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Development of a Fuzzy Intelligent System for Determining the Quality Characteristics of Cocoa Products Containing Water-in-Oil Emulsion

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ABSTRACT

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Water-in-oil emulsions as a partial substitute for cocoa butter are considered a novel approach for producing reduced-calorie cocoa products, however, the evaluation of quality characteristics of these products using traditional methods is time-consuming and dependent on human judgment. Therefore, this study aimed to investigate the effect of different concentrations of water-in-oil emulsion (0, 2, and 4% w/w) on the quality characteristics of cocoa products including enthalpy, length changes, hardness, chroma index, water activity, plastic viscosity, and overall acceptance, as well as designing an intelligent model based on fuzzy logic to predict these characteristics. The results showed that increasing emulsion concentration decreased melting enthalpy, chroma index, and overall acceptance, while water activity and plastic viscosity increased, and the lowest hardness was observed in the sample containing 2% emulsion. The designed fuzzy model showed the highest accuracy in predicting water activity (with a correlation coefficient of 0.915) and the lowest accuracy in predicting hardness (with a correlation coefficient of 0.753), and for other characteristics, the correlation coefficients were within an acceptable range, indicating the appropriate efficiency of this system in predicting the quality characteristics of cocoa products. Finally, it can be stated that the fuzzy logic system developed in this study provides an efficient, rapid, and reliable tool for predicting the quality characteristics of cocoa products, which can be used as a decision support system in quality control and formulation optimization in the chocolate industry.

1- INTRODUCTION

Cocoa (*Theobroma cacao* L.), a member of the order Malvales, family Malvaceae, and genus *Theobroma*, is one of the most economically important crops used for chocolate production. The scientific name *Theobroma*, derived from the Greek language, means "food of the gods," reflecting the historical and cultural significance of cocoa. Although the pulp of the cocoa fruit has a pleasant flavour, the beans are the most valuable component and serve as the primary raw material for manufacturing a wide variety of cocoa-based products, particularly chocolate. Cocoa and its derived products, especially chocolate, represent one of the most valuable and complex agricultural commodity chains worldwide, playing significant economic, cultural, nutritional, and even political roles. However, in recent years, the global cocoa market has experienced substantial fluctuations in supply and price, a phenomenon often referred to as the global cocoa supply crisis. This crisis has resulted from the combined effects of environmental and socio-economic factors. Global demand for cocoa continues to increase owing to the expanding chocolate industry, whereas production has failed to keep pace with market demand. Although global cocoa production was initially projected to increase by approximately 1% during the 2022–2023 season, persistent supply constraints halted this growth, and production declined to approximately 4.382 million tonnes in the 2023–2024 season. Consequently, the global price of cocoa has more than tripled over the past year, primarily because of supply shortages rather than increased production costs [1–3]. Cocoa is a rich source of bioactive compounds, particularly polyphenolic antioxidants such as catechin, epicatechin, and procyanidins, which effectively scavenge free radicals and reduce oxidative stress. In addition, cocoa beans contain methylxanthines, including theobromine and caffeine, which contribute to their stimulant properties and cognitive-enhancing effects [3]. Cocoa butter constitutes approximately 40–58% of the cocoa bean and is mainly composed of palmitic, stearic, and oleic fatty acids, which largely determine the melting behaviour, texture, and sensory quality of chocolate [4]. The global chocolate market is

currently valued at more than USD 100 billion and is expected to continue expanding, driven by increasing consumer demand for premium confectionery products and functional chocolates with improved nutritional profiles [5]. Cocoa butter serves as the continuous lipid phase in chocolate and is primarily responsible for its characteristic melting behaviour, texture, and sensory properties. However, its inherent limitations, including high thermal sensitivity, thermodynamic instability, and the vulnerability of its supply chain, pose significant challenges to the chocolate industry [6]. Moreover, diets rich in saturated fatty acids have been associated with an increased risk of hypertension, insulin resistance, and other metabolic disorders. Consequently, there is growing interest in developing alternative fat systems that can partially or completely replace cocoa butter in chocolate formulations. These alternatives include water-in-oil (W/O) emulsions, oleogels, composite hydrogels, and other structured lipid systems.

Among these approaches, W/O emulsions, consisting of finely dispersed water droplets with diameters below the oral detection threshold, have attracted considerable attention as partial cocoa butter replacers because they reduce the fat and caloric content while causing only minimal changes in the physicochemical and sensory properties of the final product. Furthermore, W/O emulsions can serve as effective delivery systems for hydrophilic bioactive compounds, facilitating the development of functional chocolate products [7]. Prosapio and Norton (2019) demonstrated that, by incorporating water-in-cocoa butter emulsions and optimizing formulation and processing conditions, it is possible to produce chocolate containing up to 40% less fat while maintaining textural and thermal properties comparable to those of conventional full-fat chocolate [8]. The evaluation of chocolate and cocoa-based product quality using conventional analytical methods is often laborious, time-consuming, and highly dependent on human judgement, which may reduce the accuracy and consistency of quality assessment [9]. Fuzzy logic is an intelligent computational approach that mimics human reasoning by allowing decisions to be made based on degrees of truth rather than binary outcomes. By integrating expert knowledge with simple inference rules, fuzzy logic provides an effective framework for

prediction and decision-making under conditions of uncertainty and imprecise information. Owing to these advantages, fuzzy logic has been widely applied in the food industry for product quality evaluation, risk assessment, process control, and optimization [10–12]. Azarmizad et al. (2022) developed a fuzzy statistical process control model for the chocolate industry and demonstrated that the fuzzy approach was more sensitive than the conventional statistical method in detecting process variations and provided a more realistic classification of product quality [13].

Despite these advances, no comprehensive study has integrated W/O emulsion technology with fuzzy logic modelling for the simultaneous evaluation and prediction of the quality characteristics of cocoa-based products. Therefore, the objective of the present study was to develop an intelligent fuzzy logic model based on experimental data and expert knowledge to evaluate and predict the nonlinear relationships among the quality attributes of cocoa-based products containing W/O emulsions. The proposed model is expected to provide an efficient decision-support tool for quality control and formulation optimization in the chocolate industry.

2- Materials and Methods

2.1. Materials

Cocoa butter (Premium, Malaysia), polyglycerol polyricinoleate (PGPR; Palsgaard, Denmark), whey protein concentrate (Hilmar, USA), soy lecithin (Cargill, Malaysia), low-fat cocoa powder (10–12% fat; Altınmarka, Türkiye), vanillin (Panda, China), fructose syrup (DE 42; Golshahd, Iran), and granulated sugar (Bistoon Sugar Company, Iran) were used in this study. All chemicals and food-grade ingredients were of commercial quality and

were used as received without further purification.

2.2. Preparation of Cocoa-Based Products Containing W/O Emulsion

Cocoa-based products containing a cocoa butter substitute (CBS)-based water-in-oil (W/O) emulsion were prepared according to the formulation presented in Table 1. Briefly, the dry ingredients, including cocoa powder, granulated sugar, and milk powder, were mixed with a predetermined amount of molten cocoa butter substitute maintained at 50 °C in a thermostatically controlled water bath (Fan Azma Gostar, Iran). The mixture was blended using a laboratory mixer (Fan Azma Gostar, Iran) until a homogeneous paste was obtained. The resulting paste was subsequently passed through a two-roll refiner (Charkhesh Machine, Iran) to reduce particle size. The remaining cocoa butter substitute, previously melted at 45 °C, was then incorporated into the refined paste. Simultaneous particle size reduction and conching were carried out using a laboratory ball mill (Mazhan Sanat Arshia, Iran) until a smooth and homogeneous chocolate mass was produced. In the final processing stage, soy lecithin, PGPR, and the CBS-based W/O emulsion with a water-to-oil ratio of 45:55 (v/v) were incorporated into the chocolate mass at three concentration levels: 0% (control), 2%, and 4% (w/w). The processing temperature was maintained at 45 °C, and mixing was continued at 95 rpm for 2 h to improve flow behavior and ensure uniform distribution of the emulsion. The chocolate mass was then moulded at 50 °C and cooled at 7 °C. After solidification, the samples were packaged in polyethylene bags and stored at 28 °C until further analyses were performed [14–16]. The detailed formulation of each treatment is presented in Table 1.

Table 1- Formulation of cocoa product containing different levels of emulsion

Ingredients (%)	Control	Treatment 1	Treatment 2
Cocoa butter substitute (CBS)	30.00	28.00	26.00
Sugar	47.00	47.00	47.00
Cocoa Powder	12.40	12.40	12.40
Lecithin	0.45	0.45	0.45
Skim milk powder	10.00	10.00	10.00
PGPR	0.05	0.05	0.05
Vanillin	0.10	0.10	0.10
CBS emulsion	0.00	2.00	4.00

2.3. Determination of Melting Enthalpy

The thermal behaviour of cocoa-based products containing different concentrations of W/O emulsion was evaluated using a differential scanning calorimeter (DSC) (Sanaf, Iran). Approximately 5 mg of each sample was accurately weighed into a hermetically sealed aluminium pan, while an empty aluminium pan was used as the reference. Prior to analysis, all samples were equilibrated at 25 °C for 24 h. Thermal scans were performed over a temperature range of 0–100 °C at a heating rate of 2 °C min⁻¹ under the instrument's standard operating conditions. The heat flow associated with the melting transition was continuously recorded throughout the heating cycle. Before sample analysis, the DSC instrument was calibrated using indium as the calibration standard (melting point: 156.6 °C; melting enthalpy: 28.45 J g⁻¹). The obtained thermograms were analysed using TA Universal Analysis 2000 software, and the melting enthalpy (ΔH , J g⁻¹) of each sample was determined from the area under the corresponding endothermic peak [15].

2.4. Measurement of Dimensional Change (ΔL)

The dimensional stability of cocoa-based products under thermal stress was evaluated by measuring the change in sample length (ΔL) according to the method described by Asghar et al. (2017), with minor modifications. The initial length of each sample was measured at three different positions using a digital caliper (accuracy: 0.01 mm; INSIZE, China), and the average value was recorded. The samples were then subjected to thermal treatment in a laboratory oven (Mettler, Germany) at 40 °C for 30 min. Following thermal exposure, the samples were removed from the oven and allowed to cool at room temperature (25 °C) for 10 min. The final length of each sample was subsequently measured at the same three positions, and the mean value was calculated. The dimensional change (ΔL) for each sample was determined as the difference between the initial and final lengths, with lower ΔL values indicating greater dimensional stability under thermal stress [16].

2.5. Hardness Measurement

To evaluate the textural properties of the cocoa products, Texture Profile Analysis (TPA) was performed using a texture analyzer (Instron, USA) equipped with a cylindrical probe of 2 mm diameter. The measurements were carried out at room temperature (25°C). The test

parameters were set to a crosshead speed of 60 mm/min, a penetration depth of 7 mm, and a 5 s interval between the two compression cycles. Each sample was placed individually on the instrument platform, and the probe descended vertically onto the sample to perform two consecutive compression cycles. Texture hardness was determined from the resulting force–time curve as the maximum force required to compress the sample during the first compression cycle (first peak force), which represents the sample's resistance to deformation [17].

2.6. Chroma Index Determination

The color characteristics of compound chocolate samples containing different levels of W/O emulsion were evaluated using a colorimeter (CR-300, Konica Minolta, Japan) based on the CIELAB color space. The color coordinates (L, a, and b) were measured, and the chroma index (C)—representing color saturation and intensity—was calculated according to Equation (1):

$$Chroma = \sqrt{a^{*2} + b^{*2}} \quad (1)$$

In Equation (1), the a^* index represents the degree of greenness or redness of the sample, with a range from −120 (pure green) to +120 (pure red). The b^* index indicates the extent to which the sample color is close to blue or yellow, with values ranging from −120 (pure blue) to +120 (pure yellow) [18, 19].

2.7. Water Activity (a_w) Determination

To evaluate the amount of free water present in cocoa products containing different levels of emulsion, the water activity of the samples was measured using a water activity meter (Novasina, Switzerland) at 27°C. This instrument operates based on the determination of the relative humidity of the headspace above the sample at equilibrium and provides an index of the amount of available water [16].

2.8. Plastic Viscosity Determination

The plastic viscosity of compound chocolate samples was determined by steady shear rheological measurements using a rotational rheometer (Physica MCR 301, Anton Paar, Austria) equipped with a flow measuring cell.

Measurements were performed at $40 \pm 0.1^\circ\text{C}$ over a shear rate range of 0–100 s^{-1} . The flow data (shear stress versus shear rate) were fitted to the Casson model (Equation 2), from which the Casson plastic viscosity was calculated.

$$\sqrt{\sigma} = \sqrt{\sigma_0} + \sqrt{\mu\delta} \quad (2)$$

In Equation (2), σ , σ_0 , μ , and δ represent the shear stress (Pa), yield stress (Pa), plastic viscosity ($\text{Pa}\cdot\text{s}$), and shear rate (s^{-1}), respectively [20].

2.9. Overall Acceptability Evaluation

To evaluate the sensory quality of cocoa products containing different levels of emulsion, a consumer acceptance test was conducted using 51 semi-trained panelists who were familiar with sensory evaluation techniques. The samples were provided to the panelists for assessment. The evaluated sensory attributes included shape and form, top surface characteristics, bottom surface characteristics, porosity, firmness and softness of texture, chewiness, and flavor, with weighting coefficients of 4, 2, 1, 2, 2, 3, and 3, respectively. A scoring scale ranging from 1 (very poor) to 5 (excellent) was used for these attributes. The overall acceptance score (Q) for each sample was calculated according to Equation (3) [20, 21].

$$Q = \frac{\sum(P \times G)}{\sum P} \quad (3)$$

In Equation (3), Q represents the overall acceptance (the quality index of the produced samples), P denotes the weighting coefficient of the attribute, and G represents the evaluation coefficient of the attribute.

2.10. Fuzzy Logic Modeling

A Mamdani fuzzy inference system (FIS) was developed using the Fuzzy Logic Toolbox of MATLAB (MathWorks Inc., Natick, MA, USA) to model and predict the quality attributes of compound chocolate samples containing different levels of W/O emulsion (0, 2, and 4%, w/w). The input variable, emulsion concentration, was represented by three linguistic terms: Low (L), Medium (M), and High (H), corresponding to emulsion concentrations of 0, 2, and 4%, respectively.

Seven output variables, including melting enthalpy (ΔH), length change (ΔL), hardness, chroma (C), water activity (aw), Casson plastic viscosity,* and overall acceptability (Q), were also described using three linguistic levels (Low, Medium, and High). Triangular membership functions were selected to represent the linguistic variables because of their simplicity and computational efficiency in fuzzy inference systems. A triangular membership function is defined by three

parameters (a, b, and c) as described in Equation (4):

$$Triangle(x; a, b, c) = \begin{cases} 0 & x \leq a \\ \frac{x-a}{b-a} & a \leq x \leq b \\ \frac{c-x}{c-b} & b \leq x \leq c \\ 0 & c \leq x \end{cases} \quad (4)$$

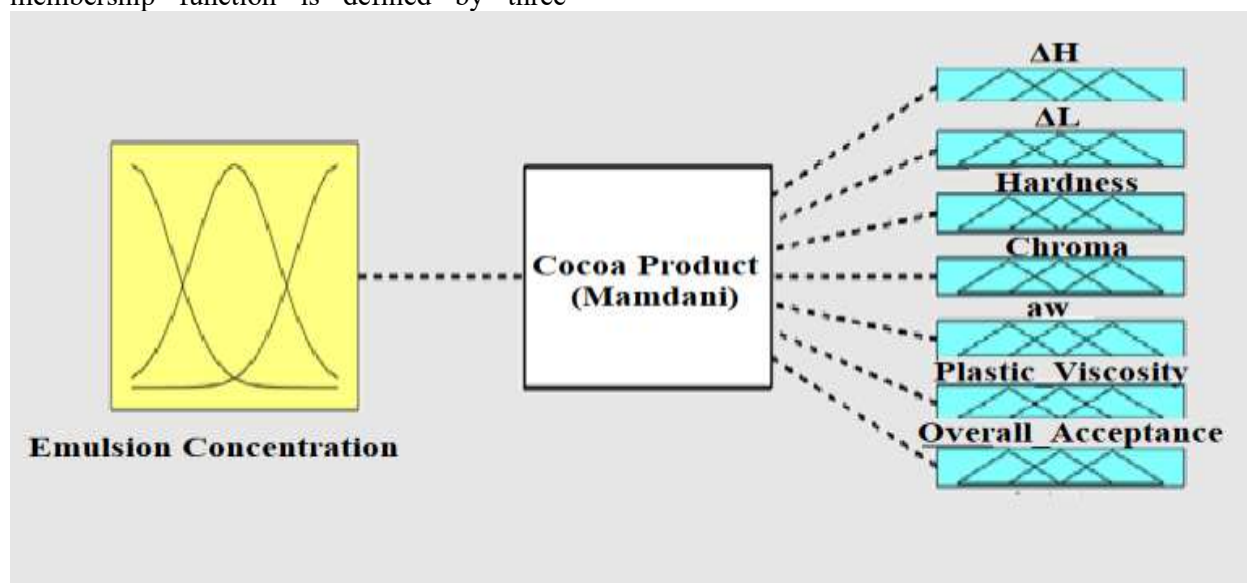


Figure1- The suggested topology of the designed fuzzy logic system in this investigation

The architecture of the proposed Mamdani fuzzy inference system is illustrated in Figure 1. The parameters (a, b, and c) defining the input and output membership functions were determined based on the experimental data to achieve the best agreement between the predicted and measured values. The parameter values used for the input membership functions are presented in Table 2, while the corresponding membership functions for the input variable and a representative output variable (length change) are shown in Figure 2. Accordingly, three fuzzy if-then rules were established, one for each linguistic level of the input variable:

Rule 1: If Emulsion concentration is Low (L), then Melting enthalpy is High (H), Length change is Low (L), Hardness is High (H),

Chroma is High (H), Water activity is Low (L), Casson plastic viscosity is Low (L), and Overall acceptability is High (H).

Rule 2: If Emulsion concentration is Medium (M), then Melting enthalpy is Medium (M), Length change is High (H), Hardness is Low (L), Chroma is Medium (M), Water activity is Medium (M), Casson plastic viscosity is Medium (M), and Overall acceptability is Medium (M).

Rule 3: If Emulsion concentration is High (H), then Melting enthalpy is Low (L), Length change is Medium (M), Hardness is Medium (M), Chroma is Medium (M), Water activity is High (H), Casson plastic viscosity is High (H), and Overall acceptability is Low (L).

Table 2- Triangular membership function parameters for emulsion concentration

The title of membership functions	Parameters of membership functions		
	A	b	c
The first membership function	0	0	2

Second membership function	0	2	4
Third membership function	0	4	4

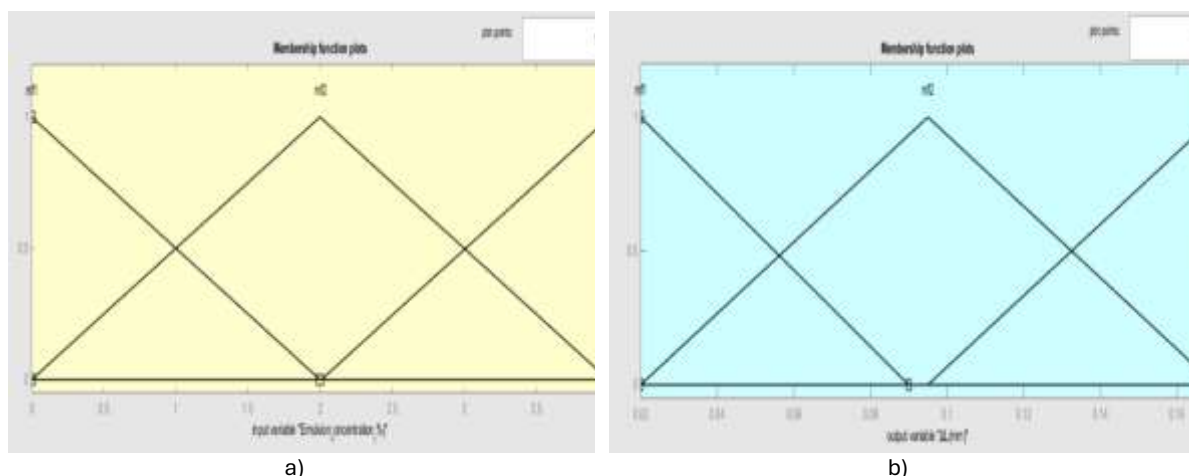


Figure 2- Membership functions: a) input (emulsion concentration) and b) output variable (ΔL)

3- Results and Discussion

3.1. Effect of Emulsion Concentration on the Properties of Compound Chocolate

Differential scanning calorimetry (DSC) is one of the most reliable analytical techniques for evaluating the thermal behavior of food systems because it directly measures the enthalpy associated with phase transitions [23]. As shown in Figure 3a, increasing the concentration of the W/O emulsion significantly reduced the melting enthalpy of the compound chocolate samples. This reduction may be attributed to the increasing number of dispersed water droplets acting as structural discontinuities within the fat crystal network. In addition, the interfacial layer formed by the emulsifier around the dispersed droplets may enhance molecular mobility, facilitating molecular rearrangement within the fat crystal network and potentially promoting the development of more stable crystalline structures. Consequently, less energy was required to disrupt the crystalline fat network during melting, resulting in lower melting enthalpy values [24]. Prosapio and Norton (2019) reported that processing temperature plays a decisive role in determining the polymorphic form of cocoa butter emulsions, with temperatures above 50°C favoring

unstable crystal forms with lower melting temperatures, whereas temperatures below 35°C promote the formation of more stable polymorphs [8]. Therefore, the reduction in melting enthalpy observed in the present study is likely associated with the combined effects of dispersed water droplets disrupting crystal continuity and processing conditions influencing fat crystallization. As illustrated in Figure 3b, dimensional change initially increased and subsequently decreased as the emulsion concentration increased. At low emulsion concentrations, dispersed water droplets likely acted as structural discontinuities within the fat crystal network, interrupting crystal continuity and reducing structural integrity. Consequently, the chocolate became more susceptible to thermal and mechanical deformation, resulting in greater dimensional changes. However, at higher emulsion concentrations, the increased droplet density likely contributed to the formation of a more interconnected structural network together with an increase in the overall viscosity of the system, thereby improving resistance to deformation and reducing dimensional change [16]. Similar observations were reported by Wan Aidah et al. (2014), who demonstrated that cocoa butter emulsions improved shape retention of chocolate up to 40°C while producing a softer texture, indicating reduced structural rigidity [25]. In contrast, Norton et al.

(2009) found that increasing the emulsion concentration to 60% caused little change in chocolate characteristics, which may be related to differences in fat composition, emulsifier type, and water-to-oil ratio among formulations [26].

Texture is one of the most important quality attributes influencing the sensory perception of chocolate, particularly its firmness and melting characteristics. Firmness is affected by several factors, including fat composition, particle size distribution, crystal structure, and storage conditions [27]. As shown in Figure 3c, firmness initially decreased and subsequently increased with increasing emulsion concentration, exhibiting an opposite trend to dimensional change. The initial reduction in firmness may be explained by disruption of the fat crystal network by dispersed droplets, whereas the subsequent increase at higher emulsion concentrations may be attributed to the formation of a more interconnected structural network and increased system viscosity. This inverse relationship suggests that structural reinforcement at higher emulsion concentrations compensated for the initial weakening of the fat crystal network. This nonlinear behavior partially agrees with the findings of You et al. (2023), who reported reduced firmness in reduced-fat chocolates containing W/O emulsions with high water-to-oil ratios, although they did not observe the subsequent increase in firmness at higher emulsion concentrations [7].

Likewise, Prosapio and Norton (2019) demonstrated that increasing the sugar concentration in the aqueous phase enhanced chocolate firmness, suggesting that texture is governed by the combined effects of formulation composition, water-to-oil ratio, and emulsion microstructure [8].

Chroma is an objective color parameter that reflects the intensity and purity of chocolate color and is widely used to monitor visual quality changes, including those associated with fat bloom development [28]. As shown in Figure 3d, chroma gradually decreased as the emulsion concentration increased. The greater number of dispersed water droplets acted as light-scattering centers within the fat matrix, thereby reducing color saturation. According to the light-scattering theory proposed by McClements (2002), increasing the

concentration of the dispersed phase enhances light scattering, leading to lower chroma values [29]. Similarly, Chanamai and McClements (2001) reported that increasing droplet concentration reduced light transmission through emulsions, resulting in a less saturated and duller appearance [30]. Therefore, the reduction in chroma observed in this study is primarily attributed to enhanced light scattering caused by dispersed droplets and may contribute to visual characteristics commonly associated with the early stages of fat bloom [16,31].

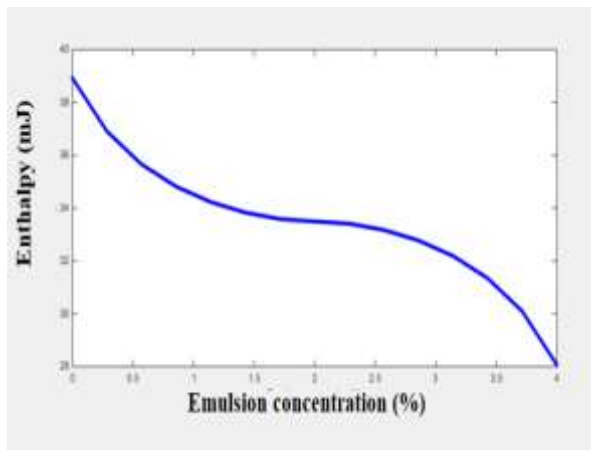
As presented in Figure 3e, water activity increased significantly with increasing emulsion concentration. This trend can be explained by the larger amount of water introduced into the chocolate matrix as the emulsion level increased. Although PGPR effectively stabilizes dispersed water droplets by reducing interfacial tension, its capacity to maintain water within a stable emulsion structure is limited. Consequently, at higher emulsion concentrations, a greater proportion of water may remain available as free water, resulting in increased water activity. These findings are consistent with those reported by Prosapio and Norton (2019), who also observed increased water activity in chocolates containing W/O emulsions [8]. In contrast, Asghar et al. (2017) reported the highest water activity in the control sample and the lowest values in chocolates containing the highest concentration of CBS-based emulsions, attributing this behavior to effective water immobilization within the emulsion structure [16]. Esmali et al. (2019) likewise reported increased water activity in heat-resistant chocolates formulated with sugar-alcohol emulsions, supporting the results obtained in the present study [32].

Plastic viscosity represents the energy required to maintain the flow of molten chocolate after yielding and reflects the internal friction between adjacent layers during flow. It is a key rheological parameter influencing chocolate processing operations such as molding and enrobing, as well as consumer mouthfeel, and is affected by particle size distribution, fat content, moisture, and emulsifier composition [33]. As shown in Figure 3f, plastic viscosity increased progressively with increasing emulsion concentration. This increase is likely

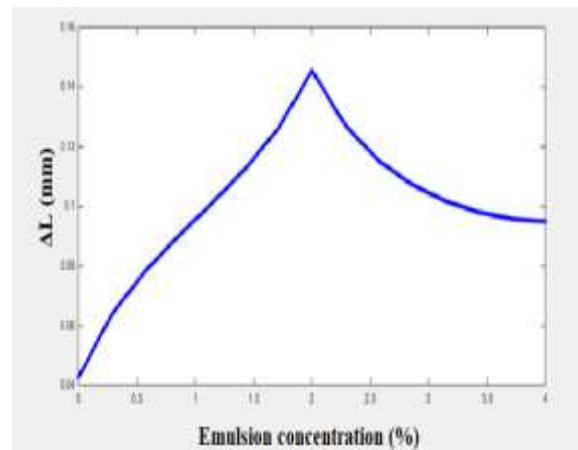
associated with the higher water-to-oil ratio together with the presence of whey protein concentrate (WPC) and fructose syrup in the aqueous phase, both of which contribute to the formation of a more flow-resistant microstructure and increase resistance to deformation during flow [34]. These findings are consistent with those reported by You et al. (2023), who demonstrated that replacing cocoa butter with W/O emulsions significantly increased chocolate viscosity. They attributed this behavior to the incorporation of the aqueous phase containing gum arabic and fructose syrup, which increased resistance to flow [7].

Overall sensory acceptance decreased progressively with increasing emulsion concentration, as shown in Figure 3g. This decline is likely associated with the reduction in chroma together with the increase in viscosity, both of which adversely affected the visual appearance and mouthfeel of the chocolate samples.

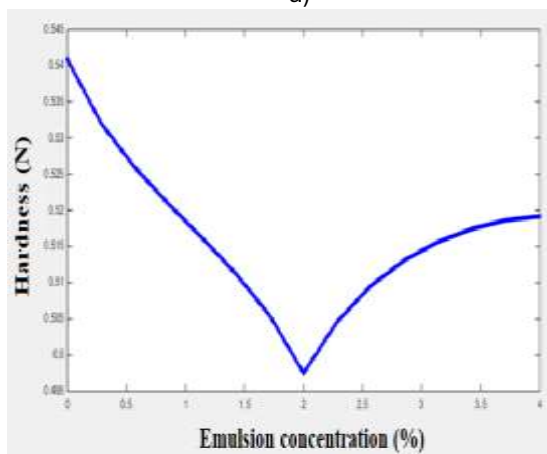
Similar observations were reported by Wan Aidah et al. (2014), who found that replacing part of the cocoa butter with W/O emulsions reduced surface gloss and consequently decreased the overall acceptability of heat-resistant milk chocolate [25]. Likewise, Asghar et al. (2017) reported that increasing the concentration of CBS-based emulsions reduced chocolate gloss because of the higher water content and enhanced sugar crystallization, thereby negatively affecting product appearance [16]. Furthermore, Biswas et al. (2017) observed lower sensory scores, particularly for flavor, in chocolates formulated with CBS compared with conventional cocoa butter chocolate [17]. Overall, these findings suggest that although increasing the emulsion concentration may improve certain thermal and functional properties, an optimum emulsion concentration is required to achieve an appropriate balance between thermal stability, rheological behavior, visual quality, and consumer acceptance.



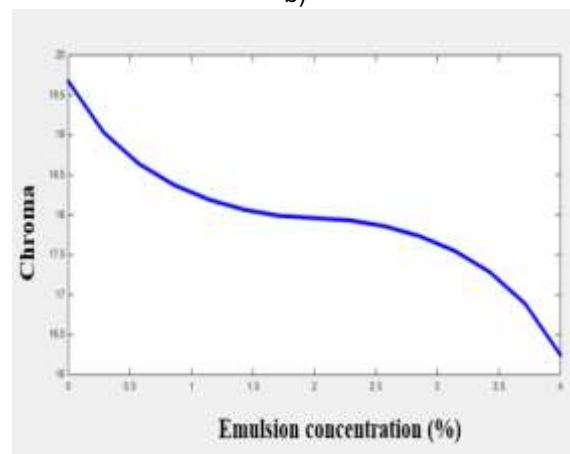
a)



b)



c)



d)

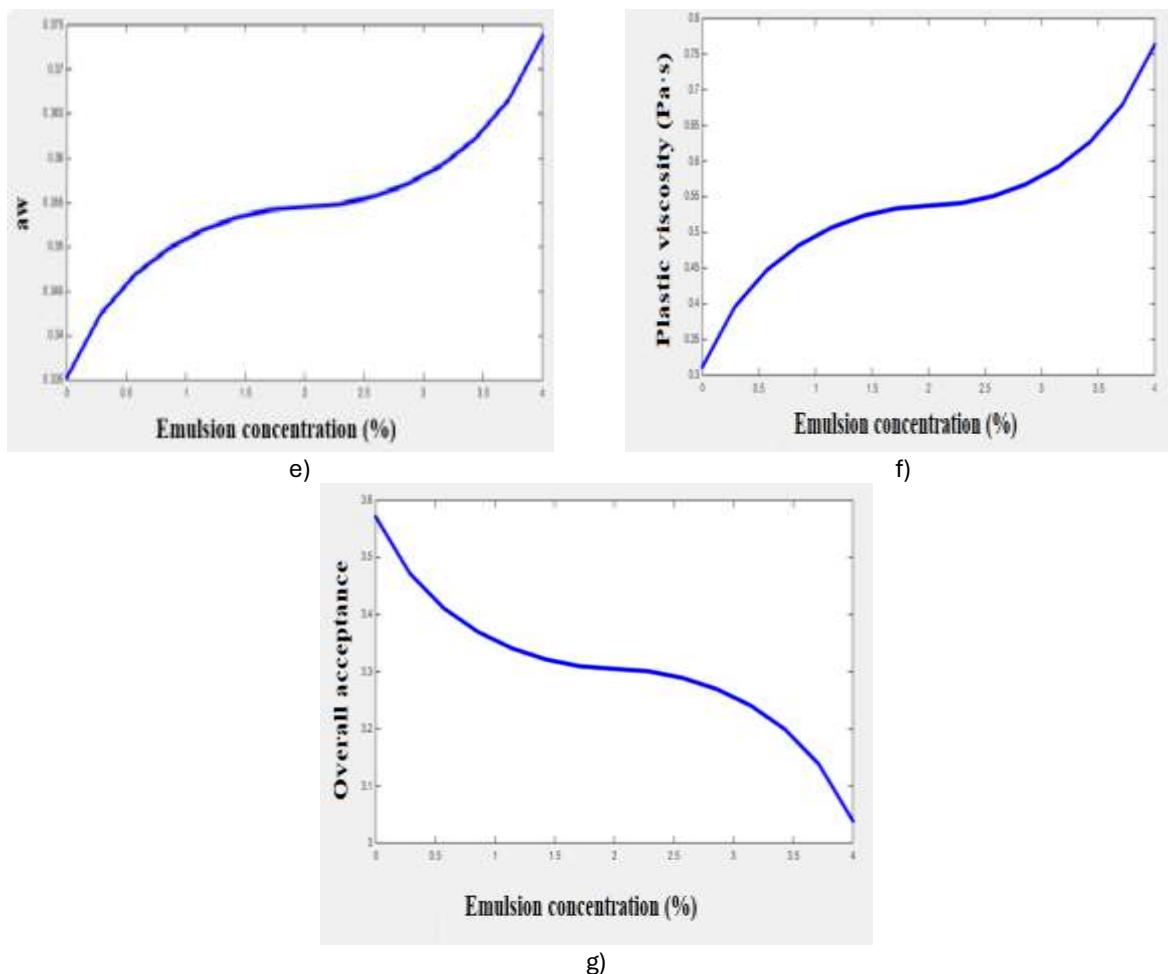


Figure 3 - Effect of emulsion concentration on a) enthalpy, b) ΔL , c) hardness, d) chroma, e) water activity, f) plastic viscosity, and g) overall acceptance

3.2. Evaluation of the Predictive Performance of the Fuzzy Logic Model

Figure 4 illustrates the output of the proposed fuzzy logic system for compound chocolate containing 1% W/O emulsion. As shown, the second to eighth columns represent the seven output variables, namely melting enthalpy, dimensional change (ΔL), firmness, chroma,

water activity, plastic viscosity, and overall acceptance. Each row corresponds to an individual fuzzy rule, while the fourth row (columns 2–8) represents the aggregated weighted outputs generated by the fuzzy inference system. This comprehensive model enables the simultaneous prediction of all quality attributes by simply specifying the emulsion concentration as the input variable.

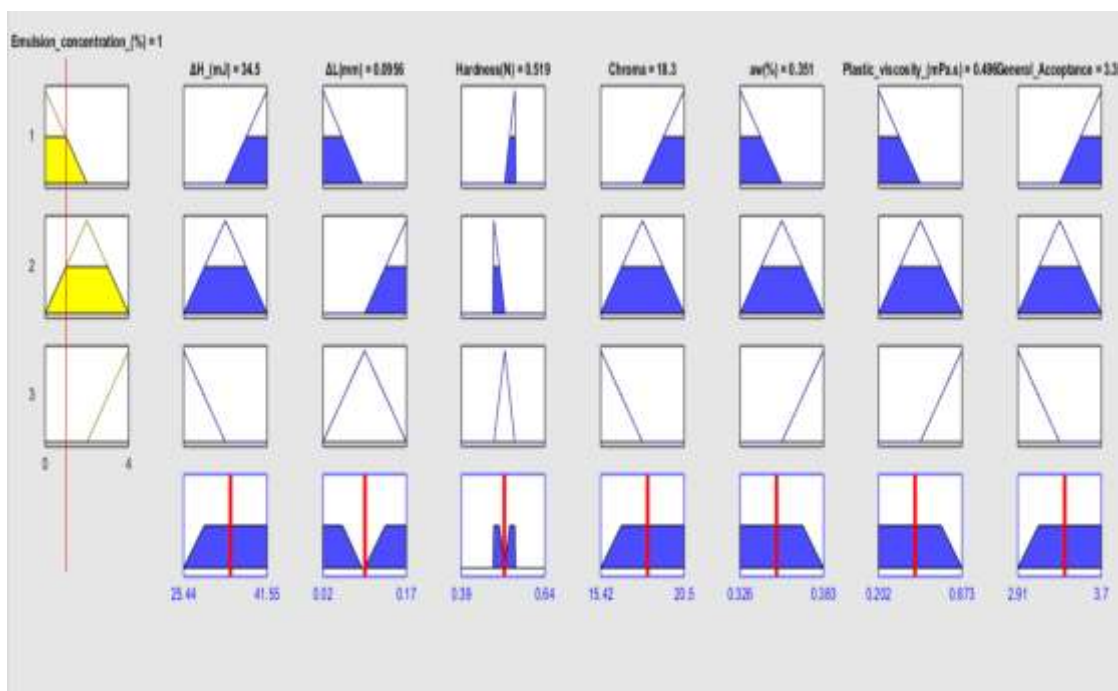
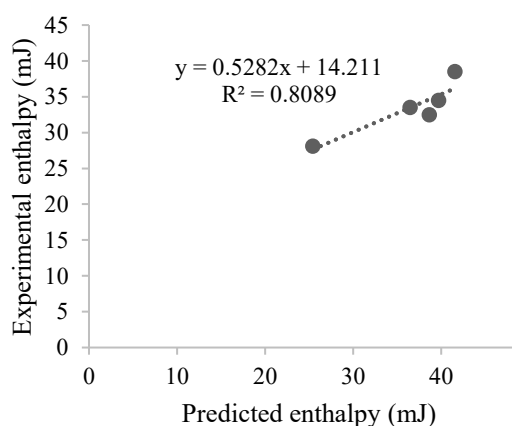


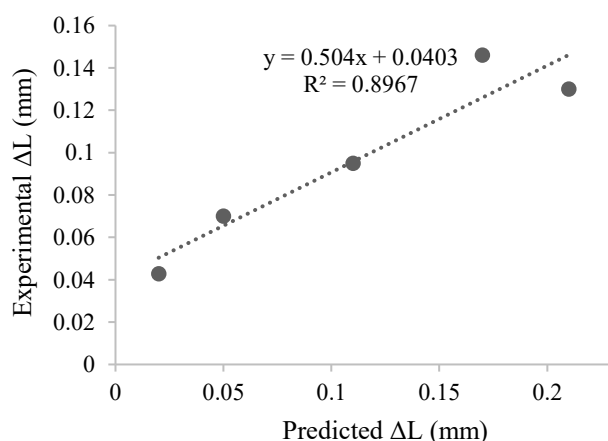
Figure 4- The output of the proposed fuzzy logic system

Figure 5 compares the experimental values with those predicted by the fuzzy logic model for all seven response variables. The relatively high coefficients of determination ($R^2 > 0.753$) indicate that the proposed model accurately predicted the quality characteristics of compound chocolate over the investigated emulsion concentrations. Among the evaluated responses, the highest predictive accuracy was obtained for water activity ($R^2 = 0.915$), whereas firmness exhibited the lowest, yet still acceptable, predictive performance ($R^2 =$

0.753). These results demonstrate that the fuzzy inference system effectively captured the nonlinear relationships between emulsion concentration and the physicochemical, rheological, and sensory properties of the product. Consequently, the developed model can be considered a reliable decision-support tool for predicting product quality while reducing the number of experimental trials required during formulation optimization.



a)



b)

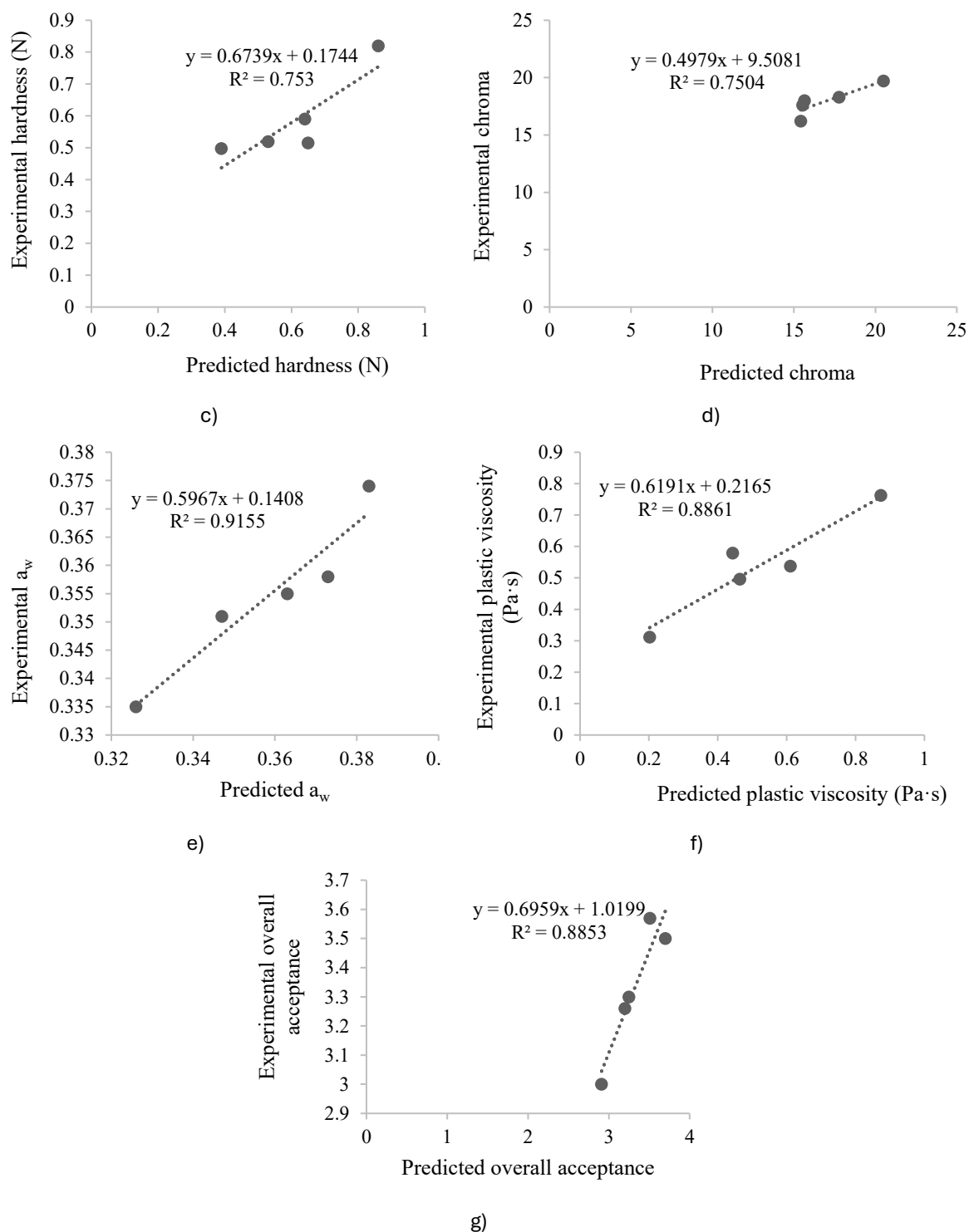


Figure 5 - Comparison of experimental and predicted values by fuzzy logic model for a) enthalpy, b) ΔL , c) hardness, d) chroma, e) water activity, f) plastic viscosity, and g) overall acceptance

The findings of the present study are consistent with previous reports demonstrating the effectiveness of fuzzy logic in food quality evaluation and process optimization. Azarmizad et al. (2022) applied a fuzzy

statistical process control approach in a chocolate manufacturing company to monitor seven quality defects, including color, flavor, acidity, sugar bloom, texture-related defects, and foreign materials. Their results showed that the fuzzy approach was more sensitive than conventional statistical methods in detecting

process variations and identifying quality deviations, thereby improving process monitoring and quality control [13]. Similarly, fuzzy logic has been successfully employed to classify cocoa pods based on physical characteristics such as length, width, weight, and bean number. The reported classification accuracy of 71.7% demonstrated the capability of fuzzy inference systems to enhance the objectivity and efficiency of decision-making in cocoa-related industries. These findings further support the applicability of fuzzy logic as a robust and efficient tool for quality prediction and optimization throughout the cocoa value chain, from raw material evaluation to chocolate processing [35].

4- Conclusion

This study investigated the influence of different concentrations of water-in-oil (W/O) emulsion on the quality characteristics of compound chocolate and developed a Mamdani fuzzy inference system to predict these properties. The results demonstrated that increasing the emulsion concentration reduced melting enthalpy, chroma, and overall sensory acceptance, while increasing water activity and plastic viscosity. Moreover, dimensional change and firmness exhibited nonlinear responses to emulsion concentration, indicating complex interactions between the emulsion microstructure and the fat crystal network. The developed fuzzy logic model successfully predicted all evaluated quality attributes with coefficients of determination (R^2) ranging from 0.753 to 0.915, demonstrating satisfactory predictive performance despite the nonlinear relationships among variables. These findings confirm that fuzzy logic is an effective modeling approach for complex food systems where conventional mathematical models may be insufficient to describe product behavior. From a practical perspective, the proposed model provides a rapid, reliable, and cost-effective decision-support tool for predicting the physicochemical, rheological, and sensory properties of compound chocolate containing W/O emulsions. Therefore, it has considerable potential for application in formulation optimization, quality control, and process development while reducing the number of experimental trials required during product development. It should be noted that the developed model was established using the

formulation and processing conditions investigated in this study. Consequently, its applicability to other chocolate formulations or processing conditions should be verified before industrial implementation. Future studies are recommended to investigate the effects of different emulsifier types and concentrations, various water-to-oil ratios, and processing conditions on the quality characteristics of compound chocolate. Furthermore, advanced artificial intelligence techniques, such as adaptive neuro-fuzzy inference systems (ANFIS) and deep neural networks, may be explored to further improve prediction accuracy and facilitate intelligent formulation optimization in chocolate manufacturing.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare that they have no conflicts of interest regarding this study.

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Author Contributions

Azar Haghighat Asiabar: Conducted the experiments, collected the data, and prepared the original draft of the manuscript. **Babak Ghanbarzadeh** and **Leila Roufegarinejad:** Conceived and supervised the project and reviewed and edited the final version of the manuscript. **Mehdi Gharekhani:** Validation and critical review of the manuscript.

AI Statement

The authors declare that no generative artificial intelligence (AI) tools were used in the writing, data analysis, interpretation of the results, or preparation of this manuscript.

5. References

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ایجاد یک سیستم هوشمند فازی برای تعیین ویژگی‌های کیفی فرآورده کاکائویی حاوی امولسیون آب در روغن

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کلمات کلیدی:

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امولسیون‌های آب در روغن به‌عنوان جایگزین جزئی کره کاکائو، رویکردی نوین برای تولید فرآورده‌های کاکائویی با کالری کاهش‌یافته محسوب می‌شوند، اما ارزیابی ویژگی‌های کیفی این فرآورده‌ها با روش‌های سنتی، زمان‌بر و وابسته به قضاوت انسانی است. از این‌رو این پژوهش با هدف بررسی تأثیر غلظت‌های مختلف امولسیون آب در روغن (صفر، ۲ و ۴ درصد وزنی) بر ویژگی‌های کیفی فرآورده‌های کاکائویی شامل آنتالپی، تغییرات طول، سفتی، شاخص کروما، فعالیت آبی، ویسکوزیته پلاستیک و پذیرش کلی و همچنین طراحی یک مدل هوشمند مبتنی بر منطق فازی برای پیش‌بینی این ویژگی‌ها انجام شد. نتایج نشان داد که افزایش غلظت امولسیون باعث کاهش آنتالپی ذوب، شاخص کروما و پذیرش کلی شد، در حالی که فعالیت آبی و ویسکوزیته پلاستیک نمونه‌ها افزایش یافت و کمترین میزان سفتی مربوط به نمونه حاوی ۲ درصد امولسیون بود. مدل فازی طراحی شده بیشترین دقت را در پیش‌بینی فعالیت آبی (با ضریب همبستگی ۰/۹۱۵) و کمترین دقت را در پیش‌بینی سفتی (با ضریب همبستگی ۰/۷۵۳) نشان داد و در سایر ویژگی‌ها نیز ضرایب همبستگی در محدوده‌ی قابل قبولی قرار داشت که بیانگر کارایی مناسب این سیستم در پیش‌بینی ویژگی‌های کیفی فرآورده‌های کاکائویی می‌باشد. در نهایت می‌توان بیان داشت که سیستم منطق فازی توسعه‌یافته در این پژوهش، ابزاری کارآمد، سریع و قابل اطمینان برای پیش‌بینی ویژگی‌های کیفی فرآورده‌های کاکائویی ارائه می‌دهد که می‌تواند به‌عنوان یک سامانه کمکی تصمیم‌گیری در کنترل کیفیت و بهینه‌سازی فرمولاسیون در صنعت شکلات مورد استفاده قرار گیرد.

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