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Mathematical Modeling of Conductive, Convective and Irradiative Drying of Cereal Based Baby Foods

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ABSTRACT

The influence of three different drying methods (conductive, convective and irradiative) on the behavior of three wet baby food mixtures during drying was studied. Conductive drying experiment was performed at drum dryer (steam pressure 6 bars; dryer velocity 7 rpm; material thickness 0.0002 m), convective drying experiment was conducted in tunnel dryer (drying temperatures 60 °C, 80 °C, 100 °C; air velocities 0.5 m/s, 1.0 m/s, 1.5 m/s; material thickness 0.005 m) and irradiative drying experiment was carried out in infrared dryer (drying temperatures 60 °C, 80 °C and 100 °C; material thickness 0.0017 m). Drying behavior of all materials was the best described by Page's mathematical model.

KEYWORDS: baby food, drum drying, infrared drying, modeling, Page's model, tunnel drying

Nomenclature

a, b, n	**drying coefficients**	*T*	**drying temperature (°C)**
K	**drying constant (1/s)**	*t*	**time (s)**
M	**moisture content (kg/kg, dry basis)**	*u*	**drum dryer velocity (rotation per minute)**
M_i	**initial moisture content (kg/kg, dry basis)**	*v*	**air velocity (m/s)**
MBE	**mean bias error**	*Y*	**dimensionless moisture content**
p	**steam pressure (bar)**	*z*	**number of parameters**
R^2	**correlation coefficient**	χ^2	**reduced chi-square**
RMSE	**root mean square error**		

1. INTRODUCTION

Traditionally dehydrated baby food can be produced using various techniques like spray drying and drum drying [1]. Products produced in these ways have very low moisture content (2 to 5%, wet basis) [1], minimizing postproduction microbial activity. Each drying process should be conducted under controlled conditions producing a dried product of desired quality at minimum cost and maximum throughput [2]. Since the components added into the wet mixtures of baby foods before drying are valuable and very expensive, their preservation during the production of baby food is of high importance. In order to achieve high production standards selection of the eligible drying method and affiliated process conditions play crucial role. Hence, selecting suitable drying method for baby food drying is very important and directly influences the quality of the end product.

The drying kinetics of food is a complex phenomenon and requires simple representations to predict the drying behavior and to optimize the drying parameters [3]. Drying kinetics is important in the analysis of moisture migration process in a solid material [4]. From the analysis of drying kinetics is possible to determine many thermo-physical and transport properties of food materials that are integrated in drying model [5]. Study on drying kinetics may allow understanding of the controlling mechanism during drying and hence influence of drying parameters on dryer design and dried product quality can be determined [4].

To describe completely the drying kinetics many transport properties like moisture diffusivity, thermal conductivity, interface heat and mass transfer coefficients should be determined [5]. Recording the moisture loss and material temperature during the drying experiment enables the calculation of mass and heat transport properties like Biot number, mass transfer coefficient, moisture diffusion coefficient and heat transfer coefficient. Jurendić and Tripalo [1] presented a way of determination of mass transport properties for different baby foods in drying process.

Mathematical modeling seems to be the first step in characterization of drying processes. Data obtained from mathematical models can be used for the conduction of further analysis (the calculation of transport properties and resistances, the parameter estimation for process design and the definition of crucial variables for the process control).

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Importance of mathematical models can be further depicted in containing very useful drying constant *K*. In the drying of food materials instead of the above mentioned transport properties the drying constant *K* can be used [6], which describes and combines all transport properties becoming the most important parameter in thin layer drying models. Knowing the *K* values, which should be obtained empirically, is possible not only to determine transport properties of the material but also bring into relation all process conditions (temperature, velocity, relative humidity, etc) and express *K* as a function of these parameters and variables.

Many mathematical models have been used to describe the drying processes, but thin layer models are the most common models used nowadays [7, 8] which can be also utilized to predict the drying time [9]. These models can be delineated as theoretical, semi-empirical and empirical.

It is therefore of high importance to describe the drying behavior of dried materials with an appropriate mathematical model and then using the drying constant *K* from the best fitting model obtain information about material transport properties.

Drum dryers (conductive dryers) are used in the food industry for drying a variety of products, such as milk product, baby foods, breakfast cereals, fruit and vegetable pulp, mashed potatoes, cooked starch, and spent yeast [10]. Thus, drum dryers are conduction dryers, the drying effect being obtained by the transfer of heat from the condensing steam inside the drums to the film of material covering their external surface [11]. Theoretical modeling of drum drying is very important for design, optimization and control of drum dryers [11]. Many researchers reported about drying of starch on drum dryer [12, 13, 14], but no literature data are available about drying behavior of cereal based baby food. For convective (tunnel) and irradiative (infrared) drying of food materials many data exist in literature, but also no data in respect to drying behavior of baby food on cereal basis can be found.

The objectives of this work were to investigate the influence of conductive, convective and irradiative drying methods on the drying behavior of three wet baby food mixtures and to propose the most suitable mathematical model for the drying curves.

2. MATERIALS AND METHODS

2.1. Materials

Three different baby food wet mixtures were dried on the drum dryer, in the tunnel dryer and infrared dryer.
Mixture 1 consists of water, wheat flour (30 %), sugar (8%), corn starch and vitamins, mixture 2 consists of water, wheat flour (25 %), soya flour, milk powder, sugar (4%) and vitamin mixture and components of mixture 3 are water, corn flour (37 %), powdered sugar (3%), vitamins and mineral mixture. All percentages are given on wet basis. Table 1 shows the chemical analysis of wet mixtures 1, 2 and 3. The initial moisture content was determined by the AOAC method no. 930.15 [15].

Table 1 Chemical composition of mixtures 1, 2 and 3 before drying in % (wet basis)

Mixture	Water	Protein	Carbohydrates	Fat	Ash
1	56	3.5	38.9	0.53	0.15
2	61	6.3	27	4.76	0.79
3	65	2.7	30.2	0.89	0.25

2.2. Experiments

Experiment 1 was conducted on the drum dryer (E 15/30, Goudsche Machinefabriek B.V, Waddinxveen, Holland). Steam pressure was 6 bars and drum dryer velocity 7 rpm (rotation per minute) during drying of all mixtures. The part of revolution of drum dryer, where material (thickness 0.0002 m) is applied was divided into 43 equidistant points around the drum dryer where point 1 is on the beginning (application of wet material) and point 43 on the end (knife) of drying. In each point around the drum dryer 2 ± 0.1 g of applied material was removed with knife, placed into aluminum trays and dried in infrared dryer (model LJ16, Mettler Toledo, Switzerland) in order to estimate the moisture content. Drying was continued until moisture content loss was less than 0.01 g in three consecutive measurements.

Experiment 2 was conducted in a pilot-plant tunnel dryer designed and manufactured at Faculty of Food Technology and Biotechnology in Zagreb, Croatia [1]. The dryer consist of a tunnel, electrical heater and fan and is equipped with controllers for air temperature, air velocity and material temperature. 50 ± 0.1 g of wet mixtures were prepared 30 minutes before drying. To conduct the drying experiments at 60 °C, 80 °C and 100 °C (±1°C) and air velocity 0.5, 1.0 and 1.5 m/s, the humid mixtures (thickness 0.005 m) were placed into aluminum trays (size: 100 mm in diameter and 5 mm high). The moisture loss was recorded in 1 min. intervals for 1 hour and later in 5 min. intervals until the end of drying by a digital balance of 0.01 g accuracy (model PB602-L, Mettler Toledo, Switzerland).

Drying was continued until moisture content loss was less than 0.01 g in three consecutive measurements.

Experiment 3 was conducted in infrared dryer (model LJ16, Mettler Toledo, Switzerland). 20 ± 0.1 g of samples were prepared 30 minutes before drying. To conduct the drying experiments at 60 °C, 80 °C and 100 °C the wet mixtures (thickness 0.0017 m) were placed into aluminum trays (size: diameter 100 mm in diameter and 5 mm high). Moisture loss was recorded in 1 min. intervals until the variation in the moisture content loss was less than 0.01 g during three measurements. The mean values were taken to conduct further analysis.

2.3. DATA ANALYSIS

The experimental data were non-dimensionalized using equation [3, 16, 17, 18]:

$$Y = \frac{M}{M_i} \quad (1)$$

Table 2 Mathematical models used to describe the drying kinetics

Name	Model
Newton	$Y = \exp(-Kt)$
Page	$Y = \exp(-Kt^n)$
Henderson Pabis	$Y = a\exp(-Kt)$
Logarithmic	$Y = a\exp(-Kt) + b$
Diffusion Approach	$Y = a\exp(-Kt) + (1-a)\exp(-Kbt)$

Drying curves were fitted with five thin layer drying models (Table 2) to find a suitable model for describing the drying behavior of mixtures 1, 2 and 3. The goodness of fit was determined using four statistical parameters such as, coefficient of correlation R^2, chi-square χ^2, mean bias error *MBE*, and root mean square error *RMSE*, where R^2 value should be higher and χ^2, *MBE* and *RMSE* values should be lower [3, 4]. Regression analysis was performed by *Statistica 7* software. Statistical parameters were calculated as follows:

Chi-square χ^2 [3]:

$$\chi^2 = \frac{1}{N-n}\sum_{i=1}^{N}(G_{\exp} - G_{pred})^2 \quad (2)$$

Mean bias error *MBE* [3]:

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(G_{\exp} - G_{pred})^2 \quad (3)$$

Root mean square error *RMSE* [19]:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(G_{\exp} - G_{pred})^2} \quad (4)$$

3. RESULTS AND DISCUSSION

3.1. Conductive drying

Table 3 Results of statistical analysis of conductive drying of baby food

Conductive drying								
Model	**Baby food**	**Drying conditions**			**Statistical analysis**			
		P (bar)	*u (rpm)*	*t (s)*	R^2	χ^2	*MBE*	*RMSE*
Newton		6	7	7.14	0.97708	0.00326	0.00022	0.01462
Page		6	7	7.14	0.99573	0.00061	0.01147	0.10711
Henderson Pabis	Mixture 1	6	7	7.14	0.99204	0.00114	-0.00114	0.0337
Logarithmic		6	7	7.14	0.99206	0.00114	$4.5x\ 10^{-9}$	$6.7x\ 10^{-5}$
Diffusion Approach		6	7	7.14	0.99204	0.00114	-0.00114	0.03376
Newton		6	7	7.14	0.97916	0.00298	-0.00056	0.02370
Page		6	7	7.14	0.99715	0.00041	0.00984	0.09919
Henderson Pabis	Mixture 2	6	7	7.14	0.99330	0.00097	-0.00209	0.04566
Logarithmic		6	7	7.14	0.99337	0.00096	$-1.8x10^{-9}$	$4.3x\ 10^{-5}$
Diffusion Approach		6	7	7.14	0.99330	0.00097	-0.00209	0.04567
Newton		6	7	7.14	0.97677	0.00312	0.00595	0.07711
Page		6	7	7.14	0.99154	0.00114	0.01878	0.13703
Henderson Pabis	Mixture 3	6	7	7.14	0.99003	0.00134	0.00582	0.07629
Logarithmic		6	7	7.14	0.99062	0.00127	$-4\ x10^{-10}$	$2\ x\ 10^{-5}$
Diffusion Approach		6	7	7.14	0.99003	0.00135	0.00582	0.0763

Moisture contents of mixtures 1, 2 and 3 were monitored in 43 equidistant points around the drum dryer over the drying period. The moisture ratio data of all mixtures were fitted into the drying models from Table 2. Detailed comparison of drying models using statistical analysis (R^2, χ^2, *MBE*, and *RMSE*) is given in Table 3. All models provided an adequate fit to experimental data where $R^2>0.97$. The highest R^2 values and the lowest χ^2, *MBE*, and *RMSE* were obtained with Page's mathematical model. This model can be also found as adequate in describing drying behavior of many food materials [7], like lemon grass [20], durian chips [21], grapes [22], carrot pomace [23] and pepper [24]. Many other examples can be found in literature. Through this experiment was confirmed wide applicability of Page's model in describing drying behavior of food materials.

Although, the baby food mixtures consist of different components with various proportions of proteins, fats, and sugars (see Table 1), the Page's model satisfactory describes the drying behavior of the materials on the drum dryer. It indicates that the drying of mixtures 1, 2 and 3 on the drum dryer does not depend on their composition, but rather on process conditions.

3.2. Convective drying

Tables 4-8 show statistical analyses for convective drying of mixtures 1, 2 and 3. All models provided an adequate fit to the experimental data for all three mixtures. Because of tendency of this work looking for the unique model which can adequately describe the drying behavior of baby foods utilizing various drying methods and process conditions, Page's model may also be assumed to be the most suitable for describing the drying behavior of all mixtures. Although, the sample thickness in tunnel dryer (0.005 m) is different than on the drum dryer (0.0002 m) the Page's model shows a high flexibility and very good applicability in both cases. This model provided the best simulation of the drying curves of kiwi [8, 25] and bay leaves [26], also. Literature data showed that other models are of high importance in describing of convective drying of food materials. For instance, drying behavior of plum [3], pumpkin [27], tomato [28], apple pomace [29], apricots [30] are best described by logarithmic model, but the diffusion model is more adequate for potato slices [31].

Table 4 Results of statistical analysis for convective drying of baby food (Newton model)

Convective drying								
Model	**Baby food**	**Drying conditions**			**Statistical analysis**			
		T (°C)	*v (m/s)*	*t (min)*	R^2	χ^2	*MBE*	*RMSE*
		60	0.5	480	0.99221	0.00165	-0.01259	0.11221
		60	1.0	480	0.99162	0.00179	-0.01421	0.11921
		60	1.5	460	0.98608	0.00285	-0.01263	0.11238
		80	0.5	355	0.98663	0.00260	-0.01429	0.11954
	Mixture 1	80	1.0	280	0.97593	0.00499	-0.01748	0.13221
		80	1.5	215	0.98595	0.00276	0.00030	0.01738
		100	0.5	230	0.98195	0.05053	0.01515	0.12308
		100	1.0	200	0.99125	0.00150	-0.00262	0.05119
		100	1.5	180	0.99301	0.00124	0.00051	0.02256
		60	0.5	480	0.98492	0.00296	-0.01327	0.11520
		60	1.0	460	0.97846	0.00377	-0.01974	0.1405
		60	1.5	440	0.98258	0.00331	-0.01512	0.12296
		80	0.5	330	0.91356	0.02512	0.00752	0.08671
Newton	Mixture 2	80	1.0	330	0.99364	0.00136	-0.00208	0.04561
		80	1.5	315	0.99893	0.00025	-0.00168	0.04099
		100	0.5	240	0.99468	0.00129	0.00001	0.00307
		100	1.0	240	0.98816	0.00244	-0.00848	0.09209
		100	1.5	200	0.99525	0.00108	-0.00273	0.05225
		60	0.5	170	0.96926	0.00626	0.01340	0.11578
		60	1.0	155	0.98150	0.00369	0.01209	0.10998
		60	1.5	130	0.99288	0.00111	-0.00115	0.03391
		80	0.5	165	0.99111	0.00156	-0.00248	0.04979
	Mixture 3	80	1.0	145	0.98787	0.00196	0.00369	0.06074
		80	1.5	125	0.97274	0.00249	0.00522	0.07224
		100	0.5	120	0.97274	0.00471	0.00543	0.07371
		100	1.0	120	0.98913	0.00188	0.00288	0.05366
		100	1.5	110	0.98506	0.00265	0.00527	0.07261

The drying time becomes shorter by increasing the air velocity and temperatures [1]. This shortening of drying time is due to enhancing the heat transfer between air and material [18]. The positive influence of the air temperature and air velocity on the drying time was also reported by Velić et al. [17] and Akpinar et al. [32].

Table 5 Results of statistical analysis for convective drying of baby food (Page's model)

Convective drying								
Model	**Baby food**	**Drying conditions**			**Statistical analysis**			
		T (°C)	*v (m/s)*	*t (min)*	R^2	χ^2	*MBE*	*RMSE*
		60	0.5	480	0.99401	0.00127	-0.00886	0.09413
		60	1.0	480	0.99389	0.00131	-0.01052	0.10257
		60	1.5	460	0.99277	0.00148	-0.0075	0.0866
		80	0.5	355	0.99315	0.00134	-0.00736	0.08579
	Mixture 1	80	1.0	280	0.98932	0.00223	-0.00599	0.07739
		80	1.5	215	0.98975	0.00201	0.00192	0.04379
		100	0.5	230	0.98222	0.04985	0.00901	0.09491
		100	1.0	200	0.99184	0.00140	-0.0051	0.07141
		100	1.5	180	0.99384	0.00109	-0.00152	0.03899
		60	0.5	480	0.98501	0.00294	-0.01475	0.12145
		60	1.0	460	0.98272	0.00303	-0.01068	0.10334
		60	1.5	440	0.98439	0.00297	-0.00923	0.09607
		80	0.5	330	0.91358	0.02511	0.00758	0.08709

Page	Mixture 2	80	1.0	330	0.99656	0.00074	-0.00191	0.04370
		80	1.5	315	0.99896	0.00024	-0.00166	0.04074
		100	0.5	240	0.99608	0.00095	-0.00305	0.05523
		100	1.0	240	0.98836	0.00241	-0.01039	0.10193
		100	1.5	200	0.99638	0.00082	-0.0051	0.07141
		60	0.5	170	0.99779	0.00046	-0.00616	0.07849
		60	1.0	155	0.99850	0.00030	-0.00028	0.01673
		60	1.5	130	0.99518	0.00075	-0.00479	0.06922
		80	0.5	165	0.99533	0.00084	-0.00886	0.09413
	Mixture 3	80	1.0	145	0.99538	0.00075	-0.00407	0.06379
		80	1.5	125	0.99521	0.00078	-0.00445	0.06669
		100	0.5	120	0.99516	0.00085	-0.00968	0.03111
		100	1.0	120	0.99739	0.00045	-0.00328	0.05724
		100	1.5	110	0.99909	0.00016	-0.00224	0.04729

Table 6 Results of statistical analysis for convective drying of baby food (Henderson and Pabis model)

Convective drying								
Model	**Baby food**	**Drying conditions**			**Statistical analysis**			
		T (°C)	*v (m/s)*	*t (min)*	R^2	χ^2	*MBE*	*RMSE*
		60	0.5	480	0.99504	0.00105	-0.00476	0.06899
		60	1.0	480	0.99537	0.00099	-0.00583	0.07735
		60	1.5	460	0.99217	0.00161	-0.00361	0.06008
		80	0.5	355	0.99351	0.00127	-0.00331	0.05753
	Mixture 1	80	1.0	280	0.98739	0.00222	-0.00189	0.04347
		80	1.5	215	0.98669	0.00261	0.00272	0.05219
		100	0.5	230	0.98273	0.04855	-0.00175	0.04183
		100	1.0	200	0.99137	0.00148	-0.00433	0.06580
		100	1.5	180	0.99381	0.00110	-0.00336	0.05797
		60	0.5	480	0.98606	0.00274	-0.00679	0.08240
		60	1.0	460	0.98638	0.00239	-0.00466	0.06826
		60	1.5	440	0.98597	0.00267	-0.00489	0.06993
		80	0.5	330	0.91478	0.02478	0.00357	0.05975
Henderson	Mixture 2	80	1.0	330	0.99528	0.00101	0.00125	0.03535
and Pabis		80	1.5	315	0.99895	0.00025	-0.00123	0.03507
		100	0.5	240	0.99580	0.00102	-0.00551	0.07423
		100	1.0	240	0.98826	0.00243	-0.00667	0.08167
		100	1.5	200	0.99577	0.00096	-0.00621	0.0788
		60	0.5	170	0.98217	0.00366	-0.00921	0.09597
		60	1.0	155	0.99144	0.00172	-0.00645	0.08031
		60	1.5	130	0.99364	0.00099	-0.00479	0.06921
		80	0.5	165	0.99182	0.00144	-0.00689	0.08301
	Mixture 3	80	1.0	145	0.99103	0.00146	-0.00498	0.07057
		80	1.5	125	0.98956	0.00170	-0.00570	0.07549
		100	0.5	120	0.97989	0.00349	-0.00851	0.09225
		100	1.0	120	0.99335	0.00115	-0.00613	0.07826
		100	1.5	110	0.99199	0.00142	-0.00656	0.08099

Table 7 Results of statistical analysis for convective drying of baby food (Logarithmic model)

Convective drying								
Model	**Baby food**	**Drying conditions**			**Statistical analysis**			
		T (°C)	*v (m/s)*	*t (min)*	R^2	χ^2	*MBE*	*RMSE*
		60	0.5	480	0.99652	0.00074	1.4×10^{-10}	1.2×10^{-5}
		60	1.0	480	0.99707	0.00063	2.9×10^{-11}	4.8×10^{-6}
		60	1.5	460	0.99285	0.00147	-3.9×10^{-10}	0.00002
		80	0.5	355	0.99456	0.00106	-5.9×10^{-10}	0.000024
	Mixture 1	80	1.0	280	0.98797	0.00212	-4.4×10^{-10}	0.000021
		80	1.5	215	0.98728	0.00249	-2.3×10^{-9}	0.000048
		100	0.5	230	0.98278	0.04844	1.4×10^{-9}	3.8×10^{-5}
		100	1.0	200	0.99587	0.00071	-4.1×10^{-9}	0.000064
		100	1.5	180	0.99544	0.00081	-3×10^{-10}	0.000017
		60	0.5	480	0.99683	0.00063	-9.7×10^{-9}	0.00010
		60	1.0	460	0.99239	0.00134	-1.9×10^{-8}	0.00014
		60	1.5	440	0.99137	0.00165	-3.8×10^{-8}	0.00019
		80	0.5	330	0.9151	0.02469	-8.3×10^{-10}	0.00003
Logarithmic	Mixture 2	80	1.0	330	0.99532	0.00100	3.7×10^{-9}	6.1×10^{-5}
		80	1.5	315	0.99899	0.00024	-5.8×10^{-10}	0.00002
		100	0.5	240	0.99757	0.00059	-1.1×10^{-9}	3.3×10^{-5}
		100	1.0	240	0.99581	0.00087	-5.5×10^{-11}	7.4×10^{-11}
		100	1.5	200	0.99804	0.00045	2.6×10^{-11}	5.1×10^{-6}
		60	0.5	170	0.99839	0.00033	-5.9×10^{-10}	0.00002
		60	1.0	155	0.99823	0.00036	-1.1×10^{-9}	0.00033
		60	1.5	130	0.99828	0.00027	-1.6×10^{-11}	0.00000
		80	0.5	165	0.99906	0.00017	-3.5×10^{-12}	0.00000
	Mixture 3	80	1.0	145	0.99767	0.00038	-2.4×10^{-11}	0.00000
		80	1.5	125	0.99868	0.00022	-1.7×10^{-11}	0.00000
		100	0.5	120	0.99690	0.00054	-1.4×10^{-10}	0.00001
		100	1.0	120	0.99874	0.00022	-4.3×10^{-10}	0.00002
		100	1.5	110	0.99797	0.00036	-5×10^{-10}	0.00002

Table 8 Results of statistical analysis for convective drying of baby food (Diffusion Approach)

Convective drying								
Model	**Baby food**	**Drying conditions**			**Statistical analysis**			
		T (°C)	*v* (m/s)	*t* (min)	R^2	χ^2	*MBE*	*RMSE*
		60	0.5	480	0.99604	0.00084	-0.00522	0.07225
		60	1.0	480	0.99619	0.00081	-0.00664	0.08149
		60	1.5	460	0.99542	0.00094	-0.00491	0.07007
		80	0.5	355	0.99575	0.00083	-0.00445	0.06671
	Mixture 1	80	1.0	280	0.99264	0.00130	-0.00325	0.05701
		80	1.5	215	0.99114	0.00174	0.00168	0.04093
		100	0.5	230	0.98284	0.04829	-0.00142	0.03768
		100	1.0	200	0.99237	0.00131	-0.00492	0.07014
		100	1.5	180	0.99391	0.00108	-0.00317	0.05630
		60	0.5	480	0.98622	0.00271	-0.00676	0.08222
		60	1.0	460	0.98809	0.00209	-0.00476	0.06899
		60	1.5	440	0.98752	0.00238	-0.00451	0.06716
		80	0.5	330	0.91371	0.02508	0.00769	0.08768
Diffusion	Mixture 2	80	1.0	330	0.99718	0.00060	-0.00109	0.03302
Approach		80	1.5	315	0.99898	0.00024	-0.00159	0.03987
		100	0.5	240	0.99747	0.00061	0.00231	0.04803
		100	1.0	240	0.99445	0.00115	-0.00757	0.087
		100	1.5	200	0.99659	0.00077	-0.00431	0.06565
		60	0.5	170	0.99645	0.00073	-0.0065	0.0806
		60	1.0	155	0.99831	0.00034	-0.00054	0.02324
		60	1.5	130	0.99567	0.00068	-0.00397	0.063
		80	0.5	165	0.99597	0.00072	-0.00765	0.08744
	Mixture 3	80	1.0	145	0.99548	0.00074	-0.00299	0.05468
		80	1.5	125	0.99512	0.00079	-0.00333	0.05769
		100	0.5	120	0.99395	0.00106	-0.00855	0.09245
		100	1.0	120	0.99727	0.00047	-0.00239	0.04898
		100	1.5	110	0.99893	0.00012	-0.00136	0.03688

3.3. Irradiative drying

Such as during conductive and convective drying the moisture content loss was monitored in the case of irradiative drying, respectively. The values obtained recording moisture contents were used to calculate the moisture ratio *Y* (Eq. 1). A non-linear regression analysis using *Statistica 6* software was performed for all five drying models (Table 2). The models provided at all temperatures an adequate fit to experimental data, but the most adequate model was Page's model showing very wide applicability, mentioned earlier in this work. It can be elucidated that the Page's model can be also used to describe the drying behavior of baby food mixtures at different temperatures in infrared dryer. Increase in drying temperature led to a decrease in drying time independent of mixture type.

Table 9 Results of statistical analysis of irradiative drying of baby food

Irradiative drying							
Model	**Baby Food**	**Drying conditions**		**Statistical analysis**			
		T (°C)	*t* (min)	R^2	χ^2	*MBE*	*RMSE*
		60	308	0.99769	0.00028	0.00139	0.03737
Newton		80	177	0.99509	0.00041	-0.00289	0.05380
		100	121	0.99801	0.00029	-0.0045	0.06705
		60	308	0.99912	0.00011	-0.00061	0.02468
Page		80	177	0.99563	0.00037	-0.00302	0.05497
		100	121	0.99872	0.00019	-0.00376	0.06129
		60	308	0.99822	0.00022	0.00151	0.03891
Henderson and Pabis	Mixture 1	80	177	0.99521	0.00040	-0.00324	0.05695
		100	121	0.99828	0.00025	-0.00503	0.07094
		60	308	0.99835	0.00019	-0.00008	0.009
Logarithmic		80	177	0.9983	0.00014	-0.00009	0.00922
		100	121	0.99955	0.00001	0.00001	0.00228
		60	308	0.99948	0.00006	-0.00150	0.03876
Diffusion Approach		80	177	0.9983	0.00014	-0.00009	0.00922
		100	121	0.99828	0.00025	-0.00503	0.07094
		60	308	0.99485	0.00059	0.00129	0.03603
Newton		80	162	0.99307	0.00107	-0.00496	0.07041
		100	121	0.99623	0.00058	-0.00621	0.07882
		60	308	0.99859	0.00016	-0.00116	0.03411
Page		80	162	0.99578	0.00065	-0.00613	0.07831
		100	121	0.99830	0.00026	-0.00516	0.07183
		60	308	0.99683	0.00037	0.00183	0.04281
Henderson and Pabis	Mixture 2	80	162	0.99386	0.00095	-0.00714	0.08447
		100	121	0.99687	0.00048	-0.00752	0.08674
		60	308	0.99707	0.00034	0.000001	0.001
Logarithmic		80	162	0.99923	0.00012	9.7×10^{-12}	3.1×10^{-6}
		100	121	0.99931	0.00011	5.5×10^{-11}	7.5×10^{-6}
		60	308	0.99913	0.0001	-0.00176	0.04197
Diffusion Approach		80	162	0.99642	0.00055	-0.00430	0.06559
		100	121	0.99687	0.00048	-0.00753	0.08675

		60	155	0.96674	0.00700	-0.00218	0.04672
Newton		80	102	0.96809	0.00689	-0.00472	0.06869
		100	63	0.96267	0.00832	-0.00235	0.04848
		60	155	0.99793	0.00044	-0.00805	0.08972
Page		80	102	0.99822	0.00039	-0.00750	0.08658
		100	63	0.99751	0.00056	-0.00849	0.09217
		60	155	0.97949	0.00435	-0.01595	0.03994
Henderson and Pabis	Mixture 3	80	102	0.98059	0.00422	-0.01761	0.13272
		100	63	0.97659	0.00525	-0.01784	0.13355
		60	155	0.99607	0.00084	$-5.4x\ 10^{-10}$	$2.3x\ 10^{-5}$
Logarithmic		80	102	0.99425	0.00126	$-2.7x\ 10^{-10}$	$1.6x\ 10^{-5}$
		100	63	0.99456	0.00123	$-3.8x\ 10^{-8}$	0.00019
		60	155	0.99647	0.00075	$6.4x\ 10^{-5}$	0.00801
Diffusion Approach		80	102	0.99497	0.00109	0.00019	0.01395
		100	63	0.97659	0.00525	-0.01785	0.13359

Differences in drying times among mixtures 1, 2 and 3 by convective and irradiative drying due to different sample weights can be observed. Drying the samples under same conditions (drying technique, temperature) the drying times of mixture 3 are shorter than those of mixtures 1 and 2. This can be a result of differences in their composition, where in mixture 3 dominates corn flour, and in other mixtures wheat and soya flour, respectively. It is known that the most important protein of corn is zein which is relatively hydrophobic and thermoplastic material [33]. Since a high quantity of free water was present in wet mixture 3 shorter drying times were expected.

4. Conclusions

Comparison of different drying methods showed that the Page's model could be adequate to describe drying behavior of mixtures 1, 2 and 3 independent of drying conditions used in this work. Page's model wide applicability was further disseminated on the conductive, convective and irradiative drying of cereal based baby foods.

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