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OPTIMIZATION OF FORMULATION AND PARAMETERS FOR BAKING *PÃES DE QUEIJO* IN A MICROWAVE OVEN

OTIMIZAÇÃO DA FORMULAÇÃO E PARÂMETROS DO ASSAMENTO DE PÃES DE QUEIJO EM FORNO DE MICRO-ONDAS

Giulia Silva Bianchini[1], Luan Alberto Andrade[2] e Joelma Pereira[1]

ABSTRACT

This study used a sequential strategy of experimental statistical design to obtain optimal formulation conditions and baking parameters for *pão de queijo* (Brazilian cheese bread), in a microwave oven. Plackett & Burman was used for screening the design of ingredients of the *pão de queijo* formulation and baking parameters in a microwave oven. The significant factors with the greatest effects on the response variables were selected for the Central Rotational Composite Design to optimize the process. The response variables analyzed in both designs were expansion, texture, weight loss, and density of *pães de queijo*. The optimization conditions achieved were 55% milk, 40% cheese, three minutes of baking time, and 80% power of the actual power of the microwave oven. The physical characteristics of *pães de queijo* formulated and baked with the optimal conditions found in this research are not similar to those baked in conventional ovens found in the literature.

Keywords: Baking; Cassava starch; Cheese; Packlett & Burman.

RESUMO

Este estudo utilizou uma estratégia sequencial de planejamento estatístico experimental para obter condições de formulação e parâmetros de cozimento otimizados para pão de queijo, em forno de micro-ondas. Plackett & Burman foi utilizado para screening design dos ingredientes da formulação do pão de queijo e dos parâmetros de cozimento em forno de micro-ondas. Os fatores significativos com maiores efeitos nas variáveis resposta foram selecionados para o Delineamento Composto Rotacional Central para otimizar o processo. As variáveis respostas analisadas nos dois planejamentos foram expansão, textura, perda de peso e densidade dos pães de queijo. As condições de otimização alcançadas foram 55% de leite, 40% de queijo, três minutos de cozimento e 80% da potência real do forno micro-ondas. As características físicas dos pães de queijo formulados e assados nas condições ótimas encontradas nesta pesquisa não são semelhantes aos assados em fornos convencionais encontrados na literatura.

Palavras-chave: *Cozimento; Polvilho; Queijo; Packlett & Burman.*

1 Department of Food Science, Federal University of Lavras - UFLA. E-mails: giu_bianchini@hotmail.com; joper@ufla.br. ORCID: https://orcid.org/0000-0002-6110-3914

2 Department of Chemistry, Federal University of Lavras - UFLA, Trevo Rotatório Professor Edmir Sá Santos, Lavras, MG, Brazil. E-mail: luanandrade@ufla.br; luandrade87@yahoo.com.br. ORCID: https://orcid.org/0000-0001-5357-3521

1 INTRODUCTION

Pão de queijo (cheese bread) is a Brazilian product, specifically from the state of Minas Gerais, which consists of a mixture of cassava starch, cheese, and other ingredients that confer a characteristic flavor, aroma, and texture (Silva; Garcia; Ferreira, 2003). It has a crispy crust and a soft crumb resembling an extruded structure (Teixeira *et al.*, 2020)

Brazilian *pão de queijo* has gained attention as a gluten-free baked product (Kazerski *et al.*, 2022) and can be consumed as an alternative food for patients allergic and intolerant to wheat proteins, in addition to being a recognized source of carbohydrates (Pereira *et al.*, 2004).

A quality standard for *pão de queijo* has not yet been established, and there is no production technology, characterization, or typification of the product. Therefore, several formulations on the market are sold and also identified as *pão de queijo*, which can be presented as already molded and frozen, in powder form for later addition of ingredients or even as a frozen dough (Minim *et al.*, 2000).

The basic ingredients used in its formulation are cassava starch (sour and/or sweet), cheese, fat, liquid (water or milk), salt, and eggs. These ingredients can be separated into two main functions: softening agents (egg yolk, fat) and structuring agents (cassava starch, eggs, milk, cheese, water, and salt), responsible for the texture and structure of the dough, respectively (Gonçalves, 2000). According to Dariva *et al.* (2021), the choice of cassava starch, native or modified, to be used in the production of cheese bread is crucial to ensure that the characteristics of the final product meet the consumers expectations.

For Pizzinato (2000), there is no standard technology for the *pão de queijo* production; however the author suggests a manufacturing process based on the method adopted by most producers. The production stages include scalding the starch with a boiling mixture of liquid, fat, and salt, mixing the other ingredients (egg and cheese), shaping, freezing, packaging, storage, and baking.

Baking is the stage in which the dough is transformed into a light, porous, and easily digestible product. *Pão de queijo* rises by incorporating air and evaporating water; the increase in volume is due to the expansion of steam and air during baking (Pizzinato, 2000).

Microwave heating has gained acceptance in domestic use and is increasing in popularity in industrial applications due to its easy and convenient application. The changing attitude of consumers and their fast-paced lifestyle has resulted in “ready-to-eat” meals for which microwaves are of great use. Microwave heating is faster than conventional cooking (gas or electric oven) and is expected to produce a more homogeneous heat treatment at a faster rate than conventional heating. Furthermore, microwave ovens are easy to operate and require less maintenance (Vadivambal and Jayas, 2010).

In conventional cooking, heat is applied to the outside of the food and gradually penetrates to the inside. In microwave cooking, heat is generated inside the food. In a microwave oven, microwaves penetrate the food and are converted into heat inside it, causing the entire food to heat up very quickly

(Ramesh, 2007). The incidence of radiation inside the domestic microwave oven during the baking of *pão de queijo* is a function of its formulation and location during baking (Bianchini *et al.*, 2024).

In addition to the advantages, some problems are associated with microwave heating, such as non-uniform temperature distribution and the large number of factors affecting microwave heat transfer behavior, such as thickness, geometry, and dielectric properties of food (related to its composition). Furthermore, several factors influence the uniformity of the electromagnetic field, such as the shape and size of the product and its arrangement in the oven (Ahmed and Ramaswamy, 2007; Bianchini *et al.*, 2024).

The adoption of microwave technology by the food industry has been slow due to technical limitations linked to the process. Ideally, the product should be heated to specified levels without overcooking, cooled quickly, and properly stored and distributed. Thus, improving oven design, food packaging, and/or its formulation by food composition should lead to better processes (Ahmed and Ramaswamy, 2007).

Therefore, this work used a sequential strategy of experimental statistical planning to obtain optimized formulation conditions and parameters for baking *pão de queijo* in a microwave oven.

2 MATERIAL AND METHODS

2.1 RAW MATERIALS AND OBTAINING PÃES DE QUEIJO

For the experiment, raw materials obtained from stores in the city of Lavras, state of Minas Gerais, Brazil, were used, namely: sweet and sour cassava starch, margarine with 80% lipids, fresh chicken egg, whole cow's milk, iodized refined salt, artisanal minas Canastra cheese (half-cured Canastra).

Pães de queijo were prepared based on the formulation proposed by Silva (2009) and pre-tests but the quantities of ingredients (levels of independent variables) were varied according to the experimental design. All the ingredients to prepare *pães de queijo*, as well as the baking time and the power of the microwave oven, were variables used in the design.

As there were many variables, a sequential strategy of experimental statistical design was adopted. This consisted of a screening design to select the most important factors, which were later used in a design that generated response surfaces with information about the optimal conditions of the studied parameters.

In the formulations, the sum of sweet and sour cassava starch represented 100% and the amount of other ingredients was calculated as a percentage of the total mass of the cassava starch. All ingredients were weighed on a semi-analytical balance.

In a bowl, the sweet and sour cassava starches were homogenized, scalded with a boiling mixture of milk, margarine, and salt, and mixed to homogenize and cool the dough. Eggs and cheese were added and mixed until the ingredients were completely dispersed. Subsequently, a cylindrical mold

(2.8 cm diameter and 2.4 cm height) was used to obtain the molded *pães de queijo* masses, which were packaged in a Styrofoam tray (23.5 cm x 18 cm x 3.3 cm) and PVC plastic film and refrigerated for 24 hours in a horizontal freezer before baking. After 24 hours, molded and frozen doughs were baked in a microwave oven (LG, model MS3047G, Brazil) according to the time and power conditions described in the design. All tests were performed in triplicate. The real power for each power level of the microwave oven was calculated according to Gallawa (2013) and is listed in Table 1.

Table 1 - Power levels indicated on the microwave oven display and their respective real power levels.

Power (%) on the microwave oven display	Calculated real power (W)
10	65
20	154
30	238
40	271
50	325
60	352
70	468
80	488
90	570
100	669

2.2 *SCREENING DESIGN*

A screening design was adopted to select the most significant variables for the final objective of this study. The Plackett-Burman factorial experimental design (PLACKETT; BURMAN, 1946) was used with 12 runs (PB-12) and three central points, totaling 15 runs. Table 2 lists the factors or independent variables and their respective levels coded as -1, 0, and + 1.

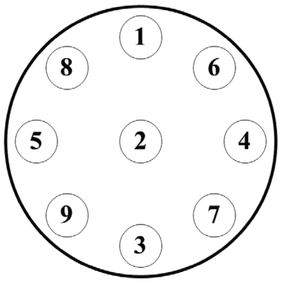
Table 2 - PB-12 runs with their respective levels in real values.

Factor	Abbreviation	Levels		
		-1	0	+1
Sweet cassava starch (%)	CS	25	50	75
Milk (%)	M	50	55	60
Margarine (%)	Ma	15	20	25
Salt (%)	S	2	3	4
Egg (%)	E	20	25	30
Cheese (%)	C	40	50	60
Baking time (minutes)	T	2	2,5	3
Microwave oven power (%)	P	70	80	90

The level of sour cassava starch was complementary to that of sweet cassava starch so that the sum of the two was 100%. Thus, when 25% sweet cassava starch was used, 75% sour cassava starch was added, and so on.

The molded and frozen *pão de queijo* dough samples prepared following the formulation determined by the PB-12 run design were distributed directly on the microwave oven plate, as illustrated in Figure 1. Immediately after, samples were baked at the power and time conditions defined in the design matrix.

Figure 1 - Arrangement of *pães de queijo* on the microwave oven plate.



Later, the responses or dependent variables were evaluated: expansion, density, texture, and weight loss of *pães de queijo* after baking, according to the methodologies described below.

2.3 EXPANSION AND DENSITY

The expansion, or expansion index, and density of *pão de queijo* were determined according to methodologies proposed by Pereira *et al.* (2004). The masses and dimensions of the molded doughs were obtained after freezing, and the baked *pães de queijo* after cooling down on the support. The masses were measured on a semi-analytical scale, and the dimensions were measured using a digital caliper.

2.4 TEXTURE

The texture of the *pão de queijo* was determined by compressive strength analysis using the Stable Micro Systems texture analyzer equipment, model TA.XT2. All tests were carried out in triplicate and after cooling down *pães de queijo* for 20 minutes after baking (approximately 25°C). The P/75 probe was used in the tests with the parameters: test and pre-test speeds of 2.0mm s^{-1}, post-test speed of 10.0mm s^{-1}, and compression distance of 50.0% of the deformation. The software used to obtain the results was Exponent Lite Express (Stable Micro Systems, 2017).

2.5 WEIGHT LOSS DURING BAKING

Weight loss was calculated by the difference between the masses of the baked *pão de queijo* and the frozen molded dough. The masses were measured on a semi-analytical scale.

2.6 CENTRAL COMPOSITE ROTATIONAL DESIGN (CCRD)

The experimental design adopted to optimize the formulation and baking conditions of *pão de queijo* in a microwave oven was a 2^4 CCRD with 8 axial points and 3 central points. The factors used were those selected by PB-12 planning and are listed in Table 3 together with their respective levels coded as -2, -1, 0, +1, and +2.

Table 3 - 2^4 CCRD factors with their respective levels in real values.

Factor	Abbreviation	Levels				
		-2	-1	0	+1	+2
Milk (%)	M	45	50	55	60	65
Cheese (%)	C	20	30	40	50	60
Baking time (minutes)	T	2	2,5	3	3,5	4
Microwave oven power (%)	P	60	70	80	90	100

The baking time and cheese levels were lower than those used in PB-12 for technological reasons. *Pães de queijo* burned up when very high levels of these factors were used.

The levels of sweet and sour cassava starches, margarine, salt, and egg were fixed in all tests at 50%, 50%, 20%, 3%, and 25%, respectively.

The procedure for carrying out the tests was similar to that of PB-12, and the responses evaluated were also the same.

2.7 STATISTICAL ANALYSIS

The Statistica software (StatSoft, 2007) was used for statistical analyses of the data obtained in the experimental design. Data obtained in the Plackett & Burman (PB) design were subjected to linear effect analysis, where the pure error was evaluated at the 5% level of significance. Significant effects were determined by p-value. Data obtained from the CCRD were subjected to linear, quadratic, and interaction effects analysis, where the pure error was also evaluated at the 5% significance level. The significance of the effects was determined by the p-value, and these were used to construct second-order models to correlate the factors (independent variables) with their responses (dependent variables). The pure error was estimated to determine the lack of fit to check the adequacy of the models. Verification of the statistical validity and predictive power of these models was carried out using the F-test, and the data were subjected to analysis of variance (ANOVA). The optimal values of the independent parameters were obtained by the desirability function.

3 RESULTS AND DISCUSSION

3.1 PLACKETT & BURMAN 12 (PB-12)

The results of the response variables obtained after the PB-12 design tests are presented in Table 4.

Table 4 - Values of the response variables of the PB-12 design tests.

Test	Factor								Response			
	CS	M	Ma	S	E	C	T	P	Ex	Tx (N)	Wl (%)	D (g mL^{-1})
1	75	50	25	2.0	20	40	3.0	90	0.99	314.64	19.70	0.75
2	75	60	15	4.0	20	40	2.0	90	0.94	41.50	15.30	0.84
3	25	60	25	2.0	30	40	2.0	70	0.94	25.99	5.63	0.83
4	75	50	25	4.0	20	60	2.0	70	0.96	41.94	5.12	0.79
5	75	60	15	4.0	30	40	3.0	70	0.96	33.06	10.05	0.75
6	75	60	25	2.0	30	60	2.0	90	0.92	29.18	7.74	0.82
7	25	60	25	4.0	20	60	3.0	70	0.93	35.03	9.28	0.83
8	25	50	25	4.0	30	40	3.0	90	0.98	172.54	16.97	0.73
9	25	50	15	4.0	30	60	2.0	90	0.99	49.89	8.34	0.58
10	75	50	15	2.0	30	60	3.0	70	0.96	45.73	8.68	0.64
11	25	60	15	2.0	20	60	3.0	90	0.92	123.59	14.45	0.81
12	25	50	15	2.0	20	40	2.0	70	1.00	32.88	4.20	0.86
13 (C)	50	55	20	3.0	25	50	2.5	80	0.97	46.29	8.22	0.74
14 (C)	50	55	20	3.0	25	50	2.5	80	0.95	53.81	8.44	0.85
15 (C)	50	55	20	3.0	25	50	2.5	80	0.96	61.71	8.47	0.77

CS (Sweet cassava starch); M (Milk); Ma (Margarine); S (Salt); E (Egg); C (Cheese);
Ex (Expansion); Tx (Texture); Wl (Weight loss); D (Density)

The expansion index values were less than or equal to 1. This was not expected since values less than 1 indicate that the *pão de queijo* after baking is smaller than before baking. This can be explained by the microwave irradiation baking method. When observing the behavior of the *pão de queijo* during the time the oven is emitting microwaves onto it, it is clear that it rises but does not have the structure to maintain its shape, withering soon after. Microwaves heat food at a molecular level, causing heat to spread from the inside to the outside (Ramesh, 2007). Thus, the problem of baking the external surface could be solved by increasing the baking time and/or microwave oven power. However, for higher levels of these variables, *pães de queijo* burned up inside, regardless of the formulation. Therefore, under the tested experimental conditions, none of the design tests reached efficient heat propagation through the *pão de queijo* to the point where it could maintain a stable structure that would allow its expansion without burning inside.

The three highest texture values were achieved with the highest levels of time and power, in agreement with the discussion above. Studies using compression tests to determine the texture of *pão de queijo* baked in electric ovens obtained approximately 18 N (Pereira, 2001; Silva *et al.*, 2009).

This value is well below those found here, which had the texture varying between test 3 (25.99N) and test 1 (314.64N), with an average of 73.85 ± 77.49N.

Nagata (2011) carried out experiments to optimize the formulation of premixes for *pão de queijo* and reported texture values that varied between 18.74N and 46.23N. However, according to the work cited, the texture should be as low as possible, as the lower the value, the softer the *pão de queijo* can be. The result cited by Nagata (2011) was proven in the sensory analysis, in which the *pão de queijo* with the lowest compression force had the greatest acceptance in terms of texture by the public.

Immediately after being baked in a microwave oven, *pão de queijo* has a soft texture to the touch. However, due to the necessary cooling period before texturometer measurements, the product's texture changed over time, becoming increasingly harder to the touch. This may be due to the retrogradation of cassava starch and may justify the high texture values found in the present study but further research is required to elucidate this observation. Bilbao-Sáinz *et al.* (2007) studied the gelatinization of wheat starch and noted that the heating mechanism influenced gelatinization since more energy was required for the gelatinization of these starch granules under microwave irradiation compared to the energy required for gelatinization of samples heated by conduction. Therefore, a suggestion for future experiments is to study the gelatinization and retrogradation of cassava starch by heating using microwave irradiation.

Another reason for the high texture values found here could be the quantities of cheese used in the formulations. According to Pereira (1998), cheese contents greater than 35% in relation to starch make the crumb heavier. Because of this, the level of cheese was reduced in the CCRD.

Machado and Pereira (2010) investigated the texture of *pães de queijo* scalded and baked in an electric oven. One of the formulations of their treatments closest to the formulation used in test 12 (32.88N texture) showed a texture of 16.64N. This difference was almost double (proportion of 1.98) between the texture values found in these experiments, distinguishing the baking methods used.

The lowest weight loss was observed in test 12, with 4.20%, and the largest was in test 1, with 19.70%. Weight loss during baking can indicate the amount of water lost through evaporation during this step, as the other reactions (caramelization, Maillard reaction, and starch gelatinization) do not significantly influence weight loss (Cardoso *et al.*, 2016). Weight loss can also be related to texture, as they appear to have a positive correlation, as seen in Table 4.

Some ingredients help retain water in *pão de queijo*, such as starches that trap water molecules in their structures (Frazier, 2015), the egg that acts as an emulsifier and binding agent (Pereira, 1998), oils and fats that, during baking, form a film on the surface of the product, which prevents water from escaping (Panificação..., 2009), and salt that in addition to trapping water due to its high water solubility, strengthens and stabilizes the gelatinized starch, making it retain more molecules and reducing moisture loss (Pereira, 1998).

In addition to the impact of the ingredients, the baking conditions are expected to interfere with the loss of water since higher values of baking time and microwave oven power provide more heat transfer in *pão de queijo*, evaporating more water . This is evidenced in the results obtained in tests 1 (higher levels of fat, time, and power) and 12 (lower levels of fat, salt, egg, time, and power), which showed the highest and lowest weight loss, respectively. Test 8 also presented a high weight loss value (16.97%) because of the the highest levels of fat, salt, egg, time, and power. The reason test 1 showed higher weight loss than test 8, even using lower levels of salt and egg, may be due to the higher amount of sweet cassava starch. According to Demiate (2007), sour cassava starch dough releases more water (syneresis) than sweet cassava starch dough.

The density of *pães de queijo* varied between 0.58g mL^{-1} (test 9) and 0.86g mL^{-1} (test 12). Values higher than those reported by Pereira (2001) in a complete and frozen formulation.

According to Pereira (2001), a lighter *pão de queijo*, with lower density values, is desirable; with a complete and frozen formulation, the author found a density of 0.44g mL^{-1}. The mentioned study proved that cheese has a positive correlation with density and that eggs have a negative correlation. The author also stated that frozen formulations present denser *pães de queijo*.

Therefore, a possible justification for the high-density values in this experiment may have been the high quantities of cheese used in the formulations. Although test 9 showed a lower density and a higher amount of cheese than test 12, which reached a higher density, it also had higher amounts of salt and egg and was baked at a higher power. Baking at a higher power implies more heat transfer in *pão de queijo* at this stage, which corresponds to more water evaporation, higher weight loss, and consequently, lower density (ratio of weight to volume).

Table 5 lists the effects of the factors on the response variables evaluated in PB-12. The statistically significant factors at the 5% level were milk and cheese for the expansion response; milk, margarine, salt, egg, cheese, time, and power for the texture response; sweet cassava starch, margarine, salt, egg, cheese, time, and power for the weight loss response; and none for the density response. As many effects were significant, only four were selected for the CCRD because a design with many effects would be unfeasible.

Table 5 - Effects and p-values of the factors evaluated in the PB-12 design for the response variables.

Factor	Expansion		Texture (N)		Weight loss (%)		Density (g mL^{-1})	
	Effect	p-value	Effect	p-value	Effect	p-value	Effect	p-value
Mean	0.958	0.000*	73.852	0.001*	10.038	0.000*	0.772	0.000*
CS (%)	-0.005	0.387	11.023	0.132	1.285	0.004*	-0.008	0.830
M (%)	-0.042	0.010*	-61.547	0.005*	-0.096	0.347	0.093	0.107
Ma (%)	-0.009	0.162	48.776	0.008*	0.571	0.018*	0.044	0.310
S (%)	0.005	0.382	-33.009	0.018*	0.779	0.010*	-0.032	0.430
E (%)	0.005	0.400	-38.865	0.013*	-1.772	0.002*	-0.087	0.118
C (%)	-0.019	0.045*	-49.207	0.008*	-3.040	0.001*	-0.049	0.276
T (min)	0.000	0.932	83.868	0.003*	5.468	0.000*	-0.038	0.371
P (%)	-0.002	0.651	86.120	0.003*	6.592	0.000*	-0.029	0.478

*statistically significant at 5% ($p<0.05$).

CS (Sweet cassava starch); M (Milk); Ma (Margarine); S (Salt); E (Egg); C (Cheese); T (Time); P (Power).

For expansion, both significant effects showed a negative correlation with the response, i.e., the smaller the amount of cheese or milk used, the higher the expansion, and vice versa.

For texture, the significant effects of milk, salt, egg, and cheese showed a negative correlation. The margarine, time, and power factors showed a positive correlation, i.e., the higher the levels of these factors, the higher texture values were obtained. Observing the module of values, the four largest effects achieved were the factors power, time, milk, and cheese, respectively. This indicates that these variables had the highest impact on the texture response, according to the PB-12 design.

For weight loss, among the significant effects, only egg and cheese showed a negative correlation, while the rest showed a positive correlation with the response. The four largest effects, in module terms, were power, time, cheese, and egg.

For density, none of the effects were significant at a level of 5%. In other words, varying the values of the factors at the levels proposed in the PB-12 design caused no significant influence on the density response. Even though it was non-significant, the milk factor had the greatest effect on density.

Therefore, the factors chosen to be evaluated in the CCRD were milk, cheese, time, and power, as they are, in the majority, those with the greatest effects on the responses.

The relationship between sweet cassava starch and sour cassava starch was expected to have a higher influence on the process because of the difference in expansion their use can cause in *pão de queijo*. However, what may justify this effect not being significant or being very low is the fact that microwave baking was not efficient for *pão de queijo* to sustain its structure when rising. The heating from the inside to the outside caused by irradiation under the conditions of this experiment did not favor the hardening of the crust of *pão de queijo*, which withered after the incidence of microwaves from the oven ceased (a fact evidenced by the results equal to or less than 1 for expansion).

Sumnu *et al.* (2007) also observed that microwave baking caused problems in bread quality, such as dense texture, hard crumb, small volume, lack of color on the surface, and high moisture loss. Specific interactions of each component of the formulation with microwave energy, known as dielectric properties, can be the cause of these problems. These properties vary significantly during heating, especially above 80°C for protein and starches. These changes can qualitatively affect the heating pattern, while such factors are not influential in conventional thermal processing (Ahmed and Ramaswamy, 2007).

Liquid water is very polar and can easily absorb microwave energy; thus, foods with high moisture have high dielectric activity, which means they receive a lot of heat generated by irradiation. Food components such as proteins, triglycerides, and carbohydrates have low dielectric activity at microwave frequencies, receiving little direct heating (Sahin and Sumnu, 2006). In this way, once cheese is defined as a concentrated product of protein and fat (Bezerra, 2008), its composition may explain its significance in this study, like milk. The dielectric properties of milk can be affected by the protein, lactose, fat, and moisture content of its composition.

3.2 2^4 CENTRAL COMPOSITE ROTATIONAL DESIGN (2^4 CCRD)

The results of the response variables after running 2^4 CCRD design tests are in Table 6.

Table 6 - Values of the response variables of the 2^4 CCRD design tests.

Factor	Dependent Variable				Independent Variable			
	M (%)	C (%)	T (min)	P (%)	E	Tx (N)	Wl (%)	D (g mL^{-1})
1	50	30	2.5	70	1.00	48.22	9.50	0.77
2	50	30	2.5	90	1.00	139.14	15.20	0.75
3	50	30	3.5	70	1.00	169.55	16.85	0.71
4	50	30	3.5	90	1.06	494.62	24.53	0.59
5	50	50	2.5	70	0.94	47.87	10.01	0.85
6	50	50	2.5	90	0.98	99.67	15.08	0.73
7	50	50	3.5	70	0.94	107.22	17.24	0.67
8	50	50	3.5	90	1.00	480.34	24.37	0.55
9	60	30	2.5	70	0.98	37.04	10.20	0.66
10	60	30	2.5	90	1.01	94.23	15.83	0.70
11	60	30	3.5	70	0.94	147.72	16.33	0.90
12	60	30	3.5	90	1.01	422.17	24.75	0.60
13	60	50	2.5	70	0.96	37.66	10.92	0.67
14	60	50	2.5	90	1.00	59.31	16.94	0.61
15	60	50	3.5	70	0.95	63.39	13.85	0.86
16	60	50	3.5	90	0.97	253.40	19.98	0.73
17	45	40	3	80	1.03	100.10	15.75	0.60
18	65	40	3	80	0.96	78.25	17.15	0.71
19	55	20	3	80	1.02	120.89	16.32	0.65
20	55	60	3	80	0.94	50.50	14.19	0.79
21	55	40	2	80	0.98	45.20	9.49	0.77
22	55	40	4	80	1.04	250.01	22.14	0.43
23	55	40	3	60	0.99	44.88	10.53	0.70
24	55	40	3	100	0.99	442.89	23.47	0.64
25 (C)	55	40	3	80	1.01	126.72	15.31	0.73
26 (C)	55	40	3	80	1.04	104.62	16.39	0.61
27 (C)	55	40	3	80	1.02	127.59	16.78	0.71

Responses: M (Milk); C (Cheese); T (time); P (Power);
E (Expansion); Tx (Texture); Wl (Weight loss); D (Density).

In this design, tests 10, 12, 17, 19, 22, 25, 26, and 27 showed expansion higher than 1, varying between 1.01 and 1.04. However, these are still low values and indicate that these *pães de queijo* only rose by 1 to 4% compared to their size before baking. Pereira (2001) obtained an average expansion value for *pães de queijo* prepared with a complete formulation of 1.39, i.e., an increase of 39% in size after baking.

The texture values remained high, varying from 37.04N to 494.62N. Tests 4, 8, 24, and 12 presented the four highest texture values, respectively, higher than 400 N. These tests reached the lowest weight losses and densities, which were lower than found in the PB-12 design. A possible explanation is that the baking conditions may have led to higher water evaporation, making the product harder but with less weight and, consequently, lower density.

Test 22 presented the lowest density value, 0.44g mL^{-1}, close to that found by Pereira (2001) (0.41g mL^{-1}). It also showed the greatest expansion and lost about 22% weight during baking. However, its texture went far beyond the value considered desirable by Machado and Pereira (2010).

Table 7 lists the values of the linear, quadratic effects, and first-order interactions of the factors on the responses evaluated in the 2^4 CCRD. The significant factors at the 5% level were the linear effects of cheese and power for the response expansion, the linear effects of milk, cheese, time, and power, the quadratic effect of power, and the effects of interactions between milk and time, milk and power, cheese and time, and time and power for the texture response, the linear effects of time and power on the weight loss response, and none for the density response.

Table 7 - Linear (L), quadratic (Q) effects, and interactions between 2^4 CCRD design factors for the response variables.

Factor	E		Tx (N)		Wl (%)		D (g mL^{-1})	
	Effect	p-value	Effect	p-value	Effect	p-value	Effect	p-value
Mean	-0.022	0.065	-42.951	0.015*	-0.098	0.784	0.028	0.382
M (%) (M)	-0.015	0.140	-6.149	0.389	0.217	0.581	0.003	0.929
M (%) (C)	-0.035	0.027*	-45.384	0.013*	-0.756	0.137	0.022	0.471
C (%) (M)	-0.025	0.060	-7.889	0.297	-0.380	0.370	0.035	0.328
C (%) (C)	0.011	0.197	165.408	0.001*	6.623	0.002*	-0.068	0.115
T (min) (M)	-0.011	0.234	23.067	0.055	-0.100	0.792	-0.026	0.435
T (min) (C)	0.029	0.041*	181.686	0.001*	6.474	0.002*	-0.079	0.089
P (%) (M)	-0.020	0.089	71.207	0.006*	0.491	0.277	0.011	0.713
P (%) (C)	0.017	0.143	-21.371	0.082	-0.755	0.188	0.006	0.875
Interaction MxC	-0.019	0.124	-32.299	0.038*	-1.523	0.058	0.129	0.054
Interaction MxT	-0.001	0.950	-37.201	0.029*	0.077	0.860	-0.012	0.739
Interaction MxP	-0.005	0.539	-31.949	0.039*	-1.153	0.095	0.004	0.913
Interaction CxT	0.000	0.993	-13.881	0.167	-0.383	0.423	-0.005	0.897
Interaction CxP	0.014	0.189	117.636	0.003*	0.868	0.152	-0.064	0.175
Interaction TxP	-0.022	0.065	-42.951	0.015*	-0.098	0.784	0.028	0.382

Responses: E (Expansion); Tx (Texture); Wl (Weight loss);
D (Density). *statistically significant at 5% ($p<0.05$).

A linear effect of a statistically significant factor represents a proportional association between this factor and the response, and the response surface is a linear function. Likewise, significant quadratic effects indicate a curvature in the response surface, and there will be critical points in the associations of factors with responses. Positive quadratic effects indicate that by increasing the factor level, the response increases exponentially (and no longer in the same proportion as the factor, as would be the case if the effect were linear).

Significant effects of interactions between two variables mean that the relationship between one factor and the response variable depends on the other factor in the interaction. For example, for *pães de queijo* in this experiment, the influence on the texture due to the amount of milk used in the formulation changes depending on the time used for baking in the microwave oven.

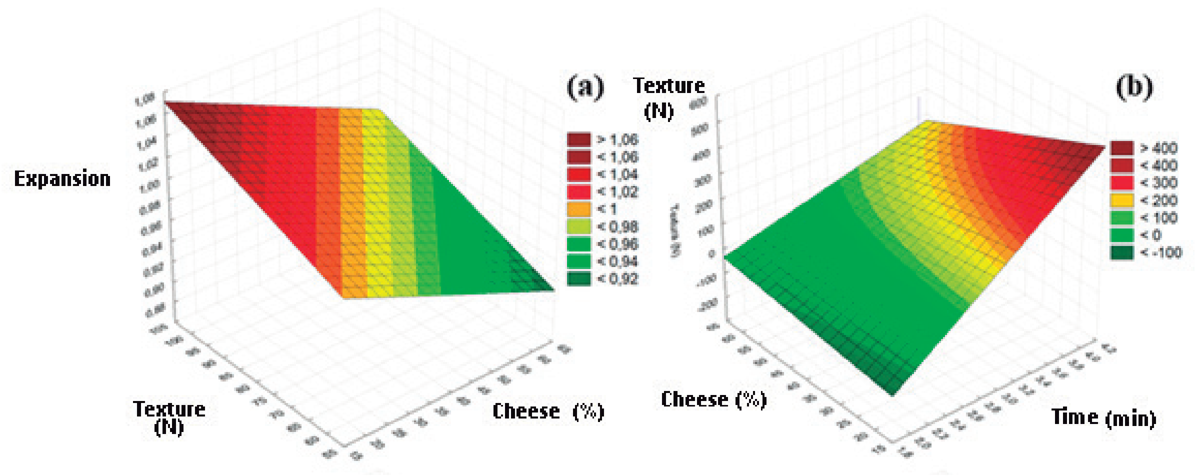
Table 8 presents the ANOVA summary for the predictive models for expansion, texture, and weight loss responses. Equation (1) describes the expansion as a function of cheese and power. Its coefficient of determination R^2 was 0.4106, which means that 41.06% of the expansion was explained by cheese and power, and 59.94% of the model's variance depended on other variables. However, the regression was considered statistically significant by ANOVA ($F_{calculated}$>F_{table}) and showed no lack of fit ($F_{calculated}$>F_{table}), illustrated in Figure 2 (a). According to the response surface, it is necessary to bake *pães de queijo* at higher powers and use less cheese in the formulation to obtain higher expansion values.

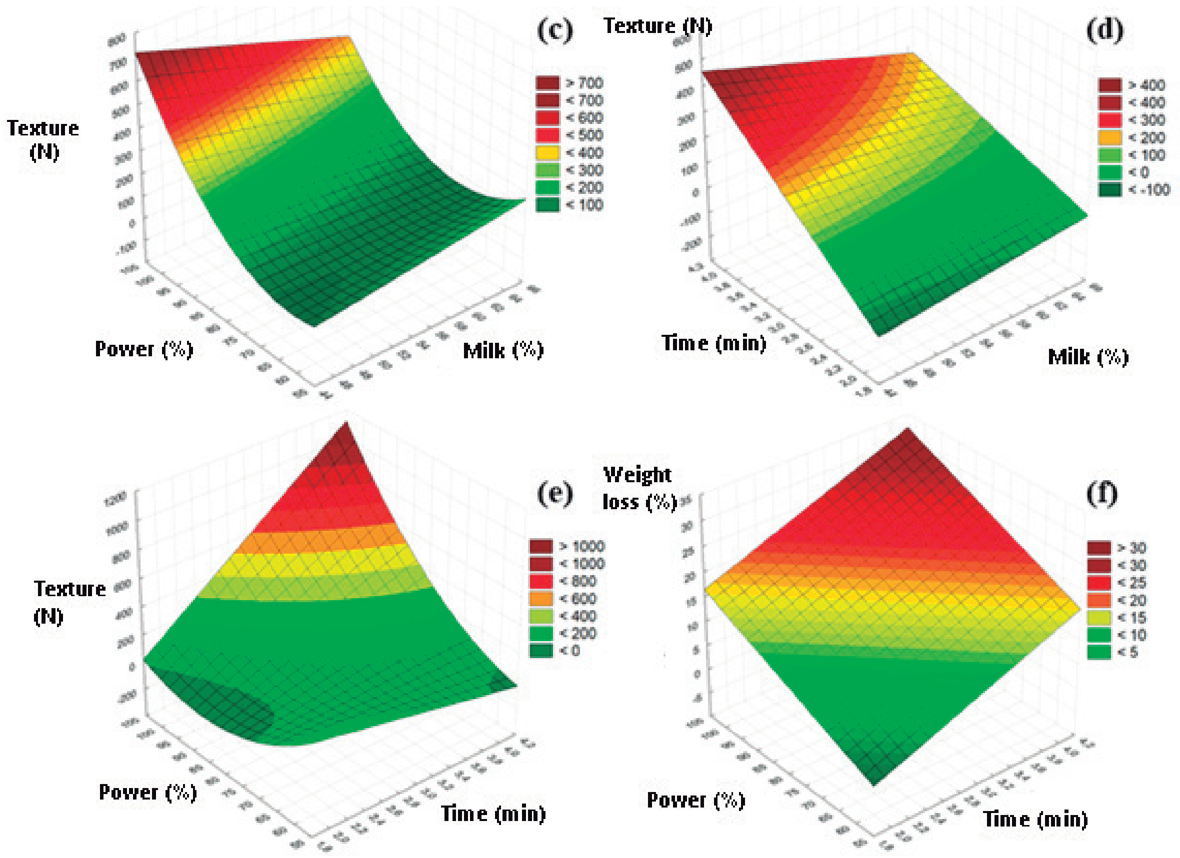
Table 8 - Summary of statistical analyses of predictive models with significant effects for response variables.

Factor	R^2	Regression		Lack of Fit		Equation
		F_{cal}	F_{tab}	F_{cal}	F_{tab}	
E	0.416	8.358*	3.400	3.666^{ns}	248.535	E = 0.991 - 0.035C + 0.029P (1)
Tx	0.9344	26.906*	2.494	13.315^{ns}	19.429	Tx = 124.459 - 42.951M - 45.384C + 165.408T + 181.686P + 69.4006P² - 32.299L*T - 37.201L*P - 31.949C*T + 117.636T*P (2)
PP	0.9324	165.442*	3.400	2.800^{ns}	248.535	Wl = 16.262 + 6.623T + 6.474P (3)

Response Factors: E (Expansion); Tx (Texture); Wl (Weight loss); D (Density). F values: F_{cal} (F calculated); F_{tab} (F table). * statistically significant at 5% (p<0.05). ns statistically non-significant at 5% (p<0.05).

Figure 2 - Response surfaces for (a) Expansion as a function of power and cheese; Texture as a function of (b) cheese and time; (c) power and milk; (d) time and milk; (e) power and time; (f) Weight loss as a function of power and time.





The non-significant lack of fit implies that the model parameters consider all significant effects for the response variable in question, i.e., there is no indication of additional effects beyond those evaluated, such as, for example, there are no interactions of higher order among design factors (StatSoft, 2007).

Equation (2) describes the texture response as a function of significant factors, which was significant according to ANOVA, presented fit, and explained 93.44% of the process. Lower texture values are desirable for *pão de queijo*; therefore, according to Figures 2 (b), (c), (d), and (e), smaller amounts of milk and cheese should be used, and doughs should be baked in a microwave oven for longer with less power, or shorter with more power.

The response to weight loss as a function of time and power is described by Equation (3). The model presented no lack of fit, was significant, and explained 93.24% of the process. According to data obtained by Pereira (2001), *pão de queijo* with a complete formulation and frozen dough loses around 12% moisture during baking in a conventional electric oven. Therefore, by interpreting Figure 2 (f), for these weight loss values, lower powers and longer times, or higher powers and shorter times, or close to the central point, are recommended.

The experiment's optimal conditions for responses with significant models were determined by the desirability function. Desirability values equal to 1 (most desirable value) were assigned to the highest expansion (1.064), lowest texture (37.04 N), and 12% weight loss. The other expansion and texture values were assigned a desirability of 0 (unacceptable value) and the weight loss values of 10% and 14% were assigned a desirability of 0.5 (somewhat acceptable).

The overall desirability was 59.9%, i.e., 59.9% of the desired responses were achieved. The optimal conditions for the ingredients and baking parameters of *pão de queijo* in a microwave oven were 55% milk, 40% cheese, 3 minutes of baking time, and 80% power of the actual power of the microwave oven.

4 CONCLUSION

The Plackett & Burman screening design identified that the quantities of milk and cheese, baking time, and oven power were the significant factors with the greatest effects on the expansion, texture, and weight loss of *pães de queijo* baked in the microwave.

To optimize the formulation and baking parameters of these *pães de queijo* with these variable responses, a CCRD was used, where the significant factors were analyzed. In this way, the optimal conditions achieved were 55% milk, 40% cheese, 3 minutes of baking time, and 80% power of the actual power of the microwave oven.

In conclusion, the physical properties (texture and expansion) of *pães de queijo* formulated and baked using optimal conditions determined in this study are not similar to those baked in conventional ovens found in the literature. Therefore, further studies are required on the impact of the ingredients and baking parameters of *pão de queijo* in the microwave oven, as well as parameters that were not considered here, such as physical-chemical and electrical properties of the ingredients and their interactions with microwaves, geometry, and positioning of products in the oven, and use of packaging.

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