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RESEARCH ARTICLE

ENVIRONMENT-CONTROLLED THIN-LAYER-DRYING OF CUT-ROSELLE: DRYING-EXPERIMENTS, EFFECTS OF DRYING-SETTINGS, DRYING-MODELS

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ABSTRACT

This research investigated how the drying-conditions affect drying-performance of Cut-Roselle (*Hibiscus_sabdariffa* L.). The experiments are conducted using Constant-Temperature-Humidity-Chamber, where varied temperatures (35,45,55,65°C) and relative humidity levels (30,35,40,45,50%) are tested. The drying process for Cut-Roselle primarily occurred during the falling-rate-period. Notably, the drying-air temperature significantly, influenced the drying-kinetics, with higher temperatures (ranging from 35 to 65°C) resulted in shorter drying-times. Relative-humidity had a lesser-impact compared to the temperature. Extended drying-periods and increased equilibrium moisture levels are observed under conditions of elevated relative-humidity and reduced temperatures. An evaluation of various thin-layer drying-models is conducted to determine the most accurate model for the drying-characteristics. The Modified-Page II model demonstrated exceptional fit quality, with R^2=0.99949. It effectively described the dehydration-behavior of Cut-Roselle within the range of the experimental drying-parameters.

KEYWORDS

Cut-Roselle; thin-layer drying; controlled-drying; mathematical-models

1. INTRODUCTION

The Roselle plant, scientifically known as (*Hibiscus sabdariffa* L.), is an annual herbaceous shrub that is a part of the *Malvaceae* family (Ahiduzzaman et al., 2021; Jamini and Aminul Islam, 2021). In different places, it has various names, such as Karkade, Rosella, Gongura, Razelle, Zobo, and Sorrel. The significant commercial-interest part of the plants are the bulbous-calyces, which are dried and wholesaled to the herbal-tea and beverage producers (Ashaye, 2013). These calyces, known for their unique sweet-tart flavor, are rich in a variety of phytochemical-compounds and antioxidants (Plotto, 2007; Ahiduzzaman et al., 2021; Alegbe et al., 2019; Hapsari et al., 2021; Tzu et al., 2007). Research has been conducted on the bioactive substances in Roselle-extract, particularly their potential use in treating obesity. The plant's antilipidemic and antidiabetic effects, as well as other medical applications, have been highlighted. For more detailed information on the Roselle plant, readings from various studies are recommended such as (Duke, 1983; Ilyas et al., 2021; Morton, 1987).

Drying processes, which are essential and time-honored methods of food preservation practiced by various communities, play a significant role in post-harvest operations for biological materials (Midilli et al., 2002; Mugi and Chand, 2022; Sacilik 2007). Their purpose is to enhance product shelf-life by positively impacting the quality of dried-goods (Chong et al., 2013; Janjai and Tung, 2005; Tajudin et al., 2019). Additionally, drying aims to facilitate longer-storage periods, reduce packaging-needs, and minimize transport-loads (Vengaiah and Pandey, 2007). To describe the drying process comprehensively, appropriate drying models based on differential equations of heat-mass transfer are used. These models account for transport phenomena within the products and their interaction with drying-agents. Understanding material properties such as moisture-diffusivity, thermal-conductivity, density, specific-heat, and interphase heat and mass transfer coefficients is essential for applying transport-equations (Karathanos, 1999). A study in 1980 reviewed various theories regarding moisture migration-mechanisms (Mujumdar, 1980). When the external-resistances to the heat-mass transfer are eliminated/reduced, and for practical design-analysis purposes, employing simple semi-empirical expressions, is often sufficient to adequately, describe drying-kinetics (Midilli et al., 2002).

A common approach to accomplish this, is the usage of thin-layers of the drying-materials when conducting the drying-experiments. Various experimental-modelling efforts on single-layer drying are found in the literature (Midilli et al., 2002). To evaluate the drying-kinetics, the weights of the drying-samples as a function of times, are experimentally measured. Various ways are used to represent the drying-curves, such as drying-rates vs times, average-moisture contents vs times, and drying-rates vs average-moisture contents (Coumans, 2000). Researchers have explored different methods for drying Roselle. A study showed Roselle-drying using a convective heat-pump (Tajudin et al., 2019). While another researcher, investigated solar drying of whole Roselle, and found that the logarithmic model effectively, described its drying behaviour (Imad, 2010a). Researchers used a conventional tray-dryer to dry Roselle at different temperatures (40-60°C) and found that the Newton-model performed better than others in fitting the experimental data (Suherman et al., 2012). Researchers carried out Roselle solar-drying using a polyethylene-plastic tunnel for 27 hours, observing that the hybrid system dried the calyxes faster than the solar-system (Hahn et al., 2012). However, in the preceding research works, no literature specifically, addressing the controlled hot-air thin-layer drying of Cut-Roselle are found. The objectives of this part of the study, therefore, are at first, to investigate the drying behaviour of Cut-Roselle (Variety-Sudanese) under controlled drying-environments. Secondly, to find, among twelve different thin-layer drying-models, the optimum model for the drying characteristic of Cut-Roselle.

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2. MATERIALS AND METHODS

Formulae for the product's moisture-content are shown in Table 1. The moisture contents in the products can be expressed on dry or wet weight basis. The moisture-ratio (*MR*) is the proportion of moisture at a specific-time to the original-moisture level, with reference to the equilibrium-moisture level. The mass-shrinkage ratio (*MSR*), which is attributable to the loss of mass, indicates significant structural-transformations or modifications in crops/materials, throughout the drying-stages. In addition, the rate of drying quantifies the velocity at which water is removed from the substance undergoing dehydration.

Table 1: Moistures Relationships

Parameters	Formula	References
Moisture Content (*MC*) (dry-basis)	$\% \, MC_{db} = \frac{W_w}{W_d} . 100$	(Essalhi et al., 2018; Mugi and Chand 2022)
Moisture Ratio (*MR*)	$MR = \frac{M - M_e}{M_0 - M_e}$	(Engin and Tulek 2014; Saeed et al. 2012)
Drying Rate (*DR*)	$DR = \frac{M_{t+dt} - M_t}{dt}$	(Imad Eldin 2010a; Engin and Tulek 2014)
Mass Shrinkage Ratio (*MSR*)	$MSR = \frac{W_t}{W_0}$	(Midilli 2001; Saeed et al., 2008)

The thin-layer drying-models, that are commonly utilized by several researchers, are shown in Table 2. These models serve to illustrate the drying-performances of agro-produce.

Table 2: Thin-Layer Drying-Models

Model name	Equation	References
Newton	$MR = exp^{(\,kt)}$	(Engin and Tulek 2014; Imad, 2010a)
Page	$MR = \ exp^{(\,kt^n)}$	(Mugi and Chand, 2022; Mghazli et al., 2017)
Modified Page	$\mathrm{MR} = \ \mathrm{exp}^{(\,(kt)^n)}$	(Engin and Tulek 2014; Imad, 2010a)
Modified Page II	$\mathrm{MR} = \ \mathrm{exp}^{(\,k(t/L^2)^n)}$	(Midilli et al., 2002; Wang et al., 2007)
Henderson and Pabis	$\mathrm{MR} = \ a.\mathrm{exp}^{(\,kt)}$	(César et al., 2020; Imad, 2010a)
Modified Hend. & Pabis	$\mathrm{MR} = a.\mathrm{exp}^{(\,kt)} + b.\mathrm{exp}^{(\,gt)} + c.\mathrm{exp}^{(\,ht)}$	(Atalay 2019; Saeed et al., 2008)
Simplified Fick's diffusion	$\mathrm{MR} = \ a.\mathrm{exp}^{(\,kt)} + c$	(Celma et al., 2007; Saeed et al., 2008)
Logarithmic	$\mathrm{MR} = \ a.\mathrm{exp}^{(\,c(t/L^2))}$	(Engin and Tulek 2014; Mghazli et al., 2017)
Two-term	$\mathrm{MR} = \ a.\mathrm{exp}^{(\,k_0t)} + \ b.\mathrm{exp}^{(k_1t)}$	(Saeed et al., 2008; Wang et al., 2007)
Two-term exponential	$\mathrm{MR} = \ a.\mathrm{exp}^{(\,kt)} + (1\ a).\mathrm{exp}^{(\,kat)}$	(Tarigan et al., 2007; Téllez et al., 2018)
Verma et al.	$\mathrm{MR} = \ a.\mathrm{exp}^{(\,kt)} + (1\ a).\mathrm{exp}^{(\,gt)}$	(Saeed et al., 2006; Saeed et al., 2008)
Diffusion approach	$\mathrm{MR} = \ a.\mathrm{exp}^{(\,kt)} + (1\ a).\mathrm{exp}^{(\,kbt)}$	(Mghazli et al., 2017; Wang et al, 2007)

2.1 Goodness-of-Fit Measurements

Statistical-measures are utilized to compare and evaluate the thin-layer drying-models (Table3). The quality and the performance of the fitted-models is then assessed, leading to the selection of the best-fit model based on experimental-data.

Table 3: Statistical-Parameters

Parameters	Formula	References
Coefficient of determination:	$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST}$	(Engin and Tulek 2014; Imad, 2010a)
Adjusted-R²:	$AR^2 = 1 - \frac{SSE/df_{error}}{SST/df_{total}}$	(Keller, 2001; Spatz, 2001)
Error sum of squares:	$SSE = \sum_{i=1}^{N} \left(MR_{exp,i} - MR_{cal,i}\right)^2$	(Basunia and Abe 2001a; Queiroz and Nebra, 2001)
Standard error of estimate:	$SEE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{cal,i}\right)^2}{N - np}}$	(Basunia and Abe 2001a; Saeed et al., 2008)
Reduced sum square error:	$RSSE = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{cal,i}\right)^2}{N}$	(Erenturk et al., 2004; Vega et al. 2007)
Root mean square error:	$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{cal,i}\right)^2}{N}}$	(Wang et al., 2007; Engin & Tulek 2014)
Mean sum of squares of errors:	$MSE = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{cal,i}\right)^2}{N - np}$	(Imad 2010a; Kingsly and Singh, 2007)

2.2 Drying-experiments descriptions

A Constant-Temperature & Humidity-Chamber (CTHC), as shown in Figure 1, (TH-1-180-L; JEIO-TECH, Co.-Korea), is used to conduct the thin-layer drying-experiments of the freshly harvested Cut-Roselle calyces (as depicted in Figure2). Four drying-temperatures between 35°C and 65°C, with 10degrees interval, in addition, to five relative-humidity levels between 30 and 50%, with 5% interval, are applied. Drying-air speed of 1m/s is used for the whole experiments. Before initiating the drying-experiments, the seed-capsules are taken-out, and the calyces are cut into pieces (Figure 2). The weight of the drying-samples is measured by A&D digital-balance (GR-200, 2000gr, 0.10mgr, Co.-Japan). All the experimental data are logged at an interval of 5minutes to a PC by means of data-acquisition-software (Rs.COM, Ver.,2.4). Method described by researchers in 2005 is used to find the initial/final moisture-contents (Ruiz, 2005). Dynamic-equilibrium moisture-contents are determined following procedures by (Basunia and Abe, 1999; Facade and Abbot, 2007). Dry-basis method is used in determining the moisture-contents, as this is appropriate to be used in modelling-purposes (Imad, 2010a; Togrul and Pehlivan, 2003). Furthermore, the weight is transformed into a dimensionless MR term, to account for variations in the initial-moisture-contents among different samples (Facade and Abbot, 2007; Fumagalli and Freire, 2007). Consequently, comparison between various drying experiments are done. In this study, fitting of 12 drying-models to the tests-data is carried using non-linear-regression techniques (Doymaz, 2007; Imad, 2010a; Saeed et al.,2008). While goodness-of-fit measures are used to compare the performances of these models.

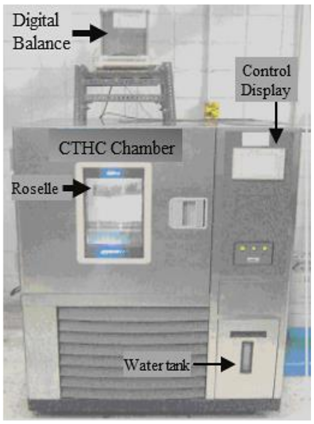

Figure 1: CTHC Chamber

Figure 2: Roselle-Plants (*L*), Cut-Roselle-Calyces (*R*)

3. RESULTS AND DISCUSSIONS

In the drying-experiments, Cut-Roselle samples (≈sixty grams) are dried from initial-moisture-contents (*IMC*), with an average of 10.0866 (*db*), to final moisture-contents (*FMC*), with an average of 0.1303 (*db*). Table4 illustrates the initial and final moisture-contents.

Table 4: IMC and FMC Moisture-Contents

RH% (%)	Temperatures(°C)							
	35		45		55		65	
	IMC	FMC	IMC	FMC	IMC	FMC	IMC	FMC
35	10.1412	0.1451	10.6463	0.1176	09.9516	0.1136	9.9286	0.1162
35	10.5434	0.1294	10.6585	0.1150	09.5034	0.1123	9.2920	0.1194
40	11.4492	0.1420	10.2459	0.1312	09.7413	0.1262	9.2131	0.1188
45	10.5221	0.1388	10.2974	0.1282	10.2127	0.1328	9.4015	0.1250
50	10.2388	0.1683	10.7421	0.1424	09.2643	0.1403	9.7377	0.1434
Aver.	10.5790	0.1447	10.5180	0.1269	09.7347	0.1250	9.5146	0.1246

3.1 Selection of the models

To evaluate the excellence of the drying-models, various criteria are considered. The drying-models are fitted to the experimental-data and their performance are evaluated using statistical-measures. The best model is the one that yield highest-values of R^2 / AR^2, and lowest errors values (MSE, SSE,SEE,RMSE,RSSE). These criteria for model selection are used to choose the best model to predict and describe the drying-performance of agriculture produce (Saeed et al.,2008; Wang et al.,2007). Average statistical-performance-measures are given in Table 5. These values are found from the fitting-process of the drying-models to the experiments-data. It's worth noting that all models showed high R^2 values (average of 0.99857) and AR^2 values (average of 0.99851), and low average values for error-parameters; namely, MSE=0.00027, SSE=0.01571, SEE=0.01378, RMSE=0.01346, and RSSE=0.00026 (Table5).

Table 5: Statistical-Measures: Drying-Models

Model	R^2	Adj_R^2	SSE	SEE	RSSE	RMSE	MSE
Newton	0.99648	0.99642	0.03850	0.02334	0.00064	0.02314	0.00065
Page	0.99901	0.99899	0.01045	0.01102	0.00017	0.01085	0.00018
Modified Page	0.99949	0.99947	0.00560	0.00945	0.00009	0.00929	0.00010
Modified Page II	0.99949	0.99946	0.00560	0.00954	0.00009	0.00929	0.00010
Henderson and Pabis	0.99805	0.99799	0.02095	0.01733	0.00035	0.01704	0.00036
Modified Hend. & Pabis	0.99876	0.99862	0.01386	0.01257	0.00023	0.01192	0.00026
Simplified Fick's diffusion	0.99876	0.99870	0.01358	0.01449	0.00023	0.01412	0.00024
Logarithmic	0.99805	0.99795	0.02142	0.01781	0.00036	0.01736	0.00038
Two-term	0.99876	0.99867	0.01398	0.01257	0.00023	0.01215	0.00025
Two-term exponential	0.99944	0.99942	0.00606	0.00965	0.00010	0.00949	0.00010
Verma et al.	0.99830	0.99821	0.01923	0.01372	0.00032	0.01337	0.00034
Diffusion approach	0.99827	0.99818	0.01934	0.01383	0.00032	0.01348	0.00034
Averages	0.99857	0.99851	0.01571	0.01378	0.00026	0.01346	0.00027

The Modified-PageII model presented the best results for R^2 (=0.99949) and AR^2 (=0.99946) out of the whole drying-models tested. It also had the lowest values for error-parameters (SSE=0.00560, SEE=0.00954, RSSE=0.00009, RMSE=0.00929, and MSE=0.00010). They are well-aligned to earlier research that supported the Modified-Page II model. For example, a study, in drying apple-pomace, found an average R^2=0.994, RMSE=0.017, and X^2 (MSE)=0.000693 (Wang et al., 2007). While Saeed et al. in their study, reported R^2=0.99931, SEE=0.011725, RMSE=0.011428, and MSE=0.000143 (Saeed et al., 2008). The statistical measures derived from fitting the experimental-data to the Modified-Page II model are given in Table 6. Furthermore, Table 7 displays the drying coefficients/constants for each of the twelve models.

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Table 6: Statistical-Measures: Modified-PageII Model

T (ºC)	RH%	R^2	Adj_R^2	SSE	SEE	RSSE	RMSE	MSE
35	30	0.99958	0.99956	0.00471	0.00909	0.00008	0.00886	0.00008
	35	0.99938	0.99935	0.00637	0.01058	0.00011	0.01031	0.00011
	40	0.99981	0.99980	0.00223	0.00626	0.00004	0.00610	0.00004
	45	0.99970	0.99968	0.00350	0.00784	0.00006	0.00764	0.00006
	50	0.99993	0.99993	0.00072	0.00354	0.00001	0.00345	0.00001
45	30	0.99961	0.99959	0.00373	0.00809	0.00006	0.00789	0.00007
	35	0.99958	0.99956	0.00438	0.00876	0.00007	0.00854	0.00008
	40	0.99938	0.99935	0.00727	0.01130	0.00012	0.01101	0.00013
	45	0.99958	0.99955	0.00407	0.00845	0.00007	0.00824	0.00007
	50	0.99971	0.99969	0.00299	0.00724	0.00005	0.00706	0.00005
55	30	0.99951	0.99949	0.00487	0.00925	0.00008	0.00901	0.00009
	35	0.99962	0.99960	0.00354	0.00788	0.00006	0.00768	0.00006
	40	0.99957	0.99955	0.00416	0.00854	0.00007	0.00832	0.00007
	45	0.99935	0.99932	0.00719	0.01123	0.00012	0.01095	0.00013
	50	0.99933	0.99930	0.00700	0.01108	0.00012	0.01080	0.00012
65	30	0.99912	0.99907	0.00971	0.01305	0.00016	0.01272	0.00017
	35	0.99959	0.99957	0.00448	0.00887	0.00007	0.00864	0.00008
	40	0.99886	0.99880	0.01477	0.01610	0.00025	0.01569	0.00026
	45	0.99951	0.99948	0.00549	0.00981	0.00009	0.00956	0.00010
	50	0.99901	0.99895	0.01076	0.01374	0.00018	0.01339	0.00019
Aver.	-	0.99949	0.99946	0.00560	0.00954	0.00009	0.00929	0.00010

Table 7: Constants & Coefficients of The Drying-Models

Model	k	k_0	k_1	n	a	b	c	g	h	l
1	0.00463	-	-		-	-	-	-	-	-
2	0.00458	-	-	0.99219	-	-	-	-	-	-
3	0.00459	-	-	0.99219	-	-	-	-	-	-
4	0.00343	-	-	0.99219	-	-	-	-	-	-0.87306
5	0.00469	-	-	-	0.98734	-	-	-	-	-
6	0.00563	-	-	-	0.37594	0.32876	0.31438	0.00618	0.00862	-
7	0.00440	-	-	-	0.99415	-	-0.00989	-	-	-
8	-	-	-	-	0.98734	-	0.00066	-	-	0.38236
9	-	0.00951	0.03868	-	0.36936	0.64933	-	-	-	-
10	0.01362	-	-	-	0.80923	-	-	-	-	-
11	0.00881	-	-	-	0.37703	-	-	0.00515	-	-
12	0.01414	-	-	-	0.36197	0.43138	-	-	-	-
Aver.	0.00685	0.00951	0.03868	0.99219	0.65779	0.46982	0.10172	0.00566	0.00862	-0.24535

3.2 Drying-Characteristics

Drying-curves for Cut-Roselle are produced by conducting twenty thin-layer drying-experiments. The objective is to investigate how Cut-Roselle behaves under various drying-conditions. These drying-curves show the material's moisture-contents vs. drying-time, under continuous/constant drying-air conditions. Figure 3 and Figure 4 display the drying-curves for Cut-Roselle in various drying-conditions. The effect of higher drying-air temperatures on drying-curves of Cut-Roselle while preserving constant-relative-humidity is evident in Figure 3. The higher the drying-air-temperatures, the more effective the drying-processes are. The results of earlier studies are consistent with this pattern (Mghazli et al., 2017; Belghit et al., 2000; Li et al., 2022; Imad, 2010b). The observed improvement is thought to be caused by the temperature increase, which increases the coefficient of heat-transfer and speeds-up the drying-processes (Methakhup et al., 2005; Tajudin et al., 2019). As Table 8 shows, the temperature at which the drying occurs had an important-influence on the drying-periods, with p-value =0.000.

Table 8: One-Way-ANOVA: Drying-times vs. Temperatures

```
Sources  DF         SS       MS       F      P
Temp      3   25701004  8567001   92.57  0.000

Error    16    1480670     92542
Total    19   27181674
S = 304.2   R-Sq = 94.55%   R-Sq(adj) = 93.53%
                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  ------+---------+---------+---------+---
35     5  3592.0  534.7                              (--*--)
45     5  1666.0  188.0             (--*--)
55     5  1021.0  184.4      (--*--)
65     5   650.0  122.1  (--*-)
                         ------+---------+---------+---------+---
                            1000      2000      3000      4000
Pooled StDev = 304.2
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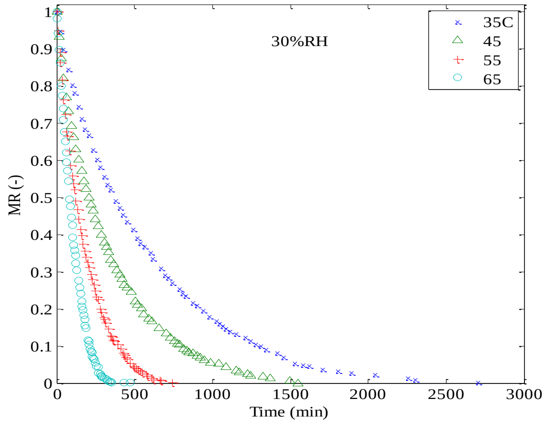

Figure 3a: MR vs drying-time (30%RH,35-65ºC)

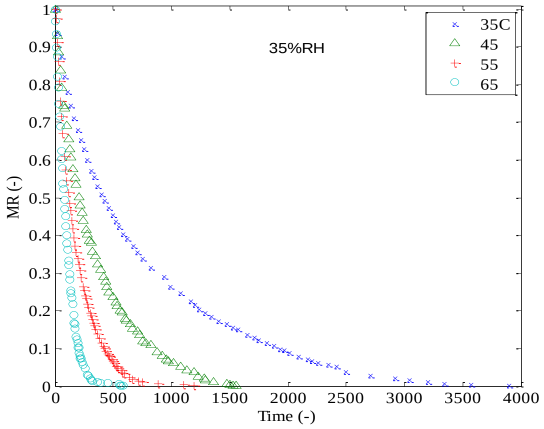

Figure 3b: MR vs drying-time (35%RH,35-65ºC)

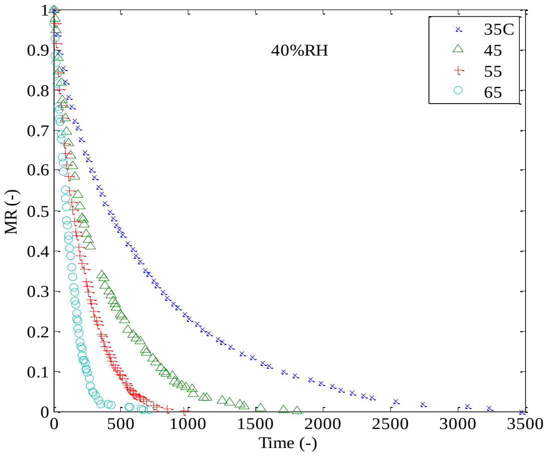

Figure 3c: MR vs drying-time (40%RH,35-65ºC)

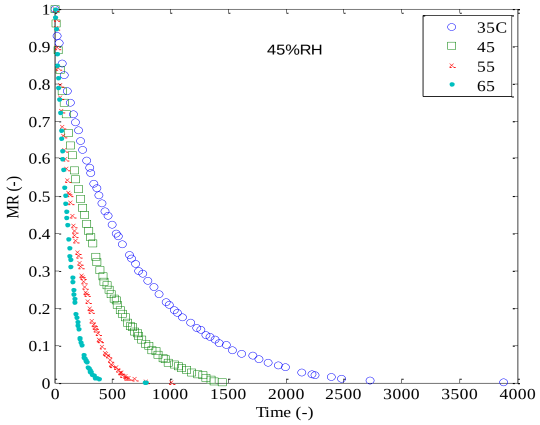

Figure 3d: MR vs drying-time (45%RH,35-65ºC)

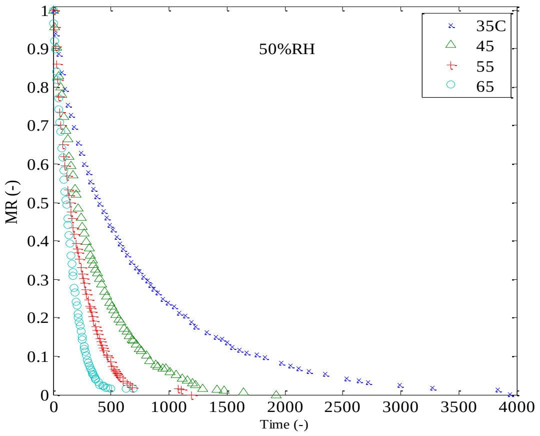

Figure 3e: MR vs drying-time (50%RH,35-65ºC)

Additionally, as the temperature rises, the disparity between saturated-vapour-pressure and partial-water vapour pressure, in drying-air increases. Given that air can only contain a finite amount of water (reaching saturation) at certain temperatures, this difference is essential for the drying-process. Furthermore, the presence of readily available free-water at the beginning of the drying-process is vital, as the water-removal rate is more pronounced during this initial-stage (Guine´et al.,2007).

Free water becomes less and less available as the drying-process is continued. Water becomes scarce in the last-stages, which causes a slow drying-process. The drying-curves of Cut-Roselle at a constant temperature are shown graphically in Figure 4, in relation to different humidity-levels. Numerous studies indicate that the influence of air-humidity on drying-process, is considerably less than the influence of the temperature of drying-air (Tarigan et al.,2007; Saeed, et al.,2008; Krokida et al.,2003;). Table 9 displays an ANOVA analysis that assesses the relationship between drying-time and relative-humidity (RH). Notably, RH had insignificant effect on the duration of the drying (p =0.978), with drying times largely, remaining consistent despite the changes in RH from 30 to 50 percent.

Table 9: One-Way-ANOVA: Times vs RH

```
Source   DF        SS       MS     F      P
RH        4    756830   189208  0.11  0.978
Error    15  26424844  1761656
Total    19  27181674
S = 1327   R-Sq = 2.78%   R-Sq(adj) = 0.00%
                       Individual 95% CIs For Mean Based on
                       Pooled StDev
Level   N  Mean  StDev  +---------+---------+---------+---------
30      4  1369   1001  (-------------*-------------)
35      4  1808   1451      (-------------*-------------)
40      4  1740   1247     (--------------*--------------)
45      4  1795   1424      (-------------*-------------)
50      4  1950   1455       (--------------*-------------)
                       +---------+---------+---------+---------
                       0       1000      2000      3000
Pooled StDev = 1327
```

Cite the Article: I.E. Saeed, Zulkhairi Zainol Abidin (2024). Environment-Controlled Thin-Layer-Drying of Cut-Roselle: Drying-Experiments,Effects of Drying-Settings, Drying-Models. *Acta Mechanica Malaysia, 7(1): 49-59.*

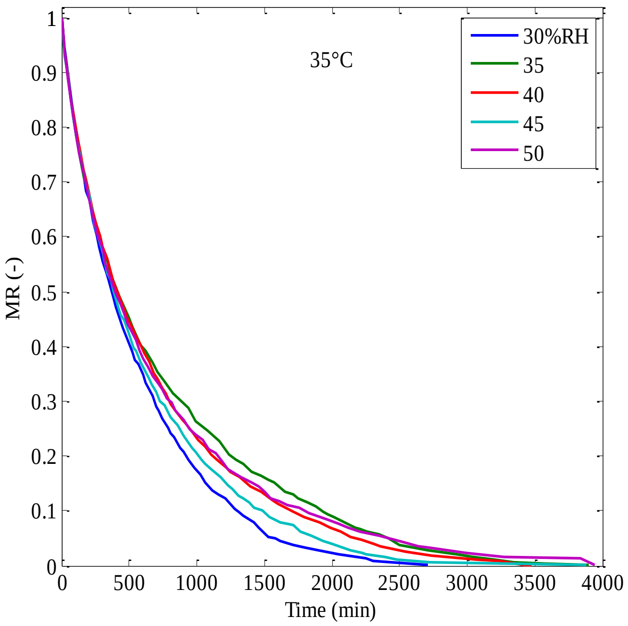

Figure 4a: Drying-curves (35ºC,30-50%RH)

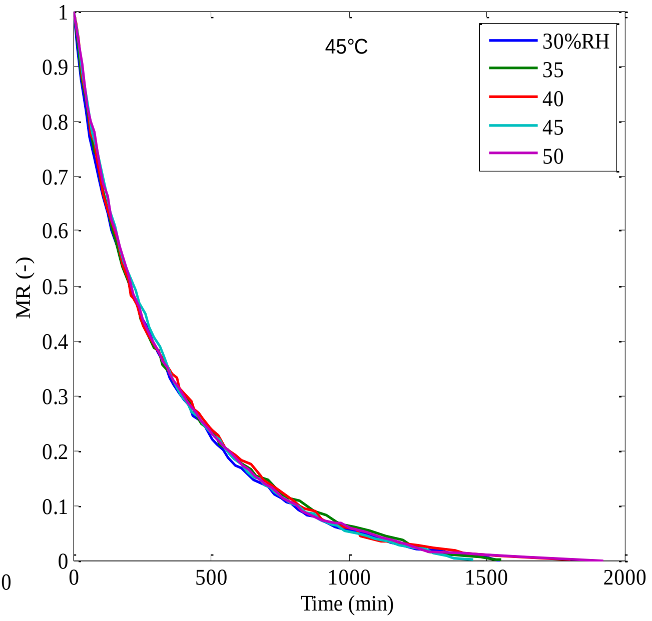

Figure 4b: Drying-curves (45ºC,30-50%RH)

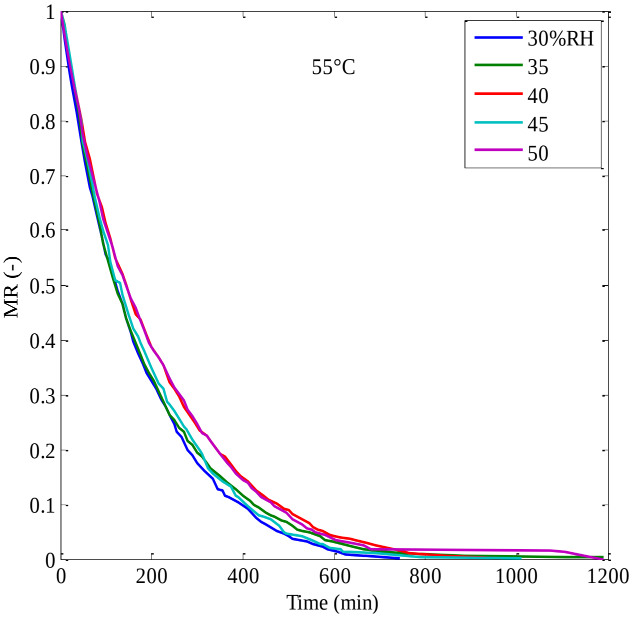

Figure 4c: Drying-curves (55ºC,30-50%RH)

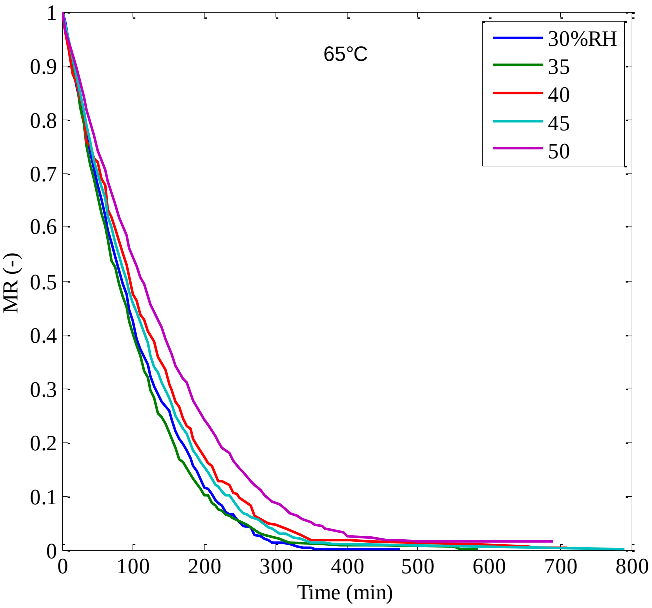

Figure 4d: Drying-curves (65ºC,30-50%RH)

When the air's humidity, during drying, is lowered (as of 50 to 30%), drying process tends to speed-up. This aligns with the findings of prior research (Saeed, et al., 2008; Krokida et al.,2003). Research by Farmer et al., stated that rising the air-humidity from 32% to 68%, when the drying temperature is 20°C, caused the drying-time for bluegrass-seeds to extend from 1.7hours to 7.3hours (Farmer et al., 1983). Additionally, researchers noted that humidity shifts impacted the constant-rate period of drying but left the falling-rate period unchanged, agreeing with other research study documented in (May et al., 1999; Saeed et al., 2008). The final moisture level of the material is greatly influenced by the drying-air's relative-humidity. As shown by researchers in 1991, this factor governs the speed at which water-vapour moves from the surface of the material to the drying-air, and also affects the material's equilibrium-moisture level (Digvi, et al., 1991). This is because, according to few studies, air with higher moisture content can hold less water compared to the drier air (Sigge et al., 1998; Fellows, 1988).

The whole drying-process for Cut-Roselle occurred exclusively through the falling-rate phase, as indicated by various studies (Nguyen and Price, 2007; Mghazli et al., 2017; Singh et al., 2008; Facade and Abbot, 2007; Imad 2010b). It suggests that diffusions are the primary physical mechanisms controlling the movement of moisture within the material (Shanmugama, and Natarajanb, 2006; Doymaz, 2007). And this process, as shown by researchers in 2008, is influenced by the moisture-content present in the drying-samples (Prachayawarakorn et al., 2008). In the process of rapid air-drying, it's generally believed that the internal-resistance of the material is the controlling factor, while resistances to mass-transfer from the outside are frequently, neglected (Kaymak-Ertekin, 2002; Singh et al., 2008). Additionally, the falling-rate-period is recognized as a typical stage in drying-process of a range of biological-substances (Tajudin et al., 2019; Karathanos, 1999; Imad 2010a, Engin and Tulek, 2014; Doymaz, 2004).

During the falling-rate phase of drying, the speed at which drying occurs is determined by the moistures concentration-gradient inside the food-substances. The internal migration of moisture, according to Nguyen and Price (2007), is driven by various factors including gradients in pressure, diffusion of liquid, movement through capillaries, and flows caused by shrinkage. The time taken to dry Cut-Roselle is significantly reduced by increasing the temperature of drying-air, which is agreed with previous researcher's results (Tajudin et al., 2019; Saeed et al., 2008). Higher temperatures result in faster evaporation, thereby reducing the drying-time necessary to reach a certain moisture content, as also noted by other studies (Vengaiah and Pandey, 2007; Saeed et al.,2008; Fumagalli and Freire, 2007). Table 10 outlines the needed drying-periods to attain certain moisture-ratios (*MR*), that indicates the completion of certain drying-process levels. For example, to attain a MR of 0.10 (which is equivalent to 90% of the drying-process), it took 3475minutes at 35°C, and 710minutes at 65°C, for drying under a relative humidity of 40%.

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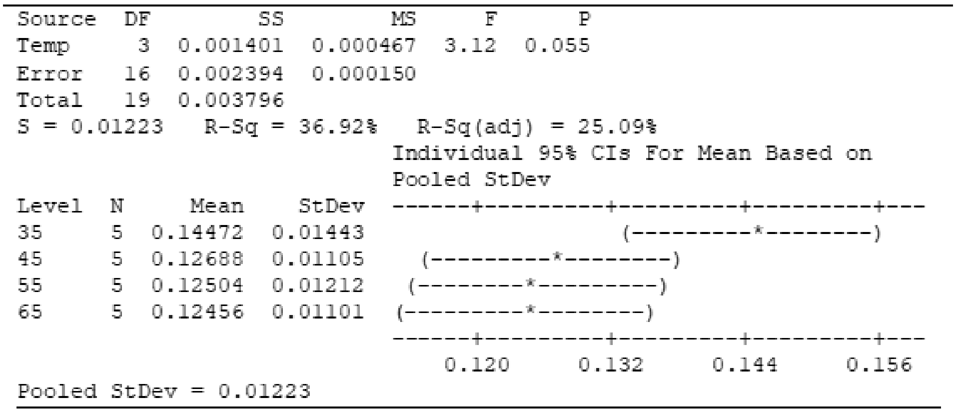
Table 10: Moisture-Ratio (*MR*) and Drying-Time

Drying Process	**MR**	**RH%**									
		30	**35**	**40**	**45**	**50**	**30**	**35**	**40**	**45**	**50**
(%)	**(-)**			**35ºC**					**45ºC**		
0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.90	45.0	45.0	45.0	50.0	45.0	25.0	25.0	30.0	30.0	35.0
50	0.50	365	420	415	385	400	210	205	200	215	215
80	0.20	920	1265	1145	1030	1145	545	560	555	575	550
90	0.10	1310	1910	1710	1515	1785	800	855	820	845	810
95	0.05	1570	2430	2185	1890	2480	1045	1075	1030	1065	1065
98	0.02	2045	3015	2740	2265	3150	1245	1280	1335	1305	1270
99	0.01	2295	3250	3160	2590	3935	1410	1355	1475	1375	1475
End	0.00	2705	3900	3475	3885	3945	1550	1555	1805	1495	1925
(%)	**(-)**			**55ºC**					**65ºC**		
0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.90	15.0	20.0	20.0	20.0	20.0	15.0	15.0	15.0	15.0	20.0
50	0.50	120	120	145	130	145	80	75	95	90	110
80	0.20	280	290	340	300	340	165	150	185	180	210
90	0.10	390	420	475	405	465	210	205	245	235	275
95	0.05	475	530	575	485	555	250	240	290	285	330
98	0.02	575	640	725	585	665	285	290	335	335	375
99	0.01	615	720	765	675	1165	320	365	560	385	425
End	0.00	745	1190	970	1010	1190	475	585	710	790	690

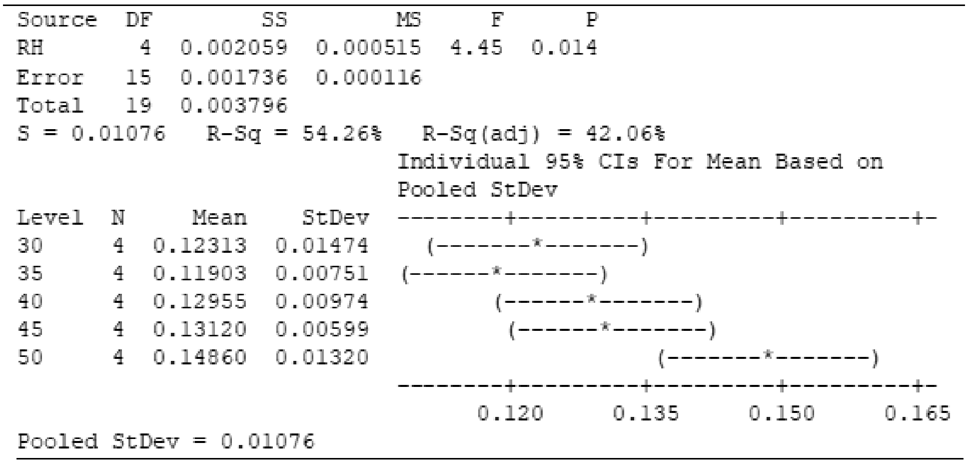
Drying of Cut-Roselle is discontinued once there's no noticeable alteration in weight with further drying. At this stage, the moisture content reaches what is known as the dynamic-equilibrium moisture-content (Togrul and Pehlivan, 2003; Saeed et al., 2008; Basunia and Abe, 2001a). The equilibrium-moisture (M_e) levels are identified through the use of the convective-oven drying approach (Cletus et al.,2008; Belghit et al., 2000; Facade and Abbot, 2007). The relationships between M_e and equilibrium-temperature (ET), and between M_e and relative-humidity (ERH) are illustrated in Figure 5. The findings show that higher-temperature of the drying-air corresponds with lower M_e ($p = 0.055$), also shortens the drying-time necessary to attain the M_e levels (Kaya, et al.2007a; Saeed et al.2006; Vergara et al., 1997; Maskan and Fahrettin, 1998). The statistical ANOVA data that show the relation between M_e and temperature is provided in Table 11. In contrast, higher-humidity level of drying-air, causes the M_e values to rise ($p = 0.014$) (Kaya et al.,2007a; Saeed et al., 2006). An ANOVA-analysis for the influences of the relative-humidity on the M_e are presented in Table 12.

Table 11: One-Way-ANOVA: M_e vs Temperatures



```
Source  DF        SS        MS     F      P
Temp     3  0.001401  0.000467  3.12  0.055
Error   16  0.002394  0.000150
Total   19  0.003796
S = 0.01223   R-Sq = 36.92%   R-Sq(adj) = 25.09%
                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level  N     Mean    StDev   ------+---------+---------+---------+---
35     5  0.14472  0.01443                   (---------*--------)
45     5  0.12688  0.01105    (---------*--------)
55     5  0.12504  0.01212   (--------*---------)
65     5  0.12456  0.01101   (---------*--------)
                             ------+---------+---------+---------+---
                                 0.120     0.132     0.144     0.156
Pooled StDev = 0.01223
```

Table 12: One-Way-ANOVA: M_e vs RH



```
Source  DF        SS        MS     F      P
RH       4  0.002059  0.000515  4.45  0.014
Error   15  0.001736  0.000116
Total   19  0.003796
S = 0.01076   R-Sq = 54.26%   R-Sq(adj) = 42.06%
                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level  N     Mean    StDev   --------+---------+---------+---------+-
30     4  0.12313  0.01474     (-------*-------)
35     4  0.11903  0.00751   (------*-------)
40     4  0.12955  0.00974          (------*-------)
45     4  0.13120  0.00599           (------*-------)
50     4  0.14860  0.01320                      (-------*-------)
                             --------+---------+---------+---------+-
                                   0.120     0.135     0.150     0.165
Pooled StDev = 0.01076
```

Generally, to obtain a lower moisture level in the final-product, it's essential for drying-air to possess a reduced relative-humidity (Coumans, 2000). Knowing the desired final moisture-content is crucial to prevent excessive-drying, which can conserve time and energy, minimize weight-reduction, and maintain product's quality. Conversely, extending drying-processes to get moisture-content lower than needed, can result in increased operational-expenses and weight-reduction, without enhancing the product's storage-safety.

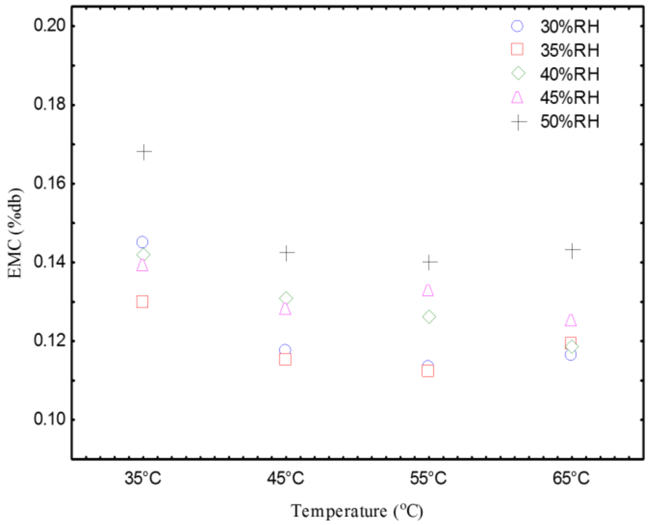


Figure 5a: M_e vs. Temperature

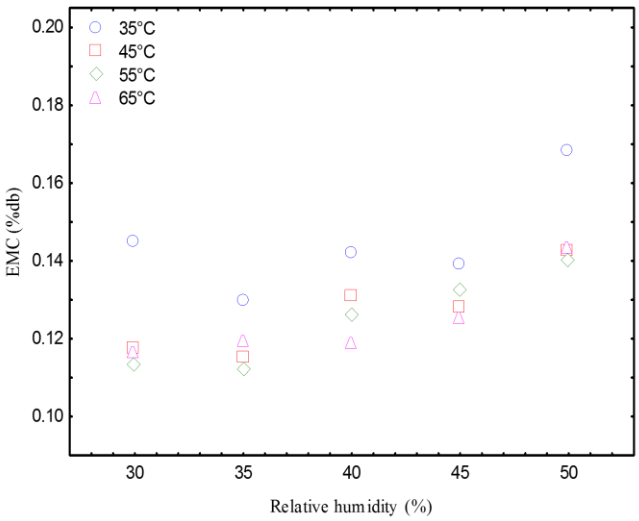


Figure 5b: M_e vs. Relative-Humidity

The alterations in structure that take place when drying are significant, and the mass-shrinkage-ratio (MSR), is a key element to consider, according to studies by Shanmugama & Natarajan,(2006),and Midilli,(2001). As given in Table 13, The calculated values of the MSR for Cut-Roselle range from 0.09173 to 0.11109. Typically, the MSR is prone to rise with an increase in relative humidity and to fall with the temperature elevation (35-65°C). Additionally, the initial-levels of moisture present in the Cut-Roselle may also have an effect on the MSR values.

Table 13: Mass-Shrinkage-Ratio (*MSR*)

Temp.	**Relative-humidity(%)**					
(°C)	**(30)**	**(35)**	**(40)**	**(45)**	**(50)**	**Aver.**
35	0.10278	0.09784	0.09173	0.09884	0.10395	0.09903
45	0.09597	0.09564	0.10058	0.09986	0.09729	0.09787
55	0.10168	0.10590	0.10485	0.10103	0.11109	0.10491
65	0.10214	0.10877	0.10954	0.10816	0.10648	0.10702
Aver.	0.10064	0.10204	0.10168	0.10197	0.10470	0.10221

Based on the findings, statistical analysis, and correlations, general-equations can be formulated for each of the tested drying-model, as outlined in Table 14. These equations can describe the relationship between the moisture-content of the drying-material (MR) and the drying-time (t), at any point during the drying-process.

Table 14: General-Equation For Drying-Models

Models-names	**Equations.**	**R^2**
Newton	$MR = exp(-0.00463t)$	0.99648
Page	$MR = exp(-0.00458\ t^{0.99219})$	0.99901
Modified-Page	$MR = exp(-(0.00459t)^{0.99219})$	0.99949
Modified-Page-II	$MR = exp(-0.00343(t\ /-0.87306^{2})^{0.99219})$	0.99949
Henderson and Pabis	$MR = 0.98734\ exp(-0.00469t)$	0.99805
Modified Hend. &Pabis	$MR = 0.37594\ exp(-0.00563t)+0.32876\ exp(-0.00618t)+0.31438\ exp(-0.00862t)$	0.99876
Simplified Fick's diffusion	$MR = 0.99415\ exp(-0.00440t)+(-0.00989)$	0.99876
Logarithmic	$MR = 0.98734\ exp(-0.00066(t/0.38236^{2}))$	0.99805
Two-term	$MR = 0.36936\ exp(-0.00951t)+ 0.64933\ \mathrm{exp}(0.03868t)$	0.99876
Two-term exponential	$MR = 0.80923\ exp(-0.01362t)+(1-0.80923)exp(-0.01362*0.80923t)$	0.99944
Verma et al.	$MR = 0.37703\ exp(-0.00881t)+(1-0.37703)exp(-0.00515t)$	0.99830
Diffusion-approach	$MR = 0.36197\ exp(-0.01414t)+(1-0.36197)exp(-0.014140.43138t)$	0.99827

4. CONCLUSIONS

This research examines the dehydration of fresh Cut-Roselle calyces, which is found to occur particularly, during the falling-rate phase. Initially, the calyces with an average moisture-level of 10.0866db, is reduced to 0.1303db, after the drying-process. The study found that, the temperature level of the drying-air, significantly, impacted the drying-rates of the Cut-Roselle, with a p-value of 0.00, indicating strong influences. Higher temperatures led to a faster drying-time for the Cut-Roselle. Moreover, lowering the relative-humidity level of drying-air, also enhanced the drying process, although the influence is less evident, with a p-value of 0.978. The equilibrium-moisture-content is also affected by changes in both the drying-air temperature and humidity, with p-values of 0.055 and 0.014, respectively. The average amount calculated for mass-shrinkage-ratio is 0.10221. Out of 12 evaluated models, the Modified-Page model II is found the most accurate in describing the drying-behavior of the Cut-Roselle, as evidenced by the highest R^2 and AR^2 values, and lowest errors-values, signifying its efficacy within the experimental-conditions.

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