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Research article

Optimization of the foam-mat drying process to develop high-quality tomato powder: A response surface methodology approach

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ABSTRACT

This research aimed to estimate the optimum formulation of process parameters in making tomato powder with optimal physicochemical properties using foam-mat drying. The egg albumin (EA) concentration (1–5%), carboxymethyl cellulose (CMC) concentration (1–1.5 %), and drying temperature (60–70 °C) were employed as independent variables in optimizing through Response Surface Methodology (RSM) in combination with Box-Behnken experimental design (BBD). Based on the total 17 runs of BBD, foam-mat dried powder showed physicochemical properties such as 0.18–0.33 g/cm^3 foam density, 178.54–350 % foam expansion, 40–94 % foam stability, 46.80–62 % water soluble index (WSI), 1.13–2.96 water absorption index (WAI), 1.51–2 °Brix TSS, 2.30–3.98 mg/100 mL ascorbic acid, 0.22–0.38 % titratable acidity, and color (L*: 29.26–48.07, a*: 9.73–16.86, and b*: 6.81–21.56). Furthermore, the ANOVA findings revealed the correlation of determination (R^2) exceeding 85 % for the models, suggesting that the interaction between the responses and the prediction of the implied model is suitable. The optimal formulation from RSM was 4.59 % EA, 0.70 % CMC, and 60 °C drying temperature. Under the optimized conditions, the experimental values were 0.19 ± 0.03 g/cm^3 foam density, 346.60 ± 3.35 % foam expansion, 89.05 ± 2.80 % foam stability, 55.56 ± 3.22 % WSI, 2.49 ± 0.09 WAI, 1.84 ± 0.15 °Brix TSS, 2.93 ± 0.10 mg/100 mL ascorbic acid, 0.39 ± 0.02 % titratable acidity, 46.95 ± 6.35 L*, 17.54 ± 1.50 a*, and 21.85 ± 0.74 b*. The optimized parameters were verified, and there was good agreement between the experimental results and the predicted values (residual standard error (RSE) ≤ 5).

1. Introduction

Tomato (*Lycopersicon esculantum*) belongs to the family Solanaceae and is considered a vital vegetable crop due to its economic and nutritional value. Tomatoes contain vitamins (A and C), phenolics, iron, minerals, dietary fibers, essential amino acids, phosphorus, organic acids, lycopene, and antioxidants [1]. The tomato production in Bangladesh increases yearly due to the high consumer demand. From 2019 to 2020, Bangladesh produced almost 415,494 metric tons of tomatoes from 70,460 acres of land [2]. However, the tomato is highly perishable due to its high water content (90–96 %), making it difficult to store and transport, resulting in heavy losses.

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Consequently, farmers tend to throw away fresh tomatoes that are not sold. The conversion of fresh tomatoes into tomato powder through drying can be an alternative to prevent wasting fresh tomatoes. The drying process of tomato reduces the water content so that rot-causing microorganisms and enzymes are inhibited, thus allowing the material to have a long shelf-life [3]. Generally, tomato drying can be accomplished naturally with sun exposure or mechanically with drum, freeze, or spray dryers. However, drum drying uses very high temperatures, reducing the nutritional value and creating unwanted odors [4]. Drying by freezer or spraying gives good quality products with good color and rehydration properties. Since these drying processes are expensive, they are only used on premium quality products [5]. Therefore, to minimize nutrients' degradation, process hard-to-dry materials, retain volatile compounds, and obtain desired properties of products such as controlled density and favorable rehydration, alternative drying methods such as foam-mat drying have received global attention over the past decade. The process offers many advantages that contribute to the preservation of food quality and the efficiency of production processes [6]. One of its primary importance lies in its ability to maintain the nutritional integrity of food products, as the foam matrix created during drying protects sensitive bioactive compounds from heat and oxidation. This method enhances rehydration properties, ensuring reconstituted products retain their original texture and sensory attributes. Beyond this, foam-mat drying reduces drying times, promoting efficiency and cost-effectiveness in food production. It significantly extends the shelf stability of various products by lowering water activity, inhibiting microbial growth, and thereby prolonging storage life. Recent studies have examined the foam-mat drying process for fruits and vegetables to develop quality powders, including yacon juice powder, mango pulp, cherry powder, papaya powder, and tomato powder [7]. Utilizing the foam-mat drying method as an alternative to traditional spray drying, coconut milk powder was produced by incorporating sodium caseinate (4 % w/v) and maltodextrin (17.5 % w/v). The resulting powder exhibits outstanding flowability, meeting the criteria for excellent flowability based on Carr's index. An economic evaluation of the scaled-up production indicates the profitability of the venture, revealing a benefit-cost ratio of 1.13, an internal rate of return of 33 %, and a break-even period of 206 days [8]. In the investigation by Kumar et al. [9], red banana (RB) pulp underwent modification with various gum derivatives, serving as a foaming agent at a concentration of 4 % w/w. The gum derivatives included acacia gum (GA), carrageenan, and gelatine (GE). To enhance foam stability, maltodextrin and carboxymethyl-cellulose (CMC) were incorporated as foam stabilizers. Introducing a foaming agent led to the formation of low-density foam, particularly with a 50 % reduction observed in RBGE, accompanied by enhanced foam stability, notably in RBGA, which exhibited a 94.42 % improvement. The resulting powders demonstrated low hygroscopicity, notably in RBGA, registering at 18.62 g per 100 g, and exhibited optimal flowability.

In foam-mat drying, liquid or semi-liquid food materials are transformed into stable foam by stirring with foaming agents and stabilizers [10]. A thin and porous mat is formed during foam-mat drying at low temperatures. Foam's structure has a large surface area, which allows water to evaporate more rapidly [11]. As part of the drying process, capillary diffusion activates moisture in the product. Compared with conventional drying, foam-mat products are porous and have better quality. In addition to its higher stability against chemical and microbial reactions and deteriorative microbial, foam-mat dried products require less handling, transportation, packaging costs and negligible energy for storage [12]. In addition, during storage, it remains free-flowing and reconstitutes well. Nevertheless, to ensure efficacy in drying, the foams must maintain a stable condition thermodynamically and mechanically to remove water while also maintaining product quality effectively.

Several factors are responsible for generating stable foam. For instance, high-molecular-weight polysaccharides such as carboxymethyl cellulose, methylcellulose, Arabic gum, xanthan gum, maltodextrin, starch, and pectin are used as foam stabilizers to provide stable gas-liquid foam. In contrast, protein-structured components such as whey proteins, soy proteins, egg whites, egg albumin, gelatin, and casein are used as foaming agents [11]. Stabilizers make foams more stable by increasing their interfacial viscoelasticity, while foaming agents create intermolecular hydrogen bonds and air bubbles in foams [13]. CMC is one of the most efficient stabilizers for emulsions, suspensions, foams, etc. Therefore, CMC is considered a suitable stabilizer for generating thermodynamically and mechanically stable foam. CMC is primarily incorporated into the food as a sodium salt [14]. On the other hand, egg albumin (EA) is one of the most utilized foaming agents in foam-mat drying. EA is a readily available natural food foaming additive with superior foaming characteristics. It rapidly adsorbs on the air-liquid interface via intermolecular interactions to form a cohesive viscoelastic film when whipped. EA produces vast volumes of thermally stable foams due to its unique protein composition. Additionally, the presence of EA as a foaming agent aids in creating pores, increasing the available specific surface area for drying [15]. Hence, CMC and EA are chosen as the foaming stabilizer and foaming agent, respectively, in the present study for the drying of tomatoes.

Therefore, optimizing the various processes to achieve stable foam is critical by selecting the appropriate foaming agent concentration, foam stabilizer concentration, whipping time, drying temperature, etc. There are numerous techniques for optimizing process parameters. Typically, Response Surface Methodology (RSM) is employed to combine statistical and mathematical tools to help develop, improve, and optimize processes [16–19]. Moreover, the RSM technique is an efficient and cost-effective alternative to using one variable at a time or full-factor experiments [20]. The most common designs of the RSM, namely the central composite design (CCD) and Box-Behnken design (BBD), have been extensively employed in a variety of investigations [16,22]. BBD, a spherical and revolving design with outstanding outcomes, has been implemented to optimize chemical and physical processes [23]. In some previous studies, the RSM was effectively used to optimize the foaming parameters for strawberry [24], tomato powder [25], *Gardenia jasminoides* Ellis [26], egg [27], white button mushroom [28], and coconut milk [8]. The novelty of the present study lies in the unexplored territory of optimizing the foam-mat drying process for tomato powder, which has been inadequately addressed in the existing literature. The present study uses an optimization approach to determine the optimal conditions for generating a stable foam that maintains its integrity throughout sequential batch drying operations. Successful optimization could have substantial implications for industries, offering the potential for increased output and producing high-quality tomato powder. By focusing on critical factors such as foaming agent concentration (EA), foam stabilizer (CMC), and drying temperature, the study employs RSM and a BBD to systematically explore and establish the optimal conditions for foam-mat dried tomato powder. The findings from this investigation

Table 1
Independent variable levels in experimental design for response surface analysis.

Independent variables	Symbols	Coded level		
		−1	0	1
Carboxymethyl cellulose (CMC) (%)	A	1	0.5	1.5
Egg albumin (%)	B	1	3	5
Temperature (°C)	C	60	65	70

Table 2
Box-Behnken design of three variables.

Run	Carboxymethyl Cellulose (CMC) %	Egg Albumin (%)	Temperature (°C)
1	1	1	70
2	1	3	65
3	0.5	1	65
4	1.5	1	65
5	1.5	3	70
6	1	3	65
7	1	3	65
8	0.5	3	70
9	1.5	5	65
10	1	5	70
11	1.5	3	60
12	1	3	65
13	0.5	5	65
14	1	1	60
15	0.5	3	60
16	1	3	65
17	1	5	60

may not only contribute to the scientific understanding of foam-mat drying but also provide practical insights for industries to enhance economic benefits and product quality in their tomato powder production processes.

2. Materials and methods

2.1. Materials

Freshly ripened tomatoes of the Raja hybrid variety were obtained from Madina Market in Sylhet, Bangladesh, and used as raw materials. As a foaming agent, fresh eggs were purchased from Madina Market in Sylhet, Bangladesh. A food-grade sodium salt of CMC (CAS No.9004-32-4) manufactured by Dalian Chem was utilized as a foam stabilizer. Analytical grade chemicals were procured from Sigma-Aldrich (US) and Merck (Germany) for this investigation.

2.2. Preparation of tomato juice powder

The preparation of tomato juice powder was done using the method of Hossain et al. [22] with few modifications. After rinsing the tomato with running water, unwanted external materials such as dust and clay were removed. The tomato juice was extracted with a juice extractor (Model: Panasonic MJ M176P, Panasonic Malaysia Sdn. Bhd., Malaysia) after they were cut with stainless steel knives. The juice was then pasteurized for 3 min at 85 °C. Foaming was performed by varying the concentrations of foaming agent (EA) and foam stabilizer (CMC) according to BBD (Tables 1 and 2) using a whipper. Each sample included 400 mL of tomato juice with different concentrations of EA (30–60 %) and CMC (40–60 %) (Table 2). The mixers were then whipped in a domestic mixer (Arno, model SX15, São Paulo, Brazil) at maximum speed (rotation speed level: 3) for 6 min for foam formation [29]. In a stainless-steel tray, tomato juice was spilled after foaming, which was then dried in an oven with forced air circulation (Model: Fanem 320, Brazil) at different temperatures (60–70 °C) based on the design shown in Table 2 and air velocity of 1.0 m/s. After drying, the samples were milled using IKA Tube Mill (IKA, Staufen, Germany) to obtain the final powdered product and packed in high-density polyethylene (HDPE) bags for future study. In a ratio of 1:20 (tomato powder to water), the dried tomato powder from the foam-mat was reconstituted with distilled water to assess the quality of the dried tomato powder. After foaming formation, foam characteristics such as expansion, density, and stability were examined, and reconstituted powder solutions were tested for water absorption index, water solubility indexes, ascorbic acid, total soluble solids, titratable acidity, and color parameters (L*, a*, and b*).

2.3. Experimental design and optimization

The effects of various concentrations of EA, CMC, and different drying temperatures on the physicochemical properties of foam-mat dried tomato powder, such as foam density, foam expansion, foam stability, WSI, WAI, TSS, ascorbic acid, titratable acidity, and color parameters (L*, a*, and b*) using the RSM technique. For generating response surface plots and optimizing process variables based on RSM, the present study used the Design-Expert version 12 (Statease Inc, Minneapolis, USA) software. The foaming studies used a BBD model of three variables with three levels. The preliminary study was used to select the factor levels [30]. High and low levels of the variables were studied as 1–5 % of EA, 1–1.5 % of CMC, and 60–70 °C of drying temperature. The current study tested 17 different combinations. According to the experimental design illustrated in Table 1, tomato juice was subjected to foaming tests. Due to the multiple interactions among independent variables that resulted in various responses, all experimental data were fitted with the second-order polynomial regression Equation (1) shown below.

$$y = a_0 + a_1x_1 + a_2x_2 + a_{11}x_1^2 + a_{22}x_2^2 + a_{12}x_1x_2 \tag{1}$$

where y is the measured response variable, x_1 and x_2 represent the independent variable levels. a_o is a constant (predicted response at the center), a_1, a_2; a_{11}, a_{22}; and a_{12} are the model's linear, quadratic, and two-factor interaction coefficients, respectively. Tests for statistical significance were carried out using the analysis of variance (ANOVA). Two variables were used to construct the response surface plots, with the value of a third factor being held constant throughout the process. An accurate geometric description of the behavioral system and valuable insights into its operation were provided by response surface plots.

Using Design Expert version 12 software, multiple responses were also optimized. The present study optimized the foaming agents (EA) and foam stabilizer (CMC) concentration and drying temperature to determine the optimal levels of three variables that would give a minimum level of foam density as well as a maximum level of foam expansion, foam stability, WSI, WAI, TSS, ascorbic acid, titratable acidity, and color properties (L*, a*, and b* values). A comparison of the predicted and experimental values was made to check the adequacy of the models. The residual standard error (RSE) percentage was calculated for each response.

2.4. Analysis of physicochemical properties of foam-mat dried tomato powder

2.4.1. Foam density

Following the foam production, a 20 mL aliquot was collected and placed in a measuring cylinder at 25 °C. The foam was then carefully placed in the measurement cylinder so that none of the incorporated air would escape and maintain its structure. Afterward, foam density was determined based on the mass/volume (g/cm^3) relationship in Equation (2).

$$\text{Foam density } (g/cm^3) = \frac{\text{Foam weight}}{\text{Foam volume}} \tag{2}$$

2.4.2. Foam expansion

The expansion of foam is proportional to the volume of air whipped into it [31]. Therefore, based on Equation (3), the relationship between the density of tomato juice (J_d) and the density of foam (F_d) was used to calculate foam expansion (F_e).

$$\text{Foam expansion } (\%) = \frac{\frac{1}{F_d} - \frac{1}{J_d}}{\frac{1}{J_d}} \times 100 \tag{3}$$

2.4.3. Foam stability

The foam stability of tomato juice was determined using a graduated measuring cylinder. It was kept for 2 h at 25 °C. The reduction of foam volume was calculated after 2 h. Equation (4) was used to figure out the percent foam stability [32].

$$\text{Foam stability } (\%) = \frac{\text{Final volume of foam after 2 hours}}{\text{Initial volume of foam at time zero}} \times 100 \tag{4}$$

2.4.4. Water solubility index

According to Belal et al. [29], the WSI of foam-mat dried powders in water was tested using 30 mL of distilled water and 3 g of sample powder. The experiment lasted 30 min at 30 °C. Following centrifugation for 30 min at 3000 rpm, a previously weighted Petri plate was then filled with the supernatant and oven dried at 105 °C until a constant weight was reached. Based on the weight of the remaining solids, the percentage WSI was calculated using Equation (5).

$$\text{WSI } (\%) = \frac{\text{weight of dry solids after centrifugation}}{\text{weight of initial dry powder sample}} \times 100 \tag{5}$$

2.4.5. Water absorption index

The remaining weight of the hydrated powder in the centrifuge was also calculated using the prior method reported by Asokapandian et al. [31]. Equation (6) was used to calculate the WAI.

Table 3
Box-Behnken design corresponding responses, foam density, foam expansion, WSI, WAI, TSS, ascorbic acid, titratable acidity, and color (L*, a*, and b* value).

Run	Foam Density (g/ cm^3)	Foam Expansion (%)	Foam Stability (%)	WSI (%)	WAI	TSS (°Brix)	Ascorbic acid (mg/100 mL)	Titratable Acidity (%)	L* value	a* value	b* value
1	0.33 ± 0.05	192.67 ± 5.78	86.00 ± 2.8	52.40 ± 3	2.66 ± 0.77	1.51 ± 0.01	3.98 ± 0.01	0.26 ± 0.01	31.77 ± 0.19	11.94 ± 0.02	10.15 ± 0.01
2	0.23 ± 0.07	300.00 ± 7.45	85.00 ± 1.7	58.00 ± 1.4	2.13 ± 0.25	1.55 ± 0.01	2.69 ± 0.01	0.34 ± 0.01	34.60 ± 0.01	15.13 ± 0.02	13.71 ± 0.01
3	0.21 ± 0.04	229.85 ± 4.47	40.00 ± 2.2	60.80 ± 2.5	1.13 ± 0.32	1.75 ± 0.01	2.81 ± 0.02	0.36 ± 0.01	29.26 ± 0.21	11.49 ± 0.01	11.83 ± 0.02
4	0.24 ± 0.04	178.54 ± 6.01	88.00 ± 2.2	54.30 ± 2.9	1.43 ± 0.56	2.00 ± 0.01	4.22 ± 0.02	0.22 ± 0.05	38.96 ± 0.09	9.73 ± 0.02	9.54 ± 0.11
5	0.30 ± 0.02	234.76 ± 1.80	94.00 ± 2	53.20 ± 2	2.12 ± 0.82	2.00 ± 0.01	2.78 ± 0.03	0.26 ± 0.07	35.89 ± 0.01	11.25 ± 0.01	12.29 ± 0.17
6	0.23 ± 0.02	300.00 ± 2.38	85.00 ± 1.7	54.32 ± 1.7	2.13 ± 1.02	1.72 ± 0.01	2.69 ± 0.05	0.34 ± 0.20	34.60 ± 0.01	11.89 ± 0.03	13.71 ± 0.04
7	0.24 ± 0.03	300.00 ± 3.58	85.00 ± 2.3	58.00 ± 2.2	2.30 ± 0.32	1.75 ± 0.11	2.30 ± 0.03	0.31 ± 0.11	30.03 ± 0.13	12.34 ± 0.01	11.78 ± 0.02
8	0.24 ± 0.04	266.67 ± 4.63	71.00 ± 1.1	62.00 ± 2.5	2.03 ± 1.06	1.70 ± 0.09	3.07 ± 0.02	0.35 ± 0.27	34.24 ± 0.01	16.20 ± 0.02	15.89 ± 0.03
9	0.19 ± 0.04	316.67 ± 7.45	85.55 ± 1.1	60.00 ± 1.7	1.71 ± 0.72	1.58 ± 0.11	3.62 ± 0.02	0.30 ± 0.35	39.95 ± 0.01	12.91 ± 0.02	17.43 ± 0.01
10	0.18 ± 0.04	340.00 ± 2.74	87.20 ± 3.4	54.40 ± 2.6	2.62 ± 1.41	1.80 ± 0.05	2.88 ± 0.01	0.38 ± 0.53	48.07 ± 0.08	16.86 ± 0.03	21.06 ± 0.12
11	0.25 ± 0.05	280.00 ± 5.74	84.00 ± 2.8	60.40 ± 2.9	2.34 ± 1.12	2.00 ± 0.07	3.46 ± 0.03	0.25 ± 0.52	42.05 ± 0.01	13.99 ± 0.03	18.77 ± 0.06
12	0.23 ± 0.05	269.67 ± 9.82	79.00 ± 1.7	53.40 ± 1.9	2.21 ± 0.02	1.80 ± 0.12	2.52 ± 0.03	0.31 ± 0.73	33.12 ± 0.04	12.18 ± 0.18	6.81 ± 0.01
13	0.18 ± 0.03	362.87 ± 9.69	82.00 ± 2.1	51.60 ± 2.7	1.98 ± 0.23	1.80 ± 0.03	3.46 ± 0.05	0.30 ± 0.34	47.92 ± 0.01	15.09 ± 0.09	21.56 ± 0.01
14	0.30 ± 0.01	211.43 ± 8.82	78.00 ± 3.5	54.23 ± 1.6	1.66 ± 0.03	2.00 ± 0.03	2.53 ± 0.01	0.36 ± 0.22	36.33 ± 0.12	12.82 ± 0.02	16.96 ± 0.07
15	0.23 ± 0.01	216.67 ± 1.39	72.00 ± 1.6	46.80 ± 3.2	1.96 ± 0.05	2.01 ± 0.03	2.98 ± 0.01	0.33 ± 0.15	39.04 ± 0.07	9.80 ± 0.02	14.63 ± 0.01
16	0.23 ± 0.01	300.00 ± 2.01	85.04 ± 1.1	53.60 ± 1.5	2.32 ± 0.05	1.79 ± 0.17	2.41 ± 0.01	0.31 ± 0.12	31.66 ± 0.01	13.94 ± 0.02	11.77 ± 0.01
17	0.26 ± 0.07	350.00 ± 2.45	82.00 ± 1.6	49.60 ± 2.2	2.96 ± 0.01	1.60 ± 0.05	3.46 ± 0.01	0.28 ± 0.10	43.21 ± 0.01	13.83 ± 0.02	19.11 ± 0.01

Data are expressed as mean ± standard deviation of the mean (n = 3). WSI: Water Solubility Index; WAI: Water Absorption Index; TSS: Total Soluble Solids.

$$\text{WAI} = \frac{\text{weight of remaining wet solids after centrifuge}}{\text{weight of initial dry powder sample}} \tag{6}$$

2.4.6. *Total soluble solids*

Using a hand refractometer (Model: 2353MASTER-53M, Atago Co., Ltd., Japan) and the method described by Zzaman et al. [33], the TSS of foam-mat dried tomato powder was calculated using the Brix scale. In brief, the refractometer was set up by placing reconstituted sample juice (1–2 drops) in its glass prism, covering it with its plate, and then taking readings as it reflected light.

2.4.7. *Ascorbic acid*

In this study, foam-mat dried tomato powder was tested for ascorbic acid content using the method described by Hoque et al. [21]. Using 3 % HPO_3, a sample volume of approximately 5 mL was diluted to 50 mL. Afterward, filtration was done using Whatman No. 2 filter paper. The 2,6 dichlorophenolindophenol was titrated with approximately 10 mL of filtrate in 10 mL HPO_3 until the endpoints turned pink, and for around 15 s, the color remained in the solution. In a beaker, 3 % HPO_3 solution was combined with 5 mL of standard ascorbic acid solution in a ratio of 5:1, and then the dye solution was put into the burette. Until the formation of the pink color, the dye solution was added and titrated, and it remained so for about 15 s. Using the formula: dye factor = 0.5/titer, the dye factor was calculated, which is the amount of ascorbic acid per mL of dye. The following formula (Equation (7)) was used to determine the content of ascorbic acid (mg/100 mL) in tomato juice:

$$\text{Ascorbic acid (mg / 100 mL)} = \frac{\text{titre} \times \text{dye factor} \times \text{volume made up} \times 100}{\text{aliquot extract taken for estimation} \times \text{weight of sample}} \tag{7}$$

2.4.8. *Titratable acidity*

The titratable acidity of the reconstituted foam-mat dry tomato powder sample was determined using the method described by

Table 4
Regression coefficients, probability and the determination coefficients corresponding responses, foam density, foam expansion, foam stability, WSI, WAI, TSS, ascorbic acid, titratable acidity, and color (L*, a*, and b* value). *$p \leq 0.05$. WSI: Water Solubility Index; WAI: Water Absorption Index; TSS: Total Soluble Solids.

Constants	Foam Density (g/cm^3)	Foam Expansion (%)	Foam Stability (%)	WSI (%)	WAI	TSS (°Brix)	Ascorbic acid (mg/100 mL)	Titratable Acidity (%)	L* value	a* value	b* value
A	0.09	0.11	0.0009*	0.26	0.25	0.25	0.08	0.0001*	0.34	0.19	0.42
B	0.003*	0.002*	0.02*	0.30	0.0006*	0.10	0.89	0.17	0.0002*	0.01*	0.003*
C	0.88	0.49	0.20	0.09	0.24	0.05*	0.75	0.47	0.13	0.12	0.18
AB	0.66	0.68	0.01*	0.006*	0.08*	0.04*	0.08	0.002*	0.005*	0.86	0.71
AC	0.39	0.08	0.35	0.001*	0.34	0.13	0.24	0.73	0.77	0.01*	0.15
BC	0.04*	1.00	0.81	0.13	0.002*	0.01*	0.01*	0.0002*	0.07	0.13	0.11
A^2	0.10	0.83	0.05*	0.06	0.0002*	0.02*	0.02*	0.01*	0.09	0.15	0.40
B^2	0.52	0.17	0.24	0.39	0.07	0.16	0.01*	0.75	0.006*	0.82	0.07
C^2	0.01*	0.02*	0.31	0.08	0.0006*	0.13	0.45	0.97	0.03*	0.20	0.05*
R^2	0.88	0.86	0.91	0.91	0.96	0.87	0.87	0.96	0.93	0.86	0.86
F-value	5.55	12.03	7.44	7.50	17.19	5.53	5.42	17.30	11.17	4.74	4.58
p-vale of model	0.02*	0.03*	0.01*	0.01*	0.001*	0.02*	0.01*	0.001*	0.002*	0.03*	0.03*
Lack of fit (*p* value)	0.82	0.71	0.54	0.85	0.90	0.67	0.60	0.80	0.33	0.83	0.78
Coefficient of variation (CV %)	9.08	7.55	6.85	3.51	6.76	5.10	9.83	4.50	5.94	8.88	16.57
Adeq precision	10.13	9.84	11.88	9.39	18.24	7.16	6.78	15.70	11.56	7.80	6.52
Fitted model	Quadratic model	Quadratic model	Quadratic model	Quadratic model	Quadratic model	Quadratic model	Quadratic model	Quadratic model	Quadratic model	Quadratic model	Quadratic model

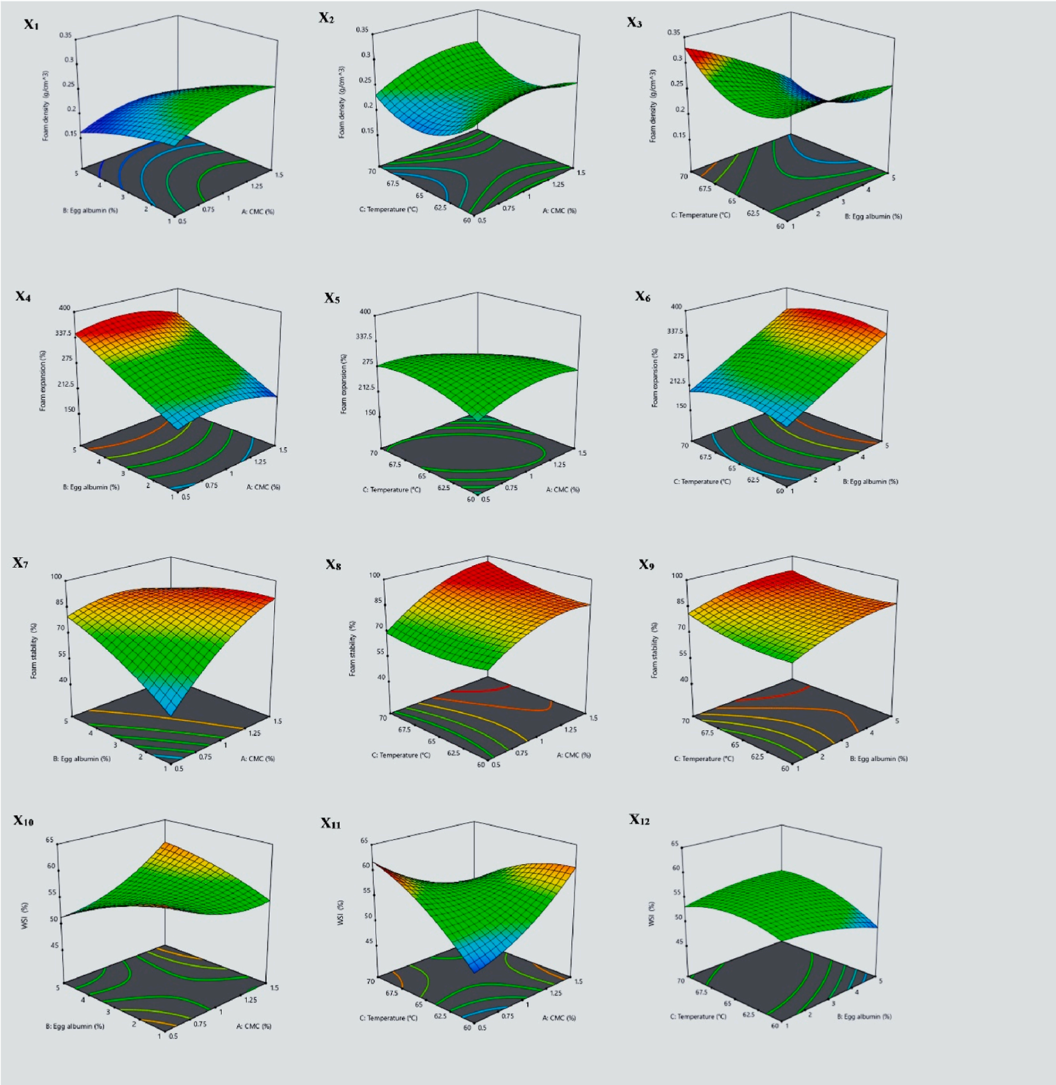

Fig. 1. Response surface plots for interaction effects of carboxymethyl cellulose (CMC), egg albumin, and temperature on foam density (X_1, X_2, X_3), foam expansion (X_4, X_5, X_6), foam stability (X_7, X_8, X_9), and WSI (X_{10}, X_{11}, X_{12}). WSI: Water Solubility Index.

Hossain et al. [22]. Exactly 10 mL of water was used to rehydrate the powder sample. Using 0.1M NaOH and two drops of phenolphthalein as an indicator, a titration was then performed. Equation (8) and Equation (9) were used to compute the percentage acidity as anhydrous citric acid.

$$\text{Weight of citric acid} = \frac{0.1\text{ M NaOH} \times \text{volume of NaOH (L)} \times 192.43}{3} \tag{8}$$

$$\text{Total acidity (\%)} = \frac{\text{weight of citric acid}}{\text{weight of sample aliquot}} \times 100 \tag{9}$$

2.4.9. Color analysis

One of the most noticeable sensory characteristics in determining food quality is color. A colorimeter (Model: PCE-CSM4) was employed to assess the color characteristics of foam-mat dried tomato powder [34]. In colorimeters, the L*, a*, and b* parameters define color. L* indicates lightness or brightness/darkness on a scale of 0–100 (black-white), a* indicates redness (0–60)/greenness (−60 to 0), and b* indicates yellowness (0–60)/blueness (−60 to 0). Before analyzing the sample, white-colored tiles were used for calibration.

3. Results and discussion

3.1. Model fitting

As shown in Table 4, multiple regression analysis was used to analyze the BBD data and correlations between the independent variables of EA (1–5 %), CMC (1–1.5 %), drying temperature (60–70 °C) and the dependent variables of foam density, foam expansion, foam stability, WSI, WAI, TSS, ascorbic acid, titratable acidity, and color parameters (L*, a*, and b* values) were developed. A second-order polynomial relationship was observed between independent and dependent variables following the analysis. The regression model and the individual model coefficients were subjected to a significance test, as illustrated in Table 4. The results revealed that the quadratic model was a good fit for all the responses, and the model developed for responses was highly significant ($p \leq 0.05$). The correlation of determination (R^2) of foam density (0.88), foam expansion (0.86), foam stability (0.91), WSI (0.91), WAI (0.96), TSS (0.87), ascorbic acid (0.87), titratable acidity (0.96), and color properties (L* (0.93), a* (0.86), and b* (0.86)) was used to evaluate the model's accuracy. The ANOVA results demonstrated that there was greater than 85 % R^2 for the models, which indicates that the interaction between the responses and predicting the implied model is appropriate [35]. To ascertain the goodness of fit, the coefficient of variation (C.V) was examined, revealing small values for all developed models, signifying a good fit [36]. Additionally, the significance of *p* values for "lack of fit" was crucial, with non-significant values observed for foam density (0.82), foam expansion (0.71), foam stability (0.54), WSI (0.85), WAI (0.90), TSS (0.67), ascorbic acid (0.60), titratable acidity (0.80), and color properties (L* (0.33), a* (0.83), and b* (0.78)), supporting model fitness. Furthermore, adequate precision values exceeding 4 were crucial for model acceptance and intended use [37]. All adequate precision values in Table 4 surpassed this threshold, leading to the conclusion that the developed models are suitable for relating process input to process output, facilitating estimation, prediction, and analysis of the process.

3.2. RSM analysis of physicochemical properties of tomato powder

3.2.1. Foam density

Whipping properties are commonly evaluated using foam density. Lower foam density can be achieved by incorporating more air during whipping. The higher the amount of air incorporated during whipping, the lower the density of the foam; yet, the whippability of foam increases with the amount of air it contains. Low-density foam accelerates water removal during the drying process by providing a greater specific surface area for drying air. In the current investigation, foam density was found in the range of 0.18–0.33 g/cm^3. According to the literature, the optimum foam density value for the foam drying process was between 0.2 and 0.5 g/cm^3. According to the statistical analysis (Table 4), model significance is indicated by an F-value of 5.55. The probability of a large F-value occurring due to noise is only 1.71 %. The *p*-value less than 0.05 was determined to be significant ($p \leq 0.05$) for the linear terms of EA (B), interactive terms of drying temperature, and EA (BC), as well as the quadratic term of drying temperature (C^2). The following regression equation (Equation (10)) for foam density was developed in terms of coded units, taking into account the effects of individual independent components as well as their significant interactions.

$$\text{Foam density}\ (\text{gm}/\text{cm}^3) = 0.232 + 0.015\,A - 0.034\,B + 0.001\,C - 0.005\,AB + 0.010\,AC - 0.028\,BC - 0.019\,\widehat{A}^2 - 0.007\,\widehat{B}^2 + 0.043\,\widehat{C}^2 \tag{10}$$

It is clear from the response surface plot (Fig. 1X_1, 1X_2, and X_3) that the foam density decreased with an increased concentration of EA. In response to the increase in EA concentration, foaming agents are transported from the aqueous phase to air-liquid interfaces, reducing surface tension. In turn, the mechanism increases the foaming ability and reduces density. The study of Tan and Sulaiman [38] reported that the foam density decreased from 0.35 to 15 g/cm^3 as the concentration of EA increased from 5 % to 20 %. After heating the foam at higher temperatures (65–70 °C), the foam density of the tomato improved. This may be associated with decreased protein aggregation and increased viscosity, which increases foaming capacity [39]. Another potential explanation could be that the partial denaturation of protein through heating might enhance foamability. However, as the temperature reached 70–80 °C, protein aggregation, solubilization, and emulsifying capacity declined. In contrast, when the CMC concentration was raised, an increase in foam density was observed. According to literature, using a high-viscosity liquid to whip or mechanically mix may prevent air from being trapped. When CMC concentration is increased, the mixture becomes more viscous, resulting in the mixture becoming too viscous to incorporate the maximum amount of air [40]. This results in increasing foam density. Indian blackberry (*Syzygium cuminii* L.) fruit pulp foam density was studied by Sahu et al. [41], and their findings strongly supported the present study.

3.2.2. Foam expansion

The amount of air incorporated into the juice during foaming is referred to as "foam expansion," and it is expressed as a percentage increase in volume. The foam expansion values for the experimental runs ranged from 178.54 % to 362.87 %. The statistical analysis (Table 4) reveals that the F-value of 12.03 represents a significant result. The following regression equation (Equation (11)) for foam expansion was developed in terms of coded units, taking into account the effects of individual independent components as well as their significant interactions.

$$\text{Foam expansion}\ (\%) = 293.93 - 8.26\,A + 69.63\,B - 3.00\,C + 1.28\,AB - 23.81\,AC + 2.19\,BC - 22.98\,\widehat{A}^2 + 1.02\,\widehat{B}^2 - 21.43\,\widehat{C}^2 \tag{11}$$

Fig. 1X_4, 1X_5, and X_6 display the effect of varying EA, CMC concentrations, and drying temperatures on the expansion volume. It can be noticed on the plot that the expansion volume rises in proportion to the enhancement in EA concentration. In contrast, with an increase in CMC concentration up to 1 %, the expansion volume increases and decreases after reaching 1 % CMC level. The subsequent decrease in foam expansion beyond 1 % concentration might be explained by an excessive amount of CMC hindering the flexibility and mobility of the foam matrix. Proteins present in EA may be responsible for the increase in expansion volume. A stable, viscoelastic interfacial film forms when the proteins in EA are whipped and interact, resulting in the formation of tomato foam and an increase in its volume [29]. Furthermore, CMC stabilizes foam by increasing its viscosity, which may explain the decrease in foam expansion with higher CMC. It has been suggested that a high-viscosity liquid would help prevent air from becoming trapped during the whipping process because it becomes too viscous at higher concentrations. Other investigations have observed a similar trend in foam expansion as a result of an increase in EA and CMC concentration, for instance, guava fruit pulp [42], mango powder [32], and papaya powder [43]. Like CMC, an increase in the drying temperature led to a moderate increase in foam volume and followed a diminishing pattern. The protein nature of the foaming agent may be responsible for the observed increase in foam volume. Whipping caused the proteins to denature in the interphase, resulting in the formation of a stable interfacial film. Therefore, the foam structure may collapse with increased drying temperature, leading to a decrease in foam expansion [44].

3.2.3. Foam stability

Rapid drying and the removal of dried material from trays are both made possible by using foam with a stable structure. It is worth noting that if the foam structure is severely damaged, it takes longer for the product to dry, resulting in a lower quality of the end product. A foam's stability is influenced by its thickness, surface permeability, bubble size distribution, and adhesion. During drainage, lamellae are thinner, and subsequently, there is a higher risk of bubble collapse. The current study showed that foam stability values ranged from 71 to 94 %. The model had a substantial F value of 7.44 and an R^2 of 0.91, indicating that it was statistically significant. The p-values less than 0.05 were determined to be significant ($p \leq 0.05$) for the linear terms of CMC (A) and EA (B), as well as the quadratic term of CMC (A^2). The following regression equation (Equation (12)) for foam stability was developed in terms of coded units, taking into account the effects of individual independent components as well as their significant interactions.

$$\text{Foam stability } (\%) = 83.81 + 10.82\text{ A} + 5.59\text{ B} + 2.78\text{ C} - 11.11\text{ AB} + 2.75\text{ AC} - 0.70\text{ BC} - 6.49\,\widehat{A}^2 - 3.44\,\widehat{B}^2 + 2.93\,\widehat{C}^2 \quad (12)$$

The response surface plot (Fig. 1X_7, 1X_8, and 1X_9) also indicated that foam stability directly correlates to the mixture's viscosity. Hence, higher EA and CMC concentrations result in more stable foam. Viscosity increases to prevent the thin layer from ripping (which results in the formation of bubbles (lamella)) and stabilize the foam by coating it with a sticky layer. This phenomenon can be explained by the increase in viscosity as well as viscoelasticity, the strength of the lamellae at the air-liquid interface, and the yield stress of the continuous phase [45]. In an investigation by Affandi et al. [46], foams were generated from a *Nigella sativa* solution through the incorporation of varying concentrations of EA (2.5 %, 8.75 %, and 15 % w/w) and CMC (0 %, 0.5 %, and 1 % w/w), employing whipping durations of 2, 5, and 8 min. The findings revealed that as the concentrations of EA and CMC increased, the stability of the foam also enhanced. The increased concentration of CMC was observed to potentially decrease surface tension, thereby promoting the formation of a robust film. By comparing the process temperatures, it was observed that gradually raising the drying temperature from 65 to 70 °C improved foam stability. Because of the increase in temperature, the absorption of proteins at interfaces is also rising. Protein adsorption of the gas-liquid interface can alter interparticle forces between foam bubbles, precluding nonpolar molecules from interacting across the interface and improving interfacial rheology. The better rheological results provide foam with greater stability while also delaying liquid drainage [39].

3.2.4. Water solubility index

A powder's WSI indicates its ability to mix homogeneously in water. The WSI for the foamed dried tomato powder varied from 46.80 to 62.00 % (Table 3). An F-value of 7.50, which is derived from the design expert statistical analysis of the model for WSI, shows that the model is significant. The following regression equation (Equation (13)) for WSI was developed in terms of coded units, taking into account the effects of individual independent components and their significant interactions.

$$\text{WSI } (\%) = 55.46 + 0.83\text{ A} - 0.77\text{ B} + 1.37\text{ C} + 3.72\text{ AB} - 5.60\text{ AC} + 1.66\text{ BC} + 2.08\,\widehat{A}^2 - 0.87\,\widehat{B}^2 - 1.94\,\widehat{C}^2 \quad (13)$$

A response surface plot (Fig. 1X_{10}, 1X_{11}, and 1X_{12}) is used to demonstrate that the WSI of foam-mat dried tomato powder reduced significantly as the EA concentration increased from 1 to 5 %. At lower concentrations (1 %), the presence of EA may contribute to the formation of a more porous and interconnected network within the tomato powder matrix. This porous structure allows for better water penetration and absorption, resulting in a higher WSI. However, as the concentration of EA increases to 5 %, it can lead to the formation of a denser and more compact structure in the foam-mat dried tomato powder. This densification could reduce the accessibility of water to the inner structure of the powder particles, limiting water penetration and solubility. Additionally, higher concentrations of EA might result in increased protein-protein interactions, leading to a tighter network that is less prone to dispersing in water [47]. Up to 65 °C, WSI increased, and then it began to decline until it reached 70 °C. A decrease in the drying time led to less time for bubbles to collapse when the drying temperature increased from 60 to 65 °C. As the porous foam structure is preserved and improved, it becomes more soluble. However, the powder's porosity and WSI were reduced due to the faster collapse of bubbles at the elevated temperature from 65 to 70 °C. Abbasi and Azizpour [45] found a similar finding for sour cherry powder. They reported that elevating the drying temperature from 50 to 65 °C led to a reduction in drying time, minimizing the opportunity for bubbles to collapse. Consequently, the porous foam structure was better preserved, directly influencing WSI. Conversely, when the temperature was further

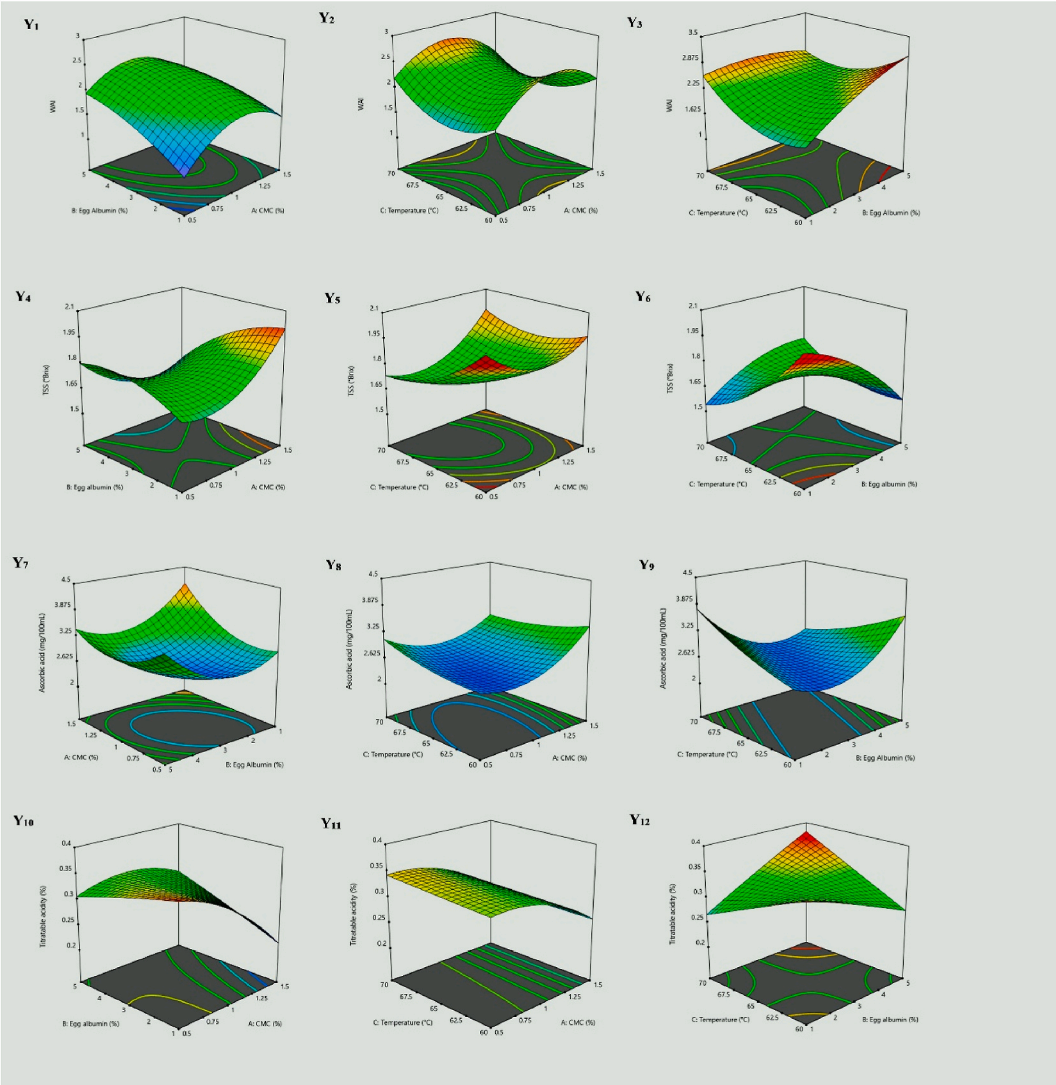

Fig. 2. Response surface plots for interaction effects of carboxymethyl cellulose (CMC), egg albumin, and temperature on WAI (Y_1, Y_2, Y_3), TSS (Y_4, Y_5, Y_6), ascorbic acid (Y_7, Y_8, Y_9), and titratable acidity (Y_{10}, Y_{11}, Y_{12}). WAI: Water Absorption Index; TSS: Total Soluble Solids.

increased from 65 to 80 °C, the higher temperature accelerated the collapse of bubbles, diminishing the porosity and WSI solubility of the powder. Besides, the effect of CMC level on the WSI of foam-mat dried tomato powder. Increasing amounts of CMC from 0.9 to 1.5 % resulted in a gradual increase in WSI. It was reported that raising the CMC concentration during the drying process resulted in increased stability of the foam structure, which caused a greater porosity of the powder. Correspondingly, the stronger the structure, the more bubbles will remain at the end of the drying process. Due to the presence of bubbles, the powder becomes more porosity and more soluble [48]. Similar results were observed when sour cherry powder was dried using the foam-mat drying technique [45].

3.2.5. Water absorption index (WAI)

The term "Water absorption Index (WAI)" relates to the water absorbability of powders; it is also called the hydration capacity. The WAI was between 1.13 and 2.96 based on the application of various combinations (Table 3). The model F-value of 17.19 indicates model significance. The following regression equation (Equation (14)) for WAI was developed in terms of coded units, taking into account the effects of individual independent components and their significant interactions.

$$WAI = 2.22 + 0.06\ A + 0.30\ B + 0.06\ C - 0.14\ AB - 0.07\ AC - 0.34\ BC - 0.51\ \widehat{A}^2 - 0.15\ \widehat{B}^2 + 0.40\ \widehat{C}^2 \quad (14)$$

in Fig. 2Y_1, 2Y_2, and 2Y_3, the response surface plot depicts the influence of varying concentrations of EA, CMC, and drying temperature on the WAI. The plot shows that the WAI of foam-mat dried tomato powder gradually improved with the increased concentration of EA from 1 to 5 %, CMC from 0.5 to 1.0 %, and the drying temperature from 65 to 70 °C. During whipping, a decrease in hydrogen bonds, denaturation, and an increase in hydrophobic groups in proteins are thought to be responsible for increasing water absorption. In an investigation, Chen et al. [49] described that proteins formerly contained hydrophobic groups, which might increase water absorption. In addition, because of the increase in the surface area caused by foaming, there may be increased contact between powder and water, resulting in an increase in WAI in tomato powder [50]. A similar pattern of increasing WAI levels was also observed in the investigation of lime juice drying [51], plum powder [52], and banana powder [53].

3.2.6. Total soluble solids

In foam-mat dried tomato powder, the level of TSS ranged from 1.51 to 2.01 °Brix (Table 3). For TSS, the model F-value of 5.53 showed that the model was significant. The following regression equation (Equation (15)) for TSS was developed in terms of coded units, taking into account the effects of individual independent components and their significant interactions.

$$\mathrm{TSS}\ (^\circ\mathrm{Brix}) = 1.72 + 0.04\ A - 0.06\ B - 0.08\ C - 0.12\ AB + 0.08\ AC + 0.17\ BC + 0.13\ \widehat{A}^2 - 0.07\ \widehat{B}^2 + 0.08\ \widehat{C}^2 \quad (15)$$

The TSS has a downtrend with an increased concentration of EA. Variations in TSS may result from a difference in the samples' final moisture content [54]. It could also be possible that the increased concentration of EA likely leads to a more substantial protein network, further limiting the mobility of water and solutes during the drying phase. As a consequence, the efficiency of the drying process decreases, causing a reduction in the concentration of TSS in the foam-mat dried powder. This phenomenon underscores the complex interplay between protein concentration and drying dynamics in influencing the quality attributes of the final product. Similar results were also reported for the foam-mat dried pineapple fruit powder by Shaari et al. [55]. Nonetheless, the TSS level in foam-mat dried tomato powder displayed an uptrend with a higher concentration of CMC from 1 to 1.5 % (Fig. 2Y_4, 2Y_5, and 2Y_6), which followed a similar trend with the findings of papaya and guava pulp [56]. The higher concentration of CMC contributes to the enhancement of TSS in foam-mat dried powder due to its hydrocolloid properties [57]. CMC, being water-soluble, forms a robust network within the foam structure, effectively entrapping and retaining soluble solids during the drying process. As the concentration of CMC increases, its water-binding capacity strengthens, facilitating the encapsulation of a greater quantity of soluble solids within the foam matrix. This results in a more concentrated and soluble final product. Additionally, the improved stability of the foam structure, achieved through the increased concentration of CMC, likely prevents the leaching or loss of soluble solids during the drying process. Therefore, the combination of CMC's hydrocolloid characteristics and its ability to enhance foam stability synergistically leads to the observed increase in TSS in the foam-mat dried powder. Besides, the variation in drying temperatures caused a gradual reduction in the TSS level of foam-mat dried tomato powder. The gradual reduction in the TSS level of foam-mat dried tomato powder with variations in drying temperatures can be elucidated by the impact of temperature on the kinetics of moisture removal and heat-sensitive components in the tomatoes [58]. At higher drying temperatures, the rate of water evaporation is accelerated, leading to a faster removal of moisture from the tomato matrix. However, elevated temperatures may also contribute to the degradation of heat-sensitive compounds such as sugars and organic acids, resulting in a decrease in TSS. This degradation is likely to be more pronounced with extended exposure to higher temperatures, explaining the observed gradual reduction in TSS. These results agree with those reported for foam-mat dried papaya powder [59].

3.2.7. Ascorbic acid

Ascorbic acid is one of the essential vitamins since it is water-soluble and heat-sensitive. The measurement of ascorbic acid is critical in processed foods that are high in Vitamin C due to the fact that most food processing involves heat. According to the experiment of 17 runs, in the foam-mat dried tomato powder, ascorbic acid concentrations ranged between 2.30 and 4.22 mg/100 mL (Table 3). The model has a significant F-value of 5.42 based on design expert statistical analysis. It seems improbable that there is a 1.83 % possibility that this large F-value is the result of noise. The following regression equation (Equation (16)) for ascorbic acid was developed in terms of coded units, taking into account the effects of individual independent components and their significant interactions.

$$\mathrm{Ascorbic\ acid}\ (\mathrm{mg}/100\ \mathrm{mL}) = 2.52 + 0.22\ A - 0.02\ B + 0.04\ C - 0.31\ AB - 0.19\ AC - 0.51\ BC + 0.43\ \widehat{A}^2 + 0.57\ \widehat{B}^2 + 0.12\ \widehat{C}^2 \quad (16)$$

The response surface variation of ascorbic acid with EA, CMC, and drying temperature (shown in Fig. 2Y_7, 2Y_8, and 2Y_9) depicted that the concentration of CMC of more than 1 % resulted in increases in the ascorbic acid content. It is possible that vitamin C content increases during drying due to CMC's hydrocolloid activity. When CMC is present in the aqueous medium, water activity decreases, reducing the extent of the hydration reaction and increasing Vitamin C stability. A comparable rise in the amount of ascorbic acid found in foam-mat dried passion fruit powder was also reported [60]. Similarly, increased EA concentration by more than 3 % also increases the ascorbic acid content in foam-mat dried tomato powder. Vitamin C retention also depends on air circulation and foam expansion when the sample is dry. When the EA concentration is high, the air bubbles may be stable since a solid interfacial film can form by denaturalizing EA protein molecules during whipping, resulting in the stability of the interfacial film. Therefore, the foam expansion occurs due to the interfacial film's ability to entrap and retain more air volume [61,62]. In the present study, tomato powder dried at 70 °C contained more ascorbic acid than those dried at 60 °C. This might be explained because a shorter drying time is required to dry at a higher temperature, hence a shorter time to degrade vitamin C [30]. In a study by Qadri and Srivastava [63], the ascorbic acid content in foam-mat dried pulp was shown to be more sensitive to variations in time than changes in drying temperature. The variations in ascorbic acid content are likely due to differences in the diluting effects of foaming agents and stabilizers and drying conditions that affect drying time and, ultimately, ascorbic acid retention.

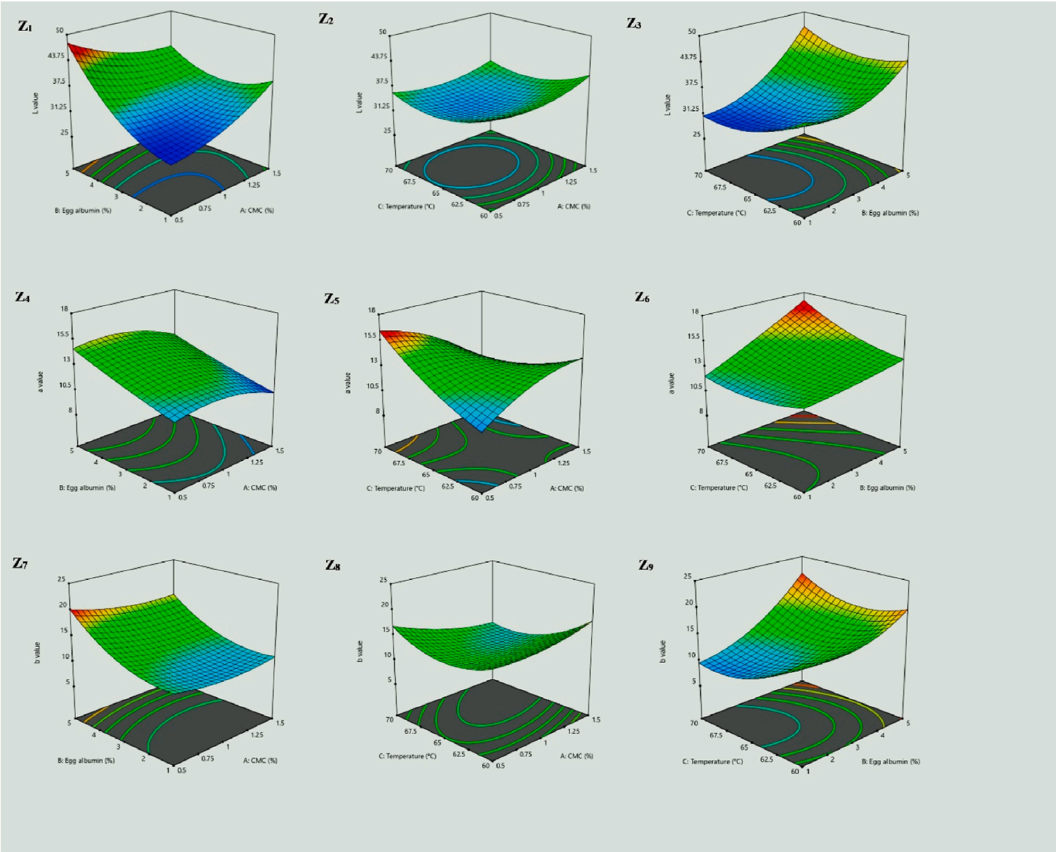

Fig. 3. Response surface plots for interaction effects of carboxymethyl cellulose (CMC), egg albumin, and temperature on color: L* value (Z_1, Z_2, Z_3), a* value (Z_4, Z_5, Z_6), and b* value (Z_7, Z_8, Z_9).

3.2.8. Titratable acidity

Fruits, such as tomatoes, have a fragrance and flavor due to the presence of citric acid, a nonvolatile organic acid. Moreover, it functions as a buffer to maintain cellular pH balance. Table 4 showed that the model F-value of 17.30 was highly significant, suggesting that the model accurately represented the relationship between EA, CMC, and drying temperature. The following regression equation (Equation (17)) for titratable acidity was developed in terms of coded units, taking into account the effects of individual independent components and their significant interactions.

$$\text{Titratable acidity}\,(\%) = 0.322 - 0.039\,A + 0.008\,B + 0.004\,C + 0.0035\,AB - 0.003\,AC + 0.050\,BC - 0.025\,\widehat{A}^2 - 0.002\,\widehat{B}^2 + 0.0002\,\widehat{C}^2 \tag{17}$$

Foam-mat dried tomato powder had an acidity content of 0.22–0.38 % (Table 3). The interaction effects of EA, CMC, and drying temperature on the titratable acidity of foam-mat dried tomato powder are shown in Fig. 2Y_{10}, 2Y_{11}, and 2Y_{12}. A modest rise in titratable acidity of foam-mat dried tomato powder was seen with increasing concentrations of EA and variations in drying temperature. This can be attributed to the complex interplay of protein interactions and the impact of temperature on the drying process [26]. EA, as a protein, has the potential to influence the retention of acidic compounds in tomatoes during drying. The protein might form complexes with organic acids or other acidic components, hindering their release and resulting in higher titratable acidity in the final powder. Additionally, variations in drying temperature can affect the kinetics of chemical reactions and the stability of organic acids, potentially leading to increased acidity. The combination of higher concentrations of EA and altered drying temperatures likely influences the preservation and release of acidic compounds in a way that contributes to the observed rise in titratable acidity in the foam-mat dried tomato powder. Similar results were reported for the titratable acidity of sour cherry powder [45]. On the contrary, the reduction in the acidity of tomato powder with an increased concentration of CMC suggests that the presence of CMC may be influencing a partial neutralization reaction in the foam void during drying [64]. CMC, being a water-soluble cellulose derivative, likely interacts with the acidic components in tomatoes, such as organic acids. The carboxyl groups in CMC may act as neutralizing agents, reacting with acidic moieties in the tomatoes to form salts or other neutral compounds. As the concentration of CMC increases, more carboxyl groups are available to participate in these neutralization reactions, leading to a gradual reduction in the acidity of the tomato powder. This phenomenon points to the role of CMC as a modifier of the chemical environment during drying, influencing the acid-base balance in the foam void and subsequently impacting the acidity of the final tomato powder product.

3.2.9. Color parameters (L*, a*, and b*)

The color of dried products is one of the most significant quality parameters determining their quality and final price. Fruit variety, ripeness, and drying processes all impact the color of final products. The quadratic equations (Equation (18), Equation (19), Equation (20)) below showed the relationship between color parameters (L*, a*, and b*) and EA, CMC, and drying temperature.

$$L^* = 32.80 + 0.80\,A + 5.35\,B - 1.33\,C - 4.42\,AB - 0.34\,AC + 2.35\,BC + 2.09\,A^2 + 4.13\,B^2 + 2.91\,C \wedge 2 \quad (18)$$

$$a^* = 13.10 - 0.59\,A + 1.59\,B + 0.73\,C - 0.11\,AB - 2.29\,AC + 0.98\,BC - 0.92\,A^2 - 0.13\,B^2 + 0.64\,C \wedge 2 \quad (19)$$

$$b^* = 11.56 - 0.74\,A + 3.83\,B - 1.26\,C - 0.46\,AB - 1.94\,AC + 2.19\,BC + 1.05\,A^2 + 2.48\,B^2 + 2.78\,C \wedge 2 \quad (20)$$

The values of L (lightness), a (redness), and b (yellowness) for foam-mat dried tomato powder at various concentrations of EA, CMC, and temperatures are shown in Table 3. It was found that the foam-mat dried tomato powder has L* values ranging from 29.26 to 48.07 (Fig. 3Z_1, 3Z_2, 3Z_3), a* values of 9.73–16.86 (Fig. 3Z_4, 3Z_5, 3Z_6), and b* values ranging from 6.81 to 21.06 (Fig. 3Z_7, 3Z_8, 3Z_9). L* (lightness) refers to color measurement along with the light-dark axis. As the L* value decreases, the sample becomes darker. In the present study, foam-mat dried tomato powder with a higher percentage of EA and CMC was found to be lighter. The reason may be that EA and CMC were colored white, as well as the presence of air, which resulted in an increase in the L* value. Furthermore, the proteins in EA might influence Maillard browning reactions during drying, affecting color development and resulting in a lighter appearance. Cakmak and Ozyurt [65] obtained similar findings in carrot juice powder using foam-mat drying techniques. However, when the temperature of the drying chamber was raised, the lightness value L* in the foam-mat dried tomato powder decreased. Further research has revealed a link between the drop in L* value and the formation of brown pigment during drying. It has also been reported that brown pigment formation increases with an increase in drying temperature. Jakkranuhwat and Kunchansombat [66] reported that lowering the drying chamber temperature from 70 to 50 °C led to a decrease in the lightness of foam-mat dried purple-fleshed sweet potato powder, with values decreasing from 52.88 ± 1.18 to 48.56 ± 1.03. On the other hand, the intensified redness observed in foam-mat dried tomato powder when the concentration of EA is increased, alongside higher temperatures, can be attributed to the Maillard reaction [29]. EA catalyzes this reaction when it interacts with the reducing sugars present in tomatoes. The Maillard reaction is a complex chemical process that occurs at elevated temperatures, resulting in browning and the development of characteristic flavors and aromas. In this context, the reaction contributes to the heightened red coloration of the tomato powder. On the other hand, an increased concentration of CMC tends to have a contrasting effect. CMC is commonly used as a thickening agent, stabilizer, and water binder in food processing and does not participate in the Maillard reaction. Instead, it acts to stabilize color by impeding reactions that lead to browning. As the concentration of CMC rises, the stabilizing effect becomes more pronounced, leading to a reduction in the redness of the foam-mat dried tomato powder. It is also clear from Fig. 3Z_7 that the synergistic effects of elevated EA concentration and higher CMC levels create a favorable environment for the generation and retention of yellow pigments, ultimately leading to heightened yellowness in the foam-mat dried tomato powder. Additionally, the Maillard reaction, a complex chemical reaction between amino acids and reducing sugars, is known to accelerate at higher temperatures. This reaction can produce brown pigments and alter the overall color of the tomato powder, potentially intensifying the yellowness [67,68]. The combined effects of CMC concentration and higher temperature may also impact the structural integrity of the foam-mat drying process, leading to increased exposure of the tomato solids to the reactive conditions, further influencing the color outcome (Fig. 3Z_8). In contrast, the reduction of yellowness in the final foam-mat dried tomato powder was observed during the intricate interplay between the elevated concentration of EA and drying chamber temperature (Fig. 3Z_9). When present in elevated EA concentrations, it enhances the structural integrity of the foam, preventing the oxidation of carotenoid pigments responsible for the characteristic yellow color in tomatoes. In addition, higher temperatures during drying may contribute to the denaturation of enzymes responsible for catalyzing reactions leading to color degradation [55].

3.3. Determination and validation of the optimal parameters

The process parameters were optimized using the generated models for various responses. The desirable responses were selected for the minimum level of foam density as well as the maximum level of foam expansion, foam stability, WSI, WAI, TSS, ascorbic acid, titratable acidity, and color (L*, a*, and b* value). The minimum level of foam density allows more air to be incorporated during the whipping process, and the more air, the higher the foaming potential. The purpose was to generate stable foams during drying operations while maintaining equal weights or importance and by limiting independent factors such as the concentration of EA, CMC, and drying temperature within the experimental range. The independent variables were optimized by the RSM/BBD using Design-Expert version 11 software. The optimal conditions were obtained through the solutions menu of Design-Expert's numerical optimization program. It was determined that the following formulation of foaming parameters was optimal for the responses: EA concentration was 4.59 %, CMC concentration was 0.70 %, and drying temperature was 60 °C. The optimum results were foam density of 0.20 g/cm^3, foam expansion of 337.58 %, foam stability of 86.30 %, WSI of 56.80 %, WAI of 2.46, TSS of 1.80 °Brix, ascorbic acid of 2.90 mg/100 mL, titratable acidity of 0.37 %, and color: L* value of 45.61, a* value of 17.99, and b* value of 21.56.

Validating the optimal conditions after they have been established is essential, and predictive models were only utilized in decision-making after being subjected to validation. The fitness of the model equations was determined under the predicted conditions, and

Table 5
Experimental values of response variables under the optimized conditions.

Optimized conditions	Carboxymethyl cellulose (CMC) (%)		0.71		
	Egg albumin (%)		4.59		
	Temperature (°C)		60		
		Target	Predicted value	Experimental value	RSE (%)
Response variables	Foam density (g/cm^3)	Minimum	0.20	0.19 ± 0.03	5
	Foam expansion (%)	Maximum	337.58	346.60 ± 3.35	3
	Foam stability (%)	Maximum	86.30	89.05 ± 2.80	3
	WSI (%)	Maximum	56.80	55.56 ± 3.22	2
	WAI	Maximum	2.46	2.49 ± 0.09	1
	TSS (°Brix)	Maximum	1.80	1.84 ± 0.05	2
	Ascorbic acid (mg/100 mL)	Maximum	2.90	2.93 ± 0.10	1
	Titratable acidity (%)	Maximum	0.37	0.39 ± 0.02	5
	L* value	Maximum	45.61	46.95 ± 6.35	3
	a* value	Maximum	17.99	17.54 ± 1.50	3
	b* value	Maximum	21.56	21.85 ± 0.74	1

RSE: Residual Standard Error; Experimental values expressed as mean ± standard deviation of the mean (n = 3). WSI: Water Solubility Index; WAI: Water Absorption Index; TSS: Total Soluble Solids.

experiments were conducted to confirm the validity of the optimized solutions. The results are tabulated in Table 5. Under the optimized conditions, it was found that the level of foam density, foam expansion, foam stability, WSI, WAI, TSS, ascorbic acid, titratable acidity, and color: L*, a*, and b* values were 0.19 ± 0.03 g/cm^3, 346.60 ± 3.35 %, 89.05 ± 2.80 %, 55.56 ± 3.22 %, 2.49 ± 0.09 %, 1.84 ± 0.15 °Brix, 2.93 ± 0.10 (mg/100 mL), 0.39 ± 0.02 %, 46.95 ± 6.35, 17.54 ± 1.50, and 21.85 ± 0.74, respectively. A comparison was made between the mean experimental values and the predicted values. The residual standard error (RSE) percentages were used to compare the predicted values with the experimental results. Specifically, for the results to be consistent with the prediction values, RSE values equal to or lower than ±5 % were considered [23]. The obtained RSE values for foam-mat dried tomato powder demonstrated no consequential disparities between the predicted and experimental values, which confirms the adequacy of the models.

4. Conclusion

In the current study, the physicochemical properties of the foam-mat dried tomato powder and the optimal foaming stabilizer, as well as foaming agent concentration for foam-mat drying, specifically EA, CMC concentration, and drying temperature, were examined. The ANOVA findings suggested that the generated models had a higher R^2 value (>85 %), small CV value, significant model F values ($p \leq 0.05$), non-significant 'Lack of fit,' and adeq precision value of more than 4. Consequently, the regression model was assessed to fit the experimental values and was determined to be well-fitted. The optimized parameters were verified, and there was good agreement between the experimental results and the projected values (residual standard error (RSE) ≤ 5). Considering all of the data, these findings indicated that optimization of the foam-mat drying process was critical since the varying concentrations of EA, CMC, and drying temperature influenced the physical and chemical properties of the tomato powders. Thus, the present study serves as a foundation for future research on foam-mat dried tomato powder in terms of flow properties, antioxidant activity, total phenolic content, drying rate, drying kinetics, effective moisture diffusivity, rehydration properties, foam bubble size and distribution, microbial safety, and sensory properties.

CRediT authorship contribution statement

Mohammad Afzal Hossain: Writing – review & editing, Supervision, Software. **Tanvir Ahmed:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Jannatul Ferdaus:** Methodology, Investigation, Formal analysis, Data curation. **Wahidu Zzaman:** Writing – review & editing, Validation, Conceptualization.

Data availability

Data will be made available on request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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