

Microwaving Expansion Kinetics of Corn Third-Generation Extruded Pellets under Different Moisture Content [†]

Liliana Acurio ^{1,2,*}, Faustine Moreau ³, Purificación García-Segovia ², Javier Martínez-Monzó ² and Marta Igual ^{2,*}

¹ G+ BioFood & Engineering Group, Department of Science and Engineering in Food and Biotechnology, Technical University of Ambato. Av. Los Chasquis & Río Payamino, Ambato 180150, Ecuador

² Food Technology Department, Universitat Politècnica de València, Camino de Vera s/n, 46021 Valencia, Spain

³ Institut Agro Dijon, 26, Boulevard Docteur Petitjean, 21000 Dijon, France

* Correspondence: lp.acurio@uta.edu.ec (L.A.); marigra@upvnet.upv.es (M.I.); Tel.: +59-3986090742 (L.A.); +34-625430677 (M.I.)

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Abstract: A Brabender Kompakt extruder KE 19/25 was used to get corn third-generation pellets using 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 and Kucuk mathematical models. The Page model best fits the experimental data, closely followed by the Midilli and 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 time with 25, 30, and 35% moisture content for mixtures is 50, 60, and 60–75 s, respectively.

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

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1. Introduction

Pellets called third-generation extruded are formed via extrusion at high moisture content, moderate temperature, and 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 the heat transfer is energetically efficient. The heat transfer is generated inside the food due to the alignment of the dipolar nature of the water molecule and ionic mechanism by an electric field when the microwave penetrates through it [2]. The combination of nonexpanding extrusion and microwave expansion is referred to as indirect expansion or 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].

Otherwise, 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 moisture content of the mixtures and microwave expanded 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 for extruder feed was adjusted to 25, 30, and 35% (wb) 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 get corn third-generation 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 corn 3G extruded pellets, the water content and characteristic dimensions of pellets samples were analyzed after 10, 20, 30, 40, 50, 60, 75, and 90 s of microwave expanded 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 (Vacuotem, 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 extrudates were determined following the methodology described by Patil et al. [10]. The width and large of 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 moisture of its mixtures (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 Page for mixtures with 25 and 35% moisture and Midilli-Kucuk for

mixture with 30% moisture. Therefore, in general terms, the Page model provided the best fit with the experimental data.

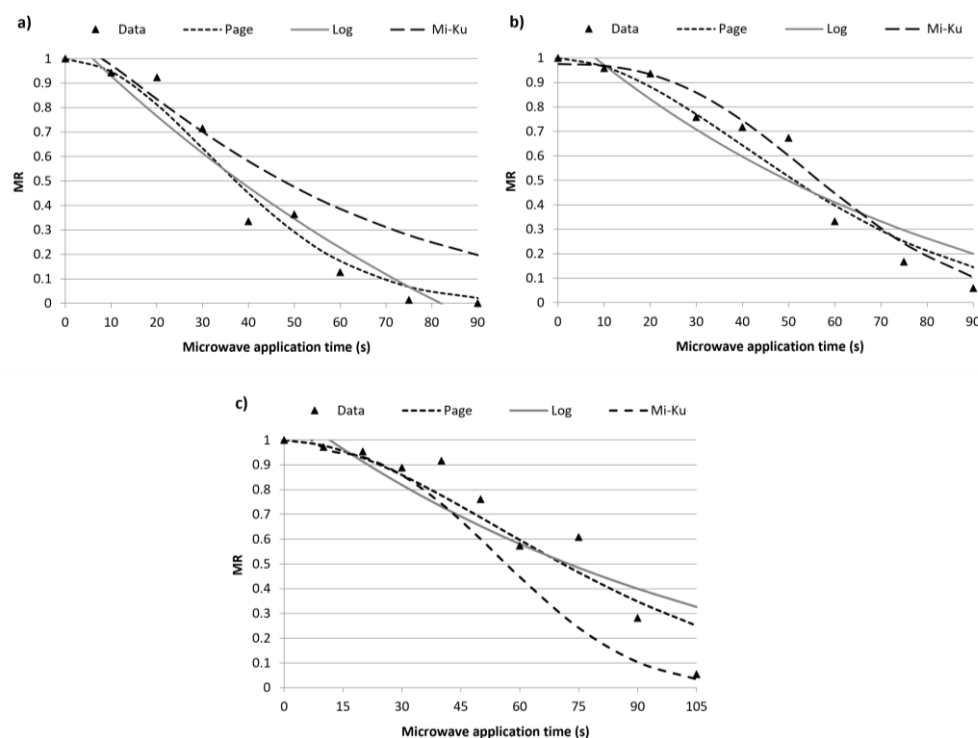


Figure 1. Microwaving expansion kinetics of corn pellets with a different water content of its mixtures ((a): 25, (b): 30, and (c): 35%) adjusted to Page, Logarithmic, and Midilli–Kucuk models.

In Table 2, the model constants for each mathematic model are exhibited. 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 the moisture content, constant n was higher than unit due to the high heating velocity during the microwave process.

Table 1. Values of the microwaving 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	a: 2.2581	a: 1.0939
		n: 1.93984	k: 0.0082	k: 0.0069
		c: -1.150	n: 1.2271	
			b: -0.0029	
	Adj. R ²	96.36	91.52	91.41
	RMSE	0.078	0.119	0.120
30	Model constants	k: 0.00054	a: 1.4349	a: 0.9752
		n: 1.81839	k: 0.0115	k: 0.00002
		c: -0.3080	n: 2.6097	
			b: -0.0006	

	Adj. R²	93.99	84.15	95.93
	RMSE	0.086	0.140	0.071
35	Model constants	k: 0.00038	a: 1.3090	a: 1.1008
		n: 1.76371	k: 0.4091	k: 0.0005
			c: -0.1780	n: 1.4632
	Adj. R²	89.07	75.83	87.98
	RMSE	0.1064	0.1582	0.0718

Adjusted regression coefficient (Adj. R²) and root mean square error (RMSE) values.

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 of 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 30 and 35% moisture in mixture expanded at 60 s.

The pellets with 35% of water content showed lower SEI and VEI values at each time, and this behavior was closely followed by the pellets with 30% of water content. In contrast, pellets with 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 are subjected to produce pellets with approximately 11–15% moisture equally dispersed throughout the pellet's volume. According to some studies, the final product has shown better expansion indexes, light structure, and crispy texture [15,16].

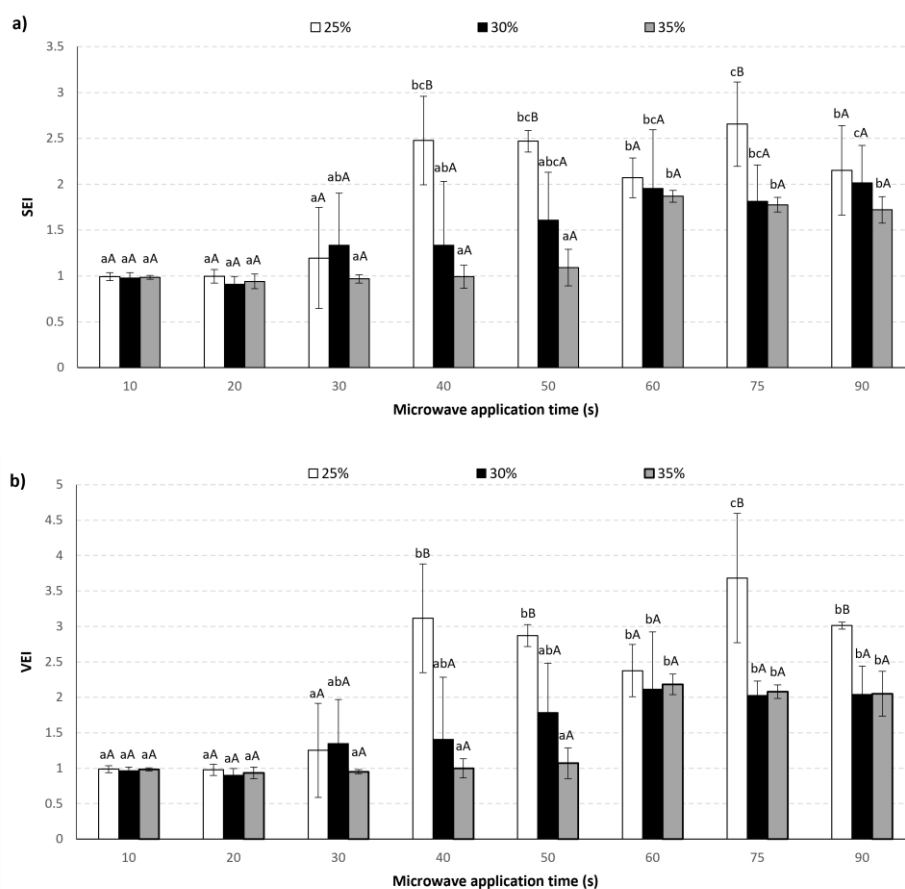


Figure 2. Evolution of SEI and VEI of the pellets as a function of the processing time for three different moisture content of its mixtures (25, 30, and 35%). Different letters (a, b, c) represent significant differences ($p < 0.05$) by microwave expanded application time and (A, B) represent significant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

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

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

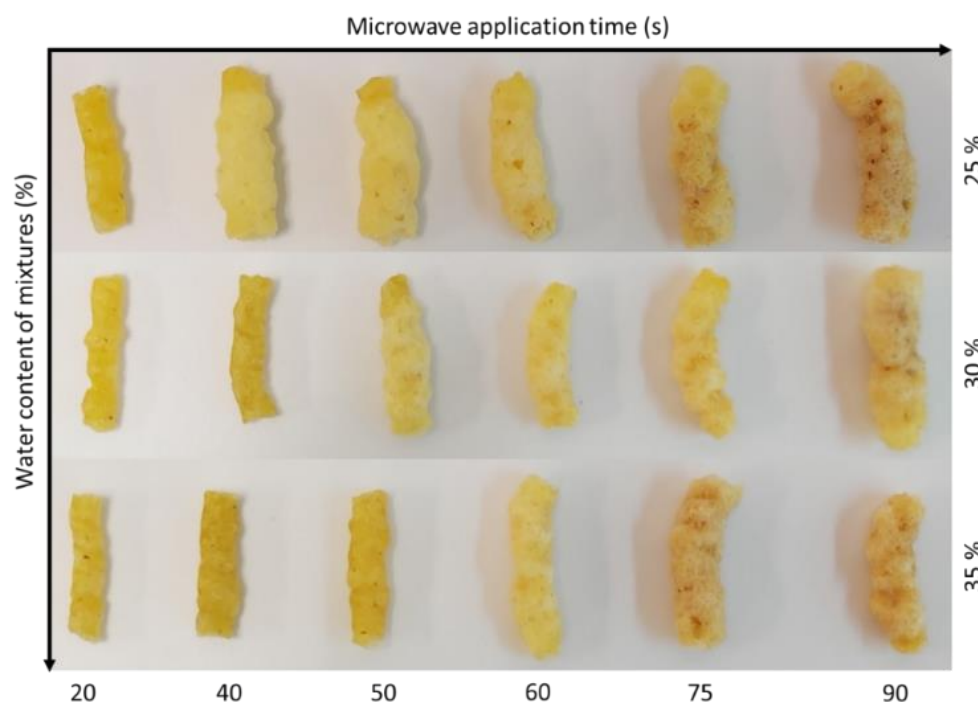


Figure 3. Evolution of the appearance as a function of the processing time for three different water content of its mixtures (25, 30, and 35%).

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 25% moisture content of mixture, while for 30% moisture content, the Midilli-Kucuk model fits the experimental data reasonably. The constant drying k showed an inversely proportional trend to the moisture content of the mixtures for Page model and a directly proportional trend for Logarithmic model. The constants n for Page and Midilli-Kucuk models were higher than 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 the 75 s of microwave application, all the pellets were burned due to the loss of moisture content during the expansion. Using empirical models for modeling expansion kinetics of corn third-generation extruded pellets during microwave expansion is important for developing a better understanding of the process at the macroscopic scale.

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Conflicts of Interest: The authors declare no conflict of interest.

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