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Drying Kinetics, Quality Attributes and Moisture Sorption Isotherms During Storage of Roselle (*Hibiscus sabdariffa*) Dried under Solar Drying Conditions

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DRYING kinetics, quality attributes and moisture sorption isotherms of roselle were investigated using a mixed-mode forced convection solar dryer. The results showed that, the moisture content decreased continuously with the drying time. The drying rates were higher at the beginning, then decreased later with decreasing the moisture content and increasing the drying time. The quality attributes of solar dried roselle (at 40°C) were as good as that of the fresh one, all the dried samples showed optimum color values. The drying process caused a sharp decrease in the microbial load for all the dried roselle samples as compared to the fresh one. The values of pH, acidity, anthocyanins, total phenols and flavonoids were also decreased as a result of the drying process. The water vapor transmission rate (WVTR) of the packaging materials was also determined. The data showed an increase in the WVTR values along with increasing the relative humidity (RH) levels. The values were slightly high in the low density polyethylene (LDPE), whereas, there was no marked difference in the WVTR values of both high density polyethylene (HDPE) and laminated polyethylene/nylon (LPE/N) bags. The results dealing with the moisture sorption isotherms showed that, the equilibrium moisture content (EMC) values for all samples were slightly high in the whole calyces, followed by roselle powder. The EMC values for the samples increased with increasing the storage RH. However, an inverse relationship was observed between the storage RH and the time required to reach equilibration for all samples. The appropriate RH for storage of solar dried roselle should be below 43% using suitable packaging materials with low WVTR such as HDPE or LPE/N bags.

Keywords: Roselle, Drying kinetics, Quality attributes, Sorption isotherms, Packaging materials, Microbial load.

Introduction

Roselle (*Hibiscus sabdariffa*), belongs to the family of Malvaceae. It is an excellent source of natural antioxidants, providing even higher levels than traditional sources such as raspberries and blueberries (Wong *et al*., 2002, Carvajal-Zarrabal *et al*., 2005, Juliani *et al*., 2009 and Daniel *et al*., 2012). In order to preserve and extend their life, roselle calyces are sold in a dry form. Traditionally, the calyces are dried by exposure to direct sunlight, despite the limitations implied, such as the lack of control of drying conditions and the eventual loss of some attributes such as antioxidant capacity. A properly designed solar dryer, which use free and renewable energy source, can alleviate the drawbacks associated with open sun drying and improve the quality of the dried product considerably (Saeed *et al*., 2008, Fudholi *et al*., 2010, Sanaa, 2010 and Vijaya Venkata Raman *et al*., 2012).

Knowledge of drying kinetics is important in the design, simulation and optimization of drying processes. It is affected by drying conditions, types of dryer and characteristics of materials to be dried. The drying curve will give information on the time necessary for a product to be dried under certain conditions (Heldman & Hartel, 1997, Senadeera *et al*., 2003, Ramaswamy & Marcotte, 2006 and Giri & Prasad, 2007).

It is well known that the moisture sorption isotherms of foodstuffs are extremely important for modelling the drying process, design and optimization of drying equipment, ingredient mixing and formulation of foods, predicting shelf-life stability, determining moisture changes which may occur during storage and selecting appropriate packaging material that optimize or maximize retention of aroma, color, texture, nutrients and biological stability. Therefore, it is extremely important to know the sorption characteristics of various dried materials (Iglesias & Chirife, 1982, Tsami et al., 1999, Debnath et al., 2002, Durakova & Menkov, 2005 and Akanbi et al., 2006).

The main objectives of this investigation were to: (1) Study the drying kinetics of roselle calyces under the solar drying conditions (40, 50 and 60°C). (2) Evaluate the quality attributes of fresh and dried roselle. (3) Investigate the effect of packaging materials on the moisture sorption isotherm of solar dried roselle (whole calyces and powder). (4) Determine the WVTR of the packaging materials (LDPE, HDPE and LPE/N bags).

Materials and Methods

Materials

Freshly harvested roselle calyces (*Hibiscus sabdariffa*) were obtained from the Horticulture Research Farm, Mallawi Agricultural Research Station, Agriculture Research Center (Minia, Egypt) and used for the study. They were dried on the day of purchase, using a mixed-mode forced convection solar dryer at 40, 50 and 60°C. The air velocity was kept constant at 1.9 – 2.4 m/s. The dried roselle calyces were ground in an electric laboratory mill to obtain powders. Three different packaging materials were used, 2 mil commercial low density polyethylene (LDPE) bags, 2 mil high density polyethylene (HDPE) bags, from Packaging Concepts and Design, a division of Bader Bag Co., Madison Heights, MN., USA., and 3 mil laminated polyethylene/nylon (LPE/N) bags from Cryovac Co., USA. (1 mil = 0.001 inch).

Methods

Drying kinetics

Drying curves were obtained by periodic determination of weight and moisture content of samples. The weight loss from the samples was recorded at certain intervals using an electronic balance with least count of 0.1g. Drying was continued till the sample attained the desired moisture level (equilibrium moisture content). The instantaneous moisture contents at any given time were computed according to Ekechukwu (1999) using the following equation:

$$M_{twb} = 1 - \left[\frac{(1 - M_{owb})\, W_o}{W_t}\right]$$

Where: M_{twb} = moisture content at time, t (decimal, wet basis); M_{owb} = initial moisture content (decimal, wet basis); W_o = initial weight of fresh product (kg); W_t = weight of product at time, t (kg) and Percentage M_{twb} = M_{twb} x 100.

Determination of color

The color characteristics of the samples were measured by a color difference meter (model color Tec-PCM, USA) using different color parameters (L, a, b) according to Francis (1983). In addition, numerical total color difference (ΔE), hue angle and color intensity (chroma) were calculated according to Shih et al. (2009) using the following equations:

$$\Delta E = [(L - L_o)^2 + (a - a_o)^2 + (b - b_o)^2]^{1/2}$$

$$\text{Hue angle} = [\tan^{1-} (b/a)]$$

$$\text{Chroma} = [(a^2 + b^2)]^{1/2}$$

Where: L_o, a_o and b_o were the L, a, and b values of the reference sample which is here the fresh sample.

Determination of pH and titratable acidity

The pH of roselle samples were determined according to the methods of the AOAC (2000). Titratable acidity (calculated as percent citric acid) was determined according to Adekunte et al. (2010).

Determination of anthocyanins

Anthocyanin pigment was measured (as cyanidin-3-glycoside mg/100g) following the method described by Ranganna (1977).

Determination of total phenols and flavonoids

Estimation of total phenols was carried out according to Musa et al. (2011) using Folin-Ciocalteu reagent, the results were expressed as mg of gallic acid equivalents/100g of sample. Total flavonoids were determined by the colorimetric method as described by Abu Bakar et al. (2009), the results were expressed as mg of quercetin equivalents/100g of sample.

Microbiological analysis

The total bacterial count was determined according to Diliello (1982) using nutrient agar media. Yeast and mould count was done using malt extract agar media according to AOAC (2000). The number of bacterial colonies, yeast and molds were counted, after incubation at 37ºC/ 48 hr for bacteria and 25ºC / 72 hr for yeast and molds, and expressed as colony forming units per gram of the sample (CFU/g).

Determination of water vapor transmission rate (WVTR)

The WVTR of the test packaging materials (LDPE, HDPE and LPE/N bags) at various storage conditions was determined as described in the method of ASTM (1987) as follows:

Three bags of the studied packaging materials were used in this study. About 6 g of desiccant was put in each bag, heat-sealed and weighed. The bags were stored at 25°C and relative humidities range from 22.50 to 92.50%. The storage period was 14 days. After that the bags were reweighed (every two days) to calculate the amount of water vapor absorbed by the desiccant. The following equation was used to calculate the WVTR:

$$WVTR = W / (A \times t)$$

Where: WVTR = Rate of water vapor transmission in g/m^2.day; W = Weight gain or loss in g.; A = Exposed area of the package material (total area of the two sides of bag) in m^2. and t = Time, during which gain or loss was observed in hours.

Determination of moisture sorption isotherms

Moisture sorption isotherms of the dried materials (whole roselle calyces and powder) were determined according to the static gravimetric method as described by Greenspan (1977), Resnik et al. (1984) and Labuza et al. (1985). Seven saturated salt solutions were used to provide a range of relative humidities (RH) from 22.5 to 92.5% at specific temperature (25°C). The salts used and their relative humidities at 25°C are given in Table 1. Triplicates of each sample (2–3g) were accurately weighed in each packaging materials, then heat sealed. These bags were placed on a plastic perforated tray in air/humidity tight plastic containers containing the saturated salt solutions, to avoid any contact between the saturated salt solutions and the samples. For equilibration of samples, the closed containers were then maintained in an incubator equipped with temperature control system with the accuracy of ± 1°C to provide the desired constant temperature of 25°C. The weight of each sample was checked using an analytical balance (with the precision of 0.0001g) initially after three days, and then at one day intervals until a constant weight was reached. The equilibrium moisture content of samples was determined by oven drying at 105°C for overnight and reported as g water/100g sample.

TABLE 1. Relative humidity values of the saturated salt solutions at 25°C.

Salts	CH_3COOK	$MgCl_2$	K_2CO_3	NaBr	NaCl	KCl	Na_2SO_4
RH %	22.50	33.00	43.00	57.70	75.30	84.30	92.50

Results and Discussion

Drying kinetics of roselle calyces

The drying curves (moisture content versus drying time) for thin layer drying of roselle calyces under the solar drying conditions (40, 50 and 60°C) are shown in Fig. 1. From which, it could be seen that the moisture content decreases continuously with the drying time. The drying process was continued until the material achieves its final moisture content at which the moisture content does not decrease substantially with increasing the drying time. This final moisture content was considered as the value of equilibrium moisture content (Ekechukwu, 1999 and Ramaswamy & Marcotte, 2006).

It is obviously observed from the figure that the moisture content is decreased faster at the initial stages of drying and thereafter became slower as drying proceeds. The drying rates were higher at the beginning of the process probably due to the evaporation of moisture from the surface of samples and later decreased with decreasing the moisture content. The accelerated drying rates may be attributed to internal heat generation. The drying time was reduced with the increased temperature (Pathare & Sharma, 2006, Doymaz, 2007, Saeed et al., 2008, Sanaa, 2010 and Suherman et al., 2012).

It is evident from these curves that the drying time required to reduce the moisture contents from the initial moisture content of 88.19% to final moisture contents of 7.45, 7.34 and 7.14% was 7, 6 and 5 hr for the drying temperatures of 40, 50 and 60°C, respectively.

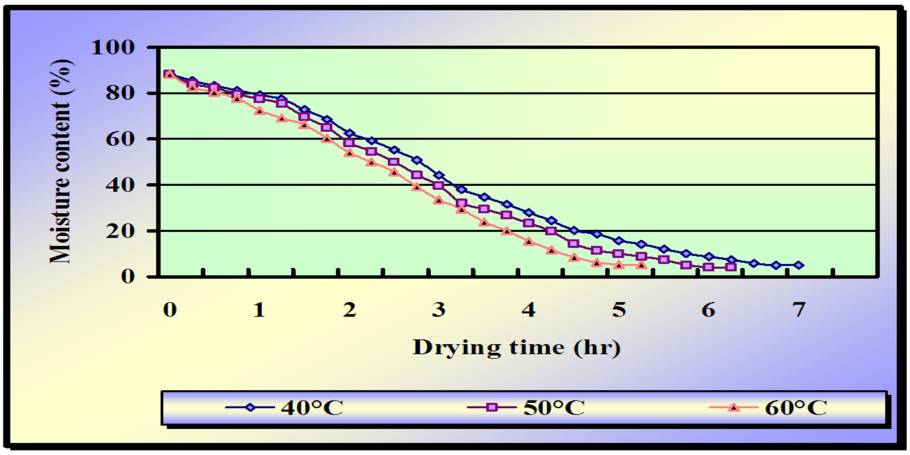

Fig. 1. Drying curves of solar dried roselle calyces.

Effect of solar drying on the quality attributes of roselle calyces

Color parameters of fresh and solar dried roselle

The Hunter color parameters (L), (a) and (b) are widely used to describe color changes during drying of food materials. However, it is recommended to use hue angle and chroma as more practical measures of color. The color degradation of the dried samples can also be expressed as a single numerical value ΔE. This value defines the magnitude of the total color difference. Preferred colors are those closer to the original color of the fresh samples (McGuire, 1992, Albanese et al., 2007 and Shih et al., 2009).

The results of color parameters (L, a, b, ΔE, hue angle and chroma) for fresh and dried roselle samples are presented in Table 2. The results showed that, L-values increased, whereas, a-values and b-values decreased for all the dried samples as compared to the fresh one. Hue angle and chroma values followed the same pattern as a-values. This could be due to the change in the values of both redness (a-value) and yellowness (b-value) as a result of the drying process. It was reported that chroma is the indicator of color saturation and intensity. The higher the values are, the more desirable they are (McGuire,1992, Albanese et al., 2007 and Shih et al., 2009). There are slight differences in brightness, redness and yellowness values of all dried samples. Consequently, slight differences in ΔE values were observed. Nevertheless, this minute total color difference can not be distinguished by the naked eye in some cases. These results were in a good agreement with the findings of Maskan (2001) and Sacilik and Unal (2005). In the light of the obtained results, it could be concluded that all the dried samples revealed optimum color values.

TABLE 2. Effect of different drying temperatures on the color parameters of roselle calyces.

Color parameters*	Fresh roselle	Dried roselle		
		40°C	50°C	60°C
L (Lightness)	20.32 ± 0.39	30.26 ± 1.73	31.86 ± 1.01	32.35 ± 1.28
a (redness/greenness)	16.98 ± 0.58	14.97 ± 1.14	14.63 ± 0.64	12.89 ± 0.16
b (yellowness/blueness)	15.52 ± 1.84	11.75 ± 1.32	11.26 ± 1.05	10.67 ± 0.74
ΔE**	00.00	10.88	12.52	13.58
Hue angle***	42.43	38.13	37.58	39.62
Chroma****	23.00	19.03	18.46	16.73

* Means of three determinations ± SD. **$\Delta E = [(L - L_o)^2 + (a - a_o)^2 + (b - b_o)^2]^{½}$

*** Hue angle = $[\tan^{1-} (b/a)]$. **** Chroma = $[(a^2 + b^2)]^{½}$

pH and titratable acidity of fresh and solar dried roselle

The pH and titratable acidity values of fresh and solar dried roselle are presented in Table 3. The results showed that the pH values were decreased from 2.83 to 2.14 as a result of drying process. Titratable acidity values followed the similar pattern as pH. These results were in a good agreement with the findings of Abou-Arab et al. (2011). Da-Costa-Rocha et al. (2014) reported that roselle calyces extracts contain a high percentage of organic acids, including citric acid (12–20%), hydroxycitric acid, hibiscus acid (13–24%), malic (2–9%) and tartaric (8%) acids as major compounds, and oxalic and ascorbic (0.02–0.05%) acids as minor compounds.

Phytochemicals composition of fresh and solar dried roselle

The results obtained for the phytochemicals of fresh and solar dried roselle (total anthocyanins, total phenolics and total flavonoids) are shown in Table 3. It could be seen that the drying process caused a decrease in the phytochemicals content for all dried roselle samples as compared with the fresh one.

Data given in Table 3 revealed that, the anthocyanin values decreased from 1156.14mg/100g for fresh roselle to 986.30, 804.81 and 751.03mg/100g (as cyanidin-3-glycoside) for the dried samples at 40, 50 and 60°C, respectively. Similar results were reported by Abou-Arab et al. (2011).

As shown in the same table (Table 3), the total phenol values decreased as a result of the drying process from 3215.24mg/100g for fresh roselle to 3155.89, 3062.08 and 2932.55mg/100g (as gallic acid) for dried samples at 40, 50 and 60°C, respectively. These results were in agreement with those reported by Abou-Arab et al. (2011).

Also, the results in the same table showed that, the values of total flavonoids decreased as a result of the drying process from 888.23mg/100g for fresh roselle to 605.64, 514.79 and 404.91mg/100g (as quercetin) for dried samples at 40, 50 and 60°C, respectively. These results were in a good agreement with the findings of Anokwuru et al. (2011).

From the obtained results it could be concluded that, 40°C or lower may be recommended as the air drying temperature for roselle calyces as it gave a product with good quality attributes and the highest phytochemicals content.

TABLE 3. Effect of drying temperatures on the pH, titratable acidity and phytochemicals of roselle calyces (dry weight basis).

Quality parameters*	Fresh roselle	Dried roselle		
		40°C	50°C	60°C
pH	2.83 ± 0.20	2.15 ± 0.04	2.14 ± 0.25	2.19 ± 0.05
Titratable acidity (%)	20.74 ± 2.01	19.03 ± 2.00	18.02 ± 1.90	17.53 ± 2.03
Total anthocyanins**	1156.14±1.27	986.30±1.24	804.81±1.43	751.03±1.45
Total phenols**	3215.24±2.50	3155.89±2.00	3062.08±1.90	2932.55±2.30
Total flavonoids**	888.23 ± 1.25	605.64 ± 1.30	514.79 ± 1.01	404.91 ± 1.22

* Means of three determinations ± SD ** mg/100g

Microbiological load of fresh and solar dried roselle

The total bacterial and fungal counts for fresh and solar dried roselle calyces are shown in Table 4. The data showed that, the drying process caused a sharp decrease in the microbial load for all dried roselle samples as compared to the fresh one. The total bacterial count decreased from 15.50×10^4 CFU/g for the fresh samples to 7.70×10^4 CFU/g for the dried samples at 60°C. The fresh samples had the highest fungal count (11.20×10^3 CFU/g), while all the dried samples had lower values, depending on the drying temperature (6.90×10^3 CFU/g for dried roselle at 60°C). This could be due to the low level of moisture content in all the dried samples which suppress the growth of microorganisms. Similar results were reported by Adebayo-tayo and Samuel (2009).

The high contamination level could be attributed to the high natural micro flora of the herbs as well as the general conditions during their cultivation, harvesting, drying, handling, processing, storage, distribution and sales.

However, it was reported that the microbial status of the dried herbal material is not so much caused by the secondary contamination during processing, but it is primarily due to the fact that plants have their own microbial flora (Abou Donia, 2008).

TABLE 4. Effect of different drying temperatures on microbiological load of roselle calyces.

Microbial load*	Fresh roselle	Dried roselle		
		40°C	50°C	60°C
Total bacterial count (10^4)	15.50	12.40	8.30	7.70
Total fungal count (10^3)	11.20	10.60	7.50	6.90

* Means of three determinations.

Water vapor transmission rate (WVTR) of packaging materials

The WVTR for the studied packaging materials (LDPE, HDPE and LPE/N bags) under storage conditions of 25°C and different relative humidity (RH) levels ranging from 22.50 to 92.50% are presented in Table 5. The obtained results showed that the WVTR values were slightly high in the LDPE, whereas, there was no marked difference in the WVTR values of both HDPE and LPE/N bags. It could also be seen that, the WVTR values increased with increasing the RH levels at a constant temperature. Similar results have been reported by Zaghloul et al. (2012) for the LDPE bags.

TABLE 5. Water vapor transmission rate values (g/m². day)* of the studied packaging materials at 25°C and different levels of RH.

RH (%) at 25°C	Types of packaging materials		
	LDPE	HDPE	Laminated PE / nylon
22.50	1.25 ± 0.13	0.21 ± 0.06	0.17 ± 0.06
33.00	1.89 ± 0.10	0.36 ± 0.09	0.32 ± 0.08
43.00	2.05 ± 0.10	0.87 ± 0.09	0.82 ± 0.08
57.70	2.82 ± 0.09	1.06 ± 0.07	1.01 ± 0.04
75.30	3.06 ± 0.07	1.66 ± 0.06	1.61 ± 0.06
84.30	3.20 ± 0.16	2.13 ± 0.07	2.06 ± 0.03
92.50	3.95 ± 0.12	2.35 ± 0.11	2.29 ± 0.10

* Means of three determinations ± SD.

Moisture sorption isotherms of solar dried roselle samples

Determination of the sorption isotherms is an indispensable stage in the study of drying of every product. It gives precious information about the hygroscopic equilibrium of the product and allows us to know the domain of stability of the products after drying (Belghit et al., 2000).

If the storage environment has a partial pressure of water vapor above or below the vapor pressure of water at the foodstuff surface, water is adsorbed or desorbed, respectively until it comes into equilibrium with that atmosphere. Exposure to that atmosphere beyond that point will cause no further change in the moisture content of the material (Vazquez et al., 1999, Menkov, 2000, Al-Muhtaseb et al., 2002 and Arslan & Togrul, 2005).

Moisture sorption isotherms of the solar dried roselle (whole calyces and powder) at 25°C and relative humidities which range from 22.50 to 92.50% are given in Tables 6 and 7. A comparison of the initial moisture content (IMC) with the final equilibrium moisture content (EMC) gave a measure of the capacity of that sample to adsorb or desorb moisture at different relative humidities, so, it was determined and included in the same tables.

TABLE 6. Effect of packaging materials and storage relative humidity on the equilibrium moisture content values and the equilibration time of solar dried whole roselle calyces.

Samples		Parameters*	Relative humidity (%) at 25°C						
			22.50	33.00	43.00	57.70	75.30	84.30	92.50
Whole roselle calyces	Without packaging	IMC (%)	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03
		EMC (%)	7.78 ± 0.02	8.60 ± 0.03	11.62 ± 0.02	12.94 ± 0.02	19.27 ± 0.04	26.76 ± 0.05	35.15 ± 0.07
		Time (day)	60	57	53	48	40	36	27
	LDPE	IMC (%)	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03
		EMC (%)	7.53 ± 0.02	8.45 ± 0.02	10.77 ± 0.04	12.30 ± 0.06	16.03 ± 0.04	18.73 ± 0.06	21.19 ± 0.05
		Time (day)	65	61	55	51	45	40	32
	HDPE	IMC (%)	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03
		EMC (%)	7.42 ± 0.02	7.87 ± 0.02	9.75 ± 0.03	11.72 ± 0.04	14.22 ± 0.02	16.72 ± 0.03	17.30 ± 0.04
		Time (day)	75	72	67	63	56	53	47
	Laminated PE / nylon	IMC (%)	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03	7.34 ± 0.03
		EMC (%)	7.39 ± 0.01	7.63 ± 0.03	9.59 ± 0.02	11.60 ± 0.01	13.95 ± 0.05	16.25 ± 0.07	17.12 ± 0.06
		Time (day)	75	72	67	63	56	53	47

* Means of three determinations ± SD. IMC = Initial moisture content. EMC = Equilibrium moisture content.

TABLE 7. Effect of packaging materials and storage relative humidity on the equilibrium moisture content values and the equilibration time of solar dried roselle powder.

Samples		Parameters*	Relative humidity (%) at 25°C						
			22.50	**33.00**	**43.00**	**57.70**	**75.30**	**84.30**	**92.50**
Roselle powder	**Without packaging**	**IMC (%)**	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02
		EMC (%)	7.76 ± 0.02	8.52 ± 0.02	10.81 ± 0.03	12.45 ± 0.04	17.91 ± 0.02	22.60 ± 0.05	30.46 ± 0.06
		Time (day)	62	60	55	51	43	38	30
	LDPE	**IMC (%)**	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02
		EMC (%)	7.51 ± 0.01	8.29 ± 0.03	10.42 ± 0.04	12.09 ± 0.04	15.20 ± 0.05	18.17 ± 0.03	20.48 ± 0.03
		Time (day)	67	64	57	54	48	43	35
	HDPE	**IMC (%)**	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02
		EMC (%)	7.37 ± 0.02	7.71 ± 0.02	9.05 ± 0.03	10.97 ± 0.05	11.93 ± 0.04	14.10 ± 0.05	16.24 ± 0.02
		Time (day)	79	75	69	66	60	56	50
	Laminated PE / nylon	**IMC (%)**	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02	7.28 ± 0.02
		EMC (%)	7.30 ± 0.02	7.54 ± 0.02	8.75 ± 0.01	10.66 ± 0.02	11.50 ± 0.04	13.69 ± 0.05	16.04 ± 0.02
		Time (day)	79	75	69	66	60	56	50

* Means of three determinations ± SD. IMC = Initial moisture content. EMC = Equilibrium moisture content.

The results showed that, at a constant temperature, the EMC values of the studied samples increased with increasing the storage relative humidity (RH) levels and vice versa. This might be due to the fact that vapor pressure of water present in foods increases with that of the surrounding atmosphere.

The EMC values were slightly high in the whole calyces, followed by roselle powder and that was a general trend in all samples. On the other hand, the samples without packaging had the highest EMC values (7.78 – 35.15 and 7.76 – 30.46%), followed by the LDPE samples (7.53 – 21.19 and 7.51 – 20.48%) for the whole calycse and powder at 22.50 – 92.50% RH, respectively. Whereas, there was no marked difference in the EMC values of both HDPE and LPE/N samples as shown in Tables 6 and 7.

Tables 6 and 7 showed the equilibration time for the solar dried whole roselle calyces and roselle powder with different packaging materials. From which it could be seen that, the HDPE and LPE/N samples required almost the same time for equilibration at any RH. It ranged from 47 to 75 days for whole calycse and from 50 to 79 days for powder depending on the storage relative humidities. Whereas, the samples without packaging required lower time (27 to 60 days) for equilibration at any relative humidity, followed by the the LDPE samples (32 to 65 days). However, an inverse relationship was observed between the storage relative humidity and the time required to reach equilibration for all samples.

The isotherm curves (Figs. 2 – 5), illustrate the evolution of the product equilibrium moisture content as a function of the relative humidity of the air surrounding the product, had sigmoidal shapes typical for food and all of these curves followed similar patterns. Similar results have been reported for different food materials (Viswanathan et al., 2003; Sanaa, 2010; Ashaye, 2013; Langova et al., 2013 and Kenawi et al., 2015).

From the obtained results it could be concluded that, the appropriate relative humidity for storage of the solar dried roselle samples under the previous storage conditions should be below 43% (at which, the food material has reached to the equilibrium with its surrounding atmosphere), using suitable packaging materials with low water vapor transmission rate such as HDPE or LPE/N bags.

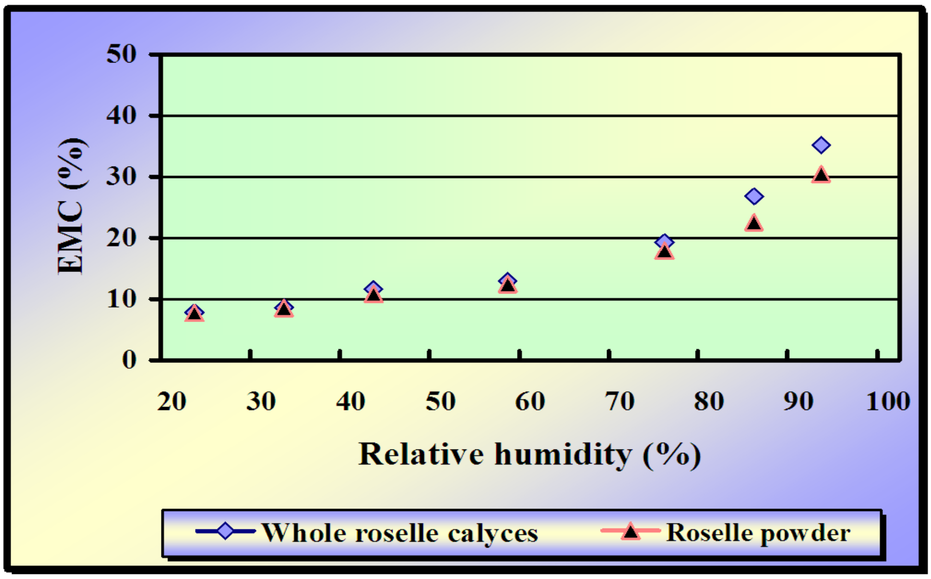

Fig. 2. Sorption isotherm curves of solar dried roselle samples (Without packaging).

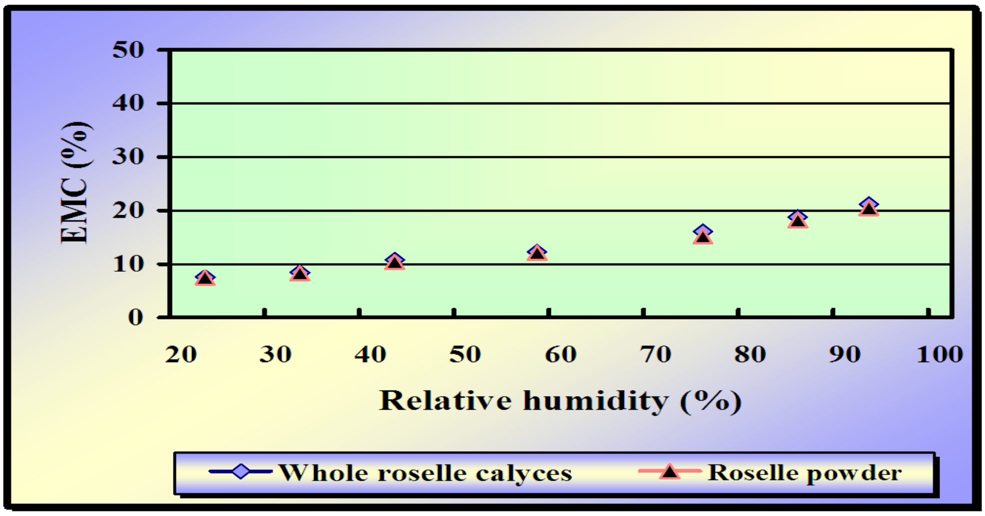

Fig. 3. Sorption isotherm curves of solar dried roselle samples (packaged in LDPE bags).

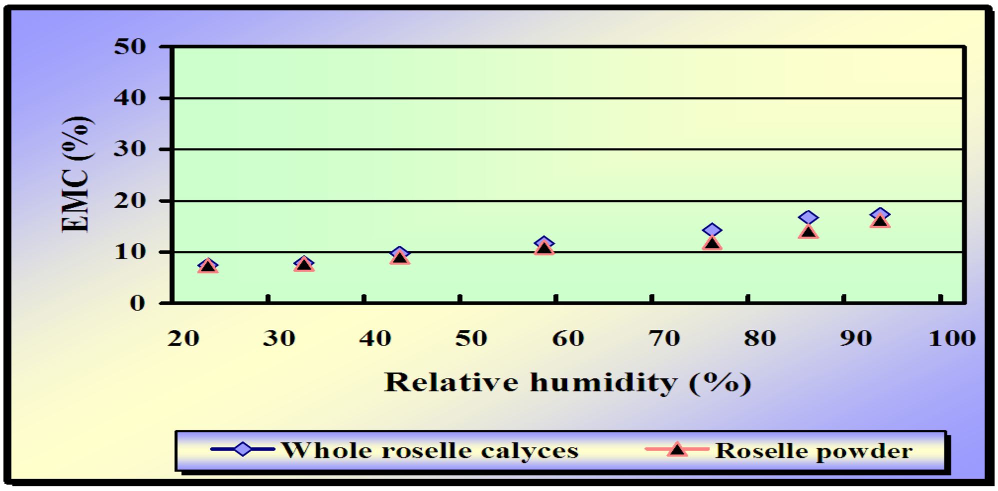

Fig. 4. Sorption isotherm curves of solar dried roselle samples (packaged in HDPE bags).

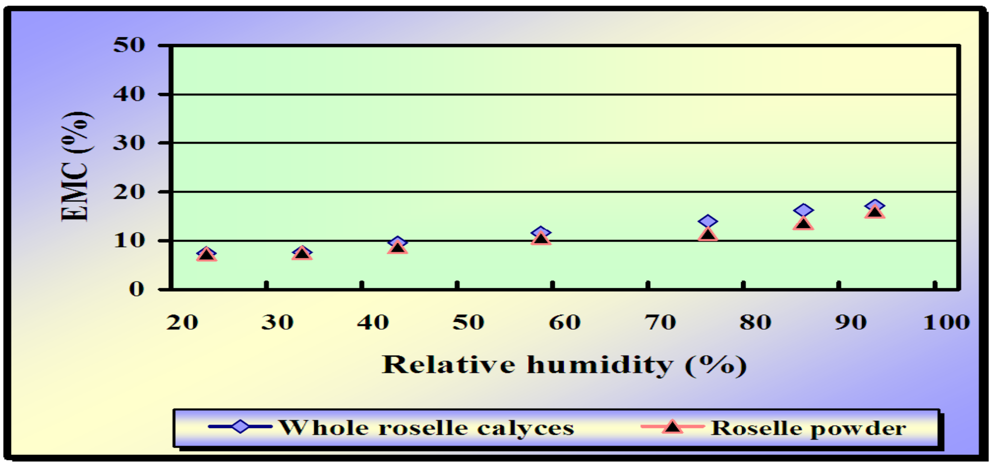

Fig. 5. Sorption isotherm curves of solar dried roselle samples (packaged in Laminated PE/nylon bags).

Conclusion

In the light of the obtained results, it could be concluded that solar drying had no remarkable changes on the quality attributes of the final products. It could be used successfully to obtain high-quality dried food materials under much higher hygienic conditions and within a shorter time as compared to sun drying. Obviously, 40°C or lower may be recommended as the air drying temperature for roselle calyces as it gave a product with good quality attributes and highest phytochemicals content. The drying process caused a sharp decrease in the microbial load for all dried roselle samples as compared to the fresh one. The appropriate RH for storage of solar dried roselle should be below 43% using suitable packaging materials with low WVTR such as HDPE or LPE/N bags.

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سلوك معدل التجفيف وخواص الجودة وخصائص التماثل الحراري لامتصاص الرطوبة خلال التخزين للكركديه المجفف تحت ظروف الطاقة الشمسية

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أجرى هذا البحث بغرض الاستفادة من الطاقة الشمسية كمصدر طبيعي للطاقة رخيص ومتجدد ويوفر عامل الأمان البيئي في حفظ المواد الغذائية . وفيه تم دراسة سلوك معدل التجفيف (منحنيات التجفيف) وخواص الجودة وخصائص التماثل الحراري لامتصاص الرطوبة أثناء التخزين للكركديه المجفف تحت ظروف الطاقة الشمسية وذلك باستخدام مجفف شمسي ذو نظام مختلط ويعمل بنظام الحمل الجبري لدفع الهواء. أظهرت النتائج أن المحتوى الرطوبي لعينات الكركديه يتناقص باستمرار مع زمن التجفيف .. وأن معدل التجفيف كان أسرع في بداية عملية التجفيف ثم انخفض بعد ذلك مع انخفاض المحتوى الرطوبي وزيادة زمن التجفيف وأدت زيادة درجة حرارة التجفيف إلى نقص ملحوظ في زمن التجفيف. بينت نتائج صفات الجودة أن نظام التجفيف بالطاقة الشمسية المستخدم قد أعطى منتجات مجففة عالية الجودة ولها قيم لون ممتازة مقارنة بمثيلتها الطازجة خاصة عند التجفيف على درجة حرارة ٤٠°م. أدت عملية التجفيف إلى انخفاض شديد في الحمل الميكروبي كما انخفضت أيضا قيم كل من الأس الهيدروجينى والحموضة – الأنثوسيانين – الفينولات والفلافونويدات الكلية لكل عينات الكركديه المجففة مقارنة بالعينات الطازجة. تم تقدير معدل نفاذ الرطوبة لمواد التعبئة والتغليف المستخدمة تحت نفس ظروف التخزين (٢٥°م ومستويات مختلفة من الرطوبة النسبية من ٢٢,٥٠ - ٩٢,٥٠ ٪) وأوضحت النتائج أن قيم معدل نفاذ الرطوبة تزداد بزيادة مستوى الرطوبة النسبية وكانت أعلى القيم لعبوات الـ LDPE في حين لم يكن هناك اختلاف ملحوظ في قيم معدل نفاذ الرطوبة لعبوات الـ HDPE والـ Laminated PE/N. تبين من دراسة خصائص التماثل الحراري لامتصاص الرطوبة أن قيم المحتوى الرطوبي المتوازن للعينات تزداد بزيادة مستوى الرطوبة النسبية للتخزين .. بينما وجدت علاقة عكسية بين درجة الرطوبة النسبية للتخزين وبين الزمن اللازم لوصول المادة الغذائية لدرجة التوازن في المحتوى الرطوبي لكل العينات .. كانت قيم المحتوى الرطوبي المتوازن لعينات الكركديه الكاملة أعلى قليلاً من قيم العينات المطحونة .. أوضحت النتائج أن أفضل مستوى رطوبة نسبية لتخزين الكركديه المجفف تحت ظروف الطاقة الشمسية يجب أن يكون أقل من ٤٣٪ وباستخدام مواد تعبئة وتغليف مناسبة ذات معدل منخفض لنفاذ الرطوبة مثل عبوات الـ HDPE والـ Laminated PE/N.