30^{c}	41.31 ± 0.005^{b}	41.35 ± 0.00^{b}	40.11 ± 0.00^{a}
A*	-10.56 ± 0.09^{a}	-0.60 ± 0.03^{b}	1.43 ± 0.01^{d}	0.44 ± 0.01^{c}
B*	28.99 ± 0.89^{c}	18.32 ± 0.01^{a}	20.91 ± 0.01^{b}	22.52 ± 0.01^{b}

The a* values of fresh and dried leaves ranged from -10.56 to 1.43. indicating that dried leaves were less green than fresh leaves. The highest a* value is exhibited by URP 100 ℃ with 0.44 while the lowest is fresh at -10.56. According to Krokida *et al.* (2001), a rise in the a* value implies a higher in red chroma, which suggests the browning reaction. Rising temperatures increased the a* values, thus exhibiting deeper chroma and higher browning rate (Maskan, 2001). Therefore, it can be concluded that negative a* value indicates that the samples have more green pigment.

Furthermore, the b* (yellowness) value for fresh *C. caudatus* and URP 60 ℃ have a significant difference ($p<0.05$) with the other samples. The highest b* value exhibited in fresh with 28.99 followed by 100 ℃, 80 ℃ and 60 ℃ at 22.52, 20.91 and 18.32, respectively. The decrease in a* and b* values could be attributed to the degradation of chlorophyll and other pigments with non-enzymatic processes (Maskan, 2001). As a result of the high energy delivered to the food material, the rate of colour degradation increased with increasing temperature (Guiné & Barroca, 2012). Therefore, the drying treatment degraded the colour quality of *C. caudatus*.

A study using an indirect solar dryer showed that drying mint and basil at 30–50 °C preserved: Total phenolic content increased significantly from approximately 1,705 mg to 8,994 mg per 100 g dry matter (DM)—while antioxidant capacity (DPPH radical scavenging activity) improved from 0.61 to 0.67 µmol/g DM; colour retention was maintained, preserving the green pigmentation (Al-Hamdani *et al.*, 2022). This suggests that moderate drying temperatures are optimal for preserving nutraceutical and sensory qualities, while still being cost-effective.

IV. CONCLUSION

The findings of this study have several important implications for the herbal, nutraceutical, and functional food industries: The observed decrease in effective moisture diffusivity (D_{eff}) with increasing temperature suggests that higher drying temperatures may not always be beneficial. While faster drying is often desirable for efficiency, it may compromise moisture migration dynamics and nutrient retention, leading to lower product quality. Industries should consider moderate drying temperatures (e.g., 60–80 °C) to balance drying time and preservation of bioactive compounds.

Second order kinetic model gave an excellent fit to experimental moisture data. As a result of increase drying temperature, an increase in drying rate. However, it was also revealed that the reduction of nutritional compound, colour, phenolic content and antioxidant activity. Thus, this research suggests the drying temperature at 60 ℃ should be considered to ensure the product quality is maintained during longer drying time. Further research on post-drying microbial stability would be valuable to confirm the practical suitability of this drying temperature.

V. ACKNOWLEDGEMENT

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