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# MODELLING OF THIN-LAYER DRYING OF OSMO-PRETREATED RED BELL PEPPER

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The paper observes a thin-layer drying behaviour of red bell pepper. The red bell pepper (192 samples) was pretreated in osmotic solution of salt of concentrations 5–20% (w/w) at osmotic solution temperatures (30–60 °C) and osmotic process durations (30–120 min) and dried at 60 °C in a locally fabricated convective dryer after preformation of osmotic dehydration pretreatment process. Experimental moisture content values obtained from the drying process were converted to moisture ratios. Seven existing thin-layer drying model equations were used for model equation fitting. The predicted and experimental (observed) moisture ratios were analysed statistically. The statistical indices and rules used to judge and select the model equation that would best describe the process were the highest values of coefficient of determination ($R^2$); the lowest values of chi-square ($\chi^2$), root mean square error (RMSE), and sum of squares error (SSE). Results showed that the two-term exponential model equation best described the drying behaviour of osmo-pretreated red bell pepper. The ranges of statistical indices of selected two-term exponential model equation are: $R^2$ (0.9389–0.9751), $\chi^2$ (0.0642–0.1503), RMSE (0.2032–0.1668), and SSE (0.6424–1.5027).

**Keywords:** osmotic dehydration; model fitting; model selection; hypertonic solution; vegetable

The red bell pepper (*Capsicum annuum*) is a fruit vegetable, which is rich in terms of nutritional and medicinal properties (Wallace et al., 2020; Slavin and Lloyd, 2012). Unfortunately, approx. 20–30% of it (and other kinds of peppers) are lost yearly during the post-harvest stage (Okunoya, 1996). One of the ways of curtailing the incidence of post-harvest losses and ensuring all year-round supply of red bell pepper is to subject it to appropriate pretreatments and efficient moisture reduction via drying.

Osmotic dehydration is one of the methods for pretreating foods, especially fruits and vegetables. It is a simultaneous movement of liquid out of a product and corresponding movement of solute into the product in a counter-current manner when the product is immersed in osmotic solution (Yadav and Singh, 2014; Tortoe, 2010). Furthermore, osmotic dehydration is the partial removal of water by direct contact of a product with a hypertonic medium, i.e. high concentration of sugar or salt solutions (Ozen et al., 2002). It is one of the simpler and more economical methods of extending the shelf life of perishable products, and it preserves the colour, flavour, and texture of foods that would be affected by heat, thereby improving the nutritional, sensory and functional characteristics of foods (Singh et al., 2006).

Drying is a simultaneous heat and mass transfer process, which is achieved by the removal of enough or predetermined moisture from food and other biological materials. The objectives of drying are the prevention of decay and spoilage of food; extension of shelf life; reduction of costs of storage, handling and transportation; and improvement of quality. There is a need for promotion of drying of fruits and vegetables in order to ensure their all-year-round supply (Kiremire et al., 2010). The best temperature range for drying fruits and vegetables was reported to be 35–75 °C (Idah et al., 2011; Phisut, 2012; Mu'azu et al., 2012).

In terms of thickness of products to be dried, drying method can be classified as either a thin layer, or deep bed. In thin-layer drying, products with approx. 15–20 cm thickness are fully exposed to drying air and drying conditions are assumed to be constant.However, in deep bed drying, product thickness exceeds 20 cm and can reach up to 45 cm (Kumar et al., 2012). Moreover, products are not exposed to the same drying conditions, which leads to formation of drying zones along the drying products. One of the relationships between the thin-layer drying and deep-bed drying is that a deep bed drying analysis is performed by taking a small part of a product undergoing deep bed drying to form a thin layer. The thin layer formed would then be subjected to numerical integration procedures along the whole dimension of the product undergoing deep bed drying. Ojediran and Raji (2010) and Raji et al. (2010) reported numerous studies on thin-layer drying of food and other agricultural products. Existing mathematical models such as Henderson and Pabis, Page, Modified Page (I and II), Thomson, Newton, and Wang and Singh have been frequently used (and are still in use) to describe the drying characteristic of certain products under thin-layer drying conditions (Ojediran and Raji, 2010). Vitázek and Havelka (2013, 2014) studied the sorption isotherms

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of agricultural products with the use of Henderson model equation. Seiiedlou et al. (2010), Faisal et al. (2013), Ojediran and Raji (2010, 2011), Ademiluyi and Abowei (2013), and Awogbemi and Ogunleye (2009) described the thin-layer drying modelling of different products. Most frequently, the indices used to evaluate and select the best models in terms of deviation between predicted values (by existing models) and observed (experimental) values were the coefficient of determination ($R^2$), chi-square value ($\chi^2$), root mean square error (RMSE), and sum of square error (SSE) statistics.

Although there exist several published works on pretreatment and drying of peppers (including red bell pepper) to different value-added products (Arslan and Ozcan, 2011; Bareh et al., 2012; Osunde and Makama-Musa, 2007; Odewole and Olaniyan, 2016; Tunde-Akintunde et al., 2011; Chaethong et al., 2012; Famurewa et al., 2006); however, attention has not really been focused on the thin-layer drying behaviour of osmo-pretreated red bell pepper. Therefore, the objective of this study was to establish the thin-layer drying model(s) that would best describe the drying behaviour of osmo-pretreated red bell pepper. The established model(s) would help to have better understanding of the process in terms of reliable prediction and estimation, system and process design, analysis, and simulation for industrial scaling up of the process in the future.

## Material and methods

### Experimental materials

Red bell pepper fruits (87% wb), common salt (NaCl) and distilled water were the major materials used for the osmotic dehydration pretreatment process. The equipment used included two water baths (HH-W420, XMTD-204 model and SL Shell Lab model), Genlab electric oven, electronic weighing balance (OHAUS 3001, capacity: 3,000 g; readability: 0.1 g; stabilization time: 3 sec) and desiccators and a locally fabricated convective dryer (Odewole and Olaniyan, 2016). The dryer basically consists of drying chamber, heating chamber and blower. The external dimensions of dryer are 56 × 56 × 86 cm, while the internal dimensions are 50 × 50 × 80 cm. Its drying chamber has three perforated trays 15 cm apart. The heating chamber is of pyramidal shape and equipped with electrical heating coil of 1.8 kW, which is directly positioned in front of the blower for faster heat circulation. The blower rated power is 373 W.

### Osmotic dehydration process

The red bell pepper fruits were deseeded after washing and manually cut into pieces to a width of approx. 3 mm using a prefabricated stainless-steel knife, and this width was maintained for all samples. The cutting was performed in order to enhance the exposure of samples to the osmotic solution. After cutting, 50 g of the red bell pepper was measured with the electronic weighing balance and used as the experimental quantity. The experimental design used was 43 factorial experiment in a randomized complete block design with three replicates, which resulted in 192 experimental runs in total.All samples were subjected to osmotic dehydration pretreatment process in hypertonic salt (NaCl) solution of four different concentrations – 5, 10, 15 and 20% (w/w), in two water baths set to four osmotic solution temperatures (30, 40, 50 and 60 °C), and left for 60-, 90-, 120- and 150-min osmotic process durations, respectively. The ratio of osmotic solution to mass of red bell pepper was 4 : 1.

### Pre-drying and drying of osmo-pretreated samples

After the osmotic dehydration pretreatment process, all pretreated samples were left under a running fan for approx. 20 min. This was conducted in order to get rid of surface water that can unnecessarily prolong the drying time. Subsequently, all osmo-pretreated samples were re-weighed using the electronic weighing balance. There was observed a reduction in mass of each sample to 40–30 g from the initial 50 g used for osmotic dehydration pretreatment. This confirmed that the osmotic dehydration took place. All samples were dried inside the fabricated convective dryer at 60 °C. The mass values of samples were recorded hourly using the electronic weighing balance until effective drying of all samples was achieved at an average moisture content of 10% (wb). The average drying time was seven hours. The data obtained (mass of samples during drying) were used to estimate the moisture content values using the procedures similar to the one in Sunmonu et al. (2018), as briefly stated below: a clean crucible was first dried in oven for approx. 30 min and then cooled in a desiccator. Cooled crucible was weighed as ($W1$) using an analytical balance. Weighed quantity of about 5 g of cut red bell pepper was then introduced into the previously dried and weighed crucible and weighed as ($W2$) before drying. This was placed in an electric oven, which was set to 105 °C for approx. 3 hours. The crucible with dried red bell pepper was then removed from the oven and immediately cooled in a desiccator and then weighed as ($W3$). The moisture content of samples was estimated as follows:

$$M\ (\%) = \frac{W2 - W3}{W2 - W1} \cdot 100 \tag{1}$$

where:
$M$ – moisture content (wet basis) at time ($t$)
$W1$ – weight of clean crucible (g)
$W2$ – weight of clean crucible plus sample (g)
$W3$ – weight of clean crucible plus dried sample (g)
$W2 - W3$ – total loss in weight (g)
$W2 - W1$ – weight of sample (g)

The average room temperature and relative humidity were approx. 30 °C and 65%, respectively.

### Model fitting and model selection

The moisture content values initially obtained from the experiment after estimation were converted to moisture ratio values using Eq. 2. This was in line with the approach adopted in Ojediran and Raji (2010).

$$MR = \frac{M - M_e}{M_o - M_e} \tag{2}$$

where:
$MR$ – moisture ratio
$M$ – moisture content at time ($t$)
$M_o$ – initial moisture content of the sample
$M_e$ – equilibrium moisture content

The conversion of moisture content to moisture ratio was conducted to make the experimental data conform to the terms of all selected seven existing thin-layer drying model equations used for model fitting (Table 1). Each equation was linearized and solved with the use of EXCEL 2016 spread sheet in order to get all the statistical indices ($R^2$, $\chi^2$, SSE and RMSE) needed to judge and select the equations that would best describe the thin-layer drying behaviour of the product. The data analysis was primarily based on the differences between predicted data (moisture ratio) by the models and the observed (experimental) data obtained from the experiment. Ranking and selection of the best models were carried out on the basis of highest $R^2$ values and lowest $\chi^2$, SSE and RMSE values.

### Model equation solution

Selected model equation that best described the process characteristics was solved in order to simplify it. The solution was performed by first substituting the values of coefficients and constants obtained at osmotic solution temperatures 30, 40, 50 and 60 °C into the selected model equation. This was followed by manual analytical style of solving mathematical equation until simplest forms of equations were obtained.

## Results and discussion

### Model performance and selection

Performance results of all seven models at each osmotic solution temperature are presented in Tables 2, 3, 4 and 5. The existing thin-layer drying model that best described the behaviour of dried osmo-pretreated red bell pepper is the one with "1st" notation under the rank column. Considering all the osmotic solution temperatures used for the pretreatment (30, 40, 50 and 60 °C), the two-term exponential model best described the behaviour of red bell pepper at drying temperature of 60 °C. Similarly, Newton model took the second position (2nd) in terms of ranking and it is thus considered the second best. The reason for different ranking of the models can be caused by different terms and number of coefficients of the terms of each model. This might have consequential impact on the numerical values of statistical indices used for adjudging the models. Furthermore, another reason might be due to the fact that several existing models had initially certain shortcomings before they were later improved. The latter statement is in agreement with Ojediran and Raji (2010), who reported that Page model was modified to correct some of the shortcomings of Henderson and Pabis model. Ojediran and Raji (2011) used the five thin-layer drying models to study the drying pattern of castor seed (*Ricinus communis*); modified Page model was reported to be the best model equation for description of the seed drying pattern. Seiiedlou et al. (2010) carried out the mathematical modelling of apple slices under

**Table 1** Seven selected existing thin-layer drying model equations

| SN | Model equation | Model name | Model code |
|---|---|---|---|
| 1 | $MR = \exp(-kt)$ | Newton | M1 |
| 2 | $MR = \exp(-kt^n)$ | Page | M2 |
| 3 | $MR = a\exp(-kt)$ | Henderson and Pabis | M3 |
| 4 | $MR = 1 + at + bt^2$ | Wang and Singh | M4 |
| 5 | $MR = a\exp(-kt) + b$ | logarithmic | M5 |
| 6 | $MR = a\exp(-kt^n) + bt$ | Midilli | M6 |
| 7 | $MR = a\exp(-kt) + (1 - a)\exp(-kat)$ | two-term exponential | M7 |

$MR$ – moisture ratio, $t$ – drying time; $a$, $b$, $n$, $k$ – model constants and coefficients

**Table 2** Model performance for 30 °C osmotic solution temperature

| Models | $R^2$ | $\chi^2$ | RMSE | SSE | Coefficients | | | | Rank |
|---|---|---|---|---|---|---|---|---|---|
| M1 | 0.9738 | 0.0781 | 0.1818 | 0.8590 | $k = 0.0815$ | | | | 2nd |
| M2 | 0.9432 | 0.1374 | 0.2299 | 1.3739 | $k = 0.0063$ | $n = 1.053$ | | | 6th |
| M3 | 0.9696 | 0.0986 | 0.1947 | 0.9861 | $k = 0.0967$ | $a = 1.0529$ | | | 4th |
| M4 | 0.9834 | 0.1149 | 0.2102 | 1.1486 | $a = -0.0615$ | $b = 1.0413$ | | | 5th |
| M5 | 0.9696 | 0.1059 | 0.1915 | 0.9531 | $k = 0.0967$ | $a = 1.037$ | $b = 0.0099$ | | 3rd |
| M6 | 0.9441 | 0.1720 | 0.2300 | 1.3756 | $k = 0.0065$ | $a = 0.0868$ | $b = 0.9621$ | $n = 0.1066$ | 7th |
| M7 | 0.9690 | 0.0723 | 0.1668 | 0.7231 | $k = 0.1037$ | $a = 0.0012$ | | | 1st |

**Table 3** Model performance for 40 °C osmotic solution temperature

| Models | $R^2$ | $\chi^2$ | RMSE | SSE | Coefficients | | | | Rank |
|---|---|---|---|---|---|---|---|---|---|
| **M1** | 0.9447 | 0.0659 | 0.1670 | 0.7251 | $k = 0.0859$ | | | | 2nd |
| **M2** | 0.9972 | 0.0936 | 0.1897 | 0.9359 | $k = 0.0189$ | $n = 1.6609$ | | | 5th |
| **M3** | 0.9393 | 0.0761 | 0.1711 | 0.7614 | $k = 0.0966$ | $a = 1.0985$ | | | 4th |
| **M4** | 0.9682 | 0.1034 | 0.1995 | 1.0343 | $a = -0.0611$ | $b = 0.0009$ | | | 7th |
| **M5** | 0.9393 | 0.0807 | 0.1671 | 0.7263 | $k = 0.0966$ | $a = 1.1701$ | $b = -0.0651$ | | 2nd |
| **M6** | 0.9969 | 0.1177 | 0.1903 | 0.9414 | $k = 0.0152$ | $a = 0.9769$ | $b = -0.0002$ | $n = 1.7470$ | 6th |
| **M7** | 0.9389 | 0.0642 | 0.1572 | 0.6424 | $k = 0.0992$ | $a = 0.8697$ | | | 1st |

**Table 4** Model performance for 50 °C osmotic solution temperature

| Models | $R^2$ | $\chi^2$ | RMSE | SSE | Coefficients | | | | Rank |
|---|---|---|---|---|---|---|---|---|---|
| **M1** | 0.9760 | 0.1012 | 0.2069 | 1.1134 | $k = 0.0711$ | | | | 2nd |
| **M2** | 0.9766 | 0.1467 | 0.2375 | 1.4669 | $k = 0.0218$ | $n = 1.4862$ | | | 6th |
| **M3** | 0.9751 | 0.1217 | 0.2164 | 1.2170 | $k = 0.0759$ | $a = 1.0699$ | | | 4th |
| **M4** | 0.9806 | 0.1390 | 0.2312 | 1.3903 | $a = -0.0553$ | $b = 0.0007$ | | | 5th |
| **M5** | 0.9753 | 0.1309 | 0.2129 | 1.1780 | $k = 0.0751$ | $a = 1.1542$ | $b = -0.0807$ | | 3rd |
| **M6** | 0.9704 | 0.1861 | 0.2393 | 1.4891 | $k = 0.0172$ | $a = 0.9662$ | $b = 0.0008$ | $n = 1.5399$ | 7th |
| **M7** | 0.9751 | 0.1073 | 0.2032 | 1.0731 | $k = 0.0772$ | $a = 0.8976$ | | | 1st |

**Table 5** Model performance for 60 °C osmotic solution temperature

| Models | $R^2$ | $\chi^2$ | RMSE | SSE | Coefficients | | | | Rank |
|---|---|---|---|---|---|---|---|---|---|
| **M1** | 0.9782 | 0.1427 | 0.2457 | 1.5692 | $k = 0.0546$ | | | | 2nd |
| **M2** | 0.8912 | 0.2758 | 0.3257 | 2.7578 | $k = 0.0018$ | $n = 2.2680$ | | | 7th |
| **M3** | 0.9770 | 0.1963 | 0.2747 | 1.9626 | $k = 0.0624$ | $a = 1.1479$ | | | 4th |
| **M4** | 0.9813 | 0.1740 | 0.2587 | 1.7404 | $a = -0.0478$ | $b = 0.0006$ | | | 3rd |
| **M5** | 0.9780 | 0.2181 | 0.2744 | 1.9632 | $k = 0.0557$ | $a = 1.2936$ | $b = -0.1501$ | | 5th |
| **M6** | 0.8615 | 0.3398 | 0.3233 | 2.7183 | $k = 0.0008$ | $a = 0.9582$ | $b = -0.0004$ | $n = 2.5436$ | 6th |
| **M7** | 0.9768 | 0.1503 | 0.2404 | 1.5027 | $k = 0.0669$ | $a = 0.7878$ | | | 1st |

convective drying; out of approx. ten model equations used, the model equation presented in Aghbashlo et al. (2009) best described the drying behaviour of product. Faisal et al. (2013) reported that Midilli model best described the drying characteristics of pretreated potato cubes dried at the maximum temperature of 80 °C, as well as thin layer drying of cassava slices in a convective dryer (Dairo et al., 2015). Furthermore, Ojediran and Raji (2010) concluded that modified Page and Page models best described the drying characteristics of EX-BORNO and SOSAT C88 millets, respectively, at drying temperature range of 30–70 °C.

## Solution and simplification of selected model equation

Table 6 presents different solutions of the selected two-term exponential model equation (coded M7 in Tables 2–5). The equations obtained after the solution are simplified for ease of use and for faster execution of computation.

**Table 6** Solutions of the two-term exponential model equation

| Osmotic solution temperature | a | k | MR = aexp(-kt) + (1 – a)exp(-kat): M7 (two-term exponential model equation) |
|---|---|---|---|
| 30 °C | 0.0012 | 0.1037 | MR = 0.0012(0.9015t) + 0.9988(0.9999t) |
| 40 °C | 0.8697 | 0.0992 | MR = 0.8697(0.9056t) + 0.1303(0.9173t) |
| 50 °C | 0.8976 | 0.0772 | MR = 0.8976(0.9257t) + 0.1024(0.9330t) |
| 60 °C | 0.7878 | 0.0669 | MR = 0.7878(0.9353t) + 0.2122(0.9487t) |

## Conclusion

The drying behaviour of osmo-pretreated red bell pepper using seven existing thin-layer drying models was studied. The two-term exponential model best described the drying behaviour of the product in osmotic solution temperature range of 30–60 °C and drying air temperature of 60 °C. The solved two-term exponential model equations can be used to predict and estimate the moisture ratios and drying times of red bell pepper pretreated in osmotic solution temperatures ranging from 30 °C to 60 °C. Moreover, these solutions can serve as useful tools for optimizing and simulating the food processing operations with a view to upscaling it to industrial level, as well in designing efficient dryers needed for the process. Values obtained for other models that were not selected can be also used as reference and guide for other similar studies in future.

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