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# Foam mat drying process optimization using response surface methodology for high-quality, low-moisture tomato powder production

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## Abstract

Tomatoes are highly perishable due to their high water content, making tomato powder production an effective preservation approach. Foam mat drying offers advantages such as faster drying, lower costs, and minimal quality loss by converting liquid tomato puree into stable foam before dehydration. However, the process optimization of key parameters such as drying temperature, drying time, and maltodextrin concentration has not been fully explored. This study employed Response Surface Methodology (RSM) with a Box–Behnken Design to determine the optimal process conditions for producing high-quality tomato powder with low moisture content and high yield. Experiments were conducted with drying temperatures of 55–65°C, drying times of 2–4 hours, and maltodextrin concentrations of 15–25%. The optimal process conditions were 63.15°C for 3.95 hours with 25% maltodextrin, producing tomato powder with a yield of 18.65% and moisture content of 2.97%. These results highlight the potential of RSM-based foam mat drying optimization for enhancing product quality and process efficiency in food dehydration technology.

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## 1. Introduction

Tomatoes are among the most widely cultivated horticultural crops in Indonesia and play a significant role in the agricultural sector. According to Statistics Indonesia, national tomato production in 2022 reached approximately 1,168,743 tons, with West Java identified as the largest producing province (1). Tomatoes are rich in essential nutrients, including vitamins, minerals, and bioactive compounds, which make them highly valued for dietary consumption (2). However, their high-water content around 94% renders them highly perishable, leading to substantial post-harvest losses if not managed properly (3).

Processing tomatoes into powder is an effective approach to extend shelf life and enhance product usability. Several drying techniques, such as freeze drying, spray drying, and drum drying, have been developed for this purpose. Foam-mat drying offers notable advantages, including lower operational costs and superior retention of sensory and nutritional qualities compared to conventional methods (4). This technique converts liquid or

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semi-liquid materials into a stable foam using foaming agents and stabilizers, increasing surface area and promoting faster drying at lower temperatures (5,6).

Previous research has investigated the influence of various drying parameters on the quality of tomato powder. Hossain et al. examined the effects of egg white and carboxymethyl cellulose (CMC) concentrations combined with different drying temperatures (2). Ramadhany et al. studied the impact of glycerol monostearate (GMS) effectively preserves key nutrients of foam mat-dried tomato (7). Excessive temperature or improper formulation can degrade nutrients and affect texture, color, and solubility. Optimizing drying temperature, foaming agent, and stabilizer concentrations is crucial for producing high-quality foam-mat dried tomato powder with desirable physicochemical properties.

Nevertheless, a comprehensive optimization of interrelated variables such as drying temperature, drying time, and maltodextrin concentration remains limited. Therefore, this study aims to optimize the foam-mat drying parameters for tomato powder production using Response Surface Methodology (RSM) with a Box–Behnken Design (BBD). The primary objective is to determine the ideal combination of drying temperature, drying time, and maltodextrin concentration to maximize product yield while minimizing moisture content. This research provides essential insights and practical recommendations for the agro-processing industry, particularly in improving the efficiency and economic value of tomato powder production.

## 2. Materials and Methods

The primary materials used in this study included fresh beef tomatoes harvested in March 2024, which were obtained from local farmers in the Lembang area, West Java, Indonesia. The research was conducted from March-June 2024 at the Postharvest Technology Laboratory, Department of Agriculture and Biosystem Engineering, Faculty of Agro-Industrial Technology, Universitas Padjadjaran, Indonesia.

### *2.1. Materials*

Supporting materials consisted of food-grade maltodextrin as the drying carrier, egg white powder as the foaming agent, and distilled water. Chemicals for analytical procedures, particularly for moisture content determination.

### *2.2. Equipments*

The equipment employed in this study included a Papalolo SS-10H Drying Stainless Steel Food Dehydrator Machine maximum 2000 W of power (Wirastar FDH-20, Indonesia), it consists of twenty trays, dimension 55 cmx 47 cmx 97 cm. Laboratory oven (Memmert, Germany) for moisture analysis, Electric muffle furnace (Nabertherm B180, England) for ash content measurement, Spectrofotometer Colorflex EZ (Hunter Lab, China), digital balance (GF-3000), high-speed mixer, laboratory grinder, and a 50-mesh Tyler sieve. The drying environment was maintained at an ambient temperature of approximately 27 ± 2°C with relative humidity around 60-70%.

### *2.3. Experimental Design*

Optimization was conducted using Response Surface Methodology (RSM) based on a Box-Behnken Design (BBD). The three independent variables optimized were:

- Drying temperature: 55°C to 65°C
- Drying time: 2 to 4 hours
- Maltodextrin concentration: 15% to 25% (w/b)

The BBD generated 17 experimental runs to assess the effects of the variables on moisture content and yield. This design was chosen for its efficiency in evaluating interactions between factors with a reduced number of trials while maintaining statistical robustness. The experimental design resulted in 17 runs and is presented in Table 1.

Table 1. Experimental design.

| Run | Factor 1 (A) | Factor 2 (B) | Factor 3 (C) |
|---|---|---|---|
| | Drying Temperature (°C) | Drying Time (Hours) | Maltodextrin Concentration (%) |
| 1 | 65 | 3 | 25 |
| 2 | 65 | 4 | 20 |
| 3 | 65 | 3 | 15 |
| 4 | 65 | 2 | 20 |
| 5 | 60 | 4 | 15 |
| 6 | 60 | 3 | 20 |
| 7 | 60 | 4 | 25 |
| 8 | 60 | 3 | 20 |
| 9 | 55 | 3 | 25 |
| 10 | 60 | 2 | 25 |
| 11 | 60 | 3 | 20 |
| 12 | 55 | 4 | 20 |
| 13 | 60 | 3 | 20 |
| 14 | 60 | 3 | 20 |
| 15 | 55 | 2 | 20 |
| 16 | 60 | 2 | 15 |
| 17 | 55 | 3 | 15 |

### *2.4. Experimental Procedures*

The experimental procedure of this study includes raw material preparation (encompassing both juice and foam preparation), the tomato powder drying process, powder production, accompanied by powder characterization.

1. Juice Preparation: Fresh tomatoes were washed, sorted, and juiced. The juice was filtered to remove seeds and pulp.
2. Foam Preparation: The filtered juice was mixed with maltodextrin according to the experimental matrix and homogenized for 2 minutes. The foaming agent used in this study was fresh egg white foam obtained by whipping egg whites using a mixer at speed 3 for 4.5 minutes. Egg white foam was then added, and the mixture was whipped for 10 minutes to create stable foam. The foaming agent condition was kept constant 3% to maintain foam stability and consistency across all experimental runs.
3. Drying Process: The prepared foam was spread uniformly on trays and dried in the dehydrator at the designated temperatures and times as per the experimental design.
4. Powder Production: The dried foam was ground into powder using a laboratory grinder and sieved through a 50-mesh sieve to ensure consistency in particle size, and the determination of both yield and moisture content as the primary response parameters.
5. Powder characterization: the tomato powders was characterized in term of ash content, solubility and colors.

### 2.5. Moisture Content Determination

Moisture content was measured using the gravimetric method by drying the sample at 105°C until a constant weight was achieved. The moisture content was calculated as:

$$MC = \frac{(A_1 - A_2)}{(A_1 - A_0)} \times 100 \quad (1)$$

Remarks:
MC: Moisture content (in % wet basis)
$A_0$: Mass of empty cup (g)
$A_1$: Mass of cup with sample before drying (g)
$A_2$: Mass of cup with sample after drying (g)

### 2.6. Yield Determination

Yield was calculated by comparing the mass of the final dried powder to the initial mass of the foamed mixture:

$$Y = \frac{M_b}{M_a} \times 100 \quad (2)$$

Remarks:
Y: Yield (%)
$M_a$: Weight of initial mass of the foamed mixture (g)
$M_b$: Weight of final powder (g)

### 2.7. Data Analysis

Experimental data were analyzed using Design Expert 13 software. ANOVA was conducted to evaluate model significance, with key indicators including the p-value (< 0.05), lack of fit (> 0.05), Adjusted $R^2$, Predicted $R^2$, and Adequacy Precision values. In response analysis, several criteria must be met, including the model must be significant ($p<0.05$), the lack of fit value must be insignificant ($p > 0.05$), the adjusted $R^2$ value and the predicted $R^2$ value have a difference of less than 0.2 and the adequate precision value must be more than 4. Optimization results with a desirability value close to 1 have characteristics that match the optimization target.

### 2.8. Model Validation

Model validation was carried out by conducting experiments under the optimal predicted conditions. The actual values obtained for moisture content and yield were compared to the predicted values to confirm the accuracy and reliability of the models. The verification results will show the accuracy of the model, as suggested by the software (8).

### 2.9. Practical Implication

The optimized drying parameters derived from this study provide practical guidance for the commercial production of tomato powder. By achieving low moisture content and high yield, the process supports improved product quality and economic efficiency, benefiting both processors and tomato farmers.

## 3. Results and Discussion

### 3.1. Moisture Content Response Analysis

The factors used in this study include drying temperature (°C), drying time (hours), and maltodextrin concentration (%). Moisture content is one of the responses analyzed to determine the best combination of factors for producing optimal tomato powder moisture content. The response surface method with the Box–Behnken Design (BBD) was used to optimize the moisture content value of tomato powder. Based on Table 2, the obtained moisture content values ranged from 3.005–4.745 %, with the lowest value found in run 1 and the highest in run 10. All values met the standard criteria for tomato powder established by Foodchem International Corporation, which specifies a maximum moisture content of 7% (9). There were five center points in the RSM experimental design (runs 6, 8, 11, 13, and 14). The average moisture content across these center points was 3.9154 ± 0.358, with a low standard deviation, indicating minimal variation and good model consistency.

The significance of drying temperature and time is consistent with the fundamental principles of heat and mass transfer during the dehydration process. Increasing the drying temperature enhances the vapor pressure gradient between the foam surface and the surrounding air, which serves as the primary driving force for the migration of water molecules out of the material (10). Higher temperatures also provide sufficient thermal energy to break the hydrogen bonds between water molecules and the food matrix, thereby accelerating the evaporation rate (11).

The porous, honeycomb-like structure of the foam greatly facilitates this process. Unlike conventional drying, the high surface-area-to-volume ratio in the foam-mat drying method allows for rapid heat penetration and efficient moisture escape, preventing the phenomenon of surface hardening that often hinders drying in non-foamed products (12). This explains why moisture content remains low despite using relatively moderate temperatures (55–65°C), which is crucial for maintaining the microbial stability and shelf life of the tomato powder (13).

### 3.2. Yield Response Analysis

The factors used include drying temperature (°C), drying time (hours), and maltodextrin concentration (%). Yield was also analyzed to determine the optimal combination of factors for maximizing tomato powder production. The response surface method with the Box–Behnken Design (BBD) was applied to optimize yield. Based on Table 2, yield values ranged from 11.83–19.64%, with the lowest found in run 16 and the highest in run 7. The average yield across the five center points (runs 6, 8, 11, 13, and 14) was 17.24 ± 0.944, and the low standard deviation indicated that the data variation was minimal and acceptable for RSM analysis.

The dominant role of maltodextrin in determining yield is closely related to its function as a carrier agent and filling agent. The addition of maltodextrin increases the total soluble solids in the initial tomato puree, which directly increases the mass of the final product after water is evaporated (14). Beyond its role as a filler, maltodextrin effectively reduces the stickiness of natural tomato sugars (such as fructose and glucose) during drying. Materials with high sugar content tend to adhere to the drying trays; however, maltodextrin is able to increase the glass transition temperature (Tg) of the mixture, making the powder easier to scrape and collect, which ultimately increases the yield (15).

The significant quadratic effects of temperature and time indicate the presence of an optimal point for these variables. Although higher temperatures initially increase yield by accelerating drying and reducing stickiness, excessive temperature exposure or overly long durations can lead to sugar caramelization or the degradation of sensitive components, which conversely makes the product harder to harvest (10). Therefore, optimization through the Box-Behnken Design is essential to find the equilibrium point for maximizing productivity without compromising product quality (16).

Table 2. Results moisture content and yield of tomato powder.

| Run | Factor 1 (A) | Factor 2 (B) | Factor 3 (C) | Response 1 | Response 2 |
|---|---|---|---|---|---|
| | Drying Temperature (°C) | Drying Time (Hours) | Maltodextrin Concentration (%) | Moisture Content (%) | Yield (%) |
| 1 | 65 | 3 | 25 | 3.055 | 17.95 |
| 2 | 65 | 4 | 20 | 3.119 | 14.81 |
| 3 | 65 | 3 | 15 | 4.308 | 12.89 |
| 4 | 65 | 2 | 20 | 3.846 | 14.86 |
| 5 | 60 | 4 | 15 | 3.388 | 11.93 |
| 6 | 60 | 3 | 20 | 4.482 | 16.80 |
| 7 | 60 | 4 | 25 | 3.284 | 19.64 |
| 8 | 60 | 3 | 20 | 4.013 | 17.36 |
| 9 | 55 | 3 | 25 | 4.497 | 18.13 |
| 10 | 60 | 2 | 25 | 4.745 | 19.02 |
| 11 | 60 | 3 | 20 | 3.621 | 15.86 |
| 12 | 55 | 4 | 20 | 4.182 | 14.49 |
| 13 | 60 | 3 | 20 | 3.847 | 17.97 |
| 14 | 60 | 3 | 20 | 3.614 | 18.20 |
| 15 | 55 | 2 | 20 | 4.516 | 15.03 |
| 16 | 60 | 2 | 15 | 4.019 | 11.83 |
| 17 | 55 | 3 | 15 | 4.227 | 12.19 |

### *3.3. Modelling in Predicting Moisture Content Response*

As shown in Table 3, the recommended RSM equation is a linear model with a significant model *p*-value (< 0.05) and an insignificant lack of fit ($p > 0.05$). Although the adjusted $R^2$ and predicted $R^2$ values differ by more than 0.2 suggesting possible model or data variation—the adequate precision value exceeds 4, indicating the model's suitability for navigating the RSM design space (17).

The ANOVA results (Table 4) show that drying temperature (A) and drying time (B) significantly affected moisture content ($p < 0.05$), whereas maltodextrin concentration (C) did not ($p > 0.05$). These findings are consistent with Effendy et al. (18), who reported that drying temperature and drying time significantly affected the moisture content of shredded coconut. The selected mathematical model for optimizing drying temperature, drying time, and maltodextrin concentration on the moisture content response of foamed tomato juice is presented in Equation (3):

$$MC = 9.93111 - 0.077350A - 0.394125B - 0.009025C \quad (3)$$

where A = drying temperature (°C), B = drying time (h), C = maltodextrin concentration (%).

Table 3. Fit statistics.

| Parameter | Result for Moisture Content Response | Result for Yield Response |
|---|---|---|
| Model | 0.0096 | 0.0012 |
| Lack of Fit | 0.4847 | 0.5562 |
| $R^2$ | 0.5728 | 0.9460 |
| Adjusted $R^2$ | 0.4742 | 0.8765 |
| Predicted $R^2$ | 0.2213 | 0.6236 |
| Adequate Precision | 8.5784 | 10.4613 |
| Standard Deviation | 0.3753 | 0.9024 |

Table 4. ANOVA  for moisture dan yield response.

| Factor | p-value for Moisture Content Response | Factor | p-value for Yield Response |
|---|---|---|---|
| A-drying temperature | 0.0121 | A-drying temperature | 0.0121 |
| B-drying time | 0.0108 | B-drying time | 0.0108 |
| C-maltodextrin concentration | 0.7392 | C-maltodextrin concentration | 0.7392 |
| | | AB | 0.7938 |
| | | AC | 0.6407 |
| | | BC | 0.7816 |
| | | $A^2$ | 0.0165 |
| | | $B^2$ | 0.0463 |
| | | $C^2$ | 0.2358 |

### *3.4. Modelling in Predicting Yield Response*

According to Table 3, the RSM-recommended model for yield is quadratic, with a significant model *p*-value (< 0.05) and an insignificant lack of fit ($p > 0.05$). The adjusted and predicted $R^2$ difference exceeds 0.2, but the adequate precision value (> 4) supports the model's reliability (10). The ANOVA analysis (Table 4) revealed that maltodextrin concentration (C), as well as the quadratic terms of drying temperature ($A^2$) and drying time ($B^2$), significantly affected yield ($p < 0.05$). In contrast, factors A, B, AB, AC, BC, and $C^2$ were not significant. Effendy et al. (18) and Fauzi et al. (17) also reported similar quadratic behavior when analyzing the yield response in foam-mat drying of shredded coconut and butterfly pea (*Clitoria ternatea*) flowers. However, in their studies, drying temperature and time were significant factors, unlike in this work.The mathematical model derived from Design Expert 13 for yield optimization is given in Equation (4):

$$Y_{ield} = -218.44050 + 6.73245A + 4.40275B + 2.00990C + 0.024500AB - 0.008800AC + 0.026000BC - 0.55110A^2 - 1.06275B^2 - 0.022810C^2 \quad (4)$$

where A = drying temperature (°C), B = drying time (h), C = maltodextrin concentration (%).

### *3.5. Influence of Factors on Response*

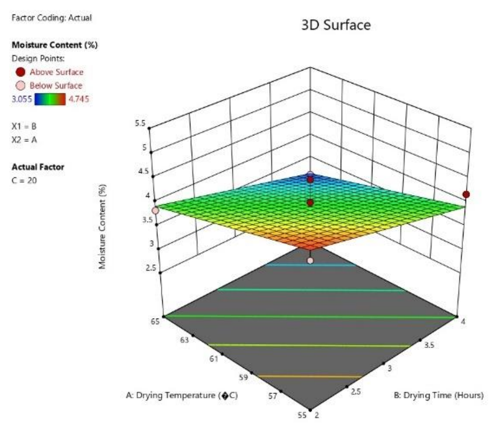
#### 3.5.1. Moisture Content Response

Figures 1a-c display the 3D surface plots based on the linear model, showing that increasing drying temperature, drying time, and maltodextrin concentration decreases moisture content, confirming the inverse relationship observed in previous RSM drying studies (17,18). The 3D response surface plots illustrate the simultaneous effects of drying parameters on the moisture content of the tomato powder. In contrast to the yield plots, these surfaces generally show a downward trend, as the objective is to minimize moisture for improved shelf stability. The plots of the moisture content response as a function of drying temperature, drying time, and maltodextrin concentration. Orange regions represent higher moisture values, while blue regions indicate lower moisture.

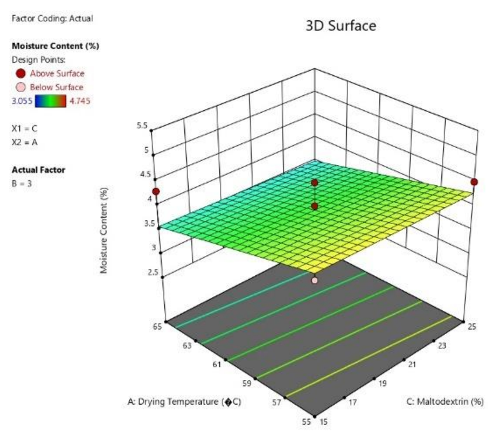
Figure 1(a) shows a significant downward slope toward the corner representing high temperature (65°C) and long drying time (4 hours). This interaction is the most critical for moisture removal. The surface demonstrates that as thermal energy increases, the molecular mobility of water within the tomato foam also increases, while the extended duration allows this moisture to migrate from the internal structure to the surface and evaporate. The relatively steep curvature along both axes confirms the ANOVA results, which identified both temperature and time as significant primary factors ($p < 0.05$).

In Figure 1(b), the moisture content is primarily driven by the temperature axis. A sharp decrease in moisture is observed as the temperature rises from 55°C to 65°C, regardless of the maltodextrin level. While the addition of maltodextrin (C) can slightly assist in moisture reduction by increasing the total solid-to-liquid ratio, the plot shows a flatter profile along the concentration axis (15% to 25%). This suggests that while maltodextrin is essential for yield and powder structure, the actual "work" of dehydration is dictated almost entirely by the thermal gradient provided by the drying temperature.

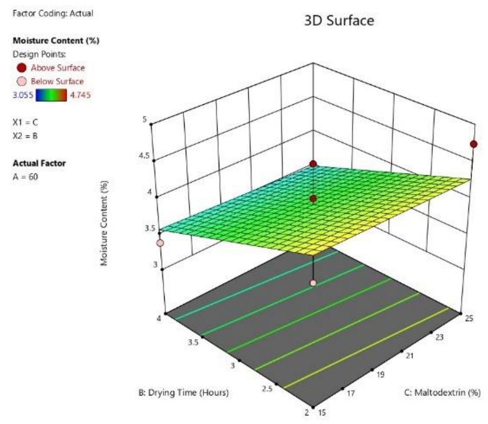
The interaction between drying time and maltodextrin concentration in Figure 1(c) follows a similar trend to plot (b). The most substantial moisture reduction occurs as drying time increases toward 4 hours. The surface indicates that at any given maltodextrin concentration, extending the drying time consistently results in a lower moisture percentage. The synergy here is found in the foam's porosity; the maltodextrin-stabilized foam maintains its air cells for a longer duration, allowing dry air to circulate effectively through the material over time, preventing the entrapment of moisture in the core of the powder.




(a)




(b)

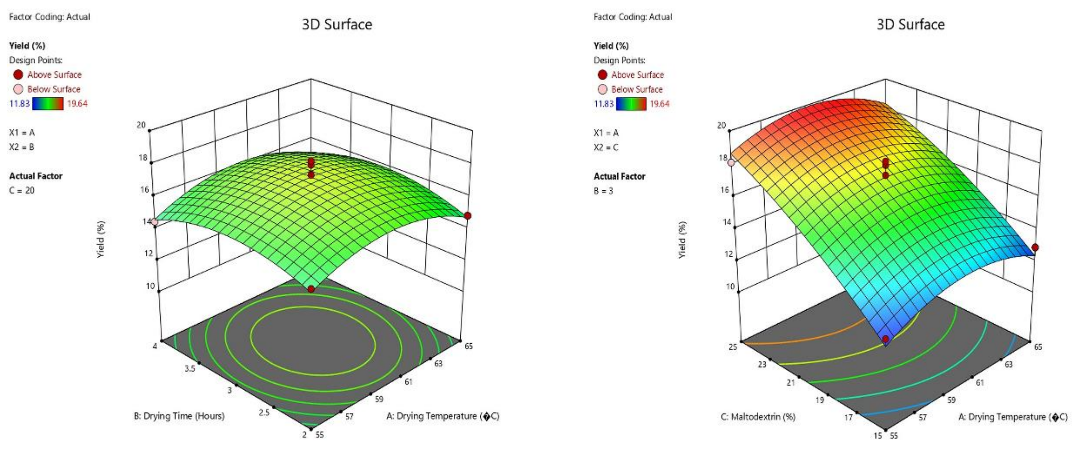



(**c**)

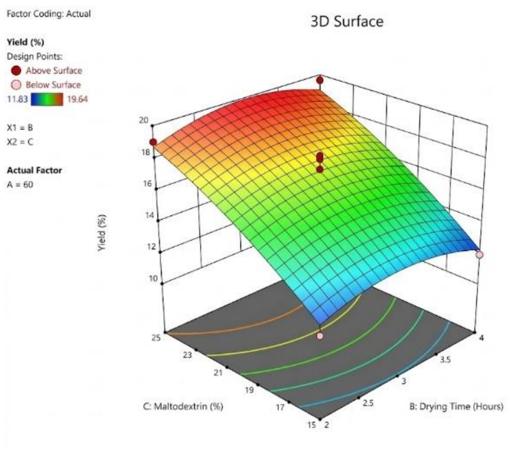
Figure 1. (a) Interaction of drying temperature (A) and drying time (B); (b) Interaction of drying temperature (A) and maltodextrin concentration (C); (c) Interaction of drying time (B) and maltodextrin concentration (C) on moisture content of tomato powder, using Design Expert software version 13.

### 3.5.2. Yield Response

The 3D response surface plots (Figure 2a-c) provide a visual representation of the interaction between independent variables and their cumulative effect on the yield of tomato powder. The yield values observed in this study ranged from 11.83% to 19.64%, with the surface shapes indicating the nature of the relationship between the factors. The blue regions indicate lower yield, while red regions represent higher yield. The interaction between drying temperature and drying time forms an upward curvature in the middle indicating the optimum zone then declines toward the extremes. Similar yield behavior was reported in the RSM optimization of foam-mat drying of fruit and vegetable juices (17).




(**a**) (**b**)




(**c**)

Figure 2. (**a**) Interaction of drying temperature (A) and drying time (B); (b) Interaction of drying temperature (A) and maltodextrin concentration (C); (c) Interaction of drying time (B) and maltodextrin concentration (C) on yield of tomato powder.

As shown in Figure 2(a), the yield increases gradually as both drying temperature and drying time move toward their higher levels (65°C and 4 hours). This upward trend suggests a synergistic effect where higher thermal energy and sufficient duration facilitate the removal of moisture, transforming the sticky tomato puree into a brittle, dry foam that is easier to scrape from the drying trays. At lower temperatures and shorter times, the product remains somewhat cohesive or "rubbery," leading to significant material loss on the trays and a lower recovery rate. However, the relatively "flat" curvature compared to other plots suggests that while these factors are important for drying kinetics, their impact on the total mass of the yield is less dominant than the carrier agent concentration.

Figure 2(b) illustrates a steep incline in yield as the maltodextrin concentration increases from 15% to 25%. This steepness confirms that maltodextrin (C) is the most influential factor in maximizing yield. The interaction shows that even at lower temperatures, increasing the maltodextrin load significantly boosts the final product weight. This is because maltodextrin directly increases the total solids content of the initial mixture. Furthermore, the plot shows that the highest yield is achieved at the intersection of high temperature (65°C) and high maltodextrin (25%), where the maltodextrin acts as a protective shield against the stickiness of tomato sugars, allowing for nearly total recovery of the solids.

The interaction between drying time and maltodextrin concentration in Figure 2(c) follows a similar pattern to plot (b). The yield is primarily driven by the concentration of the carrier agent. The surface indicates that at a high maltodextrin level (25%), the drying time has a stabilizing effect on the yield; once the product reaches its critical moisture level, the yield plateaus. The combination of 25% maltodextrin and a longer drying time (4 hours) ensures that the foam is fully dehydrated and structurally stable, preventing the powder from clumping during the harvesting process.

### *3.6. Determination of Tomato Powder Optimum Process Condition and Verification*

Table 5 presents the optimization design for foam-mat drying of tomato juice. Each response parameter (drying temperature, drying time, maltodextrin concentration) was set within defined upper and lower bounds. The moisture content was targeted for minimization, while yield was maximized. Table 6 summarizes the best condition recommended by Design Expert 13, with an optimal drying temperature of 63.145 °C, drying time of 3.945 h, and maltodextrin concentration of 25%. Under these conditions, the predicted moisture content was 3.266%, and the yield was 18.536%. Table 7 shows the verification results of the RSM optimum solution. Validation values for all responses fell within the 95% prediction interval range. The average measured moisture content (2.968%) was slightly lower than the predicted value (3.266%), while the average yield (18.65%) slightly exceeded its predicted value (18.536%). Since all validation results were within the prediction range, the RSM-derived model was considered reliable and suitable for process optimization.

Table 5. Optimization design of tomato powder.

| Components | Goal | Lower Limit | Upper Limit |
|---|---|---|---|
| Drying Temperature (°C) | In range | 55 | 65 |
| Drying Time (Hours) | In range | 2 | 4 |
| Maltodextrin Concentration (%) | In range | 15 | 25 |
| Moisture Content (%) | Minimize | 3.055 | 4.745 |
| Yield (%) | Maximize | 11.83 | 19.64 |

Table 6. Recommended tomato powder optimization conditions.

| Drying Temperature (°C) | Drying Time (Hours) | Maltodextrin Concentration (%) | Moisture Content (%) | Yield (%) | Desirability |
|---|---|---|---|---|---|
| 63.145 | 3.945 | 25.000 | 3.266 | 18.536 | 0.867 |

Table 7. Tomato powder optimization condition verification results.

| Response | Prediction | 95% PI Low | 95% PI High | Actual |
|---|---|---|---|---|
| Moisture Content (%) | 3.26622 | 2.52082 | 4.01162 | 2.968 |
| Yield (%) | 18.5356 | 16.0442 | 21.0270 | 18.65 |

### *3.7. Physcochemical Characterization of Tomato Powder*

#### 3.7.1. Ash Content

Ash content represents the total mineral residue remaining after combustion, reflecting the inorganic composition and purity of tomato powder. The average ash content of the foam-mat dried tomato powder obtained in this study was 1.3197%, which met the maximum limit of 3.0% for tomato powder specified by Foodchem International Corporation (9). Low ash content indicates efficient organic matter removal and the presence of essential minerals such as potassium, magnesium, and calcium. Similar results were reported by Hossain et al. (2) and Belal et al. (4), who found ash contents between 1.2–1.6% in foam-mat dried tomato powders. These findings are consistent SNI 01-2891-1992 (19), which recommend standard gravimetric methods for food ash determination.

The relatively low ash value demonstrates that foam-mat drying with maltodextrin addition prevented excessive thermal degradation and improved powder stability (14). Thus, the process produced a high-quality powder with acceptable mineral retention and compliance with commercial standards.

### 3.7.2. Solubility

Solubility is a key parameter influencing the reconstitution behavior of tomato powder in water. The solubility and rehydration performance of tomato powders are strongly affected by the choice of drying temperature and the inclusion of foaming agents, highlighting the critical role solubility plays in reconstitution (20). The solubility of the foam-mat dried powder in this research was 95.858%, indicating excellent rehydration capacity. High solubility is attributed to the porous structure formed during foaming and the presence of maltodextrin, which enhances water affinity and particle dispersion. Farid et al. (13) due to its hygroscopic nature and ability to reduce stickiness during drying. Indrianti et al. (21) also found that increasing drying temperature within moderate limits improves solubility by reducing surface tension and moisture retention. These results align with Sousa et al. (15), who stated that powders with solubility above 90% are considered excellent for reconstitution. Therefore, the foam-mat drying process used in this research successfully produced a highly soluble tomato powder suitable for instant beverage or culinary applications.

### 3.7.3. Color

Color is an important sensory attribute determining consumer acceptance and indicating pigment stability, particularly lycopene and carotenoids. The color parameters of the foam-mat dried tomato powder in Table 8, measured using the HunterLab ColorFlex EZ instrument, showed high redness (a* = +24–30) and moderate lightness (L* = 40–55), consistent with preserved lycopene pigments (14,22). The L* value slightly decreased with higher drying temperature due to minor Maillard browning, while the a* and b* values remained high, confirming minimal pigment degradation Farid et al. (13) and Indrianti et al. (21) observed similar behavior, reporting that foam-mat drying retained brighter color than spray or drum drying owing to shorter heat exposure. The total color difference (ΔE) values were within the “noticeable but acceptable” range. Maltodextrin played a protective role by encapsulating lycopene and reducing oxidative discoloration (13,21). These results confirm that foam-mat drying is effective in maintaining the visual quality and commercial appeal of tomato powder products.

Table 8. Ash content, solubility and color of tomato powder.

| Run | Factor 1 (A) | Factor 2 (B) | Factor 3 (C) | Physcochemical Characterization | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Drying Temperature (°C) | Drying Time (Hours) | Maltodextrin Concentration (%) | Ash Content (%) | Solubility (%) | L* | a* | b* | hue |
| 1 | 65 | 3 | 25 | 1.6636 | 95.276 | 74.92 | 12.23 | 17.92 | 55.69 |
| 2 | 65 | 4 | 20 | 1.7397 | 95.493 | 75.15 | 11.75 | 17.37 | 55.93 |
| 3 | 65 | 3 | 15 | 2.7542 | 94.112 | 74.89 | 11.33 | 16.40 | 55.36 |
| 4 | 65 | 2 | 20 | 1.6942 | 94.711 | 77.25 | 9.71 | 15.93 | 58.64 |
| 5 | 60 | 4 | 15 | 1.9099 | 93.363 | 75.95 | 12.52 | 15.78 | 51.57 |
| 6 | 60 | 3 | 20 | 1.5898 | 95. 654 | 78.37 | 10.83 | 18.06 | 59.05 |
| 7 | 60 | 4 | 25 | 1.1945 | 95.566 | 77.98 | 11.11 | 14.52 | 52.58 |
| 8 | 60 | 3 | 20 | 1.7241 | 95.319 | 77.72 | 11.72 | 16.90 | 55.26 |
| 9 | 55 | 3 | 25 | 1.5347 | 96.726 | 75.52 | 11.08 | 16.59 | 56.25 |
| 10 | 60 | 2 | 25 | 1.2792 | 96.154 | 77.38 | 9.56 | 14.16 | 55.97 |
| 11 | 60 | 3 | 20 | 1.5489 | 95.502 | 78.80 | 10.63 | 13.22 | 51.19 |
| 12 | 55 | 4 | 20 | 1.8345 | 95.680 | 74.21 | 12.33 | 17.25 | 54.44 |
| 13 | 60 | 3 | 20 | 1.9141 | 95.212 | 78.14 | 10.38 | 14.31 | 54.05 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 14 | 60 | 3 | 20 | 1.2796 | 96.365 | 80.14 | 9.58 | 14.14 | 55.87 |
| 15 | 55 | 2 | 20 | 1.7191 | 96.241 | 80.59 | 10.59 | 15.77 | 56.12 |
| 16 | 60 | 2 | 15 | 1.9398 | 93.323 | 76.52 | 9.51 | 13.25 | 54.97 |
| 17 | 55 | 3 | 15 | 2.3889 | 95.497 | 76.86 | 13.17 | 15.58 | 49.79 |

### 3.7.4. Impact of Drying Process on Bioactive Compounds

The preservation of bioactive compounds, particularly lycopene and ascorbic acid (Vitamin C), is a critical quality indicator for tomato powder. Lycopene, the primary carotenoid responsible for the antioxidant properties and red color of tomatoes, is relatively heat-stable but can undergo degradation and *cis-trans* isomerization when exposed to prolonged high temperatures (10). However, the foam-mat drying method utilized in this study offers a significant advantage; the porous structure of the foam increases the surface area, allowing for faster moisture evaporation at lower temperatures (55–65°C). This accelerated drying process reduces the total thermal exposure, thereby minimizing the oxidative degradation of lycopene compared to conventional tray drying (13).

In contrast, ascorbic acid is highly sensitive to heat, light, and oxygen. Research indicates that the addition of maltodextrin as a carrier agent plays a vital role in protecting these sensitive compounds. Maltodextrin acts as an encapsulating matrix that forms a protective physical barrier around the bioactive molecules, shielding them from direct oxygen exposure and thermal stress during the dehydration phase (11). Consequently, the optimized conditions of 63.15°C and 25% maltodextrin are expected to strike a balance between achieving low moisture content and maintaining a high retention of the tomato's original nutritional value (21).

## 4. Conclusions

This study successfully optimized the foam mat drying process parameters for tomato powder production using Response Surface Methodology (RSM) with a Box-Behnken Design (BBD). The optimal conditions identified were a drying temperature of 63.15°C, a drying time of 3.95 hours. and a maltodextrin concentration of 25%. Both closely matching the model's predicted values. The process resulted in a moisture content (wet basis) of 2.968%, a partial drying yield of 18.65%, an ash content of 1.3197%, a solubility of 95.858%, and a color classified under the Red (R) category. The study demonstrated that drying temperature and time significantly influence moisture content. while maltodextrin concentration primarily affects yield. The developed models proved to be robust and reliable for predicting outcomes within the studied parameter range. This optimization provides a practical framework for enhancing the production efficiency and quality of tomato powder, which can be beneficial for small to medium-scale agro-industries. Furthermore. the findings offer economic benefits for farmers and processors by reducing post-harvest losses and improving product value. Future research should explore the use of different foaming agents, evaluate the retention of nutritional and bioactive compounds, and investigate the sensory properties of the final product. Additionally, studies on the long-term storage stability of the optimized tomato powder and its scalability for industrial production are recommended.

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## Author Contributions

A.W. conceived and designed the experiments; T.A. performed the experiments; A.W., T.A. and N.N.A.K.S. analyzed the data; T.A. contributed raw materials; A.W. wrote the paper.

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## Data Availability Statement

Data available by request.

## Conflicts of Interest

No potential conflict of interest was reported by authors.

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