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# Investigating the Impact of Storage Conditions on Quality and Shelf Life of Full-Fat and Defatted Roasted Date Seed Powders

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## ABSTRACT

Over the past few years, the importance of food powder shelf life has gradually increased for food product producers. Consequently, the objective of this study was to investigate how storage conditions impact the quality characteristics of roasted date seed powders and to determine the predictability of their shelf life. The powders were packaged in ALP pouches and stored under various conditions. The powders' properties were assessed at seven-day intervals over a 12-week storage period. The findings indicated that both storage time and method significantly influenced the powder properties. Additionally, the powders were found to be microbiologically stable, exhibited poor flowability, and were non-hygroscopic across different storage conditions. The statistical analysis indicated that both zero-order and first-order reaction models were successful in predicting changes in moisture content and total color difference. As a result, the rate of moisture content change serves as a reliable indicator for estimating the shelf life of powders made from roasted date seeds.

## 1. Introduction

Palm date fruit processing generates seeds as a primary byproduct, this waste constitutes approximately 10-15 % of the total date production, estimated at around 900 thousand tons annually (FAO, 2019). Discarding these wastes poses environmental challenges and incurs additional handling costs. However, these byproducts are valuable sources of nutrition and potential therapeutics due to their high mineral content, dietary fibers, phenolic compounds, and antioxidants (Al-Farsi & Lee, 2008; Bouhlali et al., 2017; Ghnimi, & Kamal-Eldin, 2017, Djaoudene et al., 2023). Consequently, not utilizing this byproduct for human consumption represents a significant economic loss. Recent studies have indicated that palm date seeds can be employed as therapeutic foods for various conditions, including cough, renal stones, bronchial asthma, hyperactivity, memory impairment, blood pressure



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regulation, intestinal and uterine health, blood sugar control, and pancreatic support (Hossain, Waly, Singh, Sequeira, & Rahman, 2014; and Ahmad, & Pan, 2001). Consequently, several food experts have proposed incorporating palm date seeds into several foodstuffs such as minced beef, bakery items, chocolate, and beverages (Amany et al., 2012; Almana & Mahmoud, 1994; Platat et al., 2015; Bouaziz et al., 2017; Abdillah & Andriani, 2012; Ghnimi et al., 2015; Venkatachalam & Sengottian, 2016 and Fikry et al., 2019b). Additionally, a coffee-free caffeine-like brew made from roasted date seeds is a potential product targeting individuals seeking coffee's distinct flavor and aroma without caffeine. Also, toxicological risk assessment for date seed coffee beverages complying with the EU food safety requirements shows low acute toxicity with the daily recommended intake (Kiesler et al., 2024). Notably, in certain rural Arabian regions, a similar coffee alternative derived from roasted date seeds is traditionally consumed (Rahman et al., 2007 and Ghnimi et al., 2015). Packaged roasted date seed powder is widely available in numerous markets throughout the Kingdom of Saudi Arabia (KSA) and the United Arab Emirates (UAE) (Ghnimi et al., 2015), a comprehensive review of suitable packaging materials and optimal storage conditions for this product remains absent from the literature. The properties of food powder significantly influence various handling and processing operations, including flow from hoppers, transportation, mixing, compression, and packaging (Peleg, 1977 and Knowlton et al., 1994). Consequently, food powders are typically packaged using diverse materials to minimize quality degradation during storage, which can be caused by moisture and oxygen ingress. In the food industry, ensuring the storage stability and shelf life of food powders is essential. Shelf life refers to the maximum period during which a food product can be stored under particular environmental conditions without experiencing significant degradation in quality or consumer acceptability (Jena & Das, 2012). Factors such as temperature, humidity, oxygen, light, and water activity can accelerate food product degradation during storage. Changes in powder quality attributes over time may pose potential risks to consumers and reduce product acceptability. Therefore, ensuring product safety is paramount in the development process, guaranteeing the product maintains its desired quality until reaching the consumer (Labuza & Altunakar, 2007). Assessing the shelf life of food powders is a common approach to evaluating their quality and stability over time. However, accurately predicting the shelf life of these powders presents significant challenges. To effectively study the deterioration of powder quality, it is essential to define and utilize specific experimental quality indicators (Achour, 2006 and Labuza, 1984). When estimating the shelf life of a powdered product within its packaging, two crucial factors must be considered. First, the rate at which water vapor passes through the packaging, which depends on the packaging's characteristics and storage conditions, such as water vapor permeability, surface area, temperature, and relative humidity. Second, the powder's own moisture adsorption capacity is a significant determinant of its stability over time (Giacin & Hernandez, 1997).

In this study, both factors were modeled over time to predict the moisture content of the packaged powder. The shelf life was determined as the time it takes for the powder to reach a critical moisture level where clumping begins. Recent research has examined the storage stability and shelf life of various food powders, including those made from jackfruit, mango soy-fortified yogurt, spray-dried papaya, apple peel, guava, and mango milk powders (Kumar & Mishra, 2004; Pua et al., 2008; Chauhan & Patil, 2013; Henríquez et al., 2013; Wong & Lim, 2016; and Shishir et al., 2017). However, based on our current understanding, the stability during storage and the shelf life of full-fat roasted date seed powder (RDSP) and defatted roasted date seed powder (DRDSP) remains unexplored. This study aimed to investigate the effects of a 12-week storage period and various storage conditions on the physical properties, color, and flowability of RDSP and DRDSP. Additionally, it will examine the kinetics of moisture content and color changes over time, assessing the shelf life of both powders by monitoring moisture gain.

## 2. Material and methods

### Materials

Ten kilograms of Sukkari variety palm dates and were procured from a reputable market in Riyadh, Saudi Arabia. Aluminum foil laminated polyethylene (ALP) pouches (115 mm width x 120 mm length x 70 µm thickness) from Mansy for Packaging Materials Co. Cairo, Egypt.

### Methods

### Powder preparation

The dates were manually deseeded to separate the seeds from the flesh and then soaked in hot water for one hour to remove any remaining flesh. After soaking, the seeds were spread in a thin layer outdoors to allow surface water to evaporate. Following the method outlined by Fikry et al. (2019a), the seeds were roasted in a convection oven (Memmert, UN, Germany) at temperatures of 160°C, 180°C, and 200°C. Once roasted, the whole seeds were crushed using a laboratory grinder (RT-CR30S, 2007, Taiwan) with a 2 mm sieve and a 3 HP (3-phase) motor rotating at 450 RPM. The crushed seeds were further ground using a laboratory hammer mill (Perten, 120, Finland) with an 80 µm sieve and a 750 W (1-phase) motor. The ground seeds were then defatted following the methods of Devshony et al., (1992) and Akbari et al., (2012). Ten grams of the ground-roasted date seeds were subjected to oil extraction using a Soxhlet apparatus with n-hexane as the solvent at 135°C for two hours. Both RDSP and DRDSP samples were collected and stored in plastic containers at 5°C until further analysis.

**Storage of the powder**

To carry out the accelerated and conventional storage experiments for palm date seed powder, samples of 15 ± 0.5 g were packed into aluminum foil laminated polyethylene (ALP) pouches (115 mm width x 120 mm length x 70 µm thickness) provided by Mansy for Packaging Materials Co., Cairo, Egypt. These samples were sealed at 150±1°C under atmospheric conditions using a vertical continuous band sealer (GW-FRB-980II, Good and Well, Selangor, Malaysia). For the accelerated storage, the samples were stored at 90 ± 1% relative humidity and 38 ± 2°C, achieved with a saturated potassium nitrate solution. In contrast, the conventional storage method involved keeping the samples at 60 ± 2% relative humidity and 25 ± 2°C, maintained using magnesium nitrate salt solutions (Pua et al., 2008).

At 7-day intervals over a period of 12 weeks, one packet from each storage condition was removed from the desiccator for analysis. Various measurements were taken, including moisture content, water activity, hygroscopicity, solubility index, color attributes, bulk density, angle of repose, and degree of caking.

### Measurements

### Adsorption isotherm procedure

According to the procedure outlined by Iglesias and Chirife (1982), adsorption isotherms for the powders were measured at 25°C using the static-gravimetric method across eight relative humidity (RH) levels ranging from 11.2% to 92%. Before conducting the isotherm experiment, RDSP and DRDSP samples were dried in a vacuum oven at 30°C for 5-7 days to eliminate any remaining moisture. One-gram (±0.03 g) samples were placed in pre-weighed plastic cups and subsequently transferred to eight different desiccators, each containing saturated salt solutions of lithium chloride, magnesium chloride, magnesium nitrate, sodium nitrite, sodium chloride, ammonium sulfate, potassium acetate, potassium nitrate, potassium carbonate, and potassium chloride. To inhibit mold growth in high-humidity desiccators (≥75%), a cup containing 5 ml of toluene was included (Labuza, 1984). The samples were equilibrated in a controlled chamber at 25 ± 2°C, with weight measurements taken every two days using an electronic balance accurate to 0.001 g until weight stability was achieved (typically after six to seven weeks). The brief process of transferring, weighing, and returning the samples, which took about 30 seconds, minimized moisture absorption from the atmosphere during weighing. Equilibrium moisture content was established by drying the samples in a laboratory oven at 70°C until a constant weight was achieved (Goula et al., 2008). All measurements were conducted in triplicate.The equilibrium moisture content (Xe) data were plotted against water activity (aw) to develop moisture adsorption isotherms. The experimental data for aw and $X_e$ were then fitted using the GAB model (Equation 1) as proposed by Van den Berg (1981).

$$X_e = \frac{X_m CK\,a_w}{(1-Ka_w)(1-K\,a_w+CKa_w)} \qquad (1)$$

where $X_m$ refers to the monolayer moisture content (d.b. %), C and K denote model constants.

## Determination of permeability of packaging material

To determine the water vapor permeability, K (kg water/m$^2$/day/Pa), of the aluminum foil laminated polyethylene (ALP) pouches, Equation 2, previously utilized by T. Labuza and Riboh (1982), was applied.

$$K = \frac{dw/d\theta_p}{A_p} \qquad (2)$$

In this context, dw/d$\theta_p$ is the slope of the linear plot between the time $\theta_p$ (day) of storage and cumulative moisture gain; *w* (kg) is the weight of the silica gel in the packaging material; $A_p$(m$^2$) is the surface area of the packaging material and $P^*$ (Pa) is the saturation vapor pressure of water at the temperature of the environment chosen for the experiment.

## Moisture Content

The moisture content of palm date seed powder was determined using a moisture analyzer (model IR-200, Denver Instruments, Arvada, Colo.). Measurements were performed in triplicate.

## Water Activity

A water activity meter (AquaLab 3TE, USA) was used to determine the water activity of the powder samples. For the measurement, one gram of powder was placed into a sample cup, which was then inserted into the meter. The water activity was recorded at room temperature (25 ± 1°C).

## Hygroscopicity and Water Solubility Index (WSI)

Hygroscopicity was evaluated by determining the powder's capacity to absorb moisture from its surroundings. One gram of the powder was placed in a pre-dried and pre-weighed glass petri dish and then placed inside a sealed desiccator at room temperature (25 ± 1°C). The desiccator contained a saturated ammonium sulfate solution (150 mL) to achieve a relative humidity of 90 ± 2% (Wong & Lim, 2016). A digital hygrometer (Pro'sKit, NT-113, USA) was employed to monitor and maintain this relative humidity. After seven days, the samples were removed and weighed. The difference in weight from the initial measurement was recorded as the amount of moisture absorbed (g) per 100 g of dry solids (g/100g). The hygroscopicity of the powder was categorized according to the criteria outlined in Table 1.

**Table 1. Values used to determine hygroscopicity (%) (Niro Research Laboratory, 2003).**

| Hygroscopicity | Percentage |
|---|---|
| Non-hygroscopic | <10 |
| Slightly hygroscopic | 10.1-15 |
| Hygroscopic | 15.1-20 |
| Very hygroscopic | 20.1-25 |
| Extremely hygroscopic | >25 |

The solubility of the powder in water was assessed using the method outlined by Tuyen et al. (2010). Two and a half grams of date seed powder were thoroughly mixed with 30 ml of distilled water in a 50 ml centrifuge tube using a vortex mixer (ZX4, Velp Scientifica, Italy). The tube was then incubated in a water bath at 37°C for 30 minutes. After incubation, the mixture was centrifuged at 3500 rpm for 30 minutes at room temperature (Model 4200, Kubota, Tokyo, Japan). The supernatant was collected and transferred to a pre-dried, pre-weighed glass petri dish. This dish was dried in a convection oven (ED 23, Binder Gmbh, Germany) at 105°C for 24 hours. After drying, the dish was cooled in a desiccator and weighed. The weight of the residue, which represents the solubilized powder, was used to calculate the water solubility index (WSI), expressed as the residue weight relative to the initial powder weight.

A portable colorimeter (CR 400, Minolta Co., Osaka, Japan) was used to evaluate the color of whole palm date seeds according to the Lab color system. The instrument was calibrated using a standard white calibration plate and set to CIE Standard Illuminant C. The color index was measured in terms of lightness (L*), where L=0 denotes black and L=100 denotes white; the red/green axis (+a* for red and -a* for green); and the yellow/blue axis (+b* for yellow and -b* for blue). A standard white tile with values L* = 96.33, a* = +0.09, and b* = +1.98 served as the reference color. Each sample's color was measured in triplicate. The total color difference (ΔE) was calculated to assess color changes or degradation during the roasting process, using Equation 3 (Palou et al., 1999 and Akoy, 2014).

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (3)$$

Where, $L_0^*$, $a_0^*$ and $b_0^*$ are the color coordinates for the raw palm date seeds. $L^*$, $a^*$ and $b^*$ are the color coordinates for the roasted palm date seeds at any time.

**Bulk density**

The powder bulk density was determined by filling a 100-mL graduated cylinder approximately to the 70 mL mark with the powder. The mass and volume of the powder were recorded. Bulk density was calculated using Equation 4.

$$\rho_B = \frac{m}{V_b} \quad (4)$$

where m, is the weight of the powder and $V_b$ is the volume of the powder without tapping.

## Angle of repose

Angle of repose is defined as the angle between the horizontal and the slope of a granular material heap formed by dropping the material from a designated height. To measure the angle of repose (in degrees), a funnel with a 5 cm upper diameter was positioned 10 cm above a flat surface using a funnel holder, maintaining a 10 cm distance between the funnel's 1 cm diameter lower opening and the surface. With the funnel's lower end closed, a 5 g powder sample was poured into the funnel. The lower end was then opened, allowing the powder to form a heap on the flat surface. A protractor was used to measure the angle of repose (Teunou et al., 1995 and Amrutha et al., 2014). Table 2 presents the relationship between angle of repose and flowability.

**Table 2. The relationship between angle of repose and flowability (Copleyscientific, 2008)**

| Flowability degree | Angle of repose (°) |
|---|---|
| Excellent | 25 - 30 |
| Good | 31 - 35 |
| Fair (aid not needed) | 36 - 40 |
| Passable (may hang up) | 41 - 45 |
| Poor (must agitate, vibrate) | 46 - 55 |
| Very poor | 56 - 65 |
| Extremely poor | > 66 |

## Degree of caking

The degree of caking was determined according to the method described by Ramachandran et al. (2014). Five grams of powder were weighed and placed in a sieve. The percentage degree of caking was calculated as the weight difference using the following equation (Costa et al., 2014 and Ramachandran et al., 2014)

$$Degree\ of\ caking\ (\%) = \frac{100 * b}{a} \quad (5)$$

Where, *a* is the amount of powder used in sieving, and b is the amount of powder remaining on the sieve after sieving. The powders Degree of caking was classified as seen in Table 3.

**Table 3. Values are used to determine the degree of caking (%) (Niro Research Laboratory, 2003)**

| Caking degree | Percentage |
|---|---|
| Non-caking powder | <10 |
| Slightly caking powder | 10.1-20 |
| Caking powder | 20.1-50 |
| Very caking powder | >50 |
| Extremely caking powder | 100 |

**Kinetics of moisture content and color change during storage**

The degradation kinetics for moisture and total color difference, which are critical attributes, were analyzed using the methodologies outlined by Robertson (2009).

To determine the reaction order for changes in moisture content and color, the obtained data were fitted to a linear equation following the method described by Labuza (1982). Zero-order (Equation 6) and first-order (Equation 7) models are commonly used to describe reactions that result in a loss of food quality (Singh, 1994).

$$C = C_o \pm kt \tag{6}$$

$$lnC = lnC_o \pm k_1 t \tag{7}$$

where C is the measured moisture content or total color difference value, $C_0$ is the initial C, t is the storage time, k is the reaction rate constant for the zero-order model and $k_1$ is the reaction rate constant for the first-order model. The symbols (+) and (-) sign reveal the formation and degradation of the quality parameter respectively.

## Assessment of shelf life of the powders based on moisture gain

The rate change of moisture content of the powder over storage time is expressed as in Equation (8) (Jaya & Das, 2005).

$$X_s \frac{dX}{d\theta} = KA_p(RH\ p^* - a_w\ p^*) \tag{8}$$

Where $X_s$ (kg) is the dry weight of the powder inside the pouch; p* (Pa) is the saturation vapor pressure of water at the temperature *T* (°C) of storage; *RH* is the relative humidity of the storage environment; *K* (kg water/$m^2$/day/Pa) is the permeability of the packaging material; $A_p$ ($m^2$) is the surface area of the packaging material through which water vapor permeates; $a_w$ is the water activity of the powder at *T* (°C) and *X* (kg water/kg dry solids) is the moisture content of the powder after ɵ days of storage time.

The graphical relationship between moisture content X and storage time (days) was determined by solving Equation 8. The calculated moisture content values were compared with experimentally determined values. To find the time θ (days) needed for the powder's moisture content to increase from an initial value $X_i$ (kg water/kg dry solids) to a critical value $X_c$ (kg water/kg dry solids), Equation 9 was used:

$$\theta\ (day) = \frac{X_s\ (X_c - X_i)}{KA_p(RH\ p^* - a_w\ p^*)} \tag{9}$$

where $X_i$ is typically lower than the monolayer value $M_o$ (kg water/kg dry solids) of the powder, obtained from the GAB model (Equation 1). The critical moisture content $X_c$ is the level at which the powder begins to form lumps.

To evaluate the accuracy of the model (Equation 8) for fitting actual data, the coefficient of determination ($R^2$) (Equation 10) and the relative deviation percent (E) (Equation 11) were used for the criteria. It is commonly considered that $R^2 > 0.9$ and E value below 10% indicate a satisfactory fit for practical purposes (Fikry & Al-Awaadh, 2016; Yu, Zheng, & Li, 2013).

$$R^2 = \frac{\sum_{i=1}^{N}(X_{pred} - \overline{X_{exp}})^2}{\sum_{i=1}^{N}(X_{exp} - \overline{X_{exp}})^2} \tag{10}$$

$$E\ (\%) = \frac{100}{n}\sum_{i=1}^{N}\frac{|X_{exp} - X_{pred}|}{X_{exp}} \tag{11}$$

where, $X_{exp}$, $X_{pred}$ and $X_{exp}$ are experimental, predicted, and average moisture content values (% dry basis), respectively and N is the number of observations.

## Statistical analysis

Experimental data for all measurements were reported as mean ± standard deviation. To evaluate the impact of storage method and storage time on powder properties, including their interaction, a two-way ANOVA was performed. Both linear and non-linear regression techniques were used to model the experimental data. The data analysis was conducted using SPSS version 21 software.

# 3. Results and Discussion

## Sorption characteristics of the powders and fitting of sorption data to GAB model

The moisture sorption data for RDSP and DRDSP at 25 °C were fitted to the GAB model using the least squares method. The model constants Xm, C, and K, determined from experimental water activities (0.11-0.92) and corresponding moisture content, are presented in Table 4. The GAB model effectively described the real data, as evidenced by $R^2$ values exceeding 0.98 and E values close to zero. Figure 1 illustrates the actual and predicted equilibrium moisture content of RDSP and DRDSP. The adsorption isotherms of both RDSP and DRDSP exhibited Type III behavior according to the BET classification. Notably, the GAB model accurately fits the experimental adsorption data of several other powders, including date pits, honey, spray-dried yogurt, and freeze-dried bovine colostrum (Koç et al., 2010; Yu et al., 2013; Hossain et al., 2014, and Devi et al., 2016).

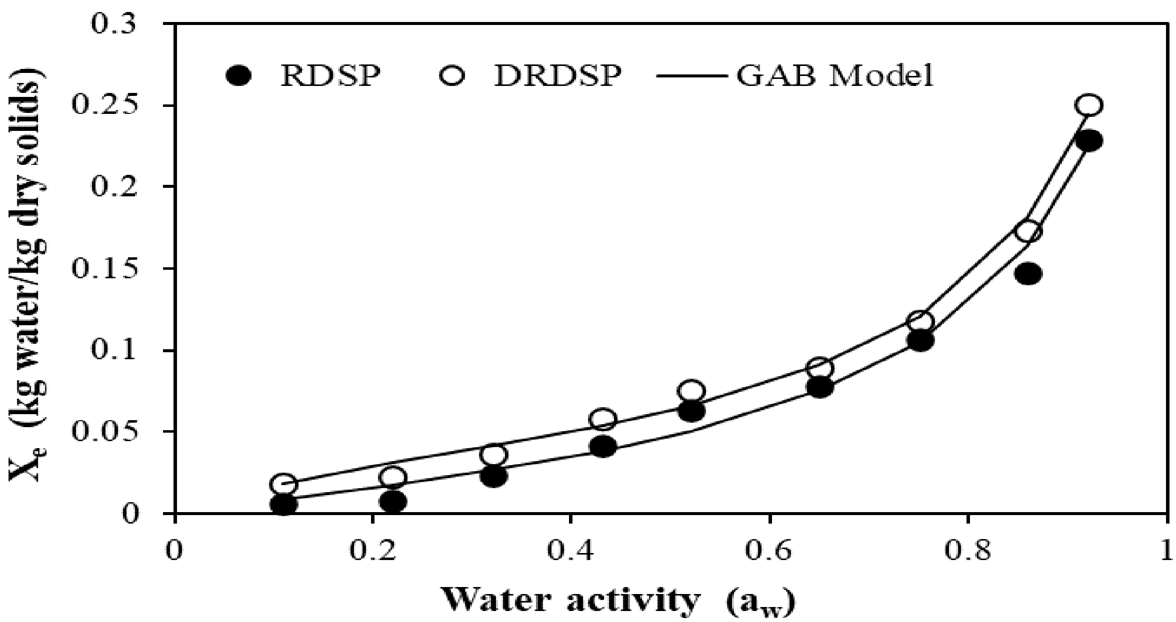


**Figure 1. Equilibrium moisture content ($X_e$) versus water activity ($a_w$) of both RDSP and DRDSP**

**Table 4. Estimated parameters and fitting criteria of the GAB model applied to the experimental data of adsorption isotherm of RDSP and DRDSP from palm date seeds**

| Model | Parameters | RDSP | DRDSP |
|---|---|---|---|
| | $X_m$ | 0.038 | 0.038 |
| | K | 0.904 | 0.909 |
| GAB | C | 2.05 | 5.91 |
| | $R^2$ | 0.989 | 0.989 |
| | SSE | 0.00047 | 0.0005 |

## Permeability of packaging material

Figure 2 shows the cumulative moisture gain over time by silica gel in ALP pouches at 25°C and 60% RH, as well as at 38°C and 90% RH. The slope of the best-fit line was calculated, and the water vapor permeability (K) values for the ALP pouches were determined using Equation 2. The pouch surface area and saturation vapor pressures of water at 38 °C and 90% RH, and 25 °C and 60% RH were 6539.03 and 3170 Pa, respectively, and were inputted into Equation 2. The results indicated permeability values (K) of $2.2 \times 10^{-7}$ and $3.8 \times 10^{-8}$ kg/m²/day/Pa for ALP pouches stored under conventional and accelerated conditions, respectively. These permeability values align closely with those reported by Jena and Das (2012) ($5.31 \times 10^{-7}$ kg/m²/day/Pa), Jaya and Das (2005) ($5.4 \times 10^{-8}$ kg/m²/day/Pa), and Muzaffar and Kumar (2017) ($6.1 \times 10^{-8}$ kg/m²/day/Pa).

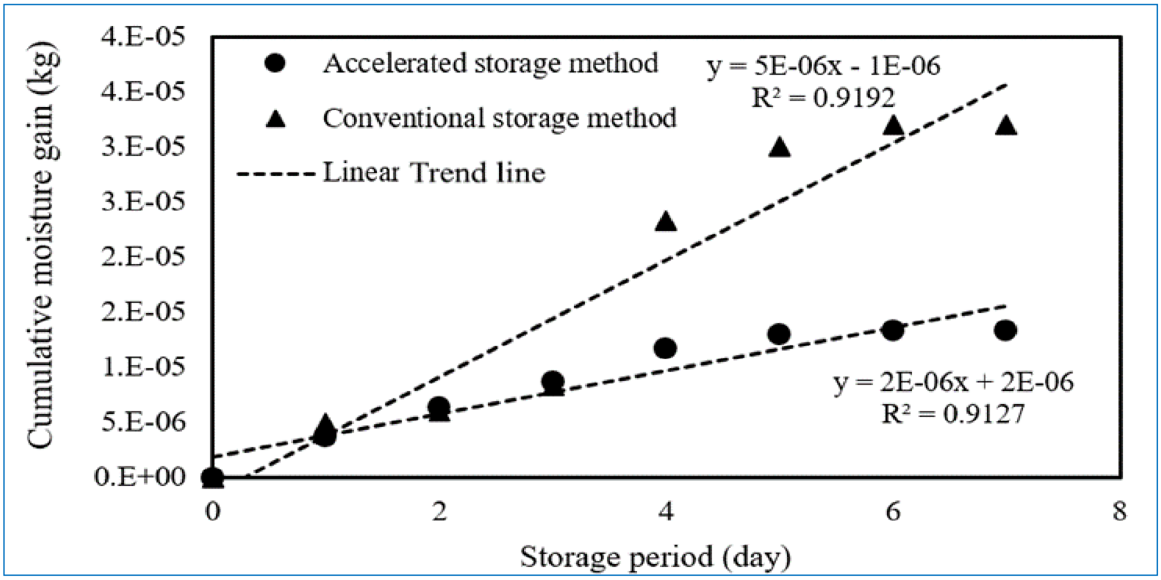


**Figure 2. Cumulative moisture gains by silica gel through ALP pouch with storage period in controlled environments**

## Impact of the storage conditions on the physical properties of the powders

Moisture content is a critical property of powders, influencing drying efficiency and attributes such as flowability, caking, and storage stability (Shrestha et al., 2007). Water activity, representing the availability of free water within a food system and its potential for chemical reactions, is another crucial parameter (Quek et al., 2007). Microbial growth is typically inhibited at low moisture levels (<5 g/100 g) and water activities (<0.3), allowing for the commercialization of dried foods under these conditions (Bolin, 1980; Lavelli & Vantaggi, 2009). Figures 3a and 3b illustrate the significant effects of storage procedure and time on moisture content and water activity. In summary, RDSP moisture content increased slightly with storage time, ranging from 1.8 to 1.97% db and 1.8 to 2.08% db under conventional and accelerated storage, respectively. Similarly, DRDSP moisture content increased significantly with storage time, ranging from 1.10 to 1.20% db and 1.10 to 1.51% db. Although water activity rose with increasing storage temperature, it remained within the safe range (below 0.3), indicating microbiological stability of both powders in ALP pouches for 12 weeks, even under accelerated conditions. These water activity values align with those reported for jamun fruit juice, watermelon, and acai powders (Quek et al., 2007; Tonon et al., 2009, and Santhalakshmy et al., 2015). Hygroscopicity is closely linked to a food's chemical, physical, and microbiological stability (Costa et al., 2014). Low hygroscopicity is desirable as high hygroscopicity leads to increased moisture absorption and subsequent flowability issues (Tonon et al., 2008). Figure 3c demonstrates a significant increase in hygroscopicity for both RDSP and DRDSP with rising storage temperature. Statistical analysis confirmed that storage method, storage period, and their interaction significantly influenced hygroscopicity. Nevertheless, both powders were classified as non-hygroscopic materials (<10%). Notably, other food powders, such as soursop powder, have also been categorized as non-hygroscopic (Costa et al., 2014). The water solubility index (WSI) of a powder quantifies its ability to dissolve in water (Santhalakshmy et al., 2015). As a crucial specification in food powders, WSI indicates powder reconstitution capacity (Ramachandran et al., 2014). Figure 3d reveals a decrease in WSI with an increasing storage period. ANOVA analysis confirmed significant effects ($p$-value $< 0.01$) of both storage period and method on WSI. Overall, WSI values for stored RDSP declined by 29% under conventional storage and 32% under accelerated storage over 12 weeks. Similarly, DRDSP WSI decreased by 27% under conventional storage and 32.5% under accelerated storage after 12 weeks.

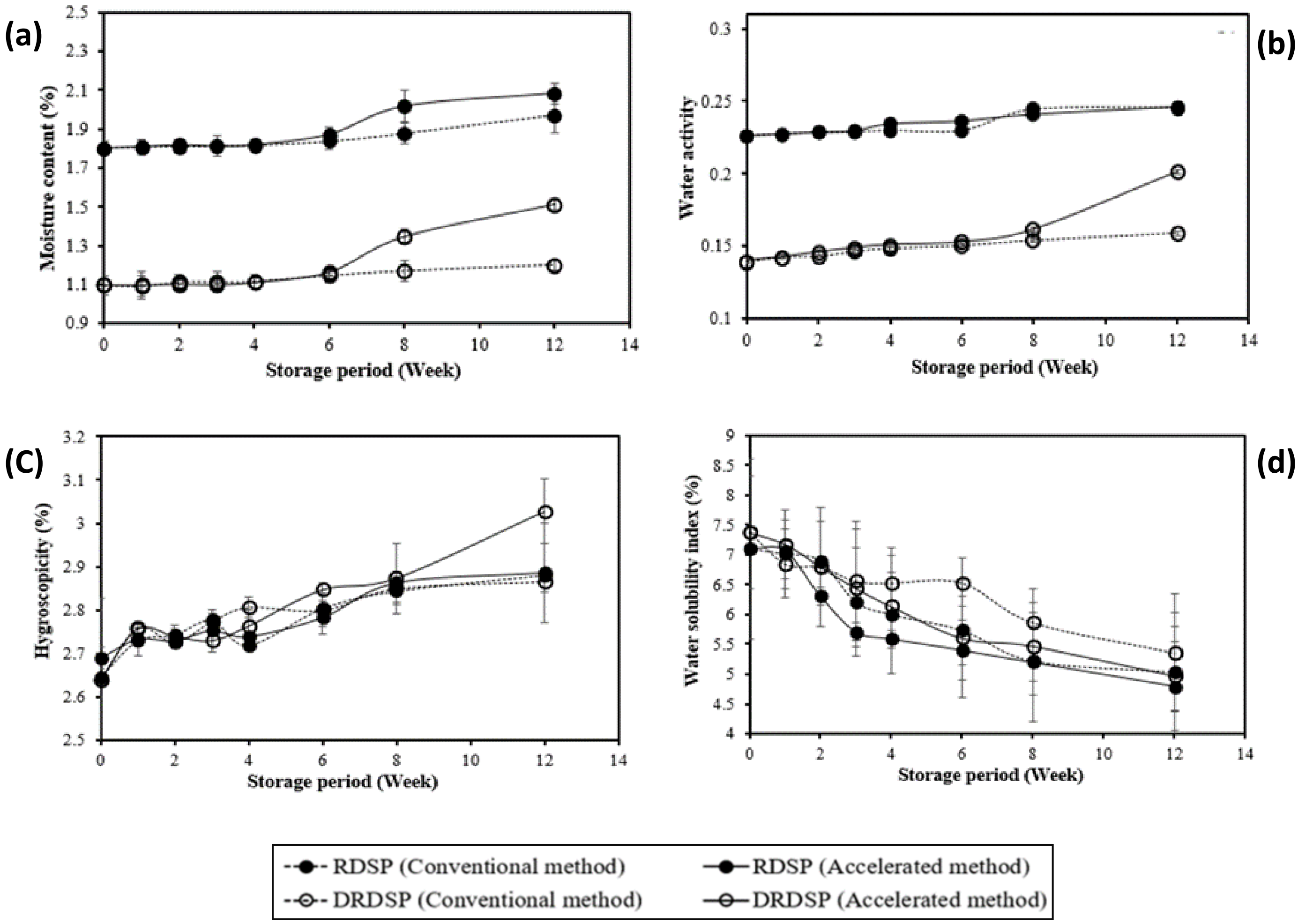


**Figure 3. Variation in moisture content, water activity, hygroscopicity, and water solubility index of the RDSP and DRDSP packed in ALP pouches under conventional and accelerated storage methods**

## Impact of storage conditions on the color attributes of the powders

Colour is regarded as an important indicator of consumer preference. Colour properties (L*-value, a*-value, b*-value, and ΔE) of the RDSP and DRDSP as affected by the storage period and storage method are shown in Figure 4. Statistical results revealed that the storage period and storage method affected significantly the L*-values and the total colour difference of the RDSP and DRDSP. However, it was found that neither storage period nor storage method affected both the a*-value and b*-value of the RDSP and DRDSP. Figure 4a indicates that the L*-value of both RDSP and DRDSP slightly decreased as the storage period increased under different storage methods. In contrast, the total colour difference of both RDSP and DRDSP increased somewhat as the storage period increased under different storage methods Figure 4d. Similar trends were observed for Papaya powder (Wong & Lim, 2016) and jackfruit powder (Pua et al., 2008).

It was suggested that the increase in moisture content during the storage period leads to a slight decrease in L*-values and an increase in total color difference. This effect may be attributed to non-enzymatic browning, which can influence changes in color attributes (L*, a*, and b*-values) (Pua et al., 2008). Reports indicate that non-enzymatic browning in stored food powders can be affected by various factors, including temperature, moisture, carbonyl compounds, organic acids, water activity (aw), oxygen (O2), and sugars (Muralikrishna et al., 1969).

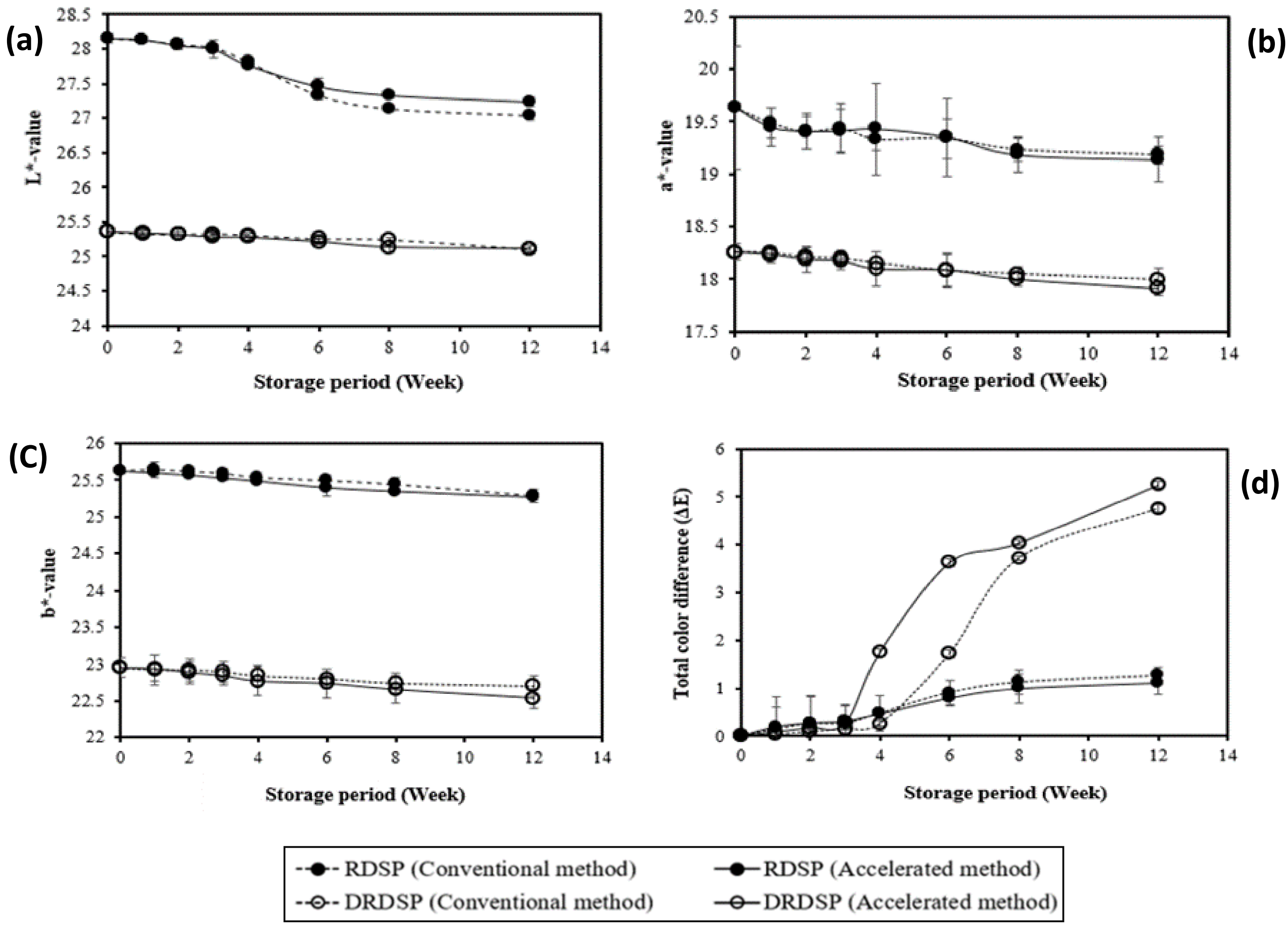


**Figure 4. Variation in colour attributes (L*-value, a*-value, b*-value, and total colour difference) of RDSP and DRDSP packed in ALP pouches under conventional and accelerated storage methods.**

## Impact of storage conditions on the flow properties of the powders

Flow characteristics, such as bulk density, degree of caking, and angle of repose, are essential for efficient packaging. Figure 5 demonstrates the impact of storage time and method on these properties for RDSP and DRDSP. Statistical analysis (Table 7) indicated that both the duration of storage and the method used significantly influenced all three flow properties for both types of powders. Figure 5a reveals that RDSP bulk density increased from 326 to 370 kg/m³ under conventional storage and from 326 to 404 kg/m³ under accelerated storage. Similarly, DRDSP bulk density increased from 314 to 398 kg/m³ under conventional storage and from 314 to 409 kg/m³ under accelerated storage. These findings align with observations for soursop powders (Chang et al., 2018). The increase in bulk density is likely attributed to moisture gain during storage, as the presence of water, which is denser than the dry solid, can elevate the bulk weight (Chegini & Ghobadian, 2005). The bulk density of stored RDSP and DRDSP under accelerated conditions increased by 7% and 2%, respectively, compared to those stored conventionally (Figure 5a). This elevation is likely due to heat absorption by particles at higher storage temperatures, reducing interparticle distance and promoting liquid bridge formation through increased interparticle forces (Aguilera et al., 1995). Similar trends have been reported for mango and soursop powders (Chauhan & Patil, 2013; Chang et al., 2018).

Figure 5b demonstrates a significant increase in the degree of caking for both RDSP and DRDSP at the sixth week of storage. Under conventional conditions, the degree of caking reached 31 ± 0.38% and 32.7 ± 0.14% for RDSP and DRDSP, respectively, by the end of the storage period. In contrast, under accelerated conditions, caking levels for RDSP and DRDSP were 22.8 ± 0.06% and 23 ± 0.03% after 12 weeks (Figure 5b). According to Table 3, both RDSP and DRDSP exhibited caking tendencies (20.1-50%). This slight increase in caking can be attributed to water absorption onto particle surfaces, forming a saturation solution that increases particle stickiness and leads to liquid bridge formation and subsequent caking (Downton et al., 1982). Similar caking behaviour has been observed in papaya and tomato powders (Liu et al., 2010; Ramachandran et al., 2014, Wong & Lim, 2016).

Angle of repose is a measure of a powder's flowability. Figure 5c demonstrates an increase in the angle of repose for both RDSP and DRDSP with prolonged storage under both conventional and accelerated conditions. These findings align with those reported for mango and papaya powders (Chauhan & Patil, 2013; Wong & Lim, 2016). Notably, angle of repose values for RDSP and DRDSP stored under accelerated conditions were approximately 2% higher than those stored conventionally (Figure 5c). Specifically, RDSP angle of repose increased from 52° to 61° under conventional storage and from 52° to 65° under accelerated storage. Similarly, DRDSP angle of repose increased from 43° to 51° and 43° to 52° under conventional and accelerated conditions, respectively. Generally, lower angles of repose indicate better powder flowability, while higher angles suggest poor flow (Carr Jr, 1965). The observed increase in angle of repose for both RDSP and DRDSP can be attributed to moisture absorption during storage. Additionally, the presence of fat in RDSP may have contributed to lump formation and reduced flowability.

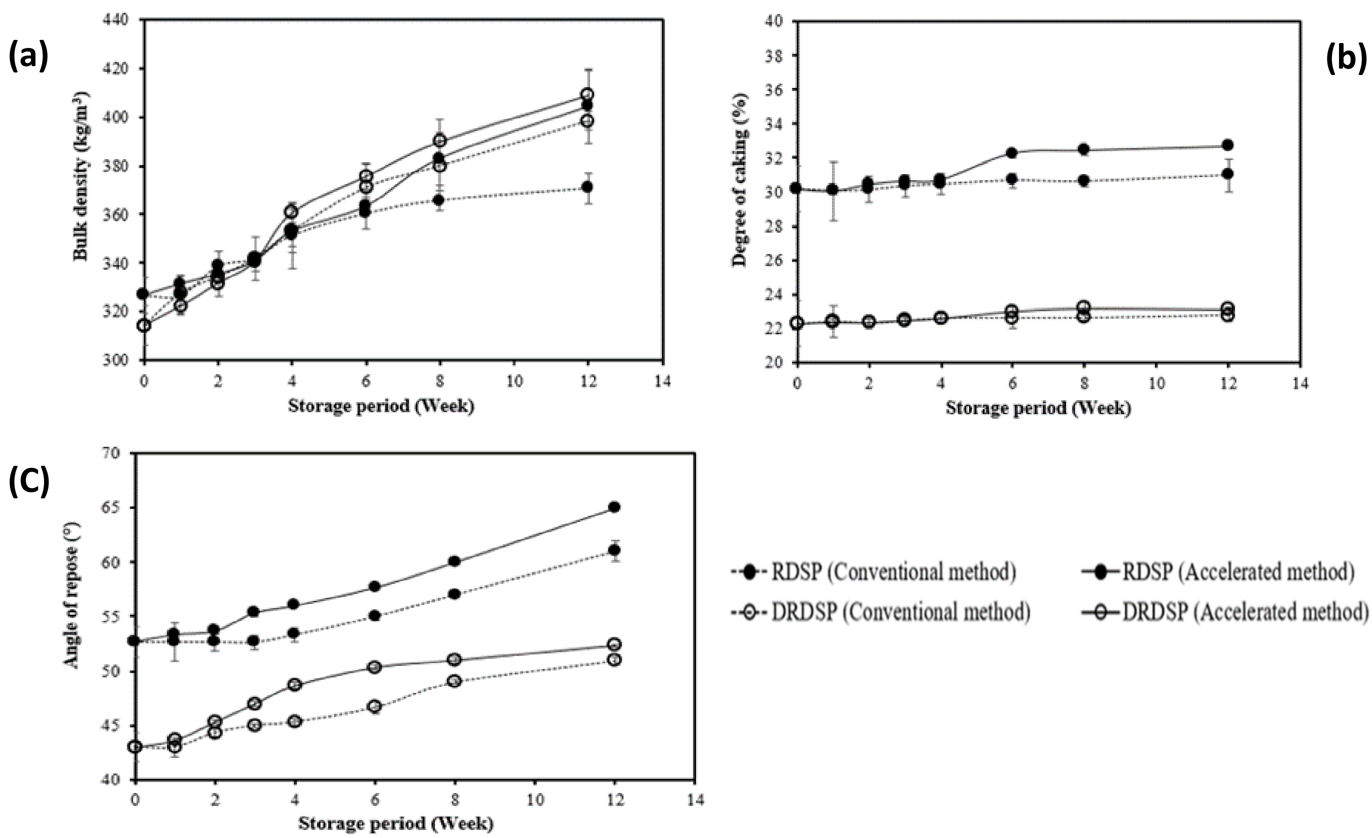


**Figure 5. Variation in bulk density, degree of caking, and angle of repose of RDSP and DRDSP packed in ALP pouches under conventional and accelerated storage methods.**

## Kinetics of quality changes in the powders during storage

Kinetic modeling is a crucial technique for understanding a system, as it describes reaction rates over storage time and helps predict alterations in food materials during storage (Van Boekel, 1996). In this study, the kinetics of changes in moisture content and total color difference were analyzed. These changes were found to fit either zero-order or first-order kinetics. The kinetic parameters from both models are detailed in Table 5. Nonlinear regression analysis showed that, except for DRDSP samples stored under conventional conditions, the changes in moisture content for all samples across different storage conditions followed first-order kinetics ($R^2 \geq 0.937$). Conversely, regression analysis revealed that changes in total color difference for all treatments followed zero-order kinetics ($R^2 \geq 0.908$). Several studies have reported the kinetics of moisture and color changes in food powders, most studies concluded that powder quality degradation follows either zero-order or first-order reaction kinetics. (Kumar & Mishra, 2004; Jaya & Das, 2005; Pua et al., 2008; Henríquez et al., 2013; and Chang et al., 2018). The higher constant rates observed for RDSP and DRDSP under accelerated storage compared to conventional conditions indicate greater moisture and color changes in these samples, suggesting that increased storage temperature accelerates quality degradation through heat-induced chemical reactions. These findings align with previous research on other food powders (Pua et al., 2008; Henríquez et al., 2013; Ramachandran et al., 2014; and Chang et al., 2018).

**Table 5. Summary of kinetic parameters of the moisture content and total color difference obtained from the kinetic models**

| Quality parameter | Powder type | Storage method | $C_o$ | k | kinetic order | $R^2$ | E% |
|---|---|---|---|---|---|---|---|
| Moisture content | RDSP | Conventional | 1.782 | 0.007 | 1 | 0.953 | 24.0 |
| | | Accelerated | 1.772 | 0.013 | 1 | 0.950 | 21.9 |
| | DRDSP | Conventional | 1.089 | 0.009 | 0 | 0.983 | 69.5 |
| | | Accelerated | 1.039 | 0.029 | 1 | 0.937 | 53.2 |
| Total color difference | RDSP | Conventional | 0.036 | 0.115 | 0 | 0.937 | 0.8 |
| | | Accelerated | 0.074 | 0.098 | 0 | 0.944 | 1.5 |
| | DRDSP | Conventional | 0.685 | 0.451 | 0 | 0.908 | 0.5 |
| | | Accelerated | 0.389 | 0.508 | 0 | 0.923 | 3.5 |

The initial moisture content ($X_i$) of the RDSP and DRDSP used in the storage study was 0.018 and 0.0109 kg water/kg dry solid, respectively. Figures 3a and 3b illustrate how the moisture content and water activity of the powders changed over the storage period. The GAB model constants obtained from these measurements are presented in Table 4. The saturated water vapor pressure (p*) values were 3170 Pa at 25°C and 6539.03 Pa at 38°C. The pouch's exposed area ($A_p$) was 0.0078 m², and the weights of dry solids ($X_s$) in the ALP pouches were 0.0147 kg for RDSP and 0.0148 kg for DRDSP. The water vapor permeability (K) values for the ALP pouches were $2.15 \times 10^{-7}$ kg/m²/day/Pa under conventional conditions and $3.84 \times 10^{-8}$ kg/m²/day/Pa under accelerated conditions. These values, along with p*, $X_s$, K, $A_p$, RH, and aw (from the GAB model), were used in Equation 8 to forecast the moisture content of the stored RDSP. Figure 6 shows a comparison between the measured and predicted moisture content values of the powder over time. The coefficient of determination ($R^2$), calculated using Equation 10, and the relative deviation percentage (E%), determined by Equation 11, for the powder stored in ALP pouches were both greater than 0.9 and less than 10%, respectively, demonstrating a strong fit of the model. The critical moisture contents ($X_c$) for RDSP were determined to be 0.0197 and 0.012 kg water/kg dry solid, marking the point where lump formation begins.

The shelf life of RDSP was defined as the duration needed to reach these critical moisture levels. Using Equation 9, the predicted shelf life of RDSP under different storage conditions was estimated. For instance, Figure 6 shows that the predicted times for RDSP moisture content to increase from an initial value of $X_i$ = 0.018 kg water/kg dry solid to the critical value of $X_c$ = 0.0197 kg water/kg dry solid were 85.66 and 81.3 days under conventional and accelerated conditions, respectively. The actual observed time for this moisture increase in RDSP was 84 days. These results validate the model's accuracy in forecasting RDSP shelf life.

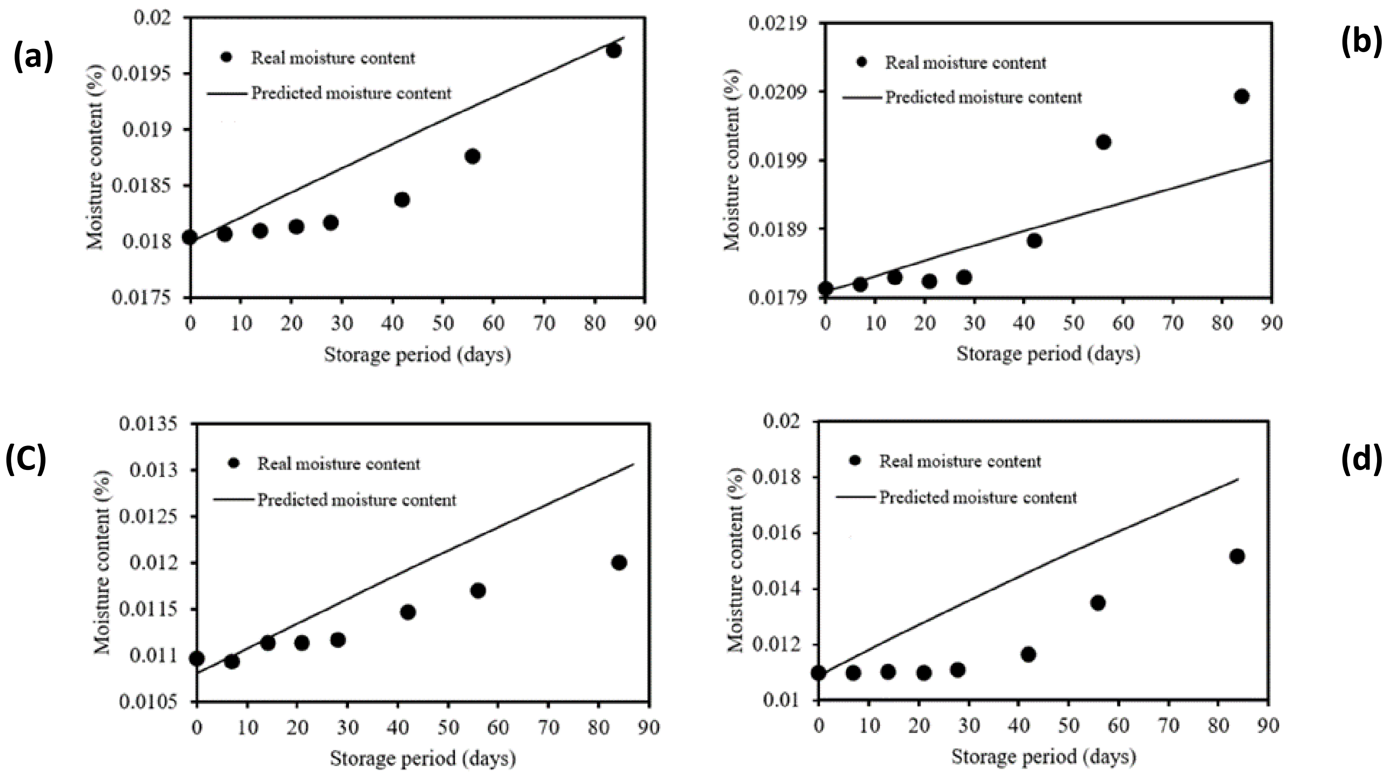


**Figure 6. Comparison between measured and predicted moisture contents of the RDSP at different treatments (a, b, c, and d refer to RDSP stored under conventional conditions, RDSP stored under accelerated conditions, DRDSP stored under conventional conditions, and DRDSP stored under accelerated conditions, respectively)**

## 4. Conclusion

Roasted palm date seed powder (RDSP) and defatted roasted palm date seed powder (DRDSP) have shown promise as nutrient-rich ingredients. This study explored the impact of different storage conditions on their properties. Findings revealed that both RDSP and DRDSP remained microbiologically stable and non-hygroscopic but exhibited poor flowability over a 12-week storage period. Zero and first-order reaction models were effective in describing the changes in moisture content and total color difference, respectively. Additionally, a predictive model for RDSP shelf life, based on moisture content changes, was successfully developed. These insights enhance the understanding of the storage behavior of these powders and their potential applications in the food industry.

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