

Article

Effect of Pre-Hydrolyzed Rice Extrudates with Different Dextrose Equivalent Values on Stability of Emulsion-Type Food for Special Medical Purposes

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Abstract

Maltodextrin is the most commonly used carbohydrate ingredient in Food for Special Medical Purposes (FSMP). However, growing evidence suggests that it may trigger intestinal inflammatory responses. Replacing maltodextrin with pre-hydrolyzed rice extrudates represents a viable approach to eliminate such adverse effects. Accordingly, this study prepared pre-hydrolyzed rice extrudates with different dextrose equivalent (DE) values and investigated their impact on the physicochemical properties of emulsion-type FMSP containing carbohydrates, casein, and soybean oil with increasing addition levels. The emulsion particle size of pre-hydrolyzed rice extrudates with different DE values showed a gradual upward trend, while the zeta potential gradually decreased. As the DE value increased, its influence on the zeta potential and viscosity of the emulsion diminished. However, samples with lower DE values contributed positively to reducing the centrifugal sedimentation rate of the emulsion, which was mainly attributed to their higher viscosity. In contrast, the turbidity and adsorption rate of emulsion samples with higher DE values were less affected by the addition level. Through turbiscan stability index and multi-index comprehensive evaluation, the optimal addition levels for pre-hydrolyzed rice extrudates with different DE values were obtained. The findings provide important insights for promoting the application of pre-hydrolyzed rice extrudates as a substitute for maltodextrin in FMSP.

Keywords: pre-hydrolyzed rice extrudates; dextrose equivalent; emulsion stability; comprehensive scores

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1. Introduction

Food for Special Medical Purposes (FSMP) are specially formulated foods designed to provide nutritional support for individuals with specific medical conditions. According

to clinical needs and target populations, FSMP can be categorized into full-nutrient formula foods, specific full-nutrient formula foods, or non-full-nutrient formula foods, and are commonly produced in powder or emulsion forms [1]. Emulsion-type FSMP offer practical advantages such as convenience and no rehydration requirement; however, their poor taste has constrained their market share. Currently, most of the FSMP are formulated with isolated nutrients such as proteins, carbohydrates, and lipids, with maltodextrin serving as the primary carbohydrate source. Maltodextrin is a polysaccharide that is more hydrophilic than starch and is formed by the partial hydrolysis of starch. Its fundamental structural units are D-glucose molecules linked into linear chains via α -1,4-glycosidic bonds. In ready-to-use liquid enteral nutrition formulations, maltodextrin functions as a thickening agent in the aqueous phase. It contributes to the stabilization of lipid microspheres within the formulation, thereby preventing phase separation during storage and ensuring homogeneous nutrient distribution. However, emerging evidence indicates that long-term consumption of maltodextrin can damage the gut [2,3], disrupt gut microbiota homeostasis [4], and promote intestinal inflammation [5]. These concerns have led to growing interest in identifying alternative, physiologically beneficial carbohydrate sources for next-generation FSMP products in China.

Grains and legumes, rich in carbohydrates, have been staple foods and a primary source of dietary energy in China. Their proven safety and nutritional value also make them promising raw materials for developing FSMP. Recent studies have explored the integration of these agricultural raw materials into FSMP formulations and achieved promising initial results. For instance, Cao et al. [6] investigated the effects of whole-grain brown rice matrices on the stability of clinical nutrition emulsions using sedimentation and creaming rates as indicators and identified optimal emulsifier–stabilizer combinations as well as best homogenization conditions. In addition, legume-based plants, such as mung beans, have also demonstrated significant potential as ingredients in FSMP owing to their rich nutritional composition, wide availability, and environmental sustainability [7]. In another study, Li et al. [8] evaluated the effects of sweet corn puree with different solid contents on the physical stability of a total-nutrient FSMP emulsion and found that a formulation containing 4% sweet corn solids maintained a uniform and stable system while retaining a rich sweet corn flavor. These findings provide a reference for the development of FSMP using agricultural products and natural food ingredients. However, adding grain-based ingredients tends to increase the viscosity of the emulsion, which limits the allowable levels of these ingredients in FSMP emulsion systems.

The textural and rheological properties of carbohydrate-rich grain matrices in FSMP formulations are often governed by their inherent gel-forming tendencies. Starch, the primary component, can form a thermoreversible gel network upon hydration and heating, leading to increased system viscosity and reduced flowability, which poses challenges for processing and patient intake. To address this, strategies aimed at disrupting or modulating this gel network are essential. The combined use of enzymatic hydrolysis with extrusion and puffing treatments for carbohydrate-rich grain matrices can effectively reduce viscosity and improve feeding flowability in FSMP formulations. Ren et al. [9] employed an enzyme-assisted twin-screw extrusion method to prepare oat flour with varying enzyme concentrations and found that the viscosity decreased with increasing amylase concentration at a constant shear rate, while a gradual transition from elastic to viscous state was observed with increasing scanning frequency. Similarly, Polo et al. [10] subjected quinoa germ powder to combined enzymatic hydrolysis and extrusion and observed enhanced solubility and a reduction in the consistency index (k) with increasing protease concentration, demonstrating improved flowability. In our previous study [11], based on the dextrose equivalent (DE) values of maltodextrin, rice flour was enzymatically pre-hydrolyzed and extruded to produce products with different DE values. The results showed

that an increase in DE value led to a gradual decrease in viscosity, improved flowability, and higher levels of rapidly digestible starch, suggesting strong potential for application in emulsion-type FSMP. In contrast to commercial rice maltodextrin produced via conventional liquefaction and saccharification processes, which typically exhibits a relatively uniform molecular weight distribution, the modified rice flour prepared through the combined enzymatic hydrolysis and extrusion technology may possess distinct particle structures and rheological properties due to its unique processing. How these potential structural differences affect its stabilizing functionality within FSMP emulsion systems has not been systematically compared or elucidated in existing studies.

Therefore, the present study investigated the effects of pre-hydrolyzed rice extrudates with different DE values as a substitute for maltodextrin. Specifically, their effects on key stability parameters of FSMP emulsions were evaluated, including particle size, zeta potential, centrifugal precipitation rate, and rheological properties. Moreover, the optimal dosage of pre-hydrolyzed rice extrudates with different DE values was determined by employing the Turbiscan Stability Index (TSI) and a comprehensive multi-index evaluation method. The results provide a theoretical and practical basis for utilizing pre-hydrolyzed rice extrudates as a maltodextrin alternative in FSMP.

2. Results and Discussion

2.1. Effect of Pre-Hydrolyzed Rice Extrudates with Different DE Values on Emulsion Particle Size

Particle size is a key indicator of emulsion stability, as excessively large droplets (Usually not exceeding 1–2 μm) are more susceptible to flocculation and aggregation owing to intermolecular forces such as van der Waals interactions, thereby compromising the stability of the emulsion system. The effects of pre-hydrolyzed rice extrudates with different DE values on emulsion particle size are shown in Figure 1.

Overall, the emulsion particle size progressively increased with higher addition levels of the rice extrudates with different DE values. However, the degree of increase in particle size was markedly lower for DE 5, DE 10, and DE 15 groups, when compared with that for DE 0 and DE 2 groups, indicating that high-DE rice extrudates exerted a weaker influence on emulsion particle size. At a 15% addition level, the particle sizes of DE 0 and DE 2 emulsions exceeded 2.00 μm (2.15 and 2.10 μm , respectively), representing approximately 3.30- and 3.20-fold increases relative to the maltodextrin emulsion (0.50 μm). According to Li et al. [12], increasing starch concentration enhances the deposition of starch granules on oil droplet surfaces, leading to the formation of larger droplets. In addition, the aggregation of starch granules can induce droplet network formation via particle bridging [13], which further impairs the emulsification process. Thus, emulsions prepared with DE 0 and DE 2 pre-hydrolyzed rice extrudates showed a significantly greater increase in particle size due to their low small-molecule sugar and high starch content, compared to those containing high-DE groups. The DE 0–12%, DE 0–15% and DE 2–15% groups exhibited noticeable flocculation within a few hours.

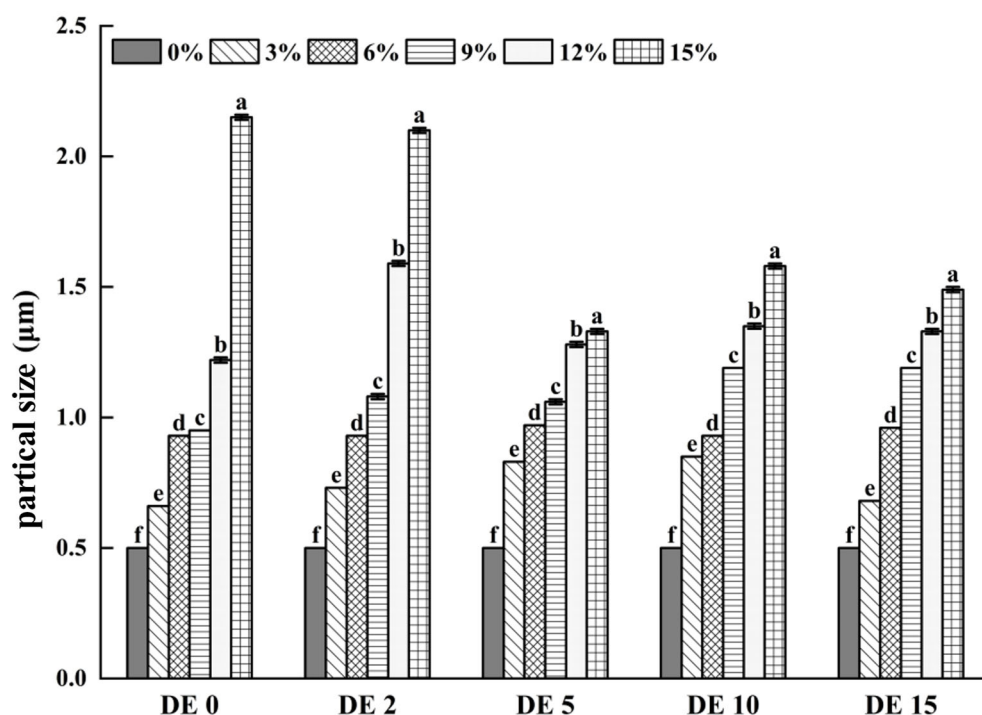


Figure 1. Particle size of the emulsion with different DE values. Note: 3%, 6%, 9%, 12%, and 15% denote the addition levels of pre-hydrolyzed rice extrudates in the emulsion. Bars with different letters at the same DE value indicate significant differences ($p < 0.05$).

2.2. Effect of Pre-Hydrolyzed Rice Extrudates with Different DE Values on Zeta Potential of Emulsion

Zeta potential is one of the key indicators of emulsion stability, reflecting the surface charge of droplets and the electrostatic interactions among dispersed proteins in the system [14,15]. A higher absolute zeta potential indicates greater emulsion stability, as stronger electrostatic repulsion between droplets can counteract van der Waals forces and prevent flocculation or aggregation [16].

The zeta potential values of emulsions prepared with pre-hydrolyzed rice extrudates with different DE values are presented in Figure 2. With increasing addition levels, all emulsions containing pre-hydrolyzed rice extrudates showed a gradual decrease in zeta potential. This change was most pronounced in the DE 0, DE 2, and DE 5 emulsions. In particular, for the DE 0 emulsion at a 15% addition level, the zeta potential decreased to -21.40 mV, a 61.43% reduction relative to the maltodextrin emulsion. In contrast, emulsions prepared with high-DE rice extrudates (DE 10 and DE 15) maintained strongly negative zeta potentials (below -50 mV in absolute value), and the shift towards zero with increasing addition level was relatively moderate. This phenomenon can be attributed to the deposition of starch granules (which are neutral or weakly charged) on the casein-coated droplet surfaces, thereby shielding the negative protein charge and reducing the effective charge density. Low-DE rice extrudates, which retain more intact granules, cause more pronounced charge shielding. Previous studies have reported that emulsions with absolute zeta potential values exceeding 30 mV are generally considered stable [17]. The charge shielding observed here primarily affected stability at high addition levels of low-DE rice extrudates. Specifically, only the DE 0–15%, DE 2–12%, and DE 2–15% formulations exhibited absolute zeta potentials below this threshold, indicating potential instability. All other formulations demonstrated good stability based on this criterion.

Overall, the addition of low-DE pre-hydrolyzed rice extrudates (DE 0, DE 2, and DE 5) had a stronger impact on emulsion stability, consistent with their greater effect on particle size.

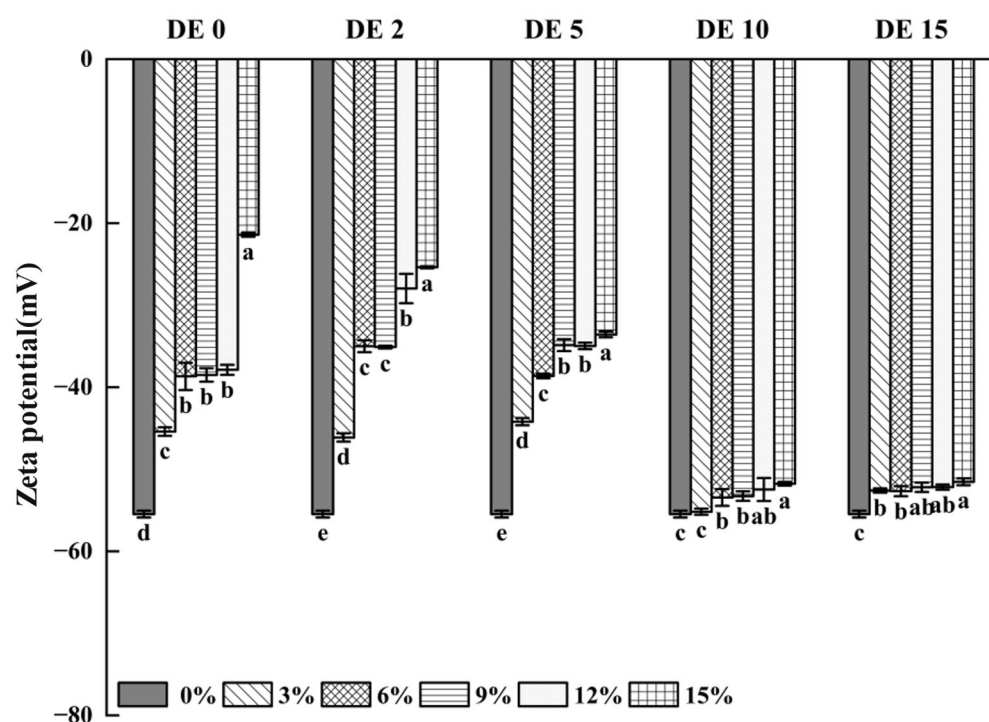


Figure 2. Zeta potential as a function of DE value for the emulsion. Bars with different letters at the same DE value indicate significant differences ($p < 0.05$).

2.3. Effect of Pre-Hydrolyzed Rice Extrudates with Different DE Values on Viscosity and Rheological Properties of Emulsions

2.3.1. Effect on Emulsion Viscosity

Amylase pretreatment substantially reduced the viscosity of rice extrudates, enabling higher addition levels in the emulsion system. As shown in Table 1, when the same proportion ($\geq 3\%$) of pre-hydrolyzed rice extrudates was added, emulsion viscosity progressively declined with increasing DE value. In particular, the emulsion containing 15% (m/v) DE 15 pre-hydrolyzed rice extrudates exhibited a viscosity of only 8.42 mPa·s, representing a 95% reduction (the most pronounced decrease observed), when compared with the DE 0 control group. This result indicated that amylase pretreatment significantly altered the structural and rheological properties of the rice matrix. With increasing DE value, starch is more extensively hydrolyzed into dextrinized starch, oligosaccharides, and small molecular sugars, which disrupts starch gelatinization, weakens the gel network, and ultimately reduces viscosity [18].

For pre-hydrolyzed rice extrudates with the same DE value, increasing addition levels affected emulsion viscosity to varying degrees. In the DE 0 and DE 2 groups, emulsion viscosity sharply increased with higher addition levels. At 15% addition level, viscosities of the DE 0 and DE 2 groups exceeded 150 mPa·s, representing 7.59- and 10.83-fold increases relative to those at 3% addition levels, respectively. As DE 0 and DE 2 represent non-hydrolyzed and mildly hydrolyzed rice extrudates, respectively, the starch molecular structure in both groups remained largely intact, and gelatinization produced a strong gel network, resulting in excessive emulsion viscosity [19]. Such high viscosity can negatively

affect emulsion fluidity, which is undesirable for clinical nutritional applications. In contrast, the effect of increasing the addition level on emulsion viscosity was far less pronounced in the DE 5, DE 10, and DE 15 groups. Even at 15% addition level, the viscosities of these emulsions remained below 25 mPa·s, corresponding to increases of only 96%, 38%, and 27%, respectively, when compared with their 3% addition counterparts. This result indicated that, as the DE value increases, further incorporation of pre-hydrolyzed rice extrudates does not cause excessive thickening of the emulsion. The relatively low viscosities of these emulsions reflect extensive degradation of starch structure—particularly in the DE 15 group, where the effect of addition level on viscosity was negligible. These findings suggested that pre-hydrolyzed rice extrudates with higher DE values exhibit favorable rheological characteristics, supporting their potential application in FSMP formulations.

Table 1. Viscosity (mPa·s) of emulsions containing pre-hydrolyzed rice extrudates across different DE values.

Groups	Additive Levels					
	0%	3%	6%	9%	12%	15%
DE 0	7.41 ± 0.22 ^f	21.86 ± 0.41 ^e	39.05 ± 0.37 ^d	63.51 ± 0.28 ^c	97.77 ± 0.90 ^b	187.86 ± 0.77 ^a
DE 2	7.41 ± 0.22 ^f	14.09 ± 0.22 ^e	30.84 ± 0.50 ^d	48.04 ± 0.49 ^c	79.60 ± 1.09 ^b	166.69 ± 0.72 ^a
DE 5	7.41 ± 0.22 ^f	11.97 ± 0.29 ^e	15.64 ± 0.26 ^d	20.28 ± 0.37 ^c	22.55 ± 0.18 ^b	23.44 ± 0.30 ^a
DE 10	7.41 ± 0.22 ^f	8.35 ± 0.34 ^e	8.84 ± 0.29 ^d	9.08 ± 0.36 ^c	11.35 ± 0.48 ^b	11.55 ± 0.34 ^a
DE 15	7.41 ± 0.22 ^b	6.61 ± 0.16 ^c	6.59 ± 0.19 ^{cd}	6.32 ± 0.32 ^e	6.51 ± 0.16 ^d	8.42 ± 0.37 ^a

Note: Values are expressed as mean ± standard deviation; different letters within the same row indicate significant differences ($p < 0.05$).

2.3.2. Influence on Steady-State Rheological Properties of the Emulsion

Steady-state rheological analysis examines the relationships between shear rate and viscosity, as well as between shear rate and shear stress, thereby providing insights into the physical properties and stability of emulsion systems. The shear rate–viscosity curves of emulsions containing pre-hydrolyzed rice extrudates with different DE values are shown in Figure 3. As the shear rate increased, the viscosities of all emulsions initially decreased and then reached a plateau. The initial reduction in viscosity may be attributed to the combined effects of Brownian motion and weak protein–protein or protein–lipid interactions, which are insufficient to counteract the increasing shear forces. Consequently, the resistance of emulsion droplets to shear decreases [20], and the droplets become more aligned under the applied flow field, leading to a reduction in viscosity [21].

The fluidity of the emulsion is a key factor affecting its clinical application. The shear rate–shear stress curves for emulsions containing pre-hydrolyzed rice extrudates with different DE values are shown in Figure 4. The flow curves of all emulsions showed a linear relationship between shear stress and shear rate, indicating Newtonian fluid behavior (i.e., constant viscosity independent of shear rate) [22]. The slope of these lines, representing the apparent viscosity, was found to be relatively low for most formulations. Notably, only the DE 0–12%, DE 0–15%, DE 2–12%, and DE 2–15% groups exhibited markedly higher viscosities. This prevalent low and constant viscosity endows the majority of the emulsions with excellent flowability and pipeline transport performance, which are critical advantages for the industrial production and clinical administration of FSMP.

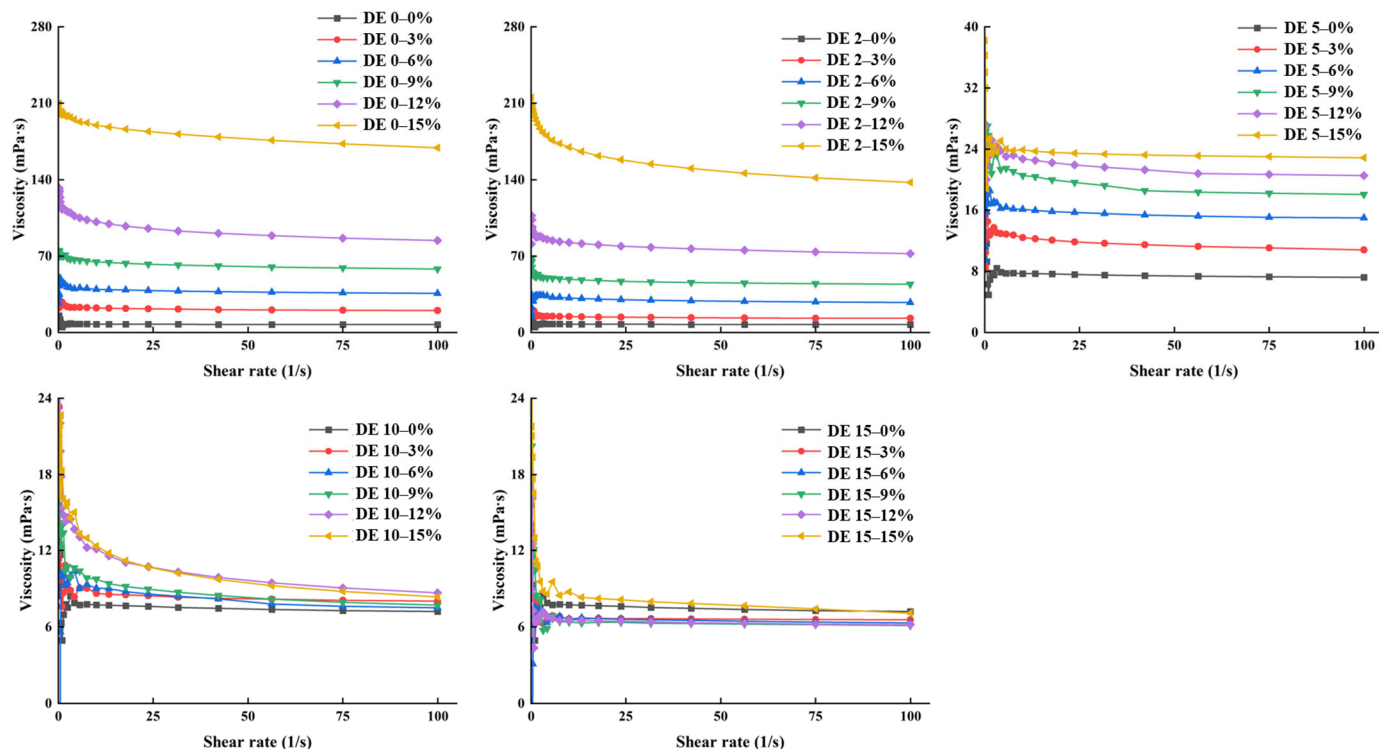


Figure 3. Curves of shear rate and viscosity of the emulsion with different DE values.

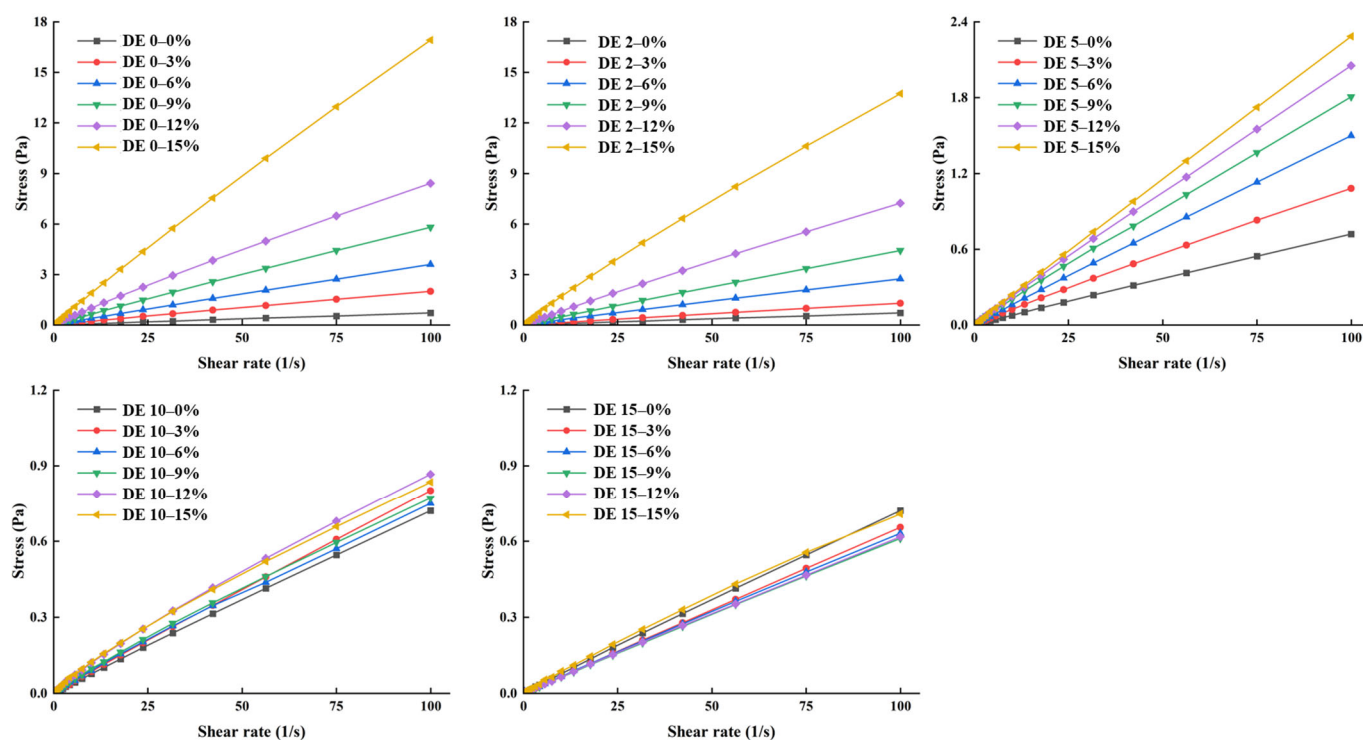


Figure 4. Curves of shear rate and shear stress changes in the emulsion with different DE values.

2.4. Effect of Pre-Hydrolyzed Rice Extrudates with Different DE Values on the Centrifugal Precipitation Rate of Emulsions

Centrifugal precipitation rate is an important indicator of the physical stability of emulsions, with lower values corresponding to higher stability [23]. Figure 5 shows the centrifugal precipitation rates of emulsions containing pre-hydrolyzed rice extrudates with different DE values. The results indicated that the centrifugal precipitation rates of

all emulsions gradually increased with the increase in the addition level of pre-hydrolyzed rice extrudates. At a 15% addition level, the centrifugal precipitation rates of emulsions containing DE 0, DE 2, DE 5, DE 10, and DE 15 rice extrudates were 7.60%, 12.06%, 10.38%, 11.95%, and 10.28%, representing increases of 3.29%, 5.81%, 4.86%, 5.75%, and 4.81%, respectively, when compared with that of maltodextrin emulsion. The relatively slower increase in the sedimentation rate observed in the DE 0 group may be attributed to its higher viscosity, when compared with those of the other groups. Furthermore, in the DE 0 group, interactions between gelatinized starch from the rice extrudate and casein might have promoted aggregation, thereby increasing the effective volume fraction of suspended particles and enhancing hindered settling and viscosity, ultimately reducing the centrifugal precipitation rate [24].

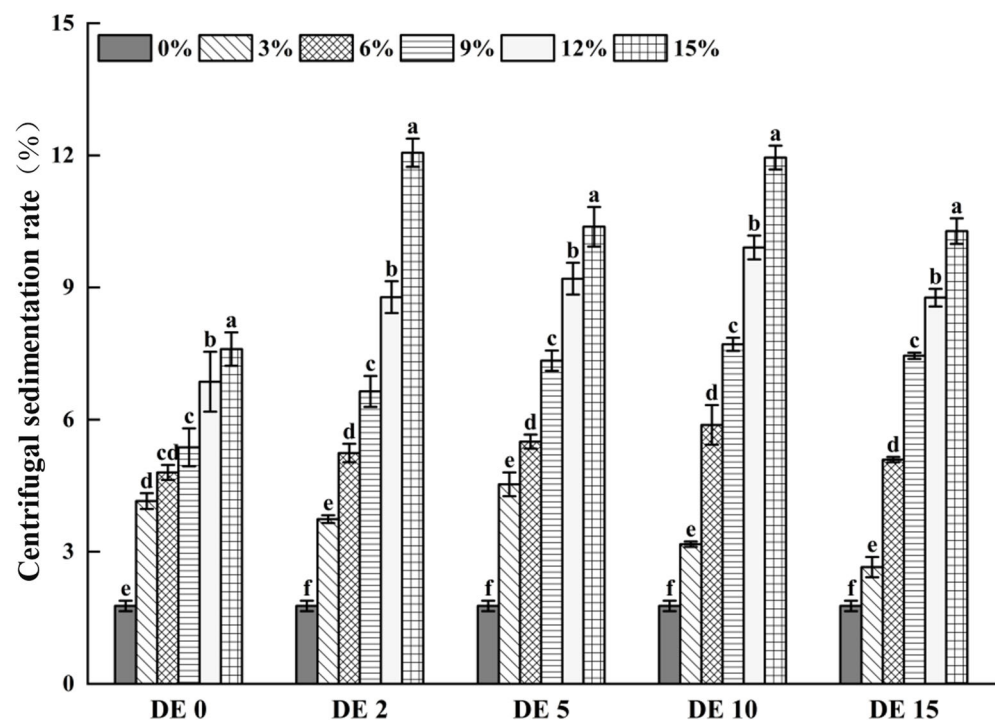


Figure 5. Centrifugal sedimentation rate as a function of DE values for the emulsion. Bars with different letters at the same DE value indicate significant differences ($p < 0.05$).

2.5. Effects of Pre-Hydrolyzed Rice Extrudates with Different DE Values on Turbidity and Absorbance Ratio of Emulsions

The turbidity of an emulsion is functionally related to the size and concentration of particles within the system [25]. Higher absorbance values at longer wavelengths indicate a greater presence of large particles in the emulsion. In addition, absorbance ratio analysis served as a rapid cross-validation and supplementary tool to laser diffraction particle size measurement (Section 2.1). This approach is based on Mie scattering theory: the scattering intensity of large particles exhibits weak dependence on wavelength (Mie regime), causing the absorbance ratio to approach unity. In contrast, scattering by small particles follows Rayleigh's law, showing high sensitivity to wavelength and thus yielding a lower ratio. Therefore, this ratio can indirectly reflect the particle size distribution characteristics of the system. As shown in Figure 6, the turbidity and absorbance ratio of emulsions containing pre-hydrolyzed rice extrudates with different DE values varied with the addition level. It can be observed from Figure 6a that turbidity increased with higher addition levels of pre-hydrolyzed rice extrudates across all DE groups. The DE 2–15% and DE 5–15%

emulsions exhibited the highest turbidity, suggesting a higher proportion of large particles. The absorbance ratios for all the samples (Figure 6b) ranged from 0.38 to 0.55, slightly exceeding the value (0.30) typically considered indicative of a stable emulsion in comparable systems [26]. Among all samples, the DE 0 emulsions exhibited generally higher absorbance ratios than the other groups, with the DE 0–12% group showing the highest value of 0.55. This indicates that the DE 0 emulsions contained a greater number of large particles, corresponding to the poorest physical stability. Similar trends were also observed in the particle size and zeta potential measurements, further supporting the destabilizing effect of low-DE rice extrudates at higher addition levels. It is noteworthy that turbidity (Figure 6a) and absorbance ratio (Figure 6b) exhibit distinct variation patterns, which can be attributed to their differing emphases in characterizing emulsion properties.

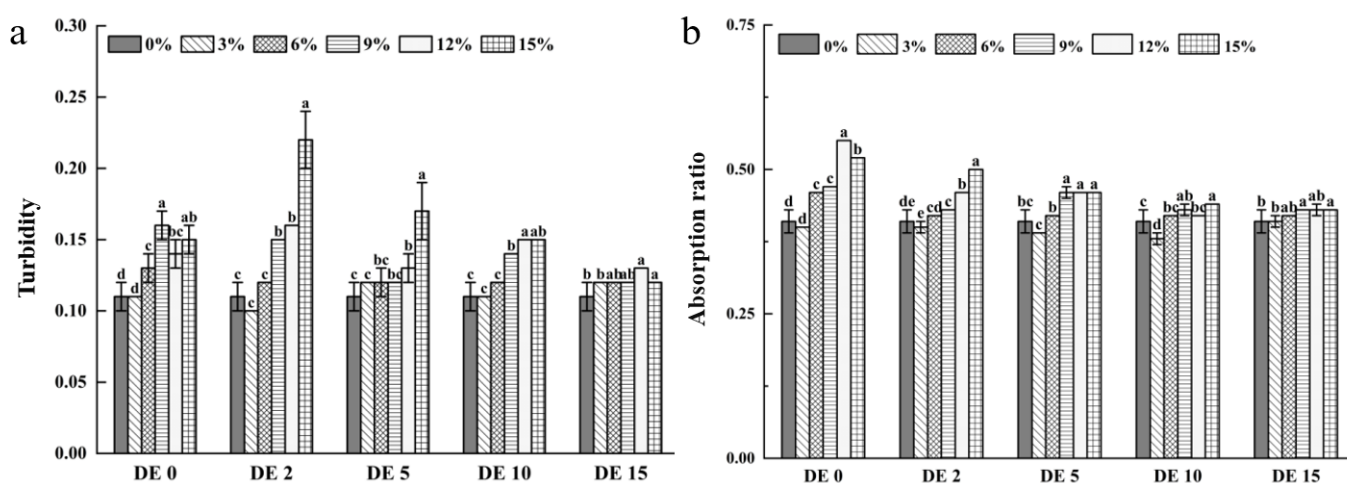


Figure 6. Turbidity (a) and absorbance ratio (b) as a function of DE value for the emulsion. Bars with different letters at the same DE value indicate significant differences ($p < 0.05$).

2.6. Multi-Weight Light Scattering Analysis of Emulsions Containing Pre-Hydrolyzed Rice Extrudates with Different DE Values

2.6.1. Effect on Turbiscan Stability Index of Emulsions

Emulsions (excluding microemulsions) are usually thermodynamically unstable systems in which droplets undergo Brownian motion and sediment under gravity, leading to various destabilization phenomena. The Turbiscan stability index (TSI) quantifies the rate of droplet movement within the emulsion, with higher TSI values indicating faster droplet migration and lower emulsion stability [27]. The TSI values of emulsions containing pre-hydrolyzed rice extrudates with different DE values are shown in Figure 7. Seven formulations—DE 0–9%, DE 2–9%, DE 2–12%, DE 5–12%, DE 5–15%, DE 10–3%, and DE 15–3%—exhibited relatively low TSI values, reflecting potentially better physical stability at these addition levels. However, notably, emulsions with low-DE rice extrudates at higher addition levels displayed improved stability, which contrasts with the results of zeta potential and centrifugal precipitation measurements. This discrepancy may be attributed to two factors: first, the higher viscosity of emulsions containing low-DE rice extrudates at elevated addition levels limits droplet movement, slowing their migration; second, the increased starch content in these emulsions may further restrict droplet mobility, thereby contributing to lower TSI values. Consequently, it should be noted that TSI measurements may underestimate the instability of highly viscous systems.

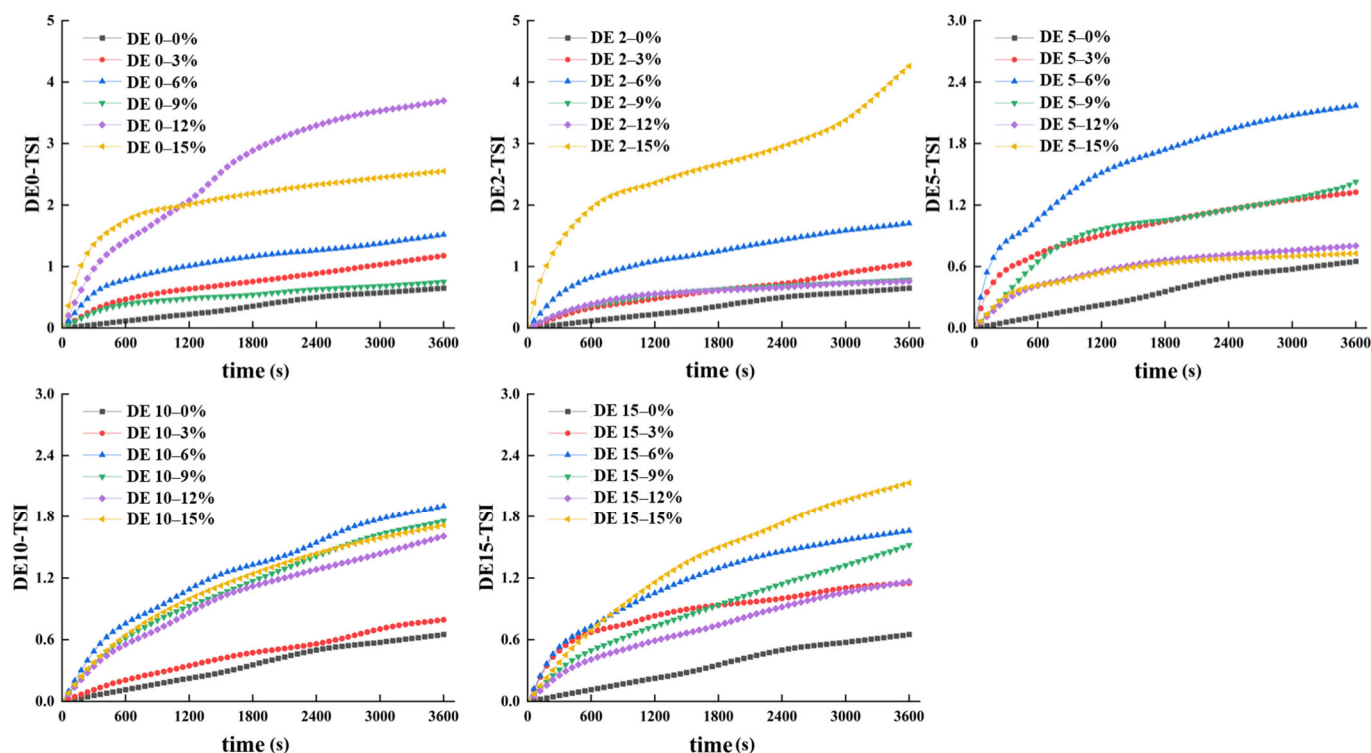


Figure 7. TSI as a function of DE values for the emulsion.

2.6.2. Effect on Backscattered Light of Emulsions

In multi-weight light scattering analysis, the backscattered light difference (ΔBS) provides a sensitive measure of emulsion stability. By monitoring ΔBS over repeated scans using a Turbiscan multiple light scattering instrument, it is possible to determine whether sedimentation, aggregation, or creaming occurs during storage, thereby reflecting the overall stability of the emulsion.

The backscattered light profiles of emulsions containing pre-hydrolyzed rice extrudates with different DE values are shown in Figures 8–12. In these plots, the curves from left to right correspond to the bottom, middle, and top regions of the emulsion, with the blue curve representing the first scan and the red curve denoting the final scan. It can be noted that the ΔBS values in the bottom region gradually increased during scanning for all samples. Emulsions formulated with high-DE rice extrudates exhibited greater ΔBS intensity, indicating more pronounced droplet sedimentation during storage. The DE 15–9% emulsion showed the highest ΔBS in the bottom region, reaching 7.00%. In contrast, the DE 0–12%, DE 0–15%, and DE 2–15% emulsions displayed a decrease in ΔBS at the top region of the emulsion, whereas the other samples showed an upward trend. The decrease in ΔBS at the top region of the emulsion indicated particle sedimentation, leading to the formation of a serum layer [28], consistent with the highest TSI values observed for these three samples. Conversely, the increase in ΔBS at the top region in the remaining samples reflected the upward movement of lighter fat droplets. In addition, all samples exhibited an overall decrease in ΔBS during scanning, to varying degrees. This phenomenon can be explained by the underlying optical mechanism: when droplets aggregate to form larger flocs, their light scattering pattern shifts, favoring forward scattering over backward scattering. As a result, the overall backscattered signal detected by the instrument decreases [29], indicating droplet aggregation and potential changes in particle size.

Taken together, these results demonstrate that the DE value significantly influences the destabilization patterns of the emulsions. Low-DE (high-viscosity) formulations, such

as DE 0–12% and DE 0–15%, primarily exhibit instability dominated by particle sedimentation and aggregation. In contrast, high-DE (low-viscosity) formulations, such as DE 15–9%, are more prone to the upward migration (creaming) of fat droplets.

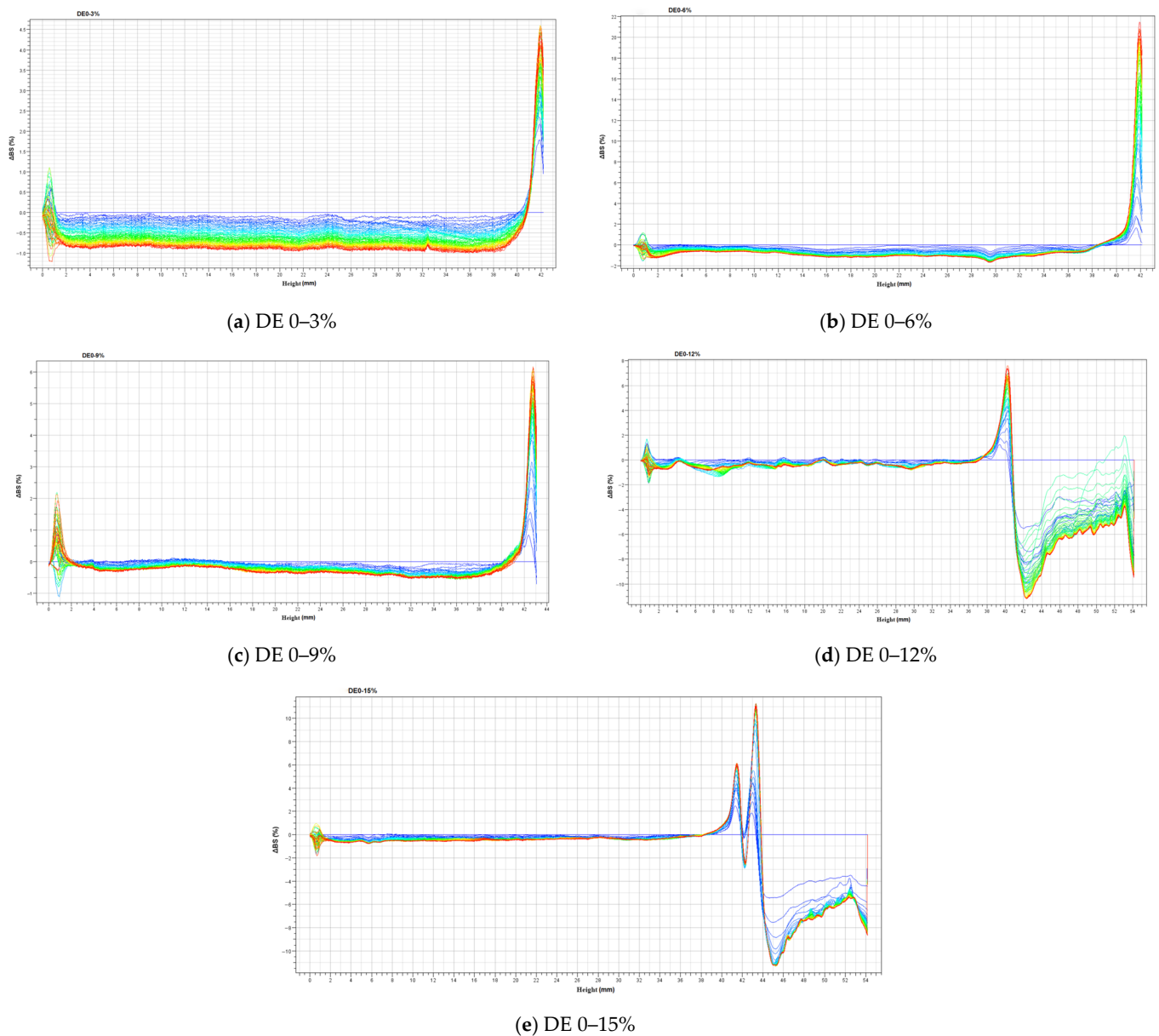


Figure 8. Backscattering (BS) profile of the native rice flour emulsion (DE 0). Blue: first scan. Red: final scan. Same for Figures 9–12.

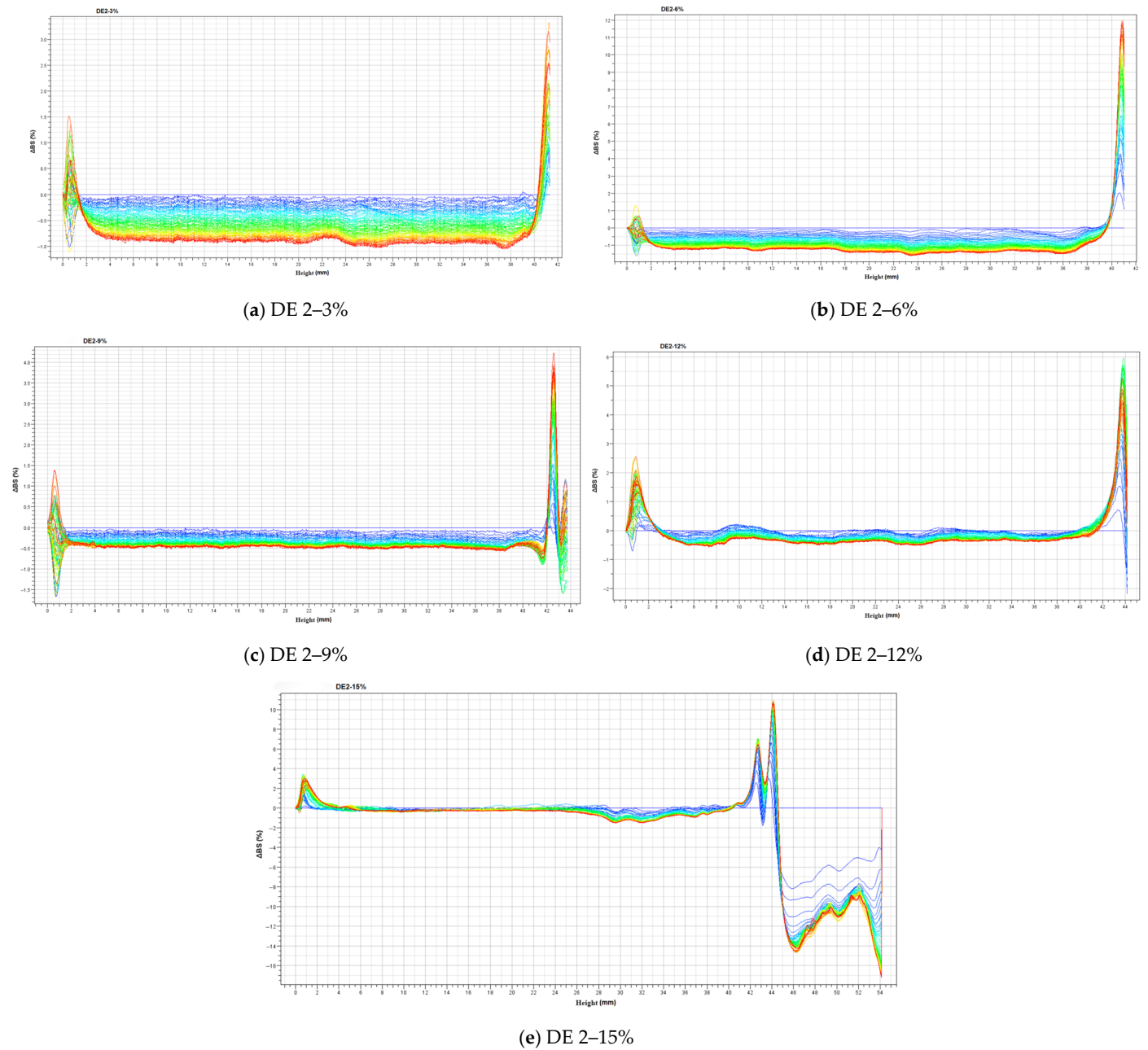
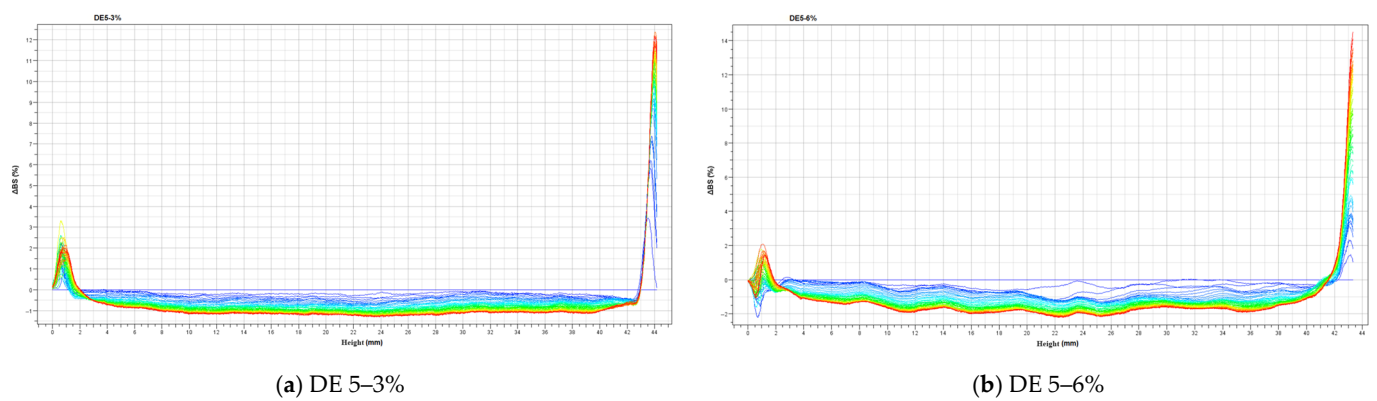


Figure 9. BS profile of the slightly hydrolyzed rice extrudate emulsion (DE 2).



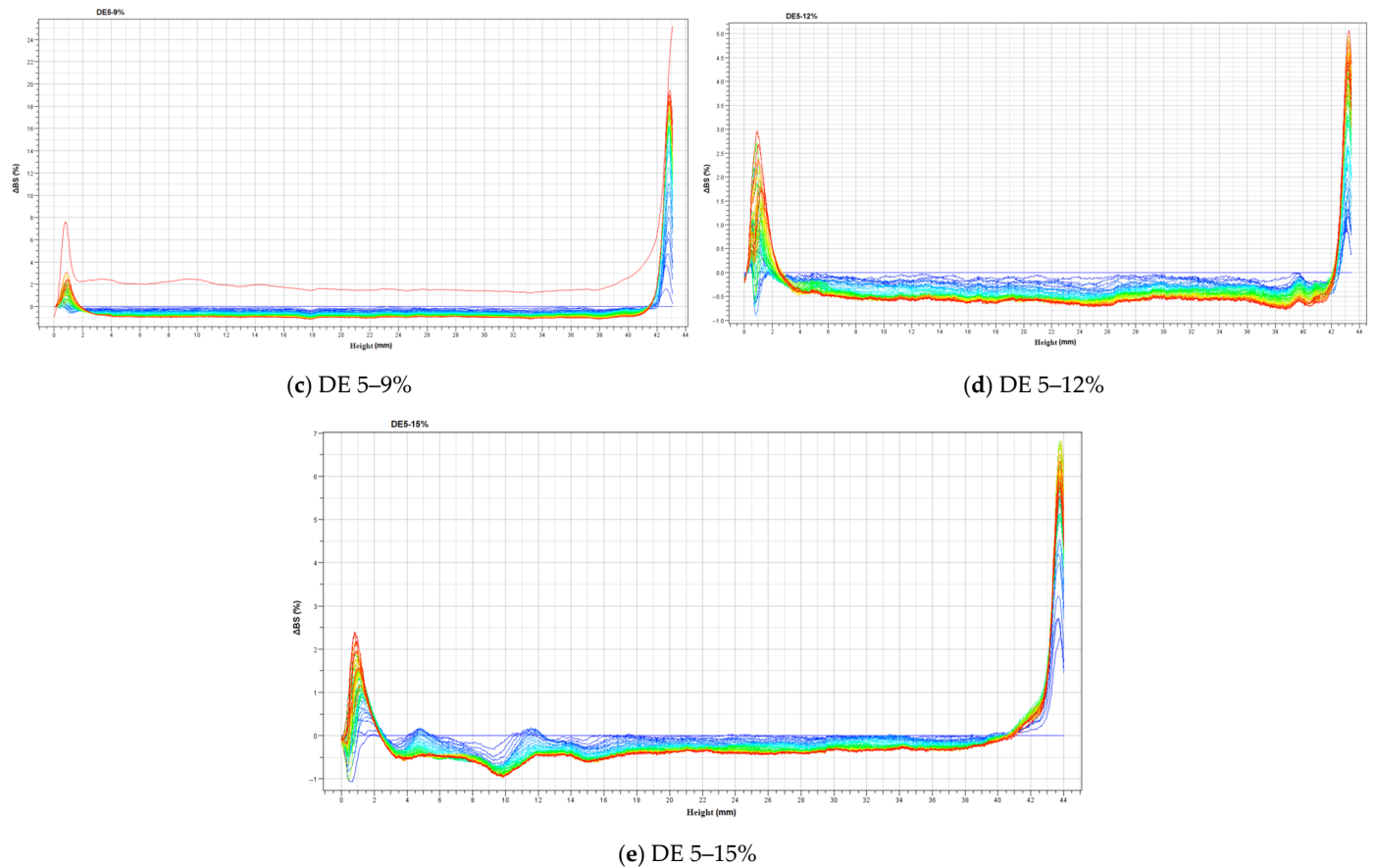
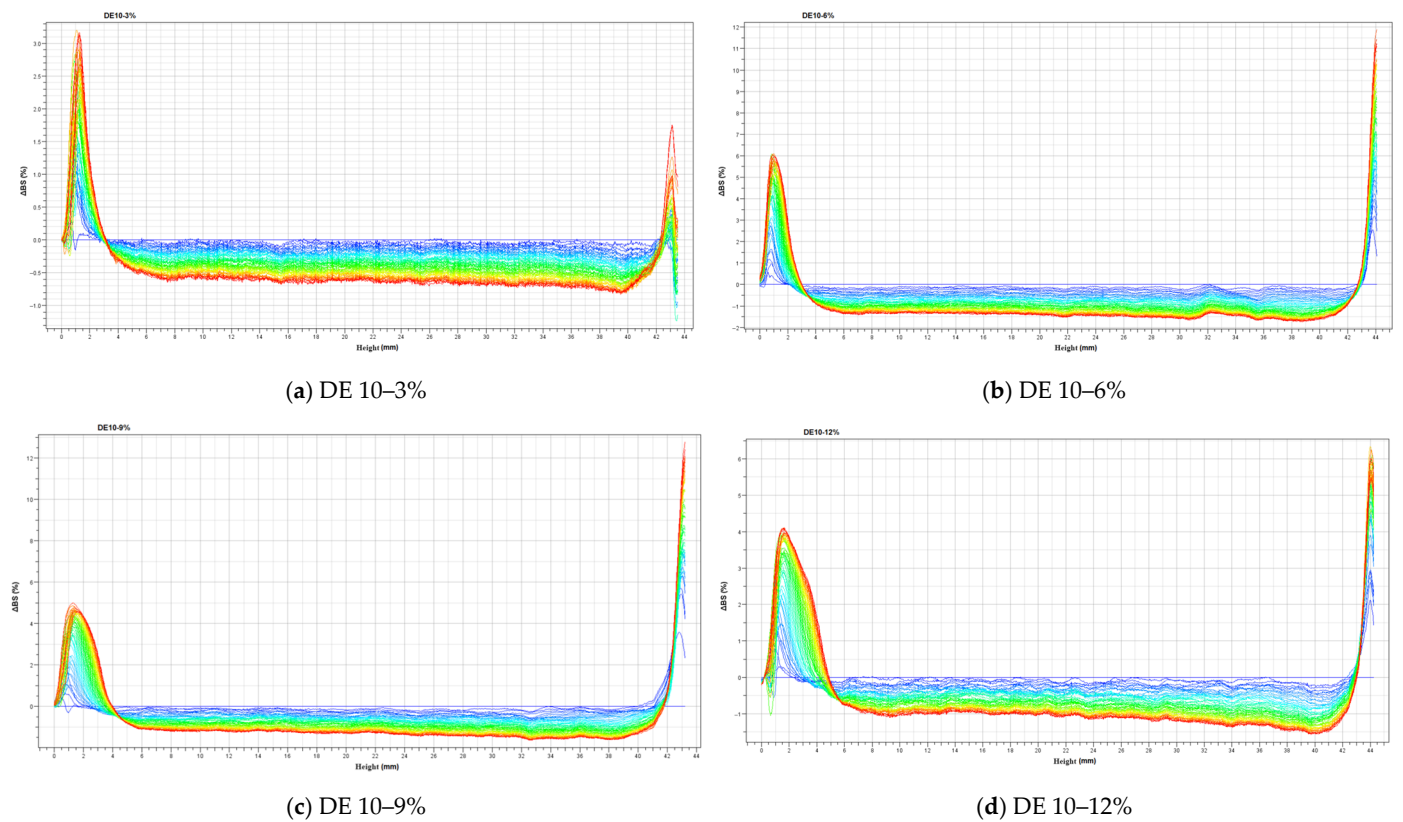
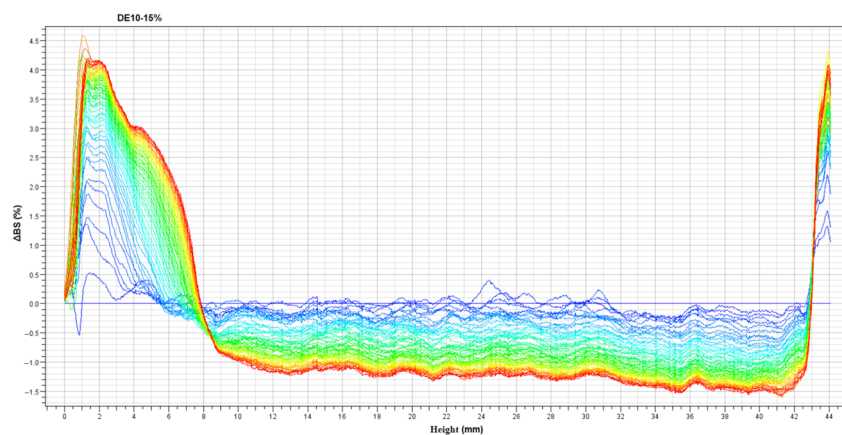
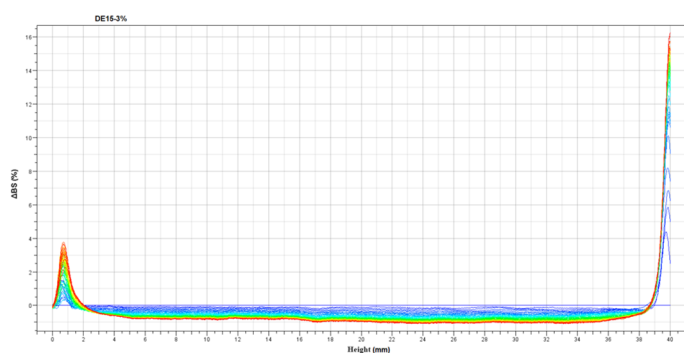


Figure 10. BS profile of the hydrolyzed rice extrudate emulsion (DE 5).

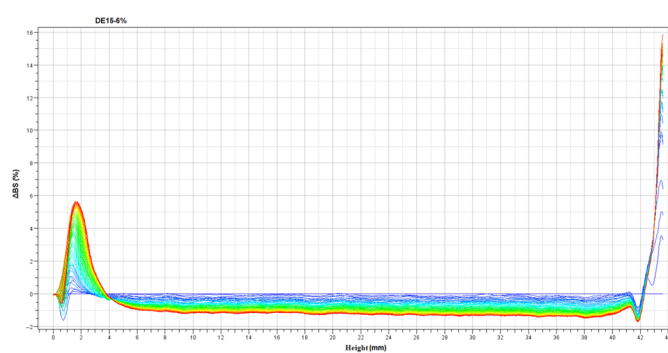




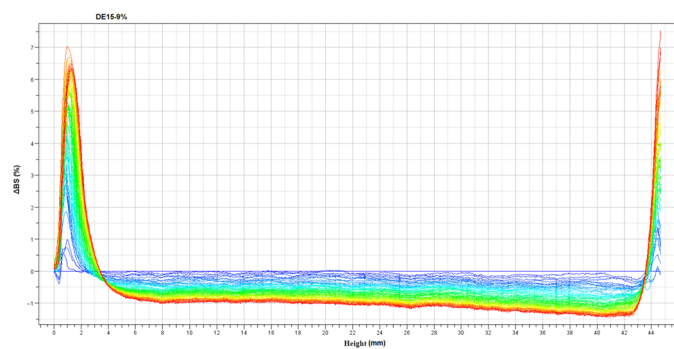
(e) DE 10–15%

Figure 11. BS profile of the hydrolyzed rice extrudate emulsion (DE 10).

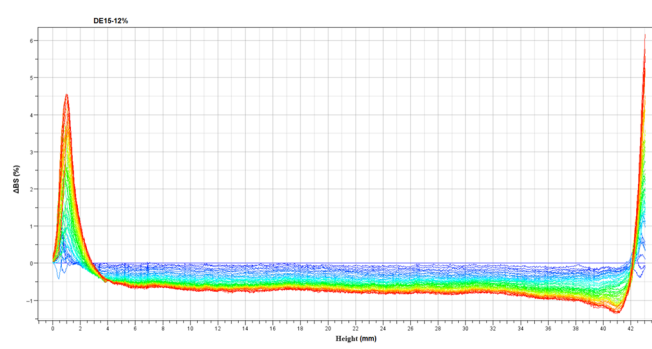
(a) DE 15–3%



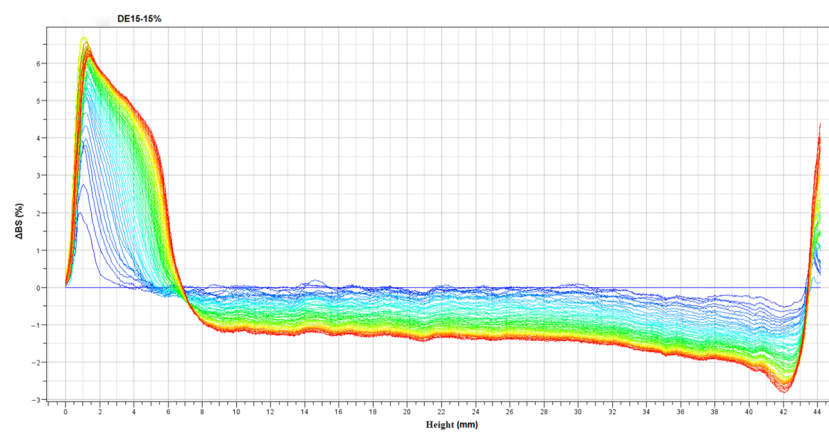
(b) DE 15–6%



(c) DE 15–9%



(d) DE 15–12%



(e) DE 15–15%

Figure 12. BS profile of the hydrolyzed rice extrudate emulsion (DE 15).

2.7. Multi-Index Comprehensive Evaluation of the Optimal Addition Level of Pre-Hydrolyzed Rice Extrudates in Emulsions

To determine the optimal addition level of pre-hydrolyzed rice extrudates with different DE values in emulsions, a multi-index comprehensive scoring method was employed to evaluate various emulsion parameters. The weight of each parameter was ascertained using the coefficient of variation (CV) method, which assigns weights based on the informational content of each parameter. This approach avoids the subjectivity of assigning weights manually and objectively reflects the relative importance of each parameter in assessing emulsion stability [30,31]. Seven parameters—particle size, zeta potential, viscosity, centrifugal precipitation rate, TSI, turbidity, and absorbance ratio—were selected for evaluation. The CV for each parameter was calculated to determine its contribution to the overall score. The mean, standard deviation, CV, and assigned weight for each parameter are summarized in Table 2.

Table 2. Weights of various evaluation indices for the emulsions with different DE values.

	MEAN	SD	CV	CW
particle size	1.17	0.39	0.33	0.13
zeta potential	−42.58	10.02	−0.24	−0.09
viscosity	37.07	48.60	1.31	0.50
centrifugal sedimentation rate	7.00	2.66	0.38	0.15
TSI	1.61	0.87	0.54	0.21
turbidity	0.14	0.02	0.18	0.07
absorbance ratio	0.44	0.04	0.09	0.03

The measured values were standardized, and the results are presented in Table 3. Since six of the parameters (all except zeta potential, which is positively correlated with stability—higher $|\zeta|$ indicates better stability) are negatively correlated with emulsion stability (i.e., lower values correspond to better stability), the standardized scores were assigned negative signs. These adjusted values were then multiplied by their corresponding parameter weights to obtain weighted scores for each indicator, and the sum of these values yielded the comprehensive stability score for each formulation (Table 4).

To facilitate visual comparison, the comprehensive scores of all emulsion groups were plotted (Figure 13), with higher scores indicating better emulsion stability. Formulations with a comprehensive score ≥ 0 were defined as “stable”, and from these, the addition levels with a score ≥ 0.35 (Dashed line) were selected as “optimal”. The comprehensive scores gradually decreased with increasing addition levels of pre-hydrolyzed rice extrudates. Notably, DE 0–12%, DE 0–15%, and DE 2–15% emulsions exhibited relatively low scores, indicating poor stability, which is consistent with the results of particle size, zeta potential, and centrifugal precipitation measurements. Based on the comprehensive score analysis, the optimal addition levels for each DE group were determined as follows: DE 0: $\leq 3\%$, DE 5: $\leq 9\%$, and DE 2, DE 10 and DE 15: $\leq 6\%$. These levels represent the optimal incorporation ranges for achieving stable emulsions when using pre-hydrolyzed rice extrudates with different DE values.

Table 3. The standardized values of various evaluation indices for the emulsion with different DE values.

Group	Particle Size	Zeta Potential	Viscosity	Centrifugal Sedimentation Rate	TSI	Turbidity	Absorbance Ratio
DE 0–3%	−1.31	−0.28	−0.31	−1.07	−0.49	−1.26	−1.05
DE 0–6%	−0.62	0.39	0.04	−0.83	−0.10	−0.31	0.60
DE 0–9%	−0.56	0.41	0.54	−0.61	−0.99	0.85	0.81
DE 0–12%	0.13	0.47	1.25	−0.05	2.40	−0.02	2.65
DE 0–15%	2.51	2.11	3.10	0.23	1.08	0.53	2.03
DE 2–3%	−1.13	−0.35	−0.47	−1.23	−0.64	−1.87	−1.07
DE 2–6%	−0.62	0.76	−0.13	−0.66	0.10	−1.00	−0.56
DE 2–9%	−0.23	0.75	0.23	−0.14	−0.95	0.63	−0.23
DE 2–12%	1.08	1.46	0.88	0.67	−0.98	1.02	0.59
DE 2–15%	2.38	1.72	2.67	1.90	3.05	4.08	1.39
DE 5–3%	−0.87	−0.16	−0.52	−0.93	−0.32	−1.23	−1.15
DE 5–6%	−0.51	0.39	−0.44	−0.56	0.64	−0.97	−0.50
DE 5–9%	−0.28	0.82	−0.35	0.13	−0.21	−0.97	0.41
DE 5–12%	0.28	0.76	−0.30	0.83	−0.93	−0.35	0.61
DE 5–15%	0.41	0.90	−0.28	1.27	−1.01	1.57	0.47
DE 10–3%	−0.82	−1.26	−0.59	−1.44	−0.94	−1.27	−1.54
DE 10–6%	−0.62	−1.08	−0.58	−0.42	0.34	−0.93	−0.50
DE 10–9%	0.05	−1.07	−0.58	0.27	0.17	−0.07	−0.31
DE 10–12%	0.46	−0.99	−0.53	1.09	0.00	0.35	−0.50
DE 10–15%	1.05	−0.92	−0.53	1.86	0.11	0.25	0.00
DE 15–3%	−1.26	−1.00	−0.63	−1.64	−0.53	−1.25	−0.82
DE 15–6%	−0.54	−1.01	−0.63	−0.72	0.06	−1.03	−0.62
DE 15–9%	0.05	−0.96	−0.63	0.17	−0.10	−1.07	−0.18
DE 15–12%	0.41	−0.96	−0.63	0.67	−0.51	−0.72	−0.36
DE 15–15%	0.82	−0.89	−0.59	1.23	0.61	−0.80	−0.21

Table 4. The scores of various evaluation indices for the emulsions with different DE values.

Group	Particle Size	Zeta Potential	Viscosity	Centrifugal Sedimentation Rate	TSI	Turbidity	Absorbance Ratio	Composite Scores
DE 0–3%	−0.17	0.03	−0.16	−0.16	−0.10	−0.09	−0.03	0.69
DE 0–6%	−0.08	−0.04	0.02	−0.12	−0.02	−0.02	0.02	0.24
DE 0–9%	−0.07	−0.04	0.28	−0.09	−0.21	0.06	0.02	0.05
DE 0–12%	0.02	−0.04	0.64	−0.01	0.50	0.00	0.08	−1.19
DE 0–15%	0.33	−0.19	1.58	0.03	0.23	0.04	0.06	−2.08
DE 2–3%	−0.15	0.03	−0.24	−0.18	−0.14	−0.13	−0.03	0.84
DE 2–6%	−0.08	−0.07	−0.07	−0.10	0.02	−0.07	−0.02	0.38
DE 2–9%	−0.03	−0.07	0.12	−0.02	−0.20	0.04	−0.01	0.17
DE 2–12%	0.14	−0.13	0.45	0.10	−0.21	0.07	0.02	−0.44
DE 2–15%	0.31	−0.15	1.36	0.29	0.64	0.29	0.04	−2.77
DE 5–3%	−0.11	0.01	−0.26	−0.14	−0.07	−0.09	−0.03	0.69
DE 5–6%	−0.07	−0.04	−0.22	−0.08	0.14	−0.07	−0.02	0.36
DE 5–9%	−0.04	−0.07	−0.18	0.02	−0.04	−0.07	0.01	0.37
DE 5–12%	0.04	−0.07	−0.15	0.12	−0.20	−0.02	0.02	0.26
DE 5–15%	0.05	−0.08	−0.14	0.19	−0.21	0.11	0.01	0.07
DE 10–3%	−0.11	0.11	−0.30	−0.22	−0.20	−0.09	−0.05	0.84
DE 10–6%	−0.08	0.10	−0.30	−0.06	0.07	−0.07	−0.01	0.35
DE 10–9%	0.01	0.10	−0.29	0.04	0.04	0.00	−0.01	0.13

DE 10–12%	0.06	0.09	−0.27	0.16	0.00	0.02	−0.02	−0.05
DE 10–15%	0.14	0.08	−0.27	0.28	0.02	0.02	0.00	−0.27
DE 15–3%	−0.16	0.09	−0.32	−0.25	−0.11	−0.09	−0.02	0.86
DE 15–6%	−0.07	0.09	−0.32	−0.11	0.01	−0.07	−0.02	0.49
DE 15–9%	0.01	0.09	−0.32	0.03	−0.02	−0.07	0.01	0.31
DE 15–12%	0.05	0.09	−0.32	0.10	−0.11	−0.05	0.01	0.25
DE 15–15%	0.11	0.08	−0.30	0.18	0.13	−0.06	0.01	−0.14

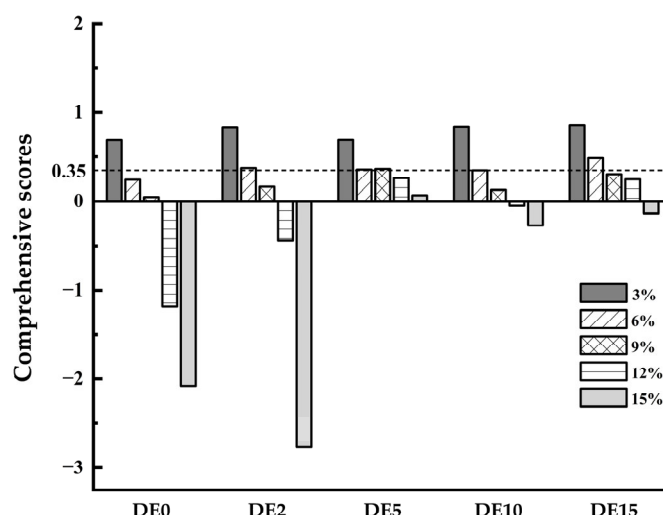


Figure 13. Comprehensive scores of the emulsion with different DE values.

3. Conclusions

The stability of emulsions containing pre-hydrolyzed rice extrudates with different DE values was systematically investigated. Emulsion stability gradually decreased with increasing rice extrudate addition levels. Steady-state rheological measurements indicated that all emulsions behaved as Newtonian fluids without shear-thinning, exhibiting good flowability. The Δ BS analysis further revealed that all emulsions underwent varying degrees of sedimentation, aggregation, or creaming during storage. A comprehensive evaluation approach, with indicator weights determined using the CV method, demonstrated that the overall stability scores progressively declined with higher addition levels of pre-hydrolyzed rice extrudates. Based on these scores, the optimal addition levels for maintaining desirable emulsion stability were determined to be as follows: $\leq 3\%$ for DE 0, $\leq 9\%$ for DE 5, and $\leq 6\%$ for DE 2, DE 10 and DE 15. Notably, the CV weighting method employed in this study is an objective weighting approach, where the assignment of weights is entirely dependent on the dispersion of each parameter within the sample dataset. In this study, the viscosity parameter accounted for approximately 50% of the total weight, reflecting the greatest variability in viscosity values among the different formulations. While this objectively captures the primary source of variation in the data, it may also imply that the comprehensive scoring model is more sensitive to changes in the rheological properties of the formulations. Future studies could consider integrating subjective and objective weighting methods (e.g., AHP-CV combined weighting). Overall, these findings provide a practical guideline for the targeted application of pre-hydrolyzed rice extrudates as a functional alternative to maltodextrin in emulsion-based FSMP formulations.

4. Materials and Methods

4.1. Materials

Indica rice was provided by Guangdong Haina Agriculture Co., Ltd. (Huizhou, China). Soybean oil was obtained from COFCO Fortune Food Marketing Co., Ltd. (Tianjin, China). Sodium caseinate (CN-EM7) was supplied by Develing International Trading (Shanghai, China) Co., Ltd. Maltodextrin (DE 15) was purchased from Shandong Xiwang Sugar Industry Co., Ltd. (Zouping, China). Food-grade thermostable α -amylase (150,000 U/mL) was acquired from Ningxia Sunson Industry Group Co., Ltd. (Yinchuan, China). All other reagents were of analytical grade and sourced from domestic suppliers.

4.2. Preparation of Pre-Hydrolyzed Rice Extrudates

Pre-hydrolyzed rice extrudates were prepared following the method of Zeng et al. [32] with slight modifications. Rice flour (100 mesh) was treated with thermostable α -amylase at activity levels of 0, 250, 500, 750, and 1000 U/g. The enzyme solutions were uniformly sprayed onto the flour, and the mixtures were pre-hydrolyzed at 95 °C for 25 min. Subsequently, the mixtures were extruded using a twin-screw extruder (FMHE36-24, Hunan Fumach Foodstuff Engineering and Technology Co., Ltd., Changsha, China) under the following conditions: an outlet temperature of 160 °C, a screw speed of 200 rpm, a feed rate of 16 kg/h, and a moisture content of 15%. After achieving steady extrusion, the extrudates were collected, dried at 50 °C for 3 h, ground to 100 mesh, and analyzed for their DE values (Table 5). All the extrudates were sealed and stored at 4 °C until further use.

Table 5. DE value determination results and sample naming.

Enzyme Dosage (U/g)	DE Value	Sample Designation
0	0.66 ± 0.01 ^e	DE 0
250	2.23 ± 0.22 ^d	DE 2
500	5.27 ± 0.35 ^c	DE 5
750	11.02 ± 0.46 ^b	DE 10
1000	15.97 ± 1.13 ^a	DE 15

Note: Different letters within the same column indicate significant differences ($p < 0.05$, $n = 3$).

4.3. Determination of DE Values

The DE value, defined as the ratio of reducing sugar content to total solids, was determined as follows. Reducing sugar content was measured according to the method of Kapoor et al. [33] with slight modifications. In brief, 2.00 g of pre-hydrolyzed rice extrudate were placed in a 50 mL centrifuge tube, mixed with 30 mL of deionized water, and shaken at 200 rpm for 30 min at room temperature. The suspension was then centrifuged at 4000 rpm for 10 min, and the supernatant was adjusted to 50 mL with deionized water. Reducing sugar content was quantified using the 3,5-dinitrosalicylic acid (DNS) colorimetric method. Total solids content was measured according to the direct drying method described in GB 5009.3—2016 Determination of moisture in foods, China [34].

The DE value was calculated as:

$$\text{DE} = \frac{\text{the reducing sugar content}}{\text{the total solid content}} \times 100\% \quad (1)$$

4.4. Preparation of the Emulsion

Emulsions were prepared according to the method of Liu et al. [35] with slight modifications. The control emulsion was formulated with 15% maltodextrin, 4% casein, 3%

soybean oil, and deionized water. In the treatment groups, maltodextrin was partially replaced with pre-hydrolyzed rice extrudates to ensure that the total carbohydrate content remained constant. The addition levels of pre-hydrolyzed rice extrudates in the emulsions were 3%, 6%, 9%, 12%, and 15%, and the samples were designated as DE x-3%, DE x-6%, DE x-9%, DE x-12%, and DE x-15%, respectively, where x denotes the DE value of the extrudates. For emulsion preparation, all the ingredients were pre-mixed and homogenized (T25, IKA Works GmbH & Co. KG, Staufen, Germany) at 10,000 rpm for 10 min at room temperature, followed by two cycles of high-pressure homogenization (SHP-60, Antos Nano Technology Co., Ltd., Suzhou, China) at 25 MPa. The resulting emulsions were sterilized at 121 °C for 15 min in an autoclave to obtain the final samples.

4.5. Emulsion Characterization

4.5.1. Particle Size and Zeta Potential

The particle size of the emulsions was determined using a laser particle size analyzer (Bettersize 2600, Bettersize Instruments Ltd., Dandong, China) at 25 °C, according to the method of Sui et al. [36] with slight modifications. The refractive indices were set to 1.330 for the aqueous phase and 1.456 for the oil phase (soybean oil). Emulsion samples were introduced to the sample cell until the obscuration reached 10–15%. Each sample was measured automatically in triplicate, and the mean value was recorded.

Zeta potential was determined using a laser particle size analyzer (Zetasizer Nano ZS90, Malvern Instruments Ltd., Worcestershire, Malvern, UK), following Tekin et al. [37] with appropriate modifications. Prior to evaluation, emulsions were diluted 100-fold with distilled water, and 1 mL of the diluted sample was injected into the sample cell. Measurements were performed at 25 °C with an equilibration time of 120 s. Each sample was analyzed in triplicate, and the mean value was reported.

4.5.2. Rheological Properties

The viscosity and steady-state rheological properties of the emulsions were assessed using a rheometer (AR-1500ex, TA Instruments Inc., New Castle, DE, USA). A 1.5 mL emulsion sample was loaded onto the sample stage and analyzed using a 40 mm parallel plate geometry at 25 °C, with a gap distance of 1 mm. After equilibration for 60 s, measurements were performed either at a constant shear rate of 10 s^{−1} (averaged over 30 points) or under a shear rate ramp from 0 to 100 s^{−1} to record variations in viscosity and shear stress.

4.5.3. Centrifugal Precipitation Rate

The centrifugal precipitation rate was determined according to Liu [35] with slight modifications. In brief, 10 g of emulsion sample (m_0) was weighed into a 15 mL centrifuge tube (Wuxi NEST Biotechnology Co., Ltd., Wuxi, China) and centrifuged at 5000 rpm for 15 min. After centrifugation, the supernatant was discarded, and the precipitate was weighed (m_1). The sedimentation rate was calculated as:

$$\text{Centrifugal sedimentation rate (\%)} = \frac{m_1}{m_0} \times 100 \quad (2)$$

4.5.4. Turbiscan Stability Analysis

The stability of the emulsions was evaluated using a multiple light scattering analyzer (Turbiscan Lab, LDS Technology Co., Ltd., Beijing, China). A 20 mL emulsion sample was transferred to a cylindrical glass cell, and measurements were performed at 25 °C. The sample was scanned at 60 s intervals, and both the TSI and backscattering intensity were recorded over a total scanning period of 3600 s.

4.5.5. Turbidity and Absorbance Ratio

The turbidity and absorbance ratio of the emulsions were determined according to Dłuzewska et al. [38] with minor modifications. Emulsion samples were diluted 500-fold with distilled water, and the absorbance was measured at 400, 660, and 800 nm using a UV–Vis spectrophotometer (Implen GmbH, Munich, Germany). The absorbance at 660 nm was employed to quantify turbidity, whereas the absorbance ratio (A_{800}/A_{400}) was used to assess emulsion stability.

4.6. Multi-Parameter Assessment for Optimizing the Addition Level of Pre-Hydrolyzed Rice Extrudates in Emulsion Formulations

A comprehensive evaluation score was calculated for each emulsion based on multiple indicators, including particle size, zeta potential, viscosity, centrifugal precipitation rate, TSI, turbidity, and absorbance ratio. The weights for these indicators in the overall score were determined using the CV method, and the CV was calculated as follows:

$$V_i = \frac{\sigma_i}{\bar{x}_i} \quad (3)$$

where V_i represents the coefficient of variation for the i -th indicator, σ_i denotes the standard deviation of the i -th indicator, and $\bar{x}_i$ is the mean value of the i -th indicator.

The weight ω_i for each indicator was determined as follows:

$$\omega_i = \frac{V_i}{\sum_{i=1}^n V_i} \quad (4)$$

To ensure comparability among indicators, each measurement was normalized as follows:

$$Z_{ij} = \frac{x_{ij} - \bar{x}_i}{\sigma_i} \quad (5)$$

where Z_{ij} represents the standardized value of the j -th sample for the i -th indicator, and x_{ij} denotes the actual measured value of the i -th indicator for the j -th sample.

Finally, a comprehensive evaluation score for each emulsion was ascertained as follows:

$$\text{Comprehensive evaluation score} = \sum_{i=1}^n \omega_i Z_{ij} \quad (6)$$

4.7. Data Statistics and Analysis

Data are presented as mean $\pm$ standard deviation from three independent replicates. Statistical analyses were performed using one-way analysis of variance (ANOVA) using SPSS 21.0 software, followed by Duncan's multiple range test for post hoc comparison. Differences were considered statistically significant at $p < 0.05$. The different lowercase letters in figures and tables denote significant differences at $p < 0.05$.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author due to containing information that could compromise the commercial interests and proprietary technology of the research partners.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DE	Dextrose equivalent
TSI	Turbiscan stability index
FSMP	Food for Special Medical Purposes
CV	Coefficient of variation

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