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Proceeding Paper

Microwave Expansion Kinetics of Third-Generation Extruded Corn Pellets under Different Moisture Contents †

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Abstract: A Brabender Kompakt extruder KE 19/25 was used to create third-generation corn pellets using a high moisture content (25, 30, and 35%) and moderate temperature. The pellets were subjected to microwave expansion, and the drying curves were fitted to Page, Logarithmic, and Midilli–Kucuk mathematical models. The Page model best fits the experimental data, closely followed by the Midilli–Kucuk model. The variables evaluated were appearance, sectional expansion index (SEI), and volumetric expansion index (VEI), and they showed a strong dependency on moisture content. According to the results, the recommended expansion times for mixtures with a 25, 30, and 35% moisture content are 50, 60, and 60–75 s, respectively.

Keywords: expanded snacks; 3G snacks; Page; Logarithmic; Midilli–Kucuk

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1. Introduction

Third-generation extruded pellets are formed via extrusion using a high moisture content and moderate temperature and are dried at ambient temperature, allowing the preservation of thermally sensitive ingredients [1]. The expansion process of these pellets can be performed by domestic microwaves to achieve a crispy texture. This methodology provides an alternative in terms of generating nutritious food, and it also reduces export costs in which the volume usually raises the final sale costs.

Electromagnetic waves with a frequency between 0.3 and 300 GHz (wavelength 1 mm to 1 m) are called microwaves. These microwaves are utilized in different areas because their heat transfer is energetically efficient. The heat is transferred into the food due to the dipolar nature of the water molecule and its alignment with the ionic mechanism by an electric field when it is penetrated by the microwave [2]. The combination of nonexpanding extrusion and microwave expansion is referred to as indirect expansion or the production of third-generation snacks. Recently, studies on microwave expansion were reported for potato flakes [3], blue corn, black beans, sweet chard [4], imitation cheese [5], and blue honeysuckle berry snacks [6].

Relatedly, scientists intending to transfer knowledge acquired experimentally to industrial applications use mathematical modeling of drying kinetics [7]. These models provide a fundamental analysis of mass transfer phenomena and apport vital information to design new equipment and optimize systems [8].

The objectives of this work were (1) to examine the influence of the moisture content of the mixtures and microwave expansion time on the appearance, sectional expansion index (SEI), volumetric expansion index (VEI), and water content of the expanded pellet, and (2) to fit the experimental data to Page, Logarithmic, and Midilli–Kucuk models.

2. Materials and Methods

2.1. Preparation of Corn 3G Extruded Pellets

Corn flour was mixed thoroughly with water, and the moisture content of the blended samples was adjusted to 25, 30, and 35% (wb) for extruder feed by mixing continuously at medium speed in a mixer (Bosch MFQ40303, Gerlingen, Germany).

A single-screw laboratory extruder (Kompakt extruder KE 19/25; Brabender, Duisburg, Germany) with a barrel diameter of 19 mm and a length diameter ratio of 25:1 was used to obtain third-generation corn pellets. The extruder was operated at a 3:1 compression ratio, loaded with prepared corn samples at a constant dosing speed of 20 rpm. The screw was rotated constantly at 120 rpm, and temperatures of barrel Sections 1–4 were set to 30, 60, 100, and 120 °C, respectively; the nozzle diameter was 3 mm. Extruded products were immediately dried at 25 °C overnight. Dried samples were stored in polyethylene bags at room temperature and used for further analysis.

2.2. Microwave Expansion

The expansion process was performed in a microwave machine (FT339, Whirlpool Corporation, MI, USA) at 1000 W/g. To evaluate the microwave expansion-kinetics and dehydration-kinetics of the different 3G extruded corn pellets, the water content and characteristic dimensions of the pellet samples were analyzed after 10, 20, 30, 40, 50, 60, 75, and 90 s of microwave expansion application time.

2.2.1. Microwave Dehydration-Kinetics

The microwave dehydration curves, obtained from the experimental water content of the samples after different process times, were fitted to the Page, Logarithmic, and Midilli–Kucuk models, as proposed by Igual et al. [9] for freeze-dried grapefruit.

Water content (x_w) was obtained by vacuum drying the samples in a vacuum oven (Vaciotem, J.P. Selecta) at 60 °C for 48 h.

2.2.2. Microwave Expansion-Kinetics

The sectional expansion index (SEI) and volumetric expansion index (VEI) of the extrudates were determined following the methodology described by Patil et al. [10]. The width and length of the expanded pellets were measured with a digital caliper.

2.3. Statistical Analysis

Non-linear regression analyses were carried out for the estimation of the kinetic parameters. Analysis of variance (ANOVA) was applied with a confidence level of 95% ($p < 0.05$) to evaluate the differences. Statgraphics Centurion XVII Software, version 17.2.04 (Statgraphics Technologies, Inc., The Plains, VA, USA) was used in both analyses.

3. Results and Discussion

3.1. Microwaving Dehydration Kinetic. Mathematical Modeling

The microwave dehydration curves of corn pellets with different mixture moisture contents (25, 30, and 35%) were obtained by plotting the moisture ratio vs. time. The experimental data were fitted to the Page, Logarithmic, and Midilli–Kucuk models. Figure 1 shows the microwave process experimental data and moisture ratio behavior. The kinetic parameters and the accuracy of the fit determined for the three models are presented in Table 1. These models coincided well with the experimental data, as seen from the adjusted regression coefficient (R^2) and the root mean square error (RMSE) values. The best fit (higher R^2) was the Page model for mixtures with 25 and 35% moisture and the Midilli–Kucuk model for the mixture with 30% moisture. Therefore, in general terms, the Page model provided the best fit with the experimental data.

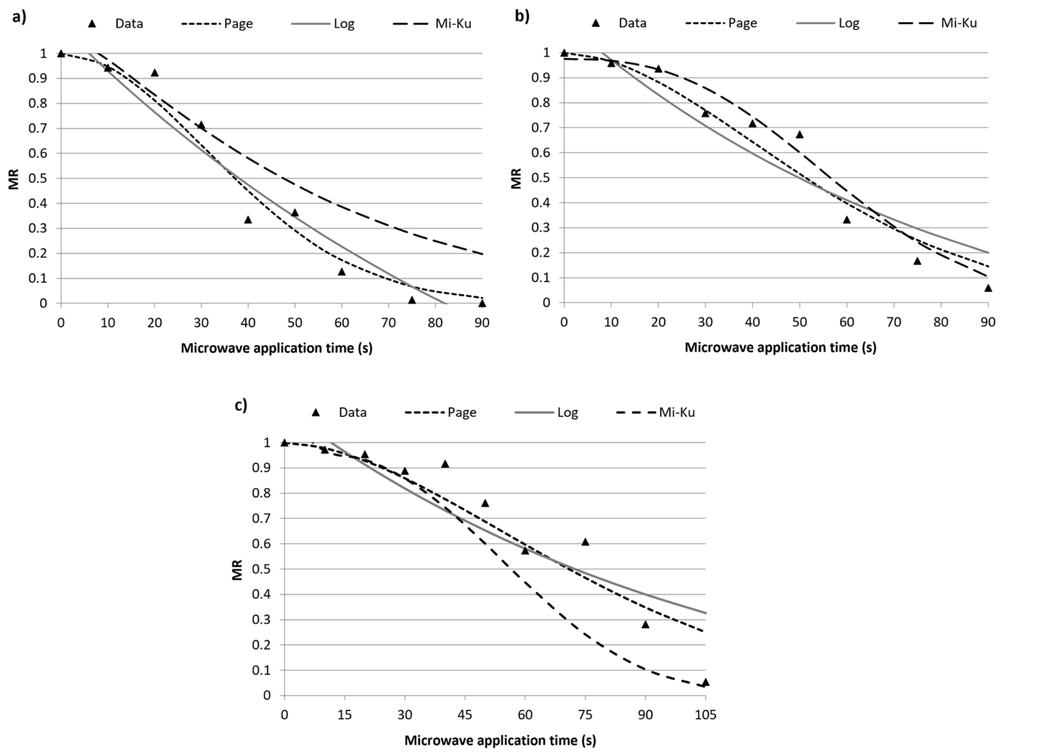

Figure 1. Microwave expansion kinetics of corn pellets with different mixture water contents ((**a**): 25, (**b**): 30, and (**c**): 35%) adjusted to Page, Logarithmic, and Midilli–Kucuk models.

Table 1. Values of the microwave expansion kinetic parameters obtained for pellets when the Page, Logarithmic, and Midilli–Kucuk models were used to fit the experimental data.

Water Content of Mixtures (%)	Model			
		Page	**Logarithmic**	**Midilli–Kucuk**
25	Model constants	k: 0.00062 n: 1.93984	a: 2.2581 k: 0.0082 c: −1.150	a: 1.0939 k: 0.0069 n: 1.2271 b: −0.0029
	Adj. R^2 RMSE	96.36 0.078	91.52 0.119	91.41 0.120
30	Model constants	k: 0.00054 n: 1.81839	a: 1.4349 k: 0.0115 c: −0.3080	a: 0.9752 k: 0.00002 n: 2.6097 b: −0.0006
	Adj. R^2 RMSE	93.99 0.086	84.15 0.140	95.93 0.071
35	Model constants	k: 0.00038 n: 1.76371	a: 1.3090 k: 0.4091 c: −0.1780	a: 1.1008 k: 0.0005 n: 1.4632 b: −0.0051
	Adj. R^2 RMSE	89.07 0.1064	75.83 0.1582	87.98 0.0718

Adjusted regression coefficient (Adj. R^2) and root mean square error (RMSE) values.

In Table 1, the model constants for each mathematic model are shown. For the Page models, the constant *k* could be related to the diffusion coefficient and the geometry of the sample. The trend of the values indicates a higher water diffusion coefficient at 25% of moisture and an inversely proportional trend to the water content; a similar effect was shown in starch-gluten-water mixtures heated by microwave [11]. The constant n is associated with the type of diffusion phenomenon (n > 1 for super-diffusion and n < 1 for sub-diffusion). According to Simpson et al. [12], this exponent should be related to the microstructure; for this reason, a fluctuation inversely proportional to the water content of the mixtures was observed. In all cases the moisture content, constant *n* was higher than the unit due to the high heating velocity during the microwave process.

3.2. Sectional Expansion Index (SEI) and Volumetric Expansion Index (VEI) and Appearance

Figure 2 shows the evolution of the sectional expansion index (SEI) and volumetric expansion index (VEI) of the pellets as a function of the processing time for three different water content mixtures. At the beginning of the process (10 to 30 s), microwave energy heated the matrix through the vibration of water molecules and the temperature of the pellets increased progressively; however, these pellets did not show significant ($p > 0.05$) changes in SEI and VEI values. Then, the pellet from the mixture with 25% moisture expanded at 40 s, while the pellets from the mixtures with 30 and 35% moisture expanded at 60 s.

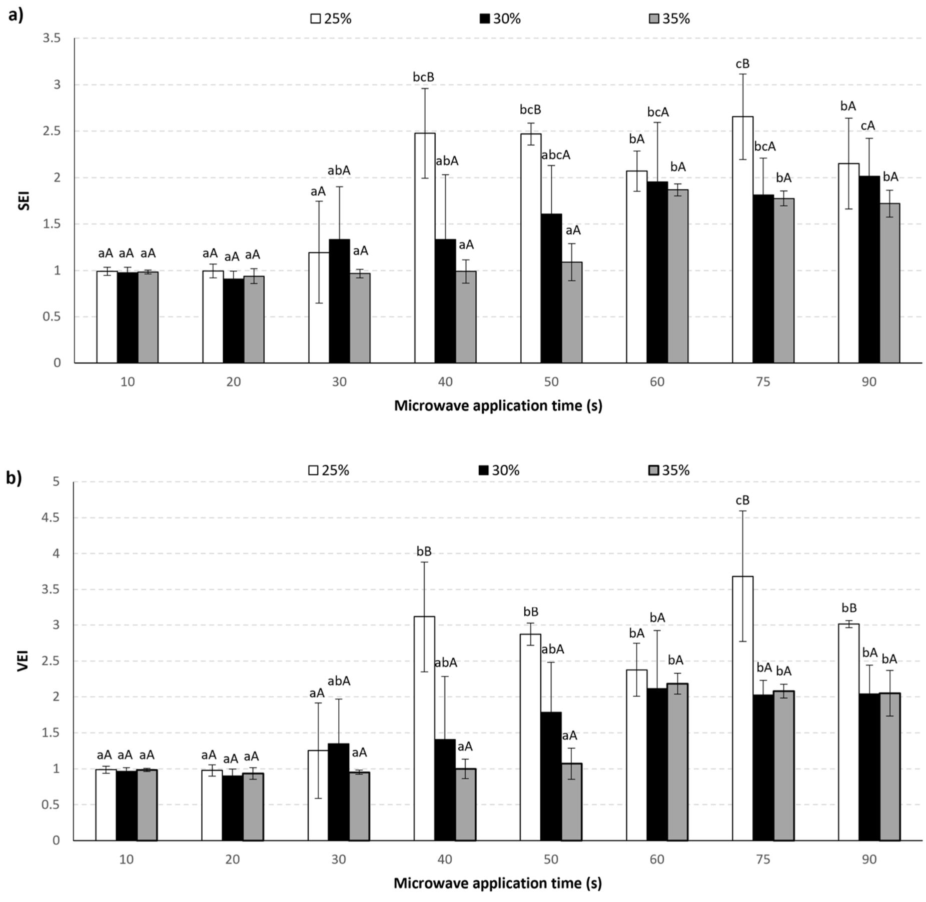

Figure 2. Evolution of SEI (subfigure **a**) and VEI (subfigure **b**) of pellets as a function of the processing time for three different mixture moisture contents (25, 30, and 35%). Different letters (a, b, and c) represent significant differences ($p < 0.05$) by microwave expanded application time and also (A, B) represent significant differences ($p < 0.05$) by water content.

The pellets with a 35% water content showed lower SEI and VEI values at each time point, and this behavior was closely followed by the pellets with a 30% water content. In contrast, pellets with a 25% water content exhibited a higher expansion index in all the application times evaluated.

According to the SEI and VEI values, the best treatment is the pellet with 25% moisture and a microwave application time of 40 s. In this case, the finished product was fully expanded with ≈2.5 in SEI and ≈3.1 in VEI. Temperature evolution during microwave expansion strongly depends on dielectric properties, which are closely determined by moisture content [13,14]. Mixtures with approximately 20–30% moisture content produced pellets with approximately 11–15% moisture equally dispersed throughout the pellet's volume. According to some studies, this final product has shown better expansion indexes, a light structure, and a crispy texture [15,16].

Figure 3 shows the appearance evolution as a function of the processing time. When 75 s of microwave was applied, expanded samples showed the darkest color in all samples. The evolution of expansion in Figure 3 corroborates the results of Figure 2.

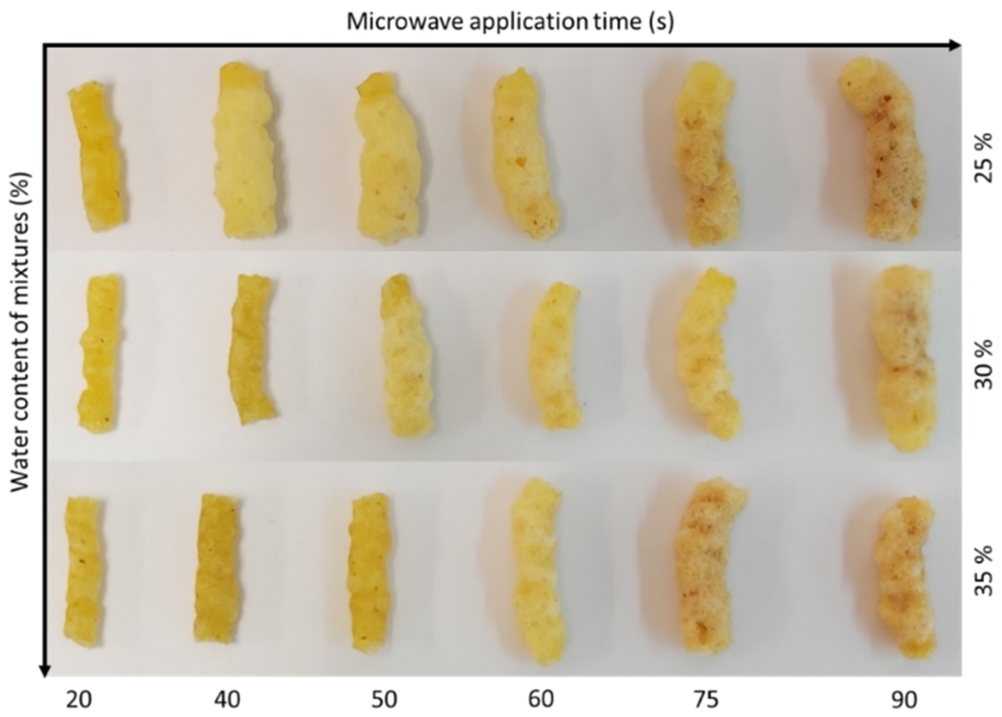

Figure 3. Evolution of appearance as a function of the processing time for three different water content mixtures (25, 30, and 35%).

The best treatment according to appearance is the pellet with 25% moisture and a microwave application time of 40 s. In this case, the finished product was fully expanded to 27 mm in length and 8.5 mm in diameter with an approximate weight of 0.35 g.

4. Conclusions

To explain the microwave expansion process behavior, three drying models available in the literature were compared using the statistical parameters of the regression coefficient (coefficient square R^2 and root mean square error RMSE). The Page model yielded better results for the mixture with a 25% moisture content, while for the mixture with a 30% moisture content, the Midilli–Kucuk model fit the experimental data reasonably. The constant drying k showed an inversely proportional trend to the moisture content of the mixtures for the Page model and a directly proportional trend for the Logarithmic model. The constants n for the Page and Midilli–Kucuk models were higher than the unit due to the high heating velocity of the microwave process. According to the appearance of SEI and VEI, the best expansion properties were exhibited in the pellet with 25% moisture and a microwave application time of 40 s. Above 75 s of microwave application, all the pellets were burned due to the loss of moisture during the expansion. Using empirical models for modeling the expansion kinetics of third-generation extruded corn pellets during microwave expansion is important for developing a better understanding of the process at the macroscopic scale.

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