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A fast and low-cost method for determining moisture content in frozen pre-fried potatoes

Método rápido e de baixo custo para determinação de umidade em batatas pré-fritas congeladas

Un método rápido y de bajo costo para determinar el contenido de humedad en papas prefritas congeladas

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ABSTRACT: The pursuit of rapid, affordable, and energy-efficient analytical methods offers an opportunity to improve quality control in the food industry. In this context, this study developed and evaluated a gravimetric method for determining moisture content in frozen pre-fried potatoes, using a conventional air fryer as an alternative to an industrial convection oven procedure adapted from AOAC Official Method 984.25. Experimental optimization was performed using a Box–Behnken design comprising 15 experimental runs, combined with response surface methodology, considering sample mass (1–3 g), heating time (5–25 min), and temperature (100–140 °C). The optimized conditions were established at 1.0 g, 17.3 min, and 120 °C, yielding a mean moisture recovery of 101.74% (95% confidence interval: 99.92–103.56%), closely matching the model-predicted value of 102.35%. Comparison with the industrial procedure, standardized at 3 h and 105 °C, involved six independent samples analyzed in triplicate, with no statistically significant mean difference detected between the methods ($p = 0.058$). Relative standard deviations were 0.59% for repeatability and 1.57% for intermediate precision. The energy assessment, based on direct measurements, revealed an average electricity consumption of 0.122 kWh per cycle for the air fryer, compared with 0.867 kWh for the convection oven, corresponding to reductions of approximately 85.9% in electricity consumption and 90.4% in heating time. These findings highlight the

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potential of conventional, low-cost equipment as an alternative analytical solution, contributing to the development of faster, more accessible, and energy-efficient procedures for industrial quality control.

Keywords: moisture determination, frozen pre-fried potatoes, gravimetric method, box–behnken design, energy efficiency.

RESUMO: A busca por métodos analíticos rápidos, acessíveis e energeticamente eficientes representa uma oportunidade para aprimorar o controle de qualidade na indústria alimentícia. Nesse contexto, este estudo desenvolveu e avaliou um método gravimétrico para determinação do teor de umidade em batatas pré-fritas congeladas, utilizando uma fritadeira de ar convencional como alternativa ao procedimento industrial em estufa de convecção, adaptado do método AOAC 984.25. A otimização experimental empregou planejamento Box–Behnken, com 15 ensaios, associado à metodologia de superfície de resposta, considerando massa da amostra (1–3 g), tempo de aquecimento (5–25 min) e temperatura (100–140 °C). A condição otimizada foi estabelecida em 1,0 g, 17,3 min e 120 °C, apresentando recuperação média de umidade de 101,74% (IC95%: 99,92–103,56%), próxima ao valor previsto pelo modelo (102,35%). A comparação com o procedimento industrial, padronizado em 3 horas a 105 °C, envolveu seis amostras independentes analisadas em triplicata, não sendo identificada diferença média estatisticamente significativa entre os métodos (p = 0,058). Os desvios-padrão relativos foram de 0,59% para repetibilidade e 1,57% para precisão intermediária. A avaliação energética, baseada em medições diretas, revelou consumo médio de 0,122 kWh por ciclo para a fritadeira, frente a 0,867 kWh para a estufa, correspondendo a reduções de aproximadamente 85,9% no consumo elétrico e 90,4% no tempo de aquecimento. Os resultados demonstram o potencial da utilização de equipamentos convencionais de baixo custo como soluções analíticas alternativas, contribuindo para o desenvolvimento de procedimentos mais rápidos, acessíveis e energeticamente eficientes no controle de qualidade industrial.

Palavras-chave: determinação de umidade, batatas pré-fritas congeladas, método gravimétrico, planejamento box–behnken, eficiência energética.

RESUMEN: La búsqueda de métodos analíticos rápidos, accesibles y energéticamente eficientes representa una oportunidad para mejorar el control de calidad en la industria alimentaria. En este contexto, el presente estudio desarrolló y evaluó un método gravimétrico para determinar el contenido de humedad en papas prefritas congeladas, utilizando una freidora de aire convencional como alternativa al procedimiento industrial en horno de convección, adaptado del método oficial AOAC 984.25. La optimización experimental se realizó mediante un diseño Box–Behnken de 15 ensayos, combinado con la metodología de superficie de respuesta, considerando la masa de la muestra (1–3 g), el tiempo de calentamiento (5–25 min) y la temperatura (100–140 °C). Las condiciones optimizadas se establecieron en 1,0 g, 17,3 min y 120 °C, obteniéndose una recuperación media de humedad del 101,74 % (intervalo de confianza del 95 %: 99,92–103,56 %), cercana al valor previsto por el modelo (102,35 %). La comparación con el procedimiento

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industrial, estandarizado en 3 horas a 105 °C, incluyó seis muestras independientes analizadas por triplicado, sin detectarse diferencias medias estadísticamente significativas entre los métodos (p = 0,058). Las desviaciones estándar relativas fueron del 0,59 % para la repetibilidad y del 1,57 % para la precisión intermedia. La evaluación energética, basada en mediciones directas, reveló un consumo eléctrico medio de 0,122 kWh por ciclo para la freidora de aire, frente a 0,867 kWh para el horno de convección, lo que representa reducciones aproximadas del 85,9 % en el consumo eléctrico y del 90,4 % en el tiempo de calentamiento. Los resultados evidencian el potencial de los equipos convencionales de bajo costo como soluciones analíticas alternativas, contribuyendo al desarrollo de procedimientos más rápidos, accesibles y energéticamente eficientes para el control de calidad industrial.

Palabras clave: determinación de humedad, papas prefritas congeladas, método gravimétrico, diseño box–behnken, eficiencia energética.

1. INTRODUCTION

The market for frozen pre-fried potatoes has expanded with the increasing consumption of convenience foods and potato-based snacks. According to the French Fries Global Market Report (TBRC, 2026), the sector is projected to reach USD 24.87 billion by 2030. In this context, product quality provides a competitive advantage, and moisture determination plays a central role because moisture content affects preservation, as reflected in shelf life, solids content, texture, and other sensory attributes that are essential to market performance (Kita, 2002; Pedreschi, 2012; Singh, 2016).

Moisture content in foods is traditionally determined by gravimetric methods. AOAC Official Method 984.25 provides a recognized reference procedure for determining moisture content in frozen French-fried potatoes using convection oven drying. Despite its established use as a reference procedure, this method presents certain limitations, including long analysis times, the need for dedicated laboratory infrastructure, and practical constraints in routine industrial applications. Consequently, rapid, low-cost, straightforward, and potentially reliable alternatives have been investigated, including near-infrared (NIR) spectroscopy, microwave drying, infrared drying, and capacitive or electrical sensors. These efforts have encouraged the development of new approaches

ISSN: 2448-0916

and the adaptation of unconventional equipment (Raschen, 2014; Nielsen, 2017; Nirmaan, 2020).

Near-infrared (NIR) spectroscopy enables rapid, nondestructive analysis with little or no sample preparation and is particularly sensitive to water. However, quantitative applications require calibration models developed and validated for the matrix under investigation, because sample temperature, composition, and physical state can affect spectra and predictive performance (Büning-Pfaue, 2003; Cen; He, 2007). Microwave drying reduces analysis time, but its accuracy depends on factors such as power, sample mass and composition, container geometry, and position within the oven; nonuniform heating may also compromise accuracy (Bouraoui; Richard; Fichtali, 1993; Datta; Raghavan, 2012).

Infrared radiation can also accelerate drying, although its performance and effects on quality depend on power, intensity, source distance, temperature, and sample thickness, with a risk of overheating under excessive exposure (Huang *et al.*, 2021). Methods based on electrical or dielectric properties enable rapid, nondestructive, and potentially continuous measurements. However, in addition to moisture content, these measurements are influenced by composition, structure, temperature, density, and measurement frequency, requiring product-specific calibration (Jha; Narsaiah; Basediya, 2011). In this context, air fryers warrant investigation because of their forced air circulation, speed, and operational simplicity. Nevertheless, potential energy or economic advantages must be confirmed through direct measurements and cost analyses that account for effective equipment capacity.

For a proposed method to be adopted reliably, it must be properly validated against analytical performance criteria established by recognized organizations. Validation ensures that the method is fit for its intended purpose and that its results are comparable with those obtained using reference methods (Remesp, 2016; DOQ-CGCRE-008, 2020).

Accordingly, this study aimed to develop, optimize, and conduct a preliminary performance evaluation of a gravimetric method for determining moisture content in

ISSN: 2448-0916

frozen pre-fried potatoes, using an air fryer for water evaporation from the samples. Additionally, the study sought to compare the performance of the proposed method with that of the reference method and to assess equipment acquisition costs and actual electrical energy consumption per cycle, directly measured using the Philips Walita NA130 air fryer and the Fanem 515 drying oven, to investigate the method's potential applicability in small-scale laboratory routines. To optimize the operating conditions, a Box–Behnken experimental design combined with response surface methodology (RSM) was employed.

2. THEORETICAL FRAMEWORK

2.1 GRAVIMETRIC METHODS AND ALTERNATIVE DRYING TECHNIQUES

An air fryer is a household appliance similar to a forced-convection oven. Its operation combines high temperature, generated by an electrical heating element, with high internal air velocity produced by fans. Air circulates rapidly, and the basket geometry promotes hot-air circulation around all parts of the food (Tecnoblog, 2022). Surface moisture evaporates rapidly because of the high heat and mass transfer coefficients associated with thin-layer drying and negligible external resistance. Once surface moisture has fully evaporated and heat diffuses into the sample, the drying rate decreases exponentially (Monteiro, 2020).

Gravimetric moisture determination is based on mass loss under specified thermal conditions. In alternative methods, heating time, temperature, and sample mass must be controlled to minimize incomplete drying and potential losses of nonaqueous components (Nielsen, 2017; AOAC International, 2019).

ISSN: 2448-0916

2.2 EXPERIMENTAL DESIGN AND ANALYTICAL PERFORMANCE

The Box–Behnken design enables investigation of linear, quadratic, and interaction effects using a small number of experiments (Box; Behnken, 1960; Ferreira *et al.*, 2007). Model fit must be interpreted using analysis of variance, residual analysis, lack-of-fit testing, and internal predictive performance (NIST/SEMATECH, 2013). Analytical method assessment involves recovery and precision, while distinguishing the absence of a statistically significant difference from equivalence (INMETRO, 2020; REMESP, 2016).

3 METHODOLOGY

3.1 SAMPLES EQUIPMENT AND MOISTURE DETERMINATION

Figure 1 presents a comparative flowchart of the procedures used to determine moisture content using the adapted industrial reference procedure and the proposed method. Frozen pre-fried potato samples obtained from an industrial facility in Perdizes, Minas Gerais, Brazil, were initially ground using a household food processor (Skymsen, model CR-4L), as shown in the first step of the flowchart, to ensure sample homogeneity.

After homogenization, the samples were weighed and divided into two portions, corresponding to the two experimental workflows shown in Figure 1: (i) an industrial gravimetric procedure adapted from AOAC 984.25, using an oven at 105 °C (Fanem, model 515) with a standardized operating time of 3 h; and (ii) the proposed method, using an air fryer (Philips Walita, model NA130).

In both methods, after drying in the oven or air fryer, the samples were transferred to a glass desiccator with a ground-glass lid containing blue silica gel (4–8 mm, analytical grade) on a porcelain plate (210 mm). They were cooled to room temperature while preventing moisture reabsorption, as illustrated in the next step of Figure 1. In the final step, common to both methods, sample mass was determined using a semi-analytical balance (Ohaus, model ARA 250) and previously tared porcelain dishes (225 mL;

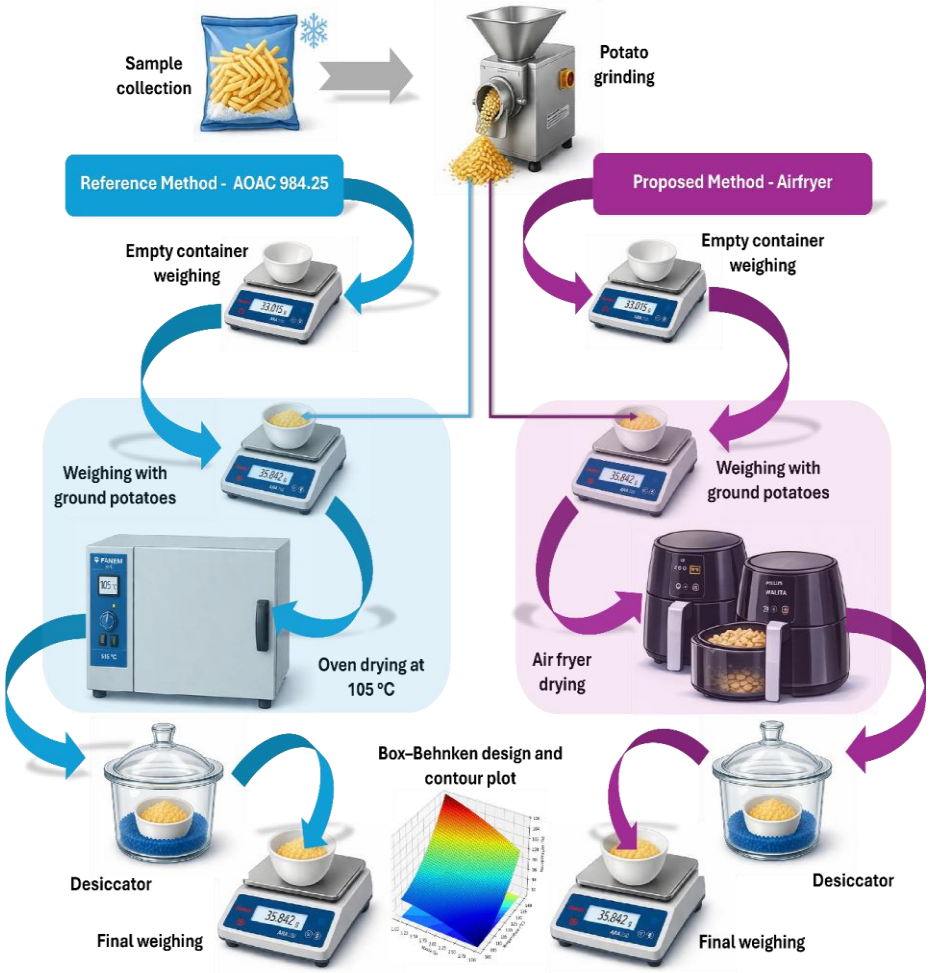
ISSN: 2448-0916

Chiarotti). Moisture content was calculated from the initial and final masses using Equation 1.

$$\%\,\text{Moisture} = 100 - \left(\frac{m_f - m_i}{m_a} \times 100\right) \quad (1)$$

m_f= final mass after drying (dish + sample); m_i= mass of the empty dish; m_a= initial sample mass

Figure 1. Flowchart of the reference and proposed procedures for moisture determination.



Source: The authors, 2026.

ISSN: 2448-0916

3.2 DRYING PROCEDURES

For moisture content determination using the conventional procedure, AOAC Official Method 984.25 – *Moisture (Loss of Mass on Drying) in Frozen French-Fried Potatoes: Convection Oven Method* was adopted as the methodological reference. However, the experimental procedure followed an operational adaptation previously standardized at the industrial facility from which the samples originated, in which the drying time was reduced from 16 to 3 hours while maintaining a temperature of 105 °C. This condition was established based on previous experimental evaluations that indicated stabilization of moisture content measurements for the specific characteristics of the product under investigation.

For the analyses, pre-weighed portions of the homogenized samples were transferred into previously dried and tared porcelain dishes and subjected to drying in a Fanem Model 515 convection oven at 105 °C for 3 hours. Following drying, the dishes containing the samples were transferred to a desiccator containing silica gel, allowed to cool to room temperature, and weighed again to determine the final mass. It should be emphasized that the procedure employed represents an operational adaptation of the reference method, and its full equivalence to the official AOAC 984.25 method was not demonstrated in the present study.

In the proposed method, previously weighed portions of the ground sample were transferred to dry, tared porcelain dishes and dried in an air fryer (Philips Walita, model NA130), as illustrated in Figure 1. Two units were used to minimize instrumental variation and improve the reliability and repeatability of the analyses. Drying conditions were defined using a Box–Behnken experimental design combined with response surface methodology (RSM). After drying, the samples were transferred to a desiccator containing silica gel, allowed to reach room temperature, and then weighed using a semi-analytical balance to determine their final mass.

ISSN: 2448-0916

3.3 BOX–BEHNKEN DESIGN AND STATISTICAL MODELING

Experimental conditions were optimized using a Box–Behnken design (Box and Behnken, 1960) combined with response surface methodology (RSM). This three-level design allows the linear, quadratic, and interaction terms of a second-order model to be estimated using few runs (Ferreira *et al.*, 2007). Actual factor levels were converted to coded units using Equation 3, and the response was fitted by ordinary least squares to the full quadratic model in Equation 4. Modeling, ANOVA, lack-of-fit testing, and residual analysis followed the NIST/SEMATECH recommendations for response surface models (NIST, 2013).

The independent variables were sample mass (1, 2, and 3 g), heating time (5, 15, and 25 min), and temperature (100, 120, and 140 °C), selected because of their direct influence on drying. Sample mass affects representativeness and layer thickness, influencing water diffusion and evaporation. Heating time is related to achieving constant mass while avoiding incomplete drying and additional losses caused by degradation. Temperature must be sufficient to promote efficient water evaporation without inducing thermal changes in the matrix, such as browning through the Maillard reaction.

Recovery was calculated as the percentage ratio of the moisture content obtained using the proposed method to that obtained using the adapted industrial reference procedure Equation 2.

$$Recovery\ (\%) = \frac{Moisture\ content\ (proposed\ method)}{Moisture\ content\ (reference\ method)} \times 100 \qquad (2)$$

Factors were coded using the relationships in Equation 3:

$$x_1 = \frac{m-2}{1}, \qquad x_2 = \frac{t-15}{10}, \qquad x_3 = \frac{T-120}{20} \qquad (3)$$

Where

ISSN: 2448-0916

m is mass in grams, t is time in minutes, and T is temperature in degrees Celsius.

Recovery was fitted to the full quadratic model in Equation 4:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} {x_1}^2 + \beta_{22} {x_2}^2 + \beta_{33} {x_3}^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \varepsilon \quad (4)$$

Where

Y is the observed recovery; β_0 is the intercept; β_i, β_{ii}, and β_{ij} are the linear, quadratic, and interaction coefficients, respectively; and ε is the random error. Errors were assumed to be independent, with zero mean and constant variance.

The coefficients of the full quadratic model were estimated by ordinary least squares using the original, unrounded experimental values. The significance of individual terms was examined using Student's t-test, with standard errors calculated from the pure-error mean square (MS = 10.32), estimated from replicated center points in the experimental design. Individual tests and 95% confidence intervals used the two degrees of freedom associated with pure error. Overall significance and model adequacy were assessed using analysis of variance (ANOVA) and a lack-of-fit test, respectively, at a significance level of 5%.

Goodness of fit was examined using R^2, adjusted R^2, and residual analysis. Internal predictive performance was assessed using the predicted residual sum of squares (PRESS) and predicted R^2, as shown in Equation 5:

$$PRESS = \sum_{i=1}^{n} \left(\frac{e_i}{1 - h_{ii}} \right)^2, \qquad R^2_{\text{predicted}} = 1 - \frac{PRESS}{SS_{\text{total}}} \quad (5)$$

ISSN: 2448-0916

where e_i is the residual for observation i, h_{ii} is the corresponding diagonal element of the model hat matrix, and SST is the total sum of squares. These indicators were interpreted jointly, considering the limited number of runs.

3.4 PRELIMINARY ASSESSMENT OF ANALYTICAL PERFORMANCE

A preliminary assessment of the analytical performance of the proposed method was conducted under the experimental conditions defined by the Box–Behnken design. It included recovery, repeatability, intermediate precision, and comparison with the industrial oven gravimetric procedure adapted from AOAC Official Method 984.25. The procedures were guided by DOQ-Cgcre (2020) and REMESP (2016).

The methods were compared using six independent samples analyzed in triplicate by both procedures. For each sample, the mean of the three determinations was calculated and subsequently compared using a two-tailed paired Student's t-test at a significance level of 5% (n = 6 pairs; df = 5). Absolute differences, expressed in percentage points, relative differences against the reference method, and the 95% confidence interval for the mean difference were calculated.

Recovery was calculated as the percentage ratio of the moisture contents determined using the proposed method and the adapted industrial reference procedure. Repeatability was assessed through three determinations of the same sample by the same analyst using the same equipment. Intermediate precision was investigated using two different units, with three determinations per unit, yielding six measurements. Results were expressed as the mean, standard deviation, and relative standard deviation (RSD, %) and interpreted considering the observed experimental variability and the operationally defined nature of moisture determination (AOAC International, 2019).

Given the limited number of independent samples and the experimental conditions investigated, the assessment was exploratory. Statistical testing was used to investigate mean differences between the methods, rather than to demonstrate equivalence or interchangeability.

ISSN: 2448-0916

3.5 ELECTRICITY CONSUMPTION MEASUREMENT AND ECONOMIC ANALYSIS

Electricity consumption was measured using a digital wattmeter connected to the equipment used in this study. Six complete 1,038 s (17.3 min) cycles of the Philips Walita NA130 air fryer and three 10,800 s (3 h) cycles of the Fanem 515 oven were considered. The oven cycles corresponded to the adapted procedure used in industrial practice. Data are presented as the mean and sample standard deviation.

The economic assessment used the average electricity price for the Brazilian industrial sector reported by Empresa de Pesquisa Energética (EPE) in the Brazilian Energy Balance 2026 (base year 2025). According to Table 7.10 of the edition consulted, the indicator for 2025 was USD 291.5 per barrel of oil equivalent (boe). Using the approximate conversion of 1 boe ≈ 1.65×10^3 kWh yielded USD 0.177/kWh, rounded to USD 0.18/kWh for the calculations. This is a national average reference price, rather than the contractual tariff of the industrial facility studied (EPE, 2026).

The approximately 16 h period refers to the duration of the conventional procedure described in the manuscript. For samples produced at the industrial facility investigated, however, the company standardized a 3 h cycle at 105 °C because its internal assessments showed stabilization of moisture results. Thus, the 3 h electricity measurement covers the full cycle of the adapted industrial procedure but does not represent implementation of the full AOAC Official Method 984.25. The energy comparison concerns the operating cycles used in this study.

4. RESULTS AND DISCUSSION

4.1 OPTIMIZATION OF EXPERIMENTAL CONDITIONS

Experimental conditions were optimized using a Box–Behnken design with moisture recovery as the response variable. Table 1 presents the experimental matrix and results, showing a substantial response range (50–107%). This variation highlights the

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strong dependence of recovery on the operating variables investigated, particularly when comparing runs at the extremes of heating time: 5 min (runs 1, 2, and 9) produced low recoveries (50–57%), whereas 25 min (runs 3, 4, 10, and 12) yielded the highest values (99–107%).

The data in Table 1 indicate that heating time had the greatest influence on the response and was the main factor responsible for increasing moisture recovery. Temperature also had a relevant effect: comparing conditions with the same mass and time but different temperatures (e.g., runs 5 and 7) shows that increasing temperature from 100 to 140 °C increased recovery. In contrast, changing sample mass within 1–3 g produced smaller response changes, indicating a secondary influence within the experimental domain investigated. The center points (runs 13–15) showed low variability (93–99%), supporting the consistency of the results and indicating good method reproducibility.

The response surfaces and contour plots in Figure 2 show the predicted variation in recovery across the experimental domain. Visual inspection indicates that recovery increases primarily with time; temperature has a more moderate positive effect, whereas mass has less influence. The more pronounced curvature along the time axis is consistent with the significant quadratic term for this variable. Slopes observed in the combined surfaces describe the fitted model but do not, by themselves, provide evidence of statistical interaction.

The Pareto chart in Figure 3 summarizes standardized effects and should be interpreted alongside the estimates in Table 2A. The linear time term ($\beta = 23.143$; $p = 0.002$), linear temperature term ($\beta = 5.159$; $p = 0.045$), and quadratic time term ($\beta = -17.303$; $p = 0.009$) were significant. The linear and quadratic mass terms and the quadratic temperature term were not significant. The mass × time ($p = 0.684$), mass × temperature ($p = 0.678$), and time × temperature ($p = 0.254$) interactions were also not significant. Therefore, the results do not support claims of interaction or synergy among the factors within the range investigated.

ISSN: 2448-0916

Table 1. Experimental matrix of the Box–Behnken design using an air fryer, showing coded and actual levels of mass, time, and temperature and the corresponding recovery responses (%).

Run No.	**Mass (g)**	**Time (min)**	**Temperature (°C)**	**Response Recovery (%)**
1	1 (-1)	5 (-1)	120 (0)	57
2	3 (1)	5 (-1)	120 (0)	50
3	1 (-1)	25 (1)	120 (0)	105
4	3 (1)	25 (1)	120 (0)	101
5	1 (-1)	15 (0)	100 (-1)	95
6	3 (1)	15 (0)	100 (-1)	92
7	1 (-1)	15 (0)	140 (1)	105
8	3 (1)	15 (0)	140 (1)	99
9	2 (0)	5 (-1)	100 (-1)	51
10	2 (0)	25 (1)	100 (-1)	99
11	2 (0)	5 (-1)	140 (1)	68
12	2 (0)	25 (1)	140 (1)	107
13	2 (0)	15 (0)	120 (0)	99
14	2 (0)	15 (0)	120 (0)	93
15	2 (0)	15 (0)	120 (0)	96

Source: The authors, 2026.

Figure 2. Pareto chart of standardized effects from the quadratic model for moisture recovery. At the 5% significance level, the linear time, linear temperature, and quadratic time terms were significant; no two-factor interaction was significant.

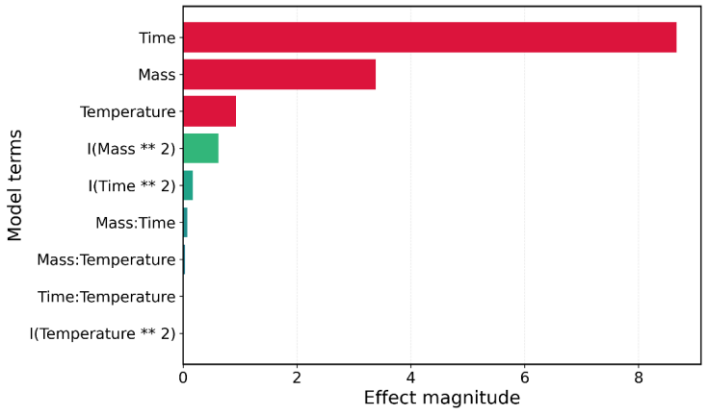

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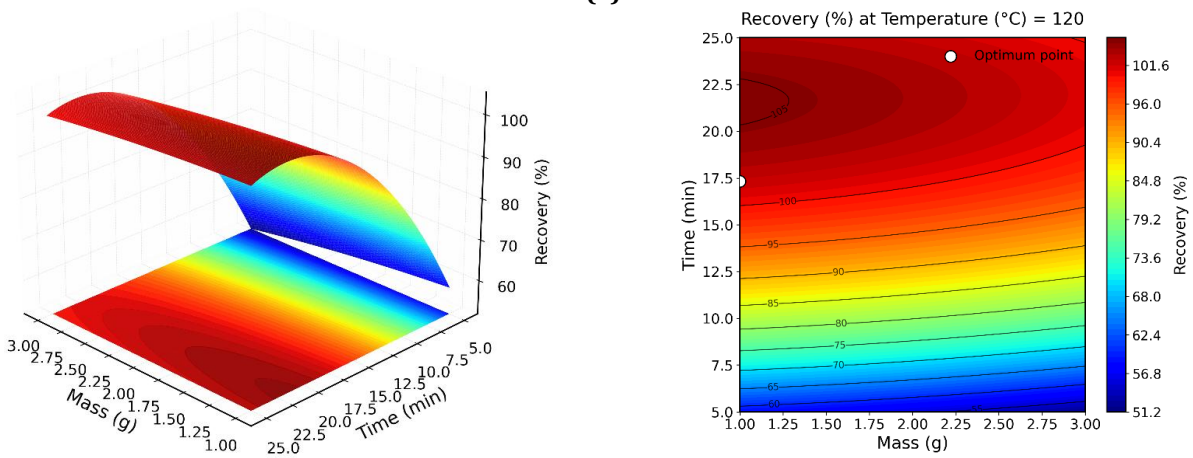
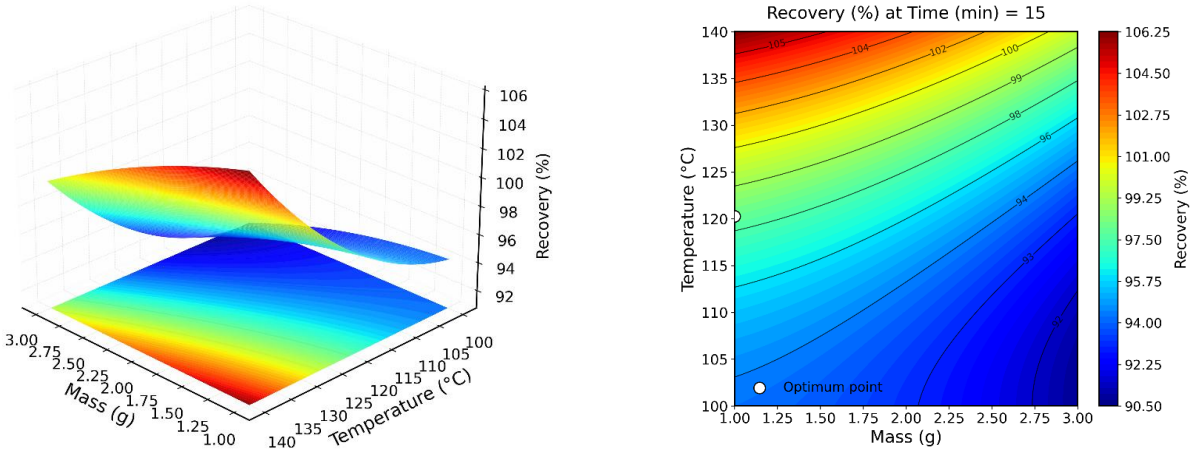
Figure 3. Response surfaces and contour projections for moisture recovery (%): (a) mass and time at 120 °C; (b) mass and temperature at 15 min; and (c) time and temperature at 2 g. The surfaces show the response predicted by the quadratic model; visual slope patterns should not be interpreted as significant interactions without confirmation by the coefficient tests presented in Table 2A.

(a)



(b)



(c)

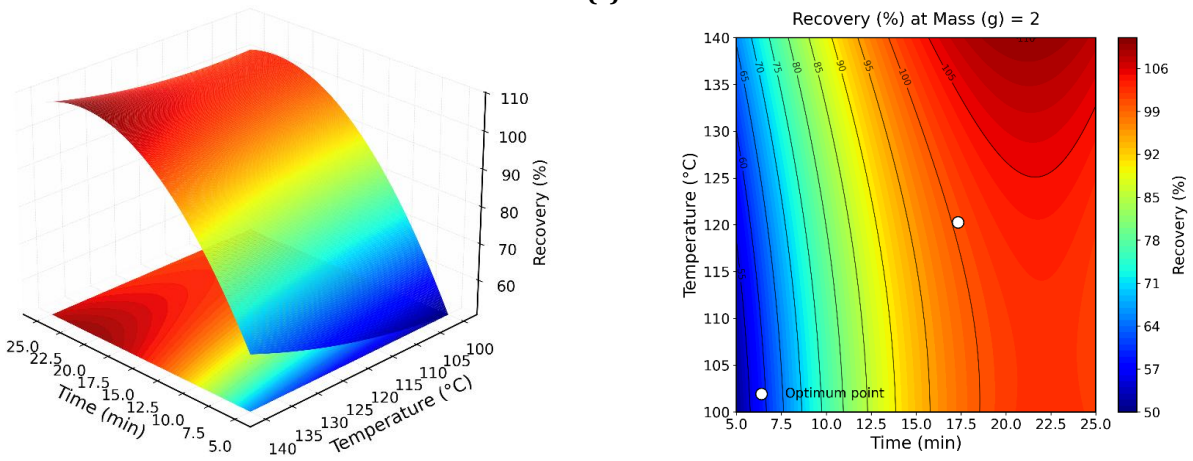


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Table 2 A. Coefficients of the full quadratic model for moisture recovery in coded variables.

Term	Coef. β	SE	t	F	p	95% CI
Intercept	96.219	1.855	51.882	2691.713	<0.001	88.240 to 104.199
Mass (linear)	−2.653	1.136	−2.336	5.455	0.145	−7.539 to 2.234
Time (linear)	23.143	1.136	20.378	415.242	0.002	18.256 to 28.029
Temperature (linear)	5.159	1.136	4.543	20.634	0.045	0.272 to 10.045
Mass² (quadratic)	−0.750	1.672	−0.449	0.202	0.697	−7.943 to 6.442
Time² (quadratic)	−17.303	1.672	−10.351	107.137	0.009	−24.496 to −10.111
Temperature² (quadratic)	2.394	1.672	1.432	2.050	0.289	−4.799 to 9.586
Mass × time	0.758	1.606	0.472	0.223	0.684	−6.153 to 7.668
Mass × temperature	−0.771	1.606	−0.480	0.231	0.678	−7.682 to 6.139
Time × temperature	−2.546	1.606	−1.586	2.514	0.254	−9.457 to 4.364

Source: The authors, 2026.

The full quadratic model was significant [$F(9,5) = 72.065$; $p < 0.001$], explained 99.23% of the observed variability ($R^2 = 0.9923$), and had an adjusted R^2 of 0.9786. The residual standard error was 2.975 percentage points. The lack-of-fit test was not significant [$F(3,2) = 0.763$; $p = 0.610$], indicating that no systematic model inadequacy relative to pure error was detected. PRESS was 424.47 and predicted R^2 was 0.9266, indicating strong internal predictive performance, although these values must be interpreted considering the small number of pure-error degrees of freedom.

The fitted model in coded units is presented in Equation 6.

$$Y = 96.219 - 2.653x_1 + 23.143x_2 + 5.159x_3 - 0.750x_1^2 - 17.303x_2^2 + 2.394x_3^2 + 0.758x_1x_2 - 0.771x_1x_3 - 2.546x_2x_3 \quad (6)$$

Figure 4a plots predicted against observed values, whereas Figure 4b plots residuals against fitted values. Residuals were distributed around zero, with no evident systematic pattern on visual inspection. This graphical assessment is consistent with the absence of detectable lack of fit. However, a residuals-versus-fitted plot does not establish

ISSN: 2448-0916

normality by itself; given the limited number of observations and only five residual degrees of freedom, these diagnostics should be regarded as exploratory.

Table 2 B. Overall analysis of variance and lack-of-fit test for the full quadratic model.

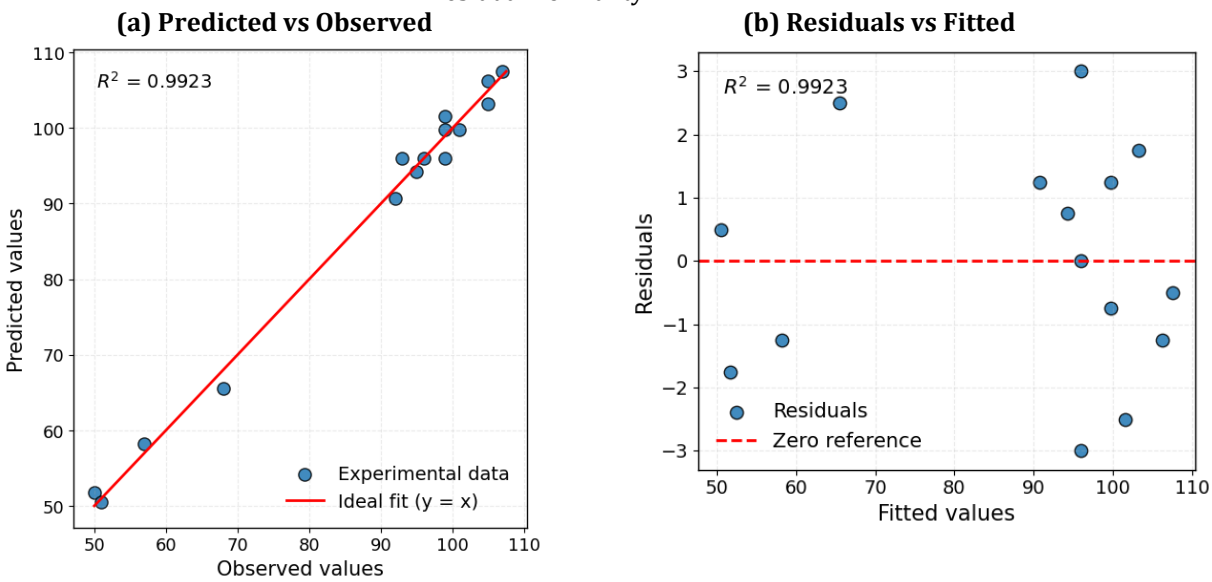
Source	SS	df	MS	F	p	Interpretation
Model	5741.884	9	637.987	72.065	<0.001	Significant
Residual	44.264	5	8.853	—	—	Total model error
Lack of fit	23.627	3	7.876	0.763	0.610	Not significant
Pure error	20.637	2	10.318	—	—	Center points
Total	5786.148	14	—	—	—	R^2 = 0.9923

Source: The authors, 2026.

No observations were excluded from the main fit. Runs 10 (observed recovery = 99.436%) and 11 (68.276%) had the largest externally studentized residuals, −2.090 and +2.090, respectively. These values remained below the Bonferroni threshold ($|t_i|$ = 6.254) and were therefore not classified as outliers under the prespecified criterion. Both runs had D_i = 0.783, exceeding the exploratory threshold of 4/n = 0.267, and were classified as potentially influential rather than invalid results. Both were retained because no documented evidence of experimental error was identified. In the sensitivity analysis, predicted recovery at the selected operating condition was 102.35% using all 15 runs, 101.49% after individually removing run 10, and 103.77% after individually removing run 11. Thus, removing each point changed the prediction by −0.86 and +1.41 percentage points, respectively, without changing the conclusion that the selected region yields recovery close to the target. Differences between the refitted models were explicitly reported to demonstrate the influence of these points and avoid post hoc exclusions based solely on statistical results.

ISSN: 2448-0916

Figure 4. (a) Predicted versus observed moisture recovery; the dashed line represents perfect agreement. (b) Residuals versus fitted values; the dashed line indicates zero residual. The absence of an evident visual pattern is consistent with the fitted model but does not replace formal tests or establish residual normality.



Source: The authors, 2026.

Desirability optimization, with 100% recovery as the target, indicated a sample mass of 1.00 g, a heating time of 17.325 min, and a temperature of 120.263 °C. For experimental implementation, 1.00 g, 17.3 min, and 120 °C were adopted, consistent with the operational resolution of the equipment and procedure. Substitution of this operating condition into the fitted expression presented below yielded a predicted recovery of 102.35%. Time had the largest effect on the response, with a positive linear component and a negative quadratic component, indicating curvature along this axis. Interpretation of the surfaces was restricted to the experimental domain investigated.

Table 2 C. Independent confirmation of the selected operating condition.

Parameter	Result
Operating condition	1.00 g; 17.3 min; 120 °C
Number of independent samples	6 (triplicate per method)
Model-predicted recovery	102.35%
Observed recovery	101.74 ± 1.74%
95% CI for observed recovery	99.92% to 103.56%
Prediction error (observed – predicted)	−0.61 pp (−0.60% relative)

Source: The authors, 2026.

ISSN: 2448-0916

Mean recovery in the confirmation experiments was 101.74%, with a standard deviation of 1.74% and a 95% confidence interval of 99.92–103.56%. Model-predicted recovery at 1.00 g, 17.3 min, and 120 °C was 102.35%, which fell within the observed 95% confidence interval. The mean prediction error was −0.61 percentage points, equivalent to −0.60% relative to the predicted value. The small difference between the observed and predicted responses confirms the model's ability to locate an operating condition close to the target recovery within the sample set evaluated.

These conditions were used for independent confirmation and preliminary application of the proposed method in the experimental system studied. Heating was completed in 17.3 min, compared with 3 h for the adapted gravimetric procedure used in industrial practice, corresponding to an approximately 90.4% reduction in heating time. The energy comparison was based exclusively on direct wattmeter readings for the cycles performed.

4.2 PRELIMINARY ASSESSMENT OF ANALYTICAL PERFORMANCE

Accuracy describes the closeness of a measured result to an accepted reference value. Mean values obtained using the proposed reference methods for the same six samples were compared using a two-tailed paired Student's t-test. The mean absolute difference was 1.31 percentage points (95% CI: −0.06 to 2.69), with $t = 2.450$, $df = 5$, and $p = 0.058$. The 95% confidence interval included zero and p exceeded 0.05; therefore, no statistically significant difference between the means was detected. This exploratory result does not provide evidence of equivalence, similarity, or interchangeability between the methods.

ISSN: 2448-0916

Table 3. Moisture contents determined using the reference and proposed methods and results of the statistical comparison.

Sample	Reference method (%; mean ± SD)	Proposed method (%; mean ± SD)	Difference (pp)	Recovery (%)	Overall test
A	73.00 ± 0.04	74.07 ± 1.60	1.08	101.5	
B	75.80 ± 0.62	78.74 ± 1.10	2.94	103.9	
C	75.41 ± 0.63	77.63 ± 0.55	2.21	102.9	
D	75.31 ± 0.35	77.33 ± 1.17	2.01	102.7	
E	72.85 ± 0.11	72.52 ± 0.23	−0.33	99.5	
F	72.61 ± 0.37	72.55 ± 0.17	−0.05	99.9	
Paired t-test	n = 6 pairs	df = 5	95% CI: −0.06 to 2.69	p = 0.058	t = 2.450

Source: The authors, 2026.

Results for each method are presented as the mean ± standard deviation of three determinations. The paired t-test was applied to the means of the six samples, which were treated as experimental units, rather than separately to the technical replicates. Absolute difference = proposed method − adapted industrial reference procedure; pp = percentage point; 95% CI = 95% confidence interval. The t-test assesses the mean difference and does not demonstrate equivalence between methods.

Mean recovery across the six samples was 101.7%, with individual values ranging from 99.5% to 103.9%. Although the mean indicates a small overall deviation from the adapted industrial reference procedure, samples B, C, and D had recoveries above 102%, revealing between-sample heterogeneity. These results should be interpreted descriptively and do not demonstrate equivalence between the methods.

To assess repeatability, one sample was analyzed in triplicate using the proposed method; the results are presented in Table 4. Mean moisture content was 69.68%, with a standard deviation of 0.41 percentage points and an RSD of 0.59%, indicating low dispersion among determinations performed under the same conditions.

Intermediate precision was assessed using two different units, with three determinations per unit. Mean moisture content was 69.10%, with a standard deviation of 1.09 percentage points and an RSD of 1.57%. The low dispersion observed indicates within-laboratory consistency under the conditions evaluated, although studies involving more days, analysts, and equipment units could provide a more comprehensive characterization of intermediate precision.

ISSN: 2448-0916

Table 4. Repeatability and intermediate precision of the moisture determination method, expressed as mean moisture content (%), standard deviation, and relative standard deviation (RSD, %).

Parameter	Precision	Intermediate precision
Mean moisture (%)	69.68	69.10
Standard deviation	0.41	1.09
RSD (%)	0.59	1.57

Source: The authors, 2026.

4.3 METHOD APPLICATION MEASURED CONSUMPTION AND ECONOMIC ASSESSMENT

The proposed method was applied to determine moisture content in ten samples of frozen pre-fried potatoes (Table 5). Moisture contents ranged from 60.59% to 80.48%, with standard deviations of up to 0.99 percentage points, indicating low dispersion under the conditions evaluated. The observed range is consistent with values reported for similar products (Pedreschi, 2012; Kita, 2002). This application demonstrates the feasibility of the procedure for the samples, preparation, containers, and equipment investigated, without establishing its generalizability to other analytical conditions.

Table 5. Moisture contents determined using the proposed method (mean ± standard deviation).

Sample	Moisture (%)	Sample	Moisture (%)
1	80.31 ± 0.71	6	74.38 ± 0.18
2	78.55 ± 0.64	7	73.66 ± 0.18
3	80.48 ± 0.40	8	73.07 ± 0.37
4	78.91 ± 0.99	9	63.43 ± 0.65
5	75.62 ± 0.53	10	60.59 ± 0.02

Source: The authors, 2026.

Electricity consumption was recorded directly for the Philips Walita NA130 air fryer and the Fanem 515 oven. The six valid air fryer cycles had a mean consumption of 0.122 ± 0.003 kWh over 17.3 min. For the oven, the three measurements corresponding to the 3 h cycles of the adapted industrial procedure yielded a mean consumption of 0.867 ± 0.231 kWh. Only operationally valid cycles were included; records associated with operating errors were excluded in accordance with the experimental validity criterion.

The economic assessment used the average electricity price for the Brazilian industrial sector reported by Empresa de Pesquisa Energética (EPE) in the Brazilian Energy Balance 2026 (base year 2025). According to Table 7.10 of the edition consulted,

ISSN: 2448-0916

USD 291.5 per barrel of oil equivalent (boe), converted using the approximate equivalence of 1 boe = 1,650 kWh, corresponds to USD 0.177/kWh. A value of USD 0.18/kWh was adopted to simplify calculations, yielding estimated costs of USD 0.022 per air fryer cycle and USD 0.156 per 3 h oven cycle. These values are estimates based on a national average price, rather than actual tariff-based expenses at the facility.

Table 6. Operational, energy, and economic comparison between the Fanem 515 oven and the Philips Walita NA130 air fryer.

Parameter	Fanem 515 oven	Airfryer NA130
Operating temperature	105 °C	120 °C
Duration of the procedure used	3 h	17.3 min
Monitored period	3 h	17.3 min
Number of measurements included	3	6
Measured mean consumption (kWh)	0.867 ± 0.231	0.122 ± 0.003
Assumed electricity price (USD/kWh)	0.18	0.18
Energy cost for the measured period (USD)	0.156	0.022
Estimated purchase price (USD)	753.13	85.07

Source: The authors, 2026.

Consumption is expressed as the mean ± sample standard deviation for operationally valid cycles. The 3 h oven measurement corresponds to the complete cycle of the adapted industrial procedure, rather than the full official method. Across the operating cycles evaluated, the measured mean electricity consumption of the air fryer was approximately 85.9% lower than that of the oven. The heating time of the proposed method (17.3 min) was approximately 90.4% shorter than the 3 h used in the adapted industrial procedure. These results indicate operational and energy advantages under the conditions studied, but should not be directly extrapolated to the full AOAC 984.25 method or to other processing scales. The comparison is per equipment operating cycle and does not account for differences in the number of samples processed per batch.

Estimated purchase prices also indicate a lower initial investment for the air fryer, but exclude maintenance costs, service life, and processing capacity. Taken together, the results support the potential for simpler operation and lower costs under the conditions studied, without allowing direct extrapolation to other equipment or laboratory workflows.

ISSN: 2448-0916

5. CONCLUSION

This study developed and evaluated a rapid procedure for determining moisture content in frozen pre-fried potatoes using two Philips Walita NA130 air fryers, 225 mL porcelain dishes, and the experimental setup described. Box–Behnken optimization indicated a sample mass of 1.0 g, a heating time of 17.3 min, and a temperature of 120 °C, with heating time exerting the greatest influence.

The full quadratic model was significant [$F(9,5) = 72.065$; $p < 0.001$], explained 99.23% of the observed variability ($R^2 = 0.9923$), had an adjusted R^2 of 0.9786, and showed no detectable lack of fit [$F(3,2) = 0.763$; $p = 0.610$]. The predicted R^2 of 0.9266 and independent confirmation of the optimum supported strong predictive performance within the experimental domain evaluated.

The paired t-test revealed no statistically significant difference between the methods ($t = 2.450$; $df = 5$; $p = 0.058$; 95% CI: −0.06 to 2.69 percentage points), supporting the promising performance of the proposed method under the investigated conditions. Furthermore, compared with the adapted industrial oven-drying procedure, the air fryer demonstrated substantial operational and energy-saving advantages, reducing heating time by approximately 90.4% and measured mean electricity consumption per cycle by 85.9%. These findings highlight the potential of the proposed method as a rapid, cost-effective, and energy-efficient alternative for moisture determination in frozen pre-fried potatoes.

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