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Foaming, physicochemical, and sensory characteristics of foam-mat freeze-dried yogurt powder as affected by egg albumin and maltodextrin contents

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Abstract

Drying technologies for yogurt powder include spray drying, microwave vacuum drying, convective drying, and foam-mat drying. This study investigated the effects of egg albumin (EA) and maltodextrin (MD) concentrations on the foaming, physicochemical, and sensory properties of yogurt powder produced by foam-mat freeze-drying. A D-optimal mixture design was employed with two independent variables: EA (X_1) at 10–20% (w/w) and MD (X_2) at 0–10% (w/w). The responses included foam density, foam expansion, powder recovery, moisture content, bulk density, tapped density, Carr Index (CI), and Hausner Ratio (HR). The optimal formulation was achieved at 16.5% EA and 3.5% MD, yielding a foam density of 0.65 g/cm^3 and foam expansion of 52.7%. The resulting yogurt powder exhibited a recovery of 20.1%, moisture content of 3.5%, bulk and tapped densities of 0.35 and 0.38 g/cm^3, respectively, with CI = 6.98 and HR = 1.08, indicating excellent flowability and cohesiveness. Sensory evaluation showed that rehydrated yogurt with 75% water addition received the highest acceptability score (mean hedonic value = 6.0, "slightly like") for color, aroma, flavor, and texture. These findings demonstrate that the optimized foam-mat freeze-drying process effectively produces yogurt powder with desirable physical characteristics, good flow properties, and high consumer acceptability, highlighting its potential for small- and medium-scale yogurt powder production.

Keywords Yogurt, Foam-mat drying, Freeze-drying, D-optimum design, Maltodextrin, Egg albumin

1 Introduction

Yogurt is fermented milk produced by *Lactobacillus bulgaricus* and *Streptococcus thermophilus*. Some commercial microorganisms used in yogurt fermentation contain probiotics from the Bifidobacterium family, which provide health benefits; therefore, yogurt is extensively consumed due to its nutritional value [1–3]. However, its shelf life is approximately one day at 25–30 °C, five days at 7 °C, and ten days at 4 °C [4]. As a result, yogurt's shelf life can be extended by removing water through spray-drying or other dehydration methods [1, 5].

Powdered yogurt has less volume, resulting in lower transportation, packaging, and storage costs. Yogurt powder can be made into confections, baked products, chocolate flavor, wafers, and soups [5]. In Europe and North America, yogurt-flavored wafers, chocolates, and candies are gaining popularity. Other applications include dips, sauces, cheese, and dry mixes for convenience dishes [6]. However, yogurt's high nutrient content also encourages the growth of spoilage microorganisms. In this regard, freeze-drying is an effective and alternative method for extending the product shelf life [7, 8].

Freeze-drying is a dehydration technique that takes advantage of the triple point of water to produce high-quality desiccated goods. The triple point is a thermodynamic equilibrium state in which substances coexist in distinct phases, such as solid, liquid, and gas. The triple point of water occurs at 0.01 °C and 611.73 Pa [8]. Below the triple point of water, ice can sublimate. The moisture elimination has numerous advantages over conventional techniques. Although freeze-drying is one of the most effective methods for preserving microorganisms, different probiotic cultures may react differently to this method [6].

The manufacture of yogurt powder has been reported using freeze-drying [9], spray-drying [10], microwave vacuum drying [6], foam-mat drying [11, 12], and microwave-assisted foam-mat drying [5]. Foam-mat drying involves whipping semi-liquid or liquid food with air to generate stable foam. The addition of foaming agents can help stabilize the foam for longer periods, making the drying process more efficient [13, 14]. Foam mat drying is appropriate for dense, sticky, heat-sensitive, and high-sugar foods that are difficult to dry using conventional tray drying techniques [15, 16]. Several experiments of foam-mat drying used egg albumin (5–15%) and maltodextrin (5%) as foaming agents and stabilizers [17, 18].

Maltodextrins, derived from the amylolytic hydrolysis of starch, demonstrate favourable solubility in aqueous solutions [19]. They could fill, structure, and stabilize emulsions. It is worth mentioning that maltodextrins are not classified as food additives. Consequently, incorporating them into food formula enables the use of a "clean label," which is highly valued by customers. A study found that maltodextrin was an appropriate addition for altering the characteristics of egg white foam [19].

The rheological analyses indicated that as the sugar concentration in egg albumin increased, the apparent viscosity and viscoelasticity correspondingly increased. The introduction of saccharides reduces the hydrogen proton relaxation time, suggesting the existence of a hydration effect between the sugar and water [20]. Incorporating 3% saccharides into the compound egg white solution increases the surface hydrophobicity but decreases the samples' surface tension, thereby enhancing foam capacity and stability. Compound egg white solution exhibited optimal foam performance when 3% maltodextrin was incorporated, accompanied by the formation of the tiniest and most uniform bubbles [20].

Although several studies have investigated the use of egg albumin and maltodextrin individually or in other food matrices, there is limited research on their combined use in yogurt powder production, particularly using freeze-drying techniques. Previous studies have not clarified how varying concentrations of these agents influence the foaming behavior, physical characteristics, and sensory attributes of the final yogurt powder. This gap highlights the need for systematic optimization of egg albumin and maltodextrin concentrations to achieve the desired quality attributes.

Therefore, this study aimed to determine the optimal concentrations of egg albumin (as a foaming agent) and maltodextrin (as a foam stabilizer), as well as evaluate their effects on the foaming, physicochemical, and sensory properties of yogurt powder produced by freeze-drying. It was hypothesized that the incorporation of egg albumin and maltodextrin at appropriate concentrations would act synergistically to improve foam characteristics and enhance the overall physical and sensory quality of freeze-dried yogurt powder.

2 Materials and methods

2.1 Materials

Pasteurised egg albumin (EA) as a foaming agent and maltodextrin (MD) (10–12 glucose equivalent, Sigma Aldrich, St. Louis, Missouri, USA) as a foam stabilizers were purchased from an e-commerce and chemical grocery in Bandung, Indonesia. Yogurt culture ABT-07 (*Lactobacillus bulgaricus*, *Bifidobacterium lactis* and *Streptococcus thermophilus*) (CHR Hansen, Denmark) was purchased from PT. Brentag Indonesia. Yogurt drink-type (carbohydrate 9.2 g, fat 1.84 g, protein 2.06 g) was formulated using the culture ABT-07.

2.2 Foam-mat freeze-drying process

The foam-mat freeze-drying modifies the Yüksel [5] method. To generate and stabilize foam, low-fat yogurt drink was combined with EA and MD in varying proportions, with EA constituting 10–20% (weight of EA/weight of yogurt) and MD comprising 0–10% (weight of MD/weight of yogurt). Yogurt foam was mixed for 3 min at speed 8 (for whipping) with a mixer (Bolde, Altenholtz, Germany). Before freeze drying, the foam was distributed on a round plate (11 cm in diameter) and dried to a thickness of 5 mm before transferred to a deep freezer model AB-375LT (GEA, Jakarta, Indonesia) at -40 °C for 24 h. The samples were afterwards deposited in a freeze-dryer Buchi Lyovapor-200 Infinite Control (Buchi, St. Gallen, Switzerland) operating for 24 h at -55 °C condenser and 4 Pa pressure. The derived yogurt flakes were then collected and pulverised into powder for one minute using a grinder. The powders were placed in polyethylene containers and stored at 4 °C for 14 days awaiting further analysis.

2.3 Experimental design

The response surface method was employed to evaluate the influence of the foaming agent and stabilizers variables on the foam parameters modified by previous study. The optimization was determined using multi-response analysis and the intended ideal condition, utilizing the statistical software Design-Expert 11.1.2.0 (Stat-Ease, Minneapolis, Minnesota, United States) [21]. To estimate pure error, we utilised a D-optimal mixture design with 13 trials and five replicates of the central point. In the D-optimal mixture design, the following two variables were evaluated by varying the foaming agent and stabiliser proportions: egg albumin (X_1) and maltodextrin (X_2). All variables' minimum and maximum values fell between 0 and 1, while the total value remained constant as X_1 + X_2 = 1. Table 1 displays the levels of various variables and response variables.

2.4 Analysis of foam properties

2.4.1 Foam density

Foam density (*FD*) was determined as reported by Ng and Sulaiman [22]. Yogurt foam thickness was evaluated as mass per foam volume expressed grams per cubic centimetre, as shown in Eq. 1.

$$FD = \frac{w}{V} \tag{1}$$

w is the weight of foam (in grams), and V is the foam volume (in cubic centimetres).

2.4.2 Foam expansion

Foam expansion (*FE*) measures the amount of air incorporated into the yogurt foam structure. Yogurt foam expansion (calculated in percentage) was expressed by Malik and Sharma [12] and determined using the following formula:

$$FE = \frac{\mathrm{V}_1 - \mathrm{V}_0}{\mathrm{V}_0} \times 100$$

V_1 is the final volume of foamed yogurt(in cubic centimetres), and V_0 is the initial volume of the mixture(in cubic centimetres).

2.5 Analysis of powder properties

2.5.1 Moisture

The moisture content in powders was calculated using an HB-120 Halogen Moisture Analyzer (Mettler Toledo, Columbus, Ohio, USA) set at 105 °C [17].

2.5.2 Powder recovery

Powder recovery (*PR*) was defined by Fauziyah, Ifie [23]. The PR (expressed in per cent) calculation is as follows: Eq. 3

$$PR = \frac{\mathrm{SP}}{\mathrm{SF}} \mathrm{x}\, 100 \tag{3}$$

Table 1 The mixture design with egg albumin and maltodextrin as experimental variables

Run	X_1 (%)	X_2 (%)
1	20	0
2	15	5
3	17.5	2.5
4	20	0
5	10	10
6	15	5
7	20	0
8	12.5	7.5
9	20	0
10	15	5
11	10	10
12	10	10
13	10	10

Here, SP is the solid in powder, and SF is the total solid in foam.

2.5.3 Bulk and tapped densities

The bulk density (ρ_B) and tapped density (ρ_T) were measured as described in Yüksel [5] after minor modifications. ρ_B was measured by transferring 1 g of the powder into a 10 ml graduate cylinder. Without tapping the cylinder, the volume occupied by the powder was measured (Eq. 4). ρ_T was measured by tapping the loaded cylinder 15 times from a height of 10 cm, and the final volume was recorded Eq. 5. ρ_B and ρ_T was calculated using the following formulas:

$$\rho_B = \frac{\mathrm{w}}{\mathrm{V}} \tag{4}$$

$$\rho_T = \frac{\mathrm{w}}{\mathrm{Vt}} \tag{5}$$

w is the mass of powder (in grams), V is the volume of powder (in cubic centimetres), and V_t is the final tapped volume of powder (in cubic centimetres).

2.5.4 Flowability and cohesiveness

Powder flowability and cohesiveness were measured referring to the Carr index (CI) (Eq. 6) and Hausner ratio (HR) (Eq. 7), respectively as described by Yüksel [5]. The *CI* and *HR* were calculated using the following formula:

$$CI = \frac{\rho_T - \rho_B}{\rho_T} \tag{6}$$

$$HR = \frac{\rho_T}{\rho_B} \tag{7}$$

ρ_B and ρ_T are bulk density and tap density, respectively. Table 2 indicates the powder flowability classification based on the ranges of *CI* and *HR*. Powders with CI and HR values in the range of "excellent" to "passable" are acceptable. The remaining powders tend to have lower quality.

2.6 Sensory evaluation

The sensory was evaluated to determine the acceptability of rehydrated freeze-dried yogurt. The yogurt powder samples underwent rehydration by including water concentrations of 95% (F1), 85% (F2), and 75% (F3) at a temperature of 23–27 °C, followed by a physical study, specifically organoleptic evaluation (color, aroma, flavor, and texture). Thirty panellists evaluated both samples using a 9-point hedonic scale with the terms

Table 2 Classification of flowability of powder based on Carr index and Hausner ratio values

Flowability	Car index (CI)	Hausner ratio (HR)
Excellent	0–10	1.00–1.11
Good	11–15	1.12–1.18
Fair	16–20	1.19–1.25
Passable	21–25	1.26–1.34
Poor	26–31	1.35–1.45
Very poor	32–37	1.46–1.59
Very, very poor	> 38	> 1.60

"Strongly dislike" (value 1) and "strongly like" (value 9) at the left and right ends, respectively [24, 25]. Stone et al. [26]. Test samples (25 g) maintained at 8 °C were served in sanitised 50 ml disposable containers with three-digit barcodes. The sample presentation order was randomly assigned among evaluators.

2.7 Statistical analysis

The statistical software Design-Expert 11.1.2.0 analysed foam density, foam expansion, moisture, yield, bulk density, tapped density, Carr index, and Hausner Ratio. The averages of the significant sources of variation were contrasted at a significance level of p 0.05 [21], and the sensory scores were analysed using analysis of variance (ANOVA) with the parameters "sample" and "judges" as sources of variation. Using the software SPSS IBM 25 (IBM, Armonk, USA), Duncan test at a significance level of 5% was used to look for differences between means [24].

3 Results and discussion

For the estimation of pure error, a D-optimal mixed design with 13 runs and five replicates of the central point was used in the experiment. The egg albumin (X_1) and maltodextrin (X_2) variables in the D-optimal combination design were assessed by applying various foaming and stabilising agents. Foam density (Y_1), foam expansion (Y_2), moisture (Y_3), yield (Y_4), bulk density (Y_5), tapped density (Y_6), Carr index (Y_7), and Hausner ratio (Y_8) were the response variables.

3.1 Effect of foaming and stabilizing agents on yogurt foam properties

The foam density and expansion were calculated using Eqs. 1 and 2. EA and MD content had significant ($p < 0.05$) effects on foam density and expansion. In contrast, increasing EA content decreased foam density (Table 3). The density of foam is frequently used to evaluate flailing properties. As the foam is whipped, its density decreases as more air is incorporated into it [12]. This process lowers both the interfacial and surface tensions of the liquid, enabling the formation of an interfacial film that surpasses the critical thickness. A similar pattern was also noted with mango pulp [27]. The whipping capacity also increases as more air is introduced in the foam. The linear model was selected for foam

Table 3 The mixture design with egg albumin and maltodextrin as experimental variables and the experimental results of responses

Run	X_1 (%)	X_2 (%)	Y_1 (g/cm^3)	Y_2 (%)	Y_3 (%)	Y_4 (%)	Y_5 (g/cm^3)	Y_6 (g/cm^3)	Y_7	Y_8
1	20	0	0.61	57.8	3.6	24.5	0.40	0.46	11.86	1.13
2	15	5	0.67	45.2	3.4	18.3	0.35	0.38	6.90	1.07
3	17.5	2.5	0.62	56.7	3.4	22.6	0.35	0.39	10.59	1.12
4	20	0	0.60	57.7	3.5	23.9	0.41	0.47	13.37	1.15
5	10	10	0.74	32.4	3.4	14.7	0.49	0.53	8.02	1.09
6	15	5	0.67	45.5	3.5	18.3	0.35	0.37	6.82	1.07
7	20	0	0.61	57.3	3.6	24.6	0.41	0.46	12.00	1.14
8	12.5	7.5	0.68	34.4	3.4	15.4	0.42	0.45	8.22	1.09
9	20	0	0,64	57.1	3.5	24.4	0.41	0.47	13.28	1.15
10	15	5	0.69	45.8	3.4	18.6	0.36	0.38	3.53	1.04
11	10	10	0.76	32.2	3.4	14.7	0.48	0.53	9.52	1.11
12	10	10	0.72	32.9	3.5	15.0	0.47	0.50	6.17	1.07
13	10	10	0.71	32.2	3.5	14.9	0.47	0.51	9.24	1.10

X_1, Egg albumin; X_2, Maltodextrin; Y_1, Foam density; Y_2, Foam expansion; Y_3, Moisture content; Y_4, Powder recovery; Y_5, Bulk density; Y_6, Tapped density; Y_7, Carr index; and Y_8, Hausner ratio

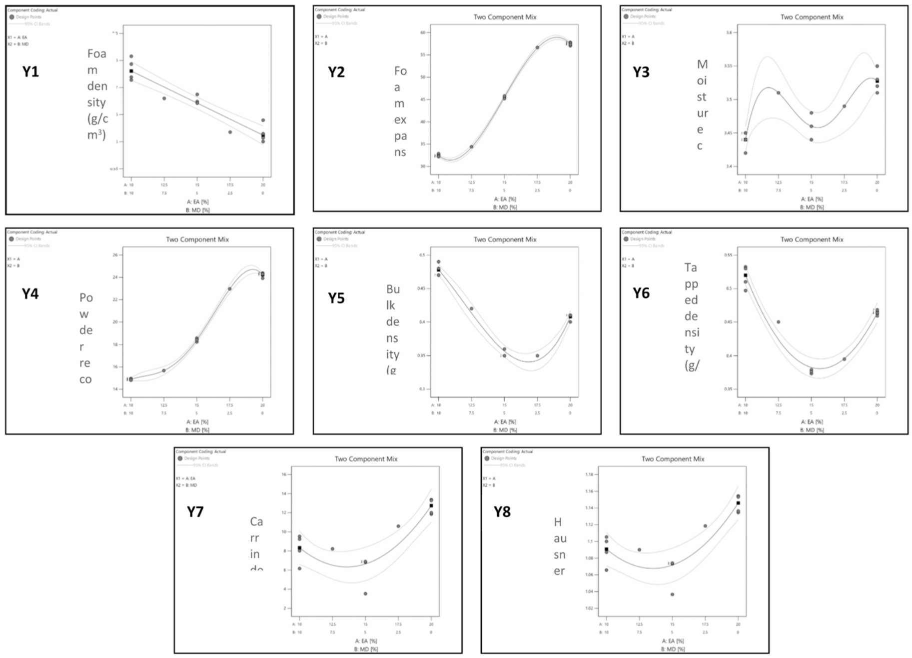

Fig. 1 Effect of egg albumin and maltodextrin on foam and powder properties. *EA* egg albumin, *MD* maltodextrin, *95% CI* 95% Confidence Interval

Table 4 ANOVA calculated for the response surface of foam and powder properties from the varying content of egg albumin and maltodextrin

Model analysis	Sum of square	Degree of freedom	Mean square	F-value	*p*-value	Lack of fit	R^2	Adjusted R^2	Predicted R^2
	Foam density (g/cm^3)								
Linear	0.0298	1	0.0298	93.4512	< 0.0001	0.8947	0.8851	0.8493	0.0298
	Foam expansion (%)								
Cubic	44.6134	1	44.6143	450.16	< 0.0001	0.5577	0.9992	0.9988	< 0.0001
	Moisture content (%)								
Linear	0.0136	1	0.0136	23.7823	0.0005	0.0354	0.6549	0.5881	0.0005
	Powder recovery (%)								
Cubic	3.2322	1	3.2322	37.5912	0.0002	0.0002	0.0016	0.9950	0.9815
	Bulk density (g/cm^3**)**								
Cubic	0.0006	1	0.0006	9.5532	0.0129	0.1579	0.9773	0.9529	0.0129
	Tapped density (g/cm^3**)**								
Quadratic	0.0307	1	0.0307	174.6745	< 0.0001	0.0759	0.9461	0.9270	< 0.0001
	Carr index								
Quadratic	39.0634	1	39.0634	15.4617	0.0028	0.1757	0.7131	0.6011	0.0028
	Hausner ratio								
Quadratic	0.0056	1	0.0056	16.4624	0.0023	0.1712	0.7364	0.6337	0.0023

density response analysis and Fig. 1 (Y_1) illustrates the influence of EA and MD on foam density.

In Table 4, the ANOVA results for foam density are displayed. Equation 8 explains how the linear equation has modified the foam density regarding the foam circumstances.

$$FD = 0.6120\,X1 + 0.7305\,X2 \tag{8}$$

Equation 8 showed that variables A (Egg Albumin) and B (Maltodextrin) positively affected the response foam density. The addition of maltodextrin can increase the viscosity of the mixture, which may hinder the incorporation of air during stirring and, in turn, positively affect the foam density [28]. The 13 runs' foam density varied, with values between 0.60 and 0.76 g/cm^3. The F-value of 93.45, with a coefficient of regression (R^2) of 0.8851, showed that the model was significant ($p < 0.05$). Table 4 summarises the model analysis, lack of fit, and R^2 analysis results. The linear model could explain the change in foam density and modification, as evidenced by the significance of model and non-significant lack of fit. The lowest numerical difference between adj-R^2 and pre-R^2 further supported the applicability of these models. In this instance, the statistical analysis revealed that the model was significant based on the variables EA ratio (X_1) and MD ratio (X_2).

The foam density value of yogurt foam showed that the minimum foam densities obtained from samples 1, 4, 7, and 9 containing 20% EA and 0% MD were 0.61 g/cm^3, 0.60 g/cm^3, 0.61 g/cm^3, 0.64 g/cm^3, respectively. In accordance with Yüksel [5], the comparison of yogurt foam containing 15% EA to the control sample revealed an approximate fourfold augmentation in foam expansion, accompanied by a reduction in foam density. A reduction in foam density accompanied the increase in foam volume. According to a report, foamed materials are less dense than non-foam materials [12]. During whipping, air bubbles were trapped in the foam, lowering its density but increasing its volume. A low foaming agent content is associated with high foam density due to the restriction of foaming agent movement from aqueous phase to air-aqueous interface [29]. Low density foam and large surface area may result in better water removal when drying.

The foam expanded significantly ($p < 0.05$) with increasing EA content as a foaming agent (Fig. 1 (Y_2)) (Table 4). These findings are consistent with the foam density results, where the sample exhibiting the highest foam expansion corresponded to the lowest foam density, and vice versa [30]. This relationship can be explained by the increased incorporation of air into the foam structure, driven by reduced surface tension, which ultimately results in lower foam density and enhanced foam expansion [31]. The model F-value of 450.16, with a coefficient of regression (R^2) of 0.9992, demonstrated that the model was significant ($p < 0.05$). In this case, EA ratio (X_1), MD ratio (X_2), ($X_1 \times {}_2$), and $X_1 \times {}_2$ (X_1-X_2) showed that the model was significant. The particular cubic model was selected to analyse foam expansion response. The effect of EA and MD on foam expansion is shown in Fig. 1 (Y_2) while the result of the ANOVA analysis on foam expansion is presented in Table 4.

The foam expansion fitted by the cubic Equation in terms of the foam conditions is described in Eq. 9:

$$FE = 57.49\,\mathrm{X1} + 32.44\,\mathrm{X2} + 2.41\,\mathrm{X1X2} + 51.93\mathrm{X1X2}\,(\mathrm{X1} - \mathrm{X2}) \tag{9}$$

According to Eq. 9, the foam expands when foaming and stabilizers agent variables increases. Increasing foaming agent content resulting from the transfer from the aqueous phase to the air-liquid interface lowers the surface tension. The ability for foaming increases due to this mechanism. Consequently, foam density decreased during mixing as more air was incorporated [12]. Consistent with this mechanism, a previous study reported that formulations containing fig fruit and maltodextrin inhibited foam expansion and disrupted foam structure due to their non-foaming components [29].

3.2 Effect of foaming and stabilizing agents on the powder properties

The powder properties of foam-mat freeze-dried yogurt are presented in Table 3. Yogurt powders moisture content ranged between 3.4% and 3.6%, which were microbiologically safe. The quadratic model was selected to analyse moisture response due to the low standard deviation, the low predicted sum of squares and the high predicted R-square. The graphic plot showing the effect of EA and MD on moisture content is depicted in Fig. 1 (Y_3). The ANOVA test on the moisture is displayed in Table 4. The result of the ANOVA showed that the model (cubic) was all significant. The moisture content fitted by a cubic equation in terms of the foam conditions is described in Eq. 10:

$$MC = 3.54\,\mathrm{X1} + 3.43\,\mathrm{X2} - 0.1597\,\mathrm{X1X2} \tag{10}$$

The F-value of 23.78, with a coefficient of regression (R^2) of 0.6549, showed that the model was significant ($p < 0.05$). The initial stage of drying, which lasted up to 6 h, showed a fast reduction in moisture, but after that, the moisture reduced more slowly and remained nearly constant for the following 20 to 24 h. The drying time for egg white foam with or lacking xanthan gum from an initial moisture content of approximately 88% wet basis (733.3% dry basis) to final moisture contents of 7.7% wet basis (8.3% dry basis) and 8.5% wet basis (9.3% dry basis) was 24 h [32].

The yogurt powder recoveries as presented in Table 3. were between 14.7% and 24.5%. The cubic model was implemented to analyse the powder recovery response since it had a low standard deviation and predicted sum of squares, but a high anticipated R-square. The graphic plot showing the effect of EA and MD on powder recovery is depicted in Fig. 1 (Y_4). The ANOVA test showed that the model (cubic) was all significant. The yield expressed in terms of the foam conditions as fitted by the linear Equation is Eq. 11:

$$PR = 24.36\,\mathrm{X1} + 14.84\,\mathrm{X2} - 4.49\,\mathrm{X1X2} + 13.02\,\mathrm{X1X2}\,(\mathrm{X1} - \mathrm{X2}) \tag{11}$$

EA and MD had a significant ($p < 0.05$) effect on the powder recovery. The model F-value of 37.59, with a coefficient of regression (R^2) of 0.9950, showed the model was significant ($p < 0.05$). The result on powder recovery showed significant decreases with increasing MD content, and a similar behaviour was observed by Darniadi et al. [17]. In general, foam-mat freeze-drying from blueberry juice, yields decreased with higher maltodextrin/whey protein isolate ratios (up to 3.2), whilst spray-dried yields increased. However, foam-mat freeze-drying gave statistically higher yields ($p < 0.05$) than spray drying at all maltodextrin/whey protein isolate ratios.

ρ_B and ρ_T are depicted in Table 3. Bulk density values were 0.35–0.49 g/cm^3 and tapped densities were 0.37–0.53 g/cm^3. Yüksel [5] examined how the amount of egg albumin affected the powder characteristics and the effectiveness of the microwave drying process for yogurt foam. They found that the bulk density was 0.44–0.63 g/cm^3 and that tapped density was 0.44–0.71 g/cm^3 (Table 3). Due to the low standard deviation and anticipated sum of squares, a high predicted R-square, the cubic model was chosen to analyse bulk density, and the quadratic model was used for tapping density response. Figure 1 (Y_5) and (Y_6) display a plot illustrating how EA and MD affect bulk and tapped densities. The ANOVA findings indicated that the quadratic and cubic models for bulk and tapped densities were statistically significant. The cubic Equation fit to the bulk and tapped densities in terms of the foam conditions is described in Eq. 13 and Eq. 14:

$$\rho_B = +0.4079\,\mathrm{X1} + 0.4779\,\mathrm{X2} - 0.3449\,\mathrm{X1X2} + 0.1867\,\mathrm{X1X2}(\mathrm{X1} - \mathrm{X2}) \quad (13)$$

$$\rho T = 0.4637\,\mathrm{X1} + 0.5198\,\mathrm{X2} - 0.4372\,\mathrm{X1X2} \quad (14)$$

EA and MD had a significant ($p < 0.05$) effect on the bulk and tapped density. The model F-value of 9.55 for bulk density and the model F-value of 174.67 for tapped density, with a coefficient of regression (R^2) of 0.9773 for bulk density and coefficient of regression (R^2) of 0.9270 for tapped density, showed the model was significant ($p < 0.05$). It confirms the study of Yüksel [5] that in all microwave output powers, the effect of EA content on bulk and tapped densities was significant ($p < 0.05$) [5]. In a study, the higher the protein molecular weight, the greater the bulk density of pineapple powder as the content of EAs increases [33].

The flowability and cohesiveness showed in Table 3 were used to analyse the flow properties of foam mat-dried yogurt powders using CI and HR. The CI and HR of optimum treatment were 3.53–13.37 and 1.07–1.15, respectively (Table 3). All EA-MD-treated yogurt powder showed good flow characteristics. This result was consistent with Yüksel [5]. The powder exhibited substantial flowability and cohesiveness, as indicated by $p < 0.05$. The response flowability and cohesiveness were assessed based on the mean model, characterised by low standard deviation, a low anticipated sum of squares, and a high predicted R-square. The visual representation of the relationship between EA and MD and the Carr index and Hausner ratio is shown in Figs. 1 (Y_7) a nd (Y_8). According to the ANOVA results, the models (quadratic) were all significant. The flowability and cohesiveness of the foam is measured using the following Equation:

$$CI = +12.75\,X_1 + 8.34\,X_2 - 15.60\,X_1X_2 \quad (15)$$

$$HR = +1.15\,X_1 + 1.09\,X_2 - 0.1866 \quad (16)$$

EA and MD had a significant ($p<0.05$) effect on the CI and HR. The model F-value of 39.06 for CI and the model F-value of 16.46 for HR, with a regression coefficient (R^2) of 0.7131 for the Carr Index and 0.7364 for Hausner Ratio, showed that the model was significant ($p<0.05$). The linear model explains the change in foam density and a modification, as evidenced by the significance of model and non-significant lack of fit. The lowest numerical difference between adj-R^2 and pre-R2 further supported the applicability of these models.

In our study, Carr Index (CI) and Hausner Ratio (HR) values confirmed that the yogurt powders exhibited excellent flowability and cohesiveness at the optimized EA and MD concentrations under freeze-drying. Similarly, Yüksel [5] reported that yogurt powders obtained by microwave-assisted foam-mat drying also demonstrated excellent flow properties (CI = 0.99–13.89; HR = 1.01–1.17) across different EA concentrations and drying powers. These consistent findings indicate that the addition of egg albumin, regardless of the drying method, can contribute to desirable flowability and cohesiveness in yogurt powders.

Table 5 The hedonic test result of the water-rehydrated yogurt products

Parameters	Hedonic score		
	F1	F2	F3
Color	3.30 ± 1.21^{a}	6.03 ± 1.10^{b}	7.17 ± 0.59^{c}
Aroma	3.93 ± 1.57^{a}	5.40 ± 1.45^{b}	6.27 ± 1.39^{c}
Flavor	3.40 ± 1.45^{a}	5.70 ± 1.42^{b}	7.07 ± 1.39^{c}
Texture	3.37 ± 1.40^{a}	5.50 ± 1.48^{b}	7.27 ± 0.83^{c}

Different letters within a column in superscript are statistically different

Hedonic scale: 1 = extremely disliked to 9 = like extremely

F1 added water of 95%, F2: added water of 85%, F3: added water of 75%

3.3 Optimization content of egg albumin and maltodextrin

Following the formulation of models for various responses, the optimisation of process parameters was conducted to balance foam quality, drying efficiency, and powder handling properties. The criteria were set to minimise foam density, moisture content, bulk and tapped densities, and flowability indices (CI and HR), while maximising foam expansion and yield. Based on these criteria, the optimal solution (desirability = 0.67) was identified at 16.5% EA and 3.5% MD. At this point, Table 3 indicates favourable foam and powder characteristics: relatively low foam density (0.65 g/cm^3) combined with moderate foam expansion (52.7%), which would support the formation of stable yet porous foams during drying; acceptable powder recovery (20.1%) with low residual moisture (3.5%); and excellent flowability and cohesiveness (CI 6.98, HR 1.08). These results suggest that the identified optimum not only improves drying performance but also ensures desirable handling properties of the final powder. To confirm whether these physicochemical advantages translate into consumer acceptability, yogurt powders produced under these optimal conditions were further subjected to sensory evaluation by panelists.

3.4 Sensory evaluation

The consistency of yogurt determines the consumer preference, and these results establish the quantity of water for yogurt rehydration to obtain a reconstituted product. Table 5 displays the mean acceptance ratings of the various rehydrated yogurts with water levels of 95% (F1), 85% (F2), and 75% (F3).

The reconstituted yogurt differed significantly (p 0.05) in color, aroma, flavor, and texture. On the hedonic scale, the mean acceptability score for the rehydrated yogurt at 75% was 6, corresponding to "Slightly like," indicating that consumers received this sample well. The present findings confirm Santos et al. [9]. , that the average acceptance rating for both and traditional and reconstituted yogurt was 70%. Regarding flavor an overall impression, the reconstituted yogurt received more favourable reviews than the regular sugar (p >0.05) [9]. The samples' appearance, smells, and textures were identical (p >5%), and no significant statistical differences existed between them. The rehydrated yogurt received an average consumer acceptance score of about eight on the hedonic scale, indicating strong consumer acceptance, a similar trend observed for the regular yogurt [9].

Therefore, the optimized foam-mat freeze-drying method using 16.5% egg albumin and 3.5% maltodextrin can be directly applied in the production of yogurt powder with excellent flowability, low moisture content, and high sensory acceptance. This approach is particularly relevant for small and medium enterprises (SMEs) seeking cost-effective and time-efficient techniques to produce lightweight, shelf-stable yogurt products with retained nutritional value. The process can also support the development of instant yogurt drinks, ready-to-use bakery ingredients, and functional food formulations.

4 Conclusions

This study examined the effects of egg albumin (EA) and maltodextrin (MD) concentration on foam, physicochemical properties, and sensory properties of yogurt powder by freeze-drying (24 h, freezing at -55 °C, and 4 Pa). Using a D-optimal design, the optimal proportions of EA and MD to be 16.5% and 3.5%, respectively, for achieving ideal foaming performance. The optimized conditions yielded a foam density of 0.65 g/cm^3, foam expansion of 52,7%, and powder recovery of 20.1%. The resulting yogurt powder had a low moisture content of 3.5%, along with bulk and tap densities of 0.35 g/cm^3 and 0.38 g/cm^3, respectively. Flowability measurements revealed a Carr Index (CI) of 6.98 and a Hausner Ration (HR) of 1.08, indicating excellent flow properties of the yogurt powder. Sensory evaluation of rehydrated yogurt powder (at 75% water) showed high panellist acceptance in terms of color, aroma, and flavor. These findings confirm the foaming with 16.5% EA and 3.5% MD prior to freeze-drying produces yogurt powder with superior physicochemical and sensory qualities. This study demonstrates the potential of foam-mat freeze-drying as an efficient technique for yogurt powder production, particularly suitable for small and medium enterprises (SMEs). The method is time-efficient and maintains high nutritional value, making it a viable solution for producing lightweight, shelf-stable yogurt products. Future studies should evaluate the application of this optimized foaming system to other dairy or plant-based products, explore alternative natural stabilizers, and assess long-term storage stability. Research on scale-up feasibility, cost–benefit analysis, and consumer acceptance, including different rehydration ratios and fortification, would further support industrial application and product development.

Author contributions

Sandi Darniadi: Conceptualisation, Methodology, Funding acquisition, Supervision, Writing - Original Draft, Writing- review & editing. Fitriyono Ayustaningwarno: Writing- review & editing, Funding acquisition. Azzahra Mutiara Ayu: Writing- review & editing. Ahmad Gunardi and Nur Fauziyah: Investigation, Methodology, Writing - Original Draft. Sri Widowati, Tien Muchtadi, Setyadjit, Ridwan Rachmat, and Idolo Ifie: Conceptualisation, Methodology, Supervision, Writing- review & editing. Uning Budiharti, Puji Widodo, and Dondy A. Setyabudi: Investigation, Methodology, Resources.

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Data availability

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

Declarations

Ethics approval and consent to participate

The studies involving human participants were reviewed and approved by the Ethics Committee of the *Komisi Etik Bidang Kimia*, *Badan Riset dan Inovasi Nasional (BRIN)*, with ethical clearance approval No: 219/KE.04/SK/08/2025. The participants provided their written informed consent to participate in this study. The study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments. The authors confirm that all human research participants provided informed consent to participate in this study.

Consent for publication

The authors confirm that all human research participants involved in the study provided explicit consent for the publication of their data and images.

Competing interests

The authors declare no competing interests.

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