Online Version: http://journal.ipb.ac.id/index.php/jtip
https://doi.org/10.6066/jtip.2026.37.3.228
Research Article

Jurnal Teknologi dan Industri Pangan/Journal of Food Technology and Industry
Vol. 37(3): 228-243 Th. 2026 ISSN: 1979-7788
Terakreditasi Kemdiktisaintek: 295/C/C3/KPT/2026

Check for updates

Physical Stability and Carotenoid Retention of a Pasteurized Red Palm Oil Emulsion Beverage during Storage

Ummi Halimah Rahmatika[1)], Vallerina Armetha[2,3)], Nur Wulandari[3,4)]*

[1)] Food Science Study Program, Faculty of Engineering and Technology, IPB University, Bogor, Indonesia
[2)] Division of Chemical Engineering, Design, and Smart Manufacture, Faculty of Engineering and Technology, IPB University, Bogor, Indonesia
[3)] Division of Food Science and Technology, Faculty of Engineering and Technology, IPB University, Bogor, Indonesia
[4)] South East Asia Food and Agricultural Science and Technology (SEAFAST) Center, IPB University, Bogor, Indonesia

Received January 20th 2026 / Revised October 16th 2026 / Accepted October 23rd 2026

ABSTRACT

Red palm oil (RPO) is a rich natural source of carotenoids (500–700 ppm) and is a promising ingredient in functional beverages to increase provitamin A intake and support the prevention of vitamin A deficiency. Thermal pasteurization and storage may affect emulsion stability and carotenoid retention, which are critical for product quality and nutritional efficacy of functional beverages. This study aimed to examine the effects of pasteurization and storage on the physical stability and carotenoid preservation of RPO emulsion beverages. The emulsion was formulated using 10% (w/w) of RPO and 4% (w/w) of whey protein concentrate (WPC) as an emulsifier, followed by rotor-stator homogenization. Pasteurization was performed by a batch thermal process at 65 °C for 30 min. The product was stored for 21 days at room temperature (±25 °C) and refrigerator (13±3 °C). The pasteurized RPO emulsion beverage exhibited particle size (D90) of 13.888±0.740 µm, zeta potential values between (−17) and (−14) mV, and carotenoid content of 30.62±2.37 mg/kg. The pasteurization increased viscosity by 2.6-fold and centrifugal creaming index by 22.82%, while oil globule morphology remained structurally intact. During storage, the emulsion beverage maintained good physical stability at both storage temperatures, with particle size (D90) of 13–16 µm and zeta potential values between (−15) and (−11) mV. Carotenoid retention remained high under refrigerated storage (27.10±1.41 mg/kg), but decreased by 17.22% at room temperature. Thus, the formulated RPO emulsion beverage maintained good physical stability and carotenoid retention, especially under refrigerated storage, highlighting its promise as a functional provitamin A beverage.

Keywords: carotenoid, functional emulsion beverage, pasteurization, physical stability, red palm oil

INTRODUCTION

Vitamin A deficiency remains a major public health concern in many developing countries, including Indonesia, where limited access to animal-based foods and fortified products continues to compromise adequate micronutrient intake (Kemenkes RI, 2020). Adequate vitamin A is essential for maintaining normal vision, supporting red blood cell production, and regulating multiple physiological functions critical to human health (Kemenkes RI, 2023). However, Indonesia possesses substantial potential to address vitamin A deficiency through the utilization of plant-derived carotenoids as provitamin A sources, particularly from palm oil. According to the Indonesian Palm Oil Association (IPOA, 2025), Indonesian crude palm oil (CPO) production reached approximately 43 million tons by September 2025. An 11% increase compared to the same period in 2024 highlights the strategic availability of palm-based resources. One of the high value derivatives of CPO is red palm oil (RPO) (BPS, 2023), which contains exceptionally high carotenoid content (500–700 ppm) (Choo, 1994; Gao *et al.,* 2023). Among these, *β*-carotene is the predominant compound and exhibits the highest vitamin A activity (Elvira-Torales *et al.*, 2019), as it is enzymatically converted in the human body into two molecules of all-trans-retinal, (Kim *et al.*, 2021). Therefore, RPO represents a highly promising and sustainable alternative source of provitamin A. Red palm oil undergoes degumming, neutralization, and deodorization processes, but it has not undergone a bleaching process, so the red color is retained (Hasibuan *et al.*, 2021). Red palm oil is also obtained from fractionation process where olein fraction of CPO become ready-to-consume RPO (Dewi *et al.,* 2023).

*Corresponding Author: E-mail: wulandari_n@apps.ipb.ac.id

Copyright © 2026 by Authors, published by Journal of Food Technology and Industry
This is an open-access article distributed under the CC BY-SA 4.0 License
https://creativecommons.org/licenses/by-sa/4.0/

Despite its nutritional potential, the direct application of RPO into beverage products remains technologically challenging due to its immiscibility with water, which severely limits its application in aqueous food systems. Therefore, an oil-in-water (O/W) emulsion is needed as a carrier system. An emulsion consists of a dispersed oil phase uniformly distributed within a continuous aqueous phase and stabilized by an emulsifier possessing both hydrophobic and hydrophilic moieties that enable interfacial adsorption and droplet stabilization (Hisprastin & Nuwarda, 2018). Emulsification of RPO in an emulsion matrix not only improves its dispersibility in the beverage but also provides protection for bioactive compounds, including carotenoids, against environmental factors, such as light and oxygen (Niakousari *et al.*, 2018). However, emulsions are inherently thermodynamically unstable systems, and their stability is strongly influenced by formulation parameters, including the oil-water ratio, pH, temperature, and the type and concentration of emulsifier (Margono *et al*., 2022).

Destabilization phenomena such as creaming, flocculation, coalescence, sedimentation, and phase separation may occur during processing and storage of emulsion, compromising product quality (Hu *et al*., 2017). The tendency of emulsion destabilization is commonly accessed using physical indicators such as particle size, creaming index, and microstructural characteristics of dispersed oil globules. In general, emulsions with smaller particle sizes exhibit greater kinetic stability, whereas larger particle sizes are more susceptible to destabilization, i.e., gravitational separation and coalescence (Pathania *et al*., 2018; Weiss *et al.,* 2009). In addition, environmental factors such as extreme pH conditions and elevated temperatures can further accelerate emulsion destabilization, highlighting the importance of robust formulation and process control in the development of stable RPO-based beverage systems (Ostbring *et al*., 2021; Sun *et al.*, 2023).

In the present research, RPO emulsion beverage was made using a combined emulsifier system consisting of Tween 80, soy lecithin, and whey protein concentrate (WPC) to increase the stability of RPO emulsion beverage. An acidic formulation and thermal pasteurization were applied to ensure microbial safety during storage (Soni & Brightwell, 2022). However, proteins are known to show reduced solubility and interfacial stability under acidic conditions (lower pH value), particularly near their isoelectric point, which may compromise their emulsifying performance (Niakousari *et al*., 2018).

To date, the stabilizing capability of WPC in acidified and pasteurized RPO emulsion systems has not been fully explored. Although Dianingsih *et al*. (2016) previously investigated the stability of an RPO emulsion beverage, their formulation differed from the present system and did not involve acidification and storage treatment. Moreover, research examining the physical characteristics and storage stability of acidified emulsion beverage systems subjected to pasteurization remains limited. Therefore, this study aimed to examine the physical properties and carotenoid retention of a pasteurized RPO emulsion beverage and to assess its stability during storage under different temperature conditions.

MATERIALS AND METHOD

Materials

Red palm oil with a carotenoid content exceeding 400 ppm was purchased from Carotino Sdn Bhd (Malaysia). Whey protein concentrate (WPC 80) was purchased from Fonterra Australia Pty Ltd (Australia). Food-grade Tween 80 was purchased from Matangi (India) and soy lecithin from Solea (Brazil). Commercial mango flavoring was purchased from PT Pondan Pangan Makmur Indonesia, citric acid from PT Golden Sinar Sakti, granulated sugar from PT Gula Putih Mataram, and demineralized drinking water from PT Sariguna Primatirta Tbk (Indonesia). For analytical purposes, n-hexane, acetone, and ethanol (analytical grade) (Merck, Germany). Distilled water and Milli-Q deionized water were processed at the IPB University Laboratory (Indonesia), while aquabidest was obtained from PT DKSH Laboratory (Indonesia).

Methods

The RPO emulsion beverage was produced using a rotor-stator homogenization method and pasteurized by a batch thermal process. The pasteurized product was then stored for 21 days under room temperature (±25 °C) and refrigerated conditions (10–15 °C). The effect of pasteurization and storage on emulsion beverage stability was periodically evaluated. Analytical measurements included pH, viscosity, physical stability (gravitational and centrifugal creaming), zeta potential, particle size, oil globules morphology, carotenoid content, and color.

Preparation of fresh RPO emulsion beverage

The RPO emulsion beverages were prepared using a two-phase formulation approach. The formulation represented as weight percentage (wt%) relative to the total weight of the final solution. The oil phase was composed of red palm oil (10 wt%), Tween 80 (0.05 wt%), and soy lecithin (2 wt%) as co-emulsifiers. The aqueous phase was composed of WPC (4 wt%) as an emulsifier, sugar (6 wt%) as a sweetener, mango flavoring (0.4 wt%), citric acid as an acidity regulator, and demineralized water. First, WPC was dispersed in demineralized water and

stirred at 750 rpm for 1 h at room temperature. To ensure complete hydration, the solution was stored in a refrigerator (4 °C) overnight (12–16 hours). Separately, the oil phase was prepared by mixing RPO, Tween 80, and soy lecithin, and stirring at 500 rpm for 15 min at room temperature. Sugar, citric acid, and mango flavoring were added to the hydrated WPC solution and stirred until fully dissolved. Next, the oil phase was gradually added to the water phase under continuous homogenization using a rotor-stator homogenizer (L4R, Silverson, England). Homogenization was performed sequentially at 10,000 rpm for 5 min, 14,000 rpm for 7 min, and 15,000 rpm for 6 min, with a 1-min resting interval between each speed stage to prevent an excessive temperature rise. The resulting emulsion beverage was then transferred to a glass beaker and immersed in a cooling water bath for 30 min to reduce its temperature and allow foam to rise to the surface. After that, the foam layer was carefully removed, yielding a fresh RPO emulsion beverage.

Pasteurization of RPO emulsion beverage

Freshly prepared RPO emulsion beverage was heated under continuous stirring using a magnetic hot plate until the temperature reached 82 °C and maintained for 1 min. The hot emulsion beverage was then aseptically filled into sterile 100 mL glass bottles fitted with aluminium caps and rubber seals, ensuring minimal headspace (hot aseptic filling). The capped bottles were tightly closed, wrapped with aluminium foil, and subjected to batch pasteurization in a water bath (1008, GFL, Germany) at 65 °C for 30 min. After pasteurization, the emulsion bottles were immediately cooled in water until they reached room temperature.

Storage of pasteurized RPO emulsion beverage

Pasteurized RPO emulsion beverages were stored for 21 days under room temperature (±25 °C) and refrigerated conditions (10–15 °C) (1-Door Refrigerator, LG, Indonesia). At the end of storage, the samples were manually shaken 30 times at an angle of 30–60° to redisperse oil droplets and maintain emulsion homogeneity (Rymaruk *et al*., 2020). This procedure was applied to simulate “shake well” instruction in commercial drink product for consumers before serving.

Characterization of RPO emulsion beverage

Fresh, pasteurized, and/or stored RPO emulsion beverages were characterized in terms of physicochemical and colloidal stability. Analysis included pH, viscosity, physical stability (gravitational and centrifugal creaming), zeta potential, particle size, the appearance of oil globules, color, and carotenoid content. Measurements were conducted at 7-day intervals during storage, except for particle size analysis, which was carried out on day 1 and day 15. Particle size was assumed not to change significantly when stored for short interval time, meanwhile other parameter tended to change faster.

pH measurement

The pH of the emulsion beverage was measured using a digital pH meter (PH 9500, Apera Instruments, China). First, pH meter was calibrated at pH 4 and pH 7 using buffer solutions. After calibration, the electrode was immersed directly into the sample, and readings were recorded after stabilization (Dari & Junita, 2020).

Viscosity and rheological analysis

Viscosity measurements were carried out using a rheometer (MCR 92, Anton Paar, Austria) equipped with a cone plate spindle (CP50) with an angle of 1°. The shear rate ranged from 0.1 to 1000 s^{-1} (Dekker *et al.,* 2022; Zhai *et al*., 2023). Viscosity values were determined at a shear rate of 100 s^{-1}. The shear stress data were used to calculate the flow behavior index (n), consistency index (K), and yield stress (τ_0) for rheological characterization.

Physical stability analysis

Gravitational stability was evaluated by monitoring the creaming during storage. Every 7 days, the volume of the unseparated emulsion layer was measured and expressed as a percentage of the total sample volume to determine the gravitational creaming index of the RPO emulsion beverage (Assar *et al*., 2023). Next, centrifugal stability was measured using a centrifuge (Universal 320R, Hettich, Germany) operated at 4000 rpm for 15 min at room temperature (25 °C). The height of the cream layer was measured and expressed as a percentage of the total sample height to obtain the centrifugal creaming index (Fadzilah *et al*., 2020).

Particle size and zeta potential analysis

Particle size analysis was carried out using Mastersizer 3000+ laser diffraction analyzer (Malvern, UK). The dispersing medium was initially analyzed with Mastersizer Xplorer software. After that, the standard operating procedure (SOP) was optimized to ensure measurement stability. The dispersant was stirred at 2000 rpm and samples were added until obscuration reached 5–15%. Measurements were conducted after 480 s of homogenization, with five repetitions of 10 s each. Results were presented as D[3,2], D[4,3], D10, D50, D90 and SPAN. Zeta potential was measured using Litesizer TM 500 particle size analyzer (Anton Paar, Austria). Samples were dispersed 400-fold with deionized water and transferred into a cuvette containing submerged electrodes. Measurements were recorded in millivolts (mV) (Raval *et al*., 2019).

Oil globules appearance analysis

The appearance of oil globules was observed using polarized microscope (CX31, Olympus, Japan) at 1000× magnification. A drop of sample was placed on a glass slide and covered with a coverslip. Micrographs of the oil globules were captured using a Sony Exmor CMOS Sensor (Japan) camera and analyzed using Betaview software (Dianingsih *et al*., 2016).

Color analysis

Color parameters (L*, a*, b*) were measured using a chromameter (CR-400, Konica Minolta, Japan). Samples were placed in a chroma container and analyzed using standard illumination (Li *et al*., 2023).

Carotenoid content analysis

Carotenoid extraction was performed by mixing 0.2 g of sample with 5.8 mL distilled water, 3 mL acetone, 3 mL n-hexane, and a few drops of ethanol. The mixture was vortexed for 1 min and centrifuged at 4000 rpm for 10 min at 5 °C. The hexane layer (upper layer) was collected and absorbance was measured at 450 nm using a UV-Vis spectrophotometer (UVmini-1240, Shimadzu, Japan) (Mohamad *et al.,* 2017; Szterk *et al.,* 2012). Carotenoid content was calculated using Equation 1 (Vinas-Ospino *et al*., 2023).

$$\text{Carotenoid content (mg/kg)} = \frac{A \times V \times 10000}{\varepsilon \times P} \quad \ldots\ldots\ldots (1)$$

A= the absorbance at 450 nm; V= the total extract volume (mL); ε= the extinction coefficient of *β*-carotene (2560); and P= the sample weight (g).

Statistical analysis

Samples were analyzed on days 0, 7, 14, and 21, with two experimental replicates for each storage condition (room and refrigerated). Each experimental replicate was determined in duplicate as technical replicates. Thus, a total 16 experimental units were evaluated and the statistical analysis was performed using Microsoft Excel 2019 and SPSS 25.0. Data normality was assessed prior to hypothesis testing. Parametric data were analyzed using independent sample t-tests to evaluate pasteurization effects on samples and factorial analysis of variance (ANOVA) followed by Tukey's post hoc test for storage effects with two factors which are storage time and storage temperature. Nonparametric data were analyzed using the Kruskal Wallis H test followed by the Mann-Whitney U test. Differences were considered statistically significant at $p<0.05$. In addition, data results were presented by mean ± standard deviation.

RESULTS AND DISCUSSION

The RPO emulsion beverage (Figure 1) showed a stable pH value of approximately 4.0 in both fresh and pasteurized samples, and no significant changes were observed during 21 days of storage under either room temperature or refrigerated condition. The formulation was intentionally adjusted to pH 4.0 to classify the emulsion beverage produced as an acidified food, thereby ensuring compliance with safety requirements for batch pasteurization. Acidification to this pH level is critical for inhibiting the growth of pathogenic microorganisms and enhancing microbial stability during storage (Hariyadi, 2019). The observed pH stability further indicates that the emulsion system was chemically stable and not susceptible to acid-base interactions, ingredient degradation, or microbial activity that could otherwise alter the hydrogen ion concentration (Mafe *et al*., 2024). These findings confirm that the selected formulation and thermal processing conditions were appropriate for maintaining physicochemical stability of the RPO emulsion beverage throughout the intended storage period.



Figure 1. Pasteurized red palm oil (RPO) emulsion beverage

Viscosity and rheological characteristics

Viscosity reflects the resistance of a fluid to flow under an applied shear force and is a critical parameter for assessing the texture and stability of emulsion-based beverages (Maheshwar, 2018). The viscosity of RPO emulsion beverage was determined at shear rate of 100 s^{-1}. Rheological analysis further enabled the determination of the flow behavior index (n), consistency index (K), and yield stress (τ_0) as summarized in Table 1. Pasteurization significantly increased the viscosity, consistency index (K), and yield stress (τ_0) of RPO emulsion beverage produced, while the flow behavior index (n) decreased ($p<0.05$), indicating a pronounced change in rheological behavior.

Table 1. Rheological characteristics of RPO emulsion beverage during storage

Sample	Viscosity (mPa.s)		Flow Behavior Index, *n*		Consistency Index, *K* (Pa.s^n)		Yield Stress, τ_0 (Pa)	
Fresh	4.4624±0.4158^x		0.9281±0.0255^x		0.0062±0.0012^x		0.0593±0.0109^x	
Pasteurized	Room temp	Refri temp	Room temp	Refri temp	Room temp	Refri temp	Room temp	Refri temp
Day 0	11.3974 ±0.2986^{Aay}	11.3974 ±0.2986^{Aay}	0.7292 ±0.0060^{Aay}	0.7292 ±0.0060^{Aay}	0.0372 ±0.0020^{Aay}	0.0372 ±0.0020^{Aay}	0.1867 ±0.0157^{Aay}	0.1867 ±0.0157^{Aay}
Day 7	9.0435 ±2.0509^{Aa}	9.8016 ±0.3355^{Aa}	0.8308 ±0.0389^{Aa}	0.7748 ±0.0129^{Aa}	0.0202 ±0.0075^{Aa}	0.0281 ±0.0024^{Aa}	0.1595 ±0.0533^{Aa}	0.0778 ±0.0119^{Aa}
Day 14	8.7768 ±0.9281^{Aa}	10.5680 ±0.5561^{Aa}	0.8570 ±0.0021^{Aa}	0.7695 ±0.0128^{Aa}	0.0160 ±0.0012^{Aa}	0.0315 ±0.0037^{Aa}	0.1745 ±0.0555^{Aa}	0.0539 ±0.0254^{Aa}
Day 21	11.3126 ±1.9783^{Aa}	10.5533 ±1.4817^{Aa}	0.7793 ±0.1087^{Aa}	0.7635 ±0.0407^{Aa}	0.0372 ±0.0223^{Aa}	0.0337 ±0.0107^{Aa}	0.0945 ±0.0945^{Aa}	0.0328 ±0.0022^{Aa}

Note: Different uppercase superscripts within the same column denote significant effect of storage time (p<0.05). Different lowercase superscripts within the same row denote significant effects of storage temperature (p<0.05). Different xy superscripts denote significant effect of pasteurization process (p<0.05). Values are expressed as means ± standard deviation.

The higher viscosity observed in the pasteurized samples compared to the fresh emulsion suggests that thermal treatment promoted structural rearrangements within the emulsion matrix, likely through enhanced protein-oil and protein-protein interactions (Liang *et al*., 2013). The *n* value of less than 1 indicated that the emulsion beverage produced showed non-Newtonian shear-thinning (pseudoplastic) behavior, in which viscosity decreases with increasing shear rate (Pal, 2024). This behavior is typical of structured fluid systems and is advantageous for beverage applications, as it facilitates easy pouring and swallowing while maintaining stability at rest (Marin-Sanchez *et al*., 2025). A lower *n* value further indicates stronger shear thinning characteristics at a given shear rate (Zalazar *et al.,* 2025). In addition, the positive τ_0 values (τ_0>0) demonstrate that the emulsion follows the characteristics of Herschel Bulkley fluid, implying the presence of a weak internal network that requires a minimum shear stress to initiate flow. The increase in τ_0 after pasteurization suggests greater resistance to movement against gravitational separation (Xiao *et al*., 2025). The consistency index (*K*), which reflects the strengths of interparticle interactions, also increased after pasteurization, indicating stronger droplet-droplet and droplet-protein associations within the emulsion system. The higher the *K* value, the stronger the bonds between the particles in the emulsion system (Ng *et al.,* 2020). Thus, the increasing K value indicated the greater resistance of the fluid to flow, and so that viscosity of the RPO emulsion beverage increased after pasteurization. The observed non-Newtonian shear-thinning behavior of the produced emulsion beverage is consistent with the previous findings. Armetha *et al.* (2022) found that RPO emulsion stabilized with WPC was Herschel-Bulkley fluid. Szulc (2022) also demonstrated that oil-in-water emulsions formulated with more than 2.5% WPC exhibit pseudoplastic behavior characterized by *n*<1 and elevated *K* values.

The increase in viscosity following pasteurization in this study can be attributed to thermal denaturation of whey proteins. It was because of pasteurization denatured the protein, that promoting intermolecular interactions and network formation within the emulsion matrix (Li *et al*., 2025a). This interpretation is supported by the research of Domian and Manko-Jurkowska (2022), who reported a significant viscosity increase in WPC-stabilized emulsions after heat treatment compared to unheated systems. The presence of heat caused polymerization of WPC which increased the steric hindrance of the polymer so that the migration of oil particles becomes slower in the emulsion system, thereby increasing steric hindrance and reducing the mobility of oil droplets, which in turn slows droplet migration and enhances physical stability (Domian & Manko-Jurkowska, 2022).

In the present study, the viscosity of RPO emulsion beverage during storage ranged between 8 and 11 mPa.s (Table 1), indicating a consistency thicker than water but still suitable for beverage applications. Storage temperature and duration did not significantly affect viscosity (p>0.05). Normah *et al.*, (2013) reported that crystallization of refined bleached and deodorized palm oil (RBDPO) at 14 °C was higher than crystal count at 22 °C. In present study, the emulsions remain fully fluid and still flowed well because the storage temperatures were relatively high to increase viscosity. The closer the temperature of a product is to its crystallization point, the more its viscosity will increase (Li *et al*., 2025b).

Rheological characterization of RPO emulsion beverage further confirmed Herschel Bulkley flow behavior with shear-thinning characteristics, as indicated by *n*<1 and τ_0>0. Due to this behavior, the higher the applied shear rate, the lower the viscosity of the emulsion beverage (Pal, 2024). Moreover, the absence of significant changes in the *n*, *K*, and τ_0 values (p>0.05) throughout storage at both storage temperatures demonstrates that the rheological characteristics of RPO emulsion beverage remained

stable over time, confirming its stability during storage and suitability as a considerable physically stable functional beverage system.

Physical stability (gravitational and centrifugal creaming index)

Gravitational creaming index showed the stability of emulsion system which was influenced by gravitational forces. The initial gravitational creaming index of emulsion beverage were at 100.00% for fresh sample and after pasteurization (day 0), whereas the decrease occurred during storage. Visually, creaming, watering-off, or phase separation did not happen in RPO emulsion beverage. The pasteurization process also did not cause a change in stability. Oil particles in fresh and pasteurized emulsion without being stored, were still homogeneously dispersed without aggregation (Xu *et al.,* 2025).

Previous studies found that the pasteurization process could increase the emulsification ability of WPC because it opened the protein structure thereby exposing the hydrophobic side. The oil-water interfacial tension decreased, and hydrophobic side of the protein was able to bind oil globules better (Domian & Manko-Jurkowska, 2022; Zhang *et al.,* 2022). This was also supported by the smaller particle size of the RPO emulsion beverage after pasteurization. The pasteurization probably caused aggregation and denaturation of the protein molecules of WPC. Denatured proteins can be in the liquid phase of the emulsion system or can be adsorbed on the oil-water interface layer, thereby allowing the hydrophobic side of the protein to be exposed to bind oil globules (Domian & Manko-Jurkowska, 2022; Zhang *et al.,* 2022). This mechanism could result in the smaller particle size that showed a more stable emulsion system, so that destabilization mechanisms such as coalescence could be prevented.

The gravitational creaming index of RPO emulsion beverages during storage is presented in Figure 2. Storage temperature had a significant effect on the gravitational creaming index (p<0.05). Creaming index decreased after being stored for 7 days and remained stable until the 21st day (p>0.05). Significant creaming occurred after 7 days could be caused by inadequate WPC to enhance viscosity of continuous phase. Particle movement could be slowed down when the viscosity of emulsion was higher. As a result, excessive water in the system moved to the lower layer of the emulsion gravitationally (Xiao *et al*., 2025). However, the upper layer of the system remained as emulsified state.

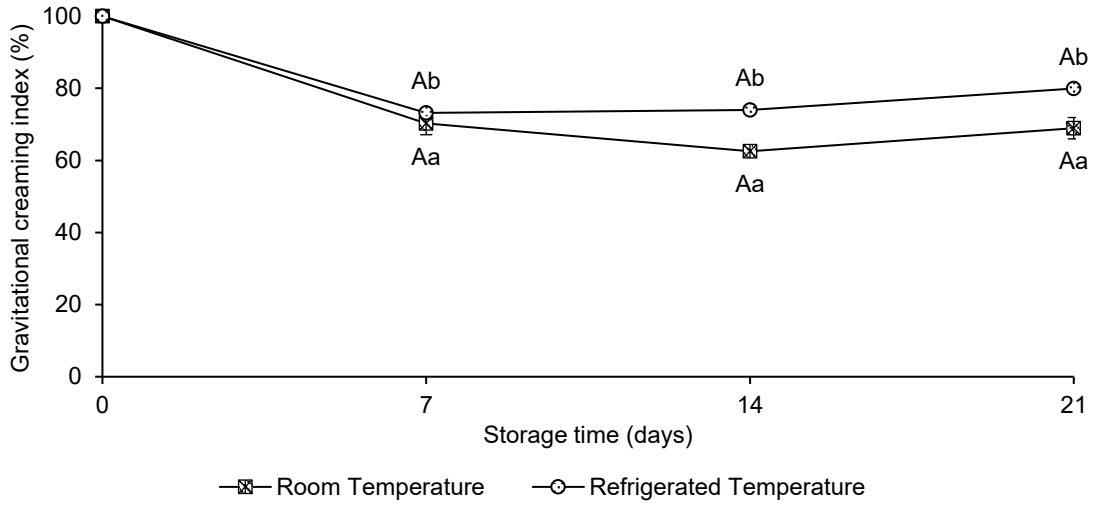
Samples in refrigerator had better gravitational stability than those stored at room temperature (p<0.05) and remained stable until the 21st day (p>0.05). Weekly shaking provided a homogenization effect which reduced the size of oil particle (Aji, 2012). The smaller the particle size, the greater the stability of the emulsion (Gila *et al.,* 2022). The slower movement of oil particles at refrigerator temperatures can be due to the oil starting to approach its freezing point so it prevented coalescence with other particles. Research by Widyasaputra *et al*. (2022) found that at low temperatures, the stability of the emulsion was better.

During storage, phase separation happened in RPO emulsion beverage where creaming occurred rapidly until there was a clear layer of water at the bottom of the RPO emulsion beverage and it was influenced by gravity. This phenomenon was also called watering-off. During storage, destabilization such as flocculation and coalescence occurred over time, due to the protein and calcium content in the emulsion system. The difference in density between water and oil also resulted in tendency of oil to rise to the top layer and interactions between oil particles occurred (Xu *et al.,* 2022; Xu *et al.,* 2025). The watering-off phenomenon generally had no effect on the quality of commercial products because the oil globules in the emulsion did not change and remained stable. With agitation or shaking, the emulsion system will be redispersed and usually does not significantly affect consumer acceptance (Xu *et al.,* 2025).

Centrifugal creaming index showed the stability of an emulsion system which is influenced by centrifugal force. Components with different specific gravities will separate into a cream layer, serum layer, and sediment. The results of centrifugal creaming index of RPO emulsion beverages can be seen in Table 2.

Pasteurization had a significant effect on centrifugal creaming index of RPO emulsion beverage (p<0.05). The stability of pasteurized sample was better than fresh sample. This was supported by research conducted by Zhou *et al*. (2021) who investigated the interfacial rheological characteristics of oil-water interface structure of whey protein isolate by combining acid pH and heat treatment. At pH 3, without heating, the oil-water interface film formed, produced thick/thin like water fluid characteristics. However, heat treatment caused the interfacial film structure to become more solid or elastic, resulting in a more stable emulsion system.

The heat treatment denatured the protein from WPC, so that the hydrophobic side of the protein became exposed and increased its hydrophobicity. This side attracted oil particles around it, thereby accelerating interfacial absorption by protein. The presence of heat changed the protein structure to become simpler thereby increasing its surface activity (Pan *et al.,* 2021; Wittmus *et al.,* 2024; Zhou *et al.,* 2021). Thus, the combination of pasteurization and acidic pH increased the stability of RPO emulsion beverage.



Note: Different uppercase within the same line denote significant effects of storage time (p<0.05). Different lowercase between lines denote significant effects of storage temperature (p<0.05)

Figure 2. Gravitational creaming index of RPO emulsion beverage during storage

Table 2. Centrifugal creaming index RPO emulsion beverage during storage

Sample	Centrifugal Creaming Index (%)	
Fresh	24.50 ± 0.00^{x}	
Pasteurized	Room temperature	Refrigerated temperature
Day 0	30.09 ± 0.09^{Aay}	30.09 ± 0.09^{Aay}
Day 7	27.69 ± 1.56^{Aa}	29.08 ± 0.72^{Aa}
Day 14	29.50 ± 2.50^{Aa}	28.50 ± 2.00^{Aa}
Day 21	28.77 ± 1.02^{Aa}	30.16 ± 0.65^{Aa}

Note: Different uppercase superscripts within the same column denote significant effects of storage time (p<0.05). Different lowercase superscripts within the same row denote significant effects of storage temperature (p<0.05). Different xy superscripts denote significant effect of pasteurization process (p<0.05). Values are expressed as means ± standard deviation.

During storage, temperature and storage time had no significant effect on the centrifugal creaming index of RPO emulsion beverage (p>0.05) (Table 2). This is because the centrifugal method is an accelerated process compared to the gravitational method, thereby saving time (Gila *et al.,* 2022). When compared with gravitational stability, after 7 days of storage, the RPO emulsion beverage reached maximum phase separation.

Particle size and zeta potential

Particle size of fresh and pasteurized sample did not have significant changes, for particle size of D[3,2], D[4,3], D10, D50, D90, and SPAN value during the first 24 hours (p>0.05) (Table 3). Particle size other than D10 decreased, while the D10 increased after pasteurization. D10 showed that there were 10% of particle smaller than 1.425±0.007 μm. The D10 increased in particle size after being stored for 24 hours. In the present study, the increasing particle size of D10 could be caused by small size particles that had larger surface area so there was not enough WPC to cover all parts of the oil particles. It is also supported by heat treatment that caused oil particles to move and coalesce with other small particles, thereby increasing the particle size (Sharma *et al.,* 2022).

In general, particle size of D[3,2], D[4,3], D50, D90, and SPAN value in fresh sample were higher than in pasteurized samples. The pasteurization probably caused aggregation and denaturation of the protein molecules of WPC. Denatured proteins can be in the liquid phase of the emulsion system or can be adsorbed on the oil-water interface layer, thereby allowing the hydrophobic side of the protein to be exposed to bind oil globules (Domian & Manko-Jurkowska, 2022; Zhang *et al.,* 2022).

The particle size of RPO emulsion beverage did not change significantly after being stored for 15 days (p>0.05) (Table 3 and Figure 3). The presence of WPC was able to maintain the emulsion particle size. This was also supported by stable zeta potential during storage (Table 4). This was in line with research by Luo *et al.* (2020), who concluded that vigorous shaking by hand could be an alternative to emulsification. After reversible destabilization occurred, shaking by hand returned the emulsion to its original condition.

Table 3. Particle size (μm) of RPO emulsion beverages in fresh, pasteurized and stored states

Sample	Storage Time	D[3,2]	D[4,3]	D10	D50	D90	SPAN
Fresh	-	3.539±0.120^{x}	8.880±0.580^{x}	1.425±0.007^{x}	6.932±0.821^{x}	18.872±1.465^{x}	2.527±0.089^{x}
Pasteurized, room temperature	Day 1	3.436±0.175^{Aa}	8.314±0.775^{Aa}	1.479±0.018^{Aa}	5.785±0.847^{Aa}	16.674±2.205^{Aa}	2.628±0.006^{Aa}
	Day 15	3.347±0.072^{Aa}	9.730±2.218^{Aa}	1.468±0.024^{Aa}	5.246±0.239^{Aa}	15.452±0.227^{Aa}	2.674±0.170^{Aa}
Pasteurized, refrigerated	Day 1	3.360±0.010^{Aax}	6.722±0.213^{Aax}	1.504±0.020^{Aax}	5.226±0.134^{Aax}	13.888±0.740^{Aa} ^{x}	2.368±0.084^{Abx}
	Day 15	3.286±0.103^{Aa}	6.760±0.796^{Aa}	1.447±0.018^{Aa}	5.354±0.601^{Aa}	13.791±1.980^{Aa}	2.293±0.116^{Ab}

Note: Different uppercase superscripts within the same column denote significant effects of storage time (p<0.05). Different lowercase superscripts within the same row denote significant effects of storage temperature (p<0.05). Same x superscripts denote insignificant effect of pasteurization process (p>0.05). Values are expressed as means ± standard deviation.

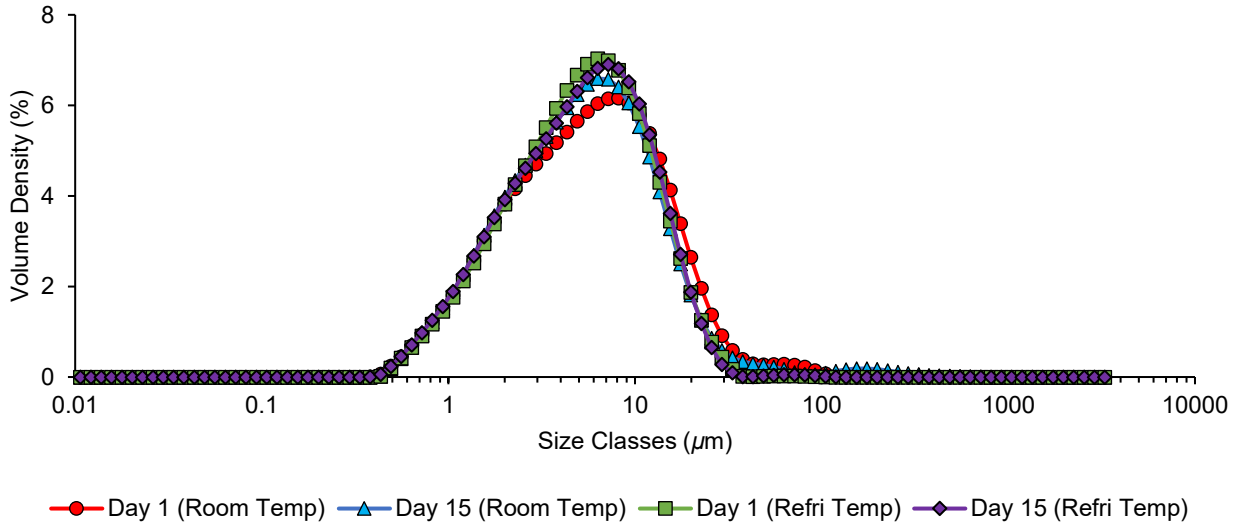


Figure 3. Particle size distribution of RPO emulsion beverage during storage

Table 4. Zeta potential of RPO emulsion beverages in fresh, pasteurized, and stored states

Sample	Zeta Potential (mV)	
Fresh	−17.4±0.40^{x}	
Pasteurized	Room temperature	Refrigerated temperature
Day 0	−14.35±2.95^{Aax}	−14.35±2.95^{Aax}
Day 7	−11.60±0.80^{Aa}	−15.80±0.50^{Aa}
Day 14	−13.55±0.75^{Aa}	−11.65±1.25^{Aa}
Day 21	−11.90±0.20^{Aa}	−12.35±1.45^{Aa}

Note: Different uppercase superscripts within the same column denote significant effects of storage time (p<0.05). Different lowercase superscripts within the same row denote significant effects of storage temperature (p<0.05). Same x superscripts denote insignificant effect of pasteurization process (p>0.05). Values are expressed as means ± standard deviation.

Meanwhile, the SPAN value at room temperature was greater than at refrigerator. The greater the SPAN value, the wider the particle size distribution, so that the particle size in an emulsion system was less homogeneous. The lower the storage temperature, the lower SPAN value. At refrigerated temperature, the movement of oil particles could be slow down because the oil in emulsion approached its freezing point, which hinders particle coalescence (Li *et al.,* 2025b). Thus, the particle size of RPO emulsion beverage remained stable during storage, even though the SPAN value was different between room temperature and refrigerated temperature storage.

Zeta potential showed the number of electric charges in emulsion system. The presence of electric charge provided a repulsive force between particles, thereby preventing the particles from coalescing. The greater the zeta potential, the more stable an emulsion system was (Sridharan *et al*., 2020). Zeta potential of fresh and pasteurized sample presented in Table 4. Zeta potential of RPO emulsion beverage ranged from −20 to −10 mV, which indicated that the repulsive force between the particles was relatively

low, so there was a tendency for the emulsion system to be unstable (Sridharan *et al.,* 2020). Pasteurization process had no significant effect on zeta potential of RPO emulsion beverages (p>0.05). This is because the relatively low pasteurization temperature (65 °C) was insufficient to induce significant changes in the zeta potential. The relatively low magnitude of zeta potential was not independently evidence of poor emulsion stability, because the system contained WPC and other emulsifying components.

A negative zeta potential value indicates that the negative electric charge is more than the positive charge on the surface of the particle. The results of this study were different from the research of Sriprablom *et al*. (2019), zeta potential in soybean oil emulsions stabilized using WPI was positive at pH 3–4 and negative at pH 5–7. When the pH of the system was below the isoelectric point of the protein, the zeta potential was positive. Meanwhile, when the pH of the system was above the protein isoelectric point, the zeta potential was negative. Zeta-potential values were also affected by emulsifiers other than WPC. The presence of soy lecithin also influenced the zeta potential value. In the study by Yussof *et al*. (2023), nano dispersion system using soy lecithin at pH 2–8 remained negative. The combination of WPC and soy lecithin increased the negative charge in RPO emulsion beverage system so that at pH 4, the zeta potential was still negative. After the pasteurization process, the zeta potential value decreased, but did not differ significantly. It was supported by pH value that remained 4 after pasteurization. Kupikowska-Stobba *et al.*, (2024) found that zeta potential value was affected directly by pH value which showed charged molecules in emulsion. During storage, temperature and storage time had no significant effect on zeta potential of RPO emulsion beverage (p>0.05) (Table 4). This could be caused by hand shaking treatment carried out at the end of storage, providing a homogenization effect which reduced the size of the oil particles (Aji, 2012). By reducing the particle size, the zeta potential of RPO emulsion beverage returned to its original state. The stability of emulsion also supported by creaming index that remained stable during storage that in line with zeta potential value.

This negative and not significantly different zeta potential value was possibly caused by electrostatic repulsion of negative charges from WPC after the RPO emulsion beverage was pasteurized, thus maintaining the stability of the emulsion during storage. This was supported by research of Sridharan *et al.* (2020) that showed similar phenomenon of pea flour emulsion that contained 0.2–0.3% protein had negative zeta potential. This condition could be seen from the watering-off phenomenon that occurred in RPO emulsion beverage, which the emulsion at the upper layer remained stable. Even if watering-off showed the free water moved to the lower layer, but it was not permanent because hand shaking redispersed the emulsion back to its original state.

Oil globules appearance

The appearance of oil globules of fresh and pasteurized RPO emulsion beverage tended to be uniform (Figure 4A and 4B). Pasteurization did not affect the oil globules. This could be due to the denaturation of WPC caused protein molecules to adsorb at oil-water interface. This supported by research of Domian and Manko-Jurkowska (2022), which showed similar phenomenon when thermal treatment applied on low-fat WP-stabilized emulsions. Bridging flocculation that occurred in emulsion systems could be one of the causes of large particle sizes (Niu *et al.,* 2020). The appearance of the RPO emulsion beverage globules was relatively stable at both storage temperature after being stored for 21 days (Figure 4C and 4D). The size of the oil globules was confirmed by the particle size of the RPO emulsion beverage, which did not change significantly during storage. Oil globules in the samples tended to coalesce and flocculate over time.

On the 21st day, the samples stored at room temperature had deformed particle as seen in Figure 4D (c). Compared to samples stored at room temperature, the microstructure of the emulsion stored at refrigerated temperature was more solid and sturdy. This was in line with research by Karthik and Anandharamakrishnan (2016), who found that deformation of oil globules in emulsions stored at higher temperatures was caused by rupture of the interface layer in the emulsion system. In addition, when stored at refrigerated temperature, the oil in the emulsion system was near its freezing point so it tended to maintain its particle structure (Li *et al.,* 2025b).

Color

The L* value indicates the brightness or lightness of a sample (Baghabrishami & Goli, 2023). The a* value indicates the tendency of the sample to be red (+) or green (-). The b* value indicates the tendency of the sample to be yellow (+) or blue (-). The ΔE value shows the change or difference in sample color compared to the standard color (Li *et al.,* 2023). The results of color analysis of RPO emulsion beverage were presented in Table 5.

The L* value showed a bright color because value of 0 indicated a black color and 100 indicated a white color (Li *et al.,* 2023). The a* value indicated the color of the sample tended to be reddish because the value (+) indicated a red color. The b* value indicated the sample color was yellow because the value (+) indicated yellow. Pasteurization process did not have a significant effect on the L*, a*, and b* values of RPO emulsion beverage (p>0.05). This is because the fairly low temperature treatment during pasteurization

(65 °C) was insufficient to significantly alter the brightness of the RPO emulsion beverage. This was also in line with research by Dongho Dongmo *et al*. (2014), who found that heating crude palm oil at temperature of 50–120 °C for 30 min did not reduce the levels of carotenoids, which were pigment compounds, significantly.

The ΔE value of pasteurized sample was 3.24±0.25 compared to fresh one. Overall, the non-significant differences in the L*, a*, and b* values were reflected in the ΔE value of the RPO emulsion beverage. Color differences between the fresh and pasteurized samples on day 0 were caused by the acidic pH and heating that reduced the intensity of carotenoid color pigments (Yadav & Prabha, 2014). This affected the color of the RPO emulsion beverage, which contained 10% RPO rich in carotenoids.

During storage, temperature and storage time did not have a significant effect on the L*, a*, b*, and ΔE values of RPO emulsion beverages (p>0.05) (Table 5). The high L* value in samples was due to white WPC so the brightness of the sample was high. The a* value was positive because the red-orange colored RPO contributed to the positive value. The high positive b* values in the samples were attributed to the combination of red-orange RPO and white WPC, along with the addition of orange mango flavoring, which enhanced yellowness. A small ΔE value indicated a small color difference in RPO emulsion beverage during storage compared to day 0.

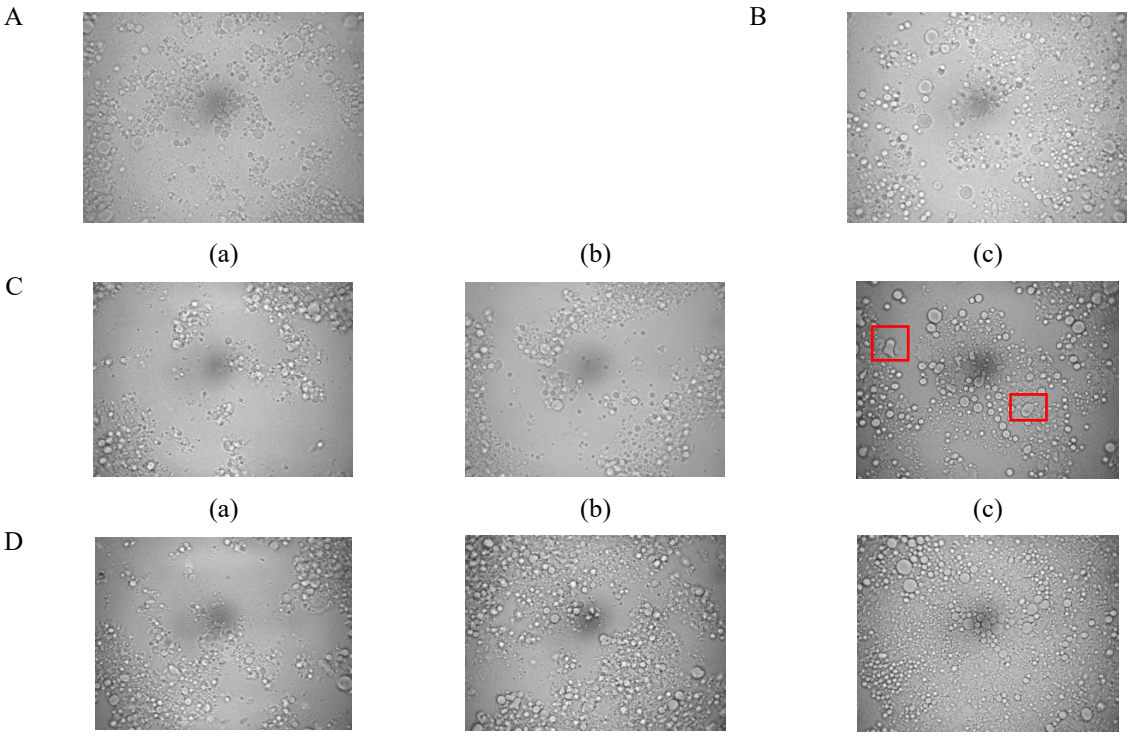


Figure 4. Appearance of oil globules (highlight by red box) in RPO emulsion beverages: (A) fresh; (B) pasteurized; (C) room temperature storage at day 7 (a), day 14 (b), and day 21 (c); (D) refrigerated storage at day 7 (a), day 14 (b), and day 21 (c)

Table 5. Color parameters of RPO emulsion beverages in fresh, pasteurized, and stored states

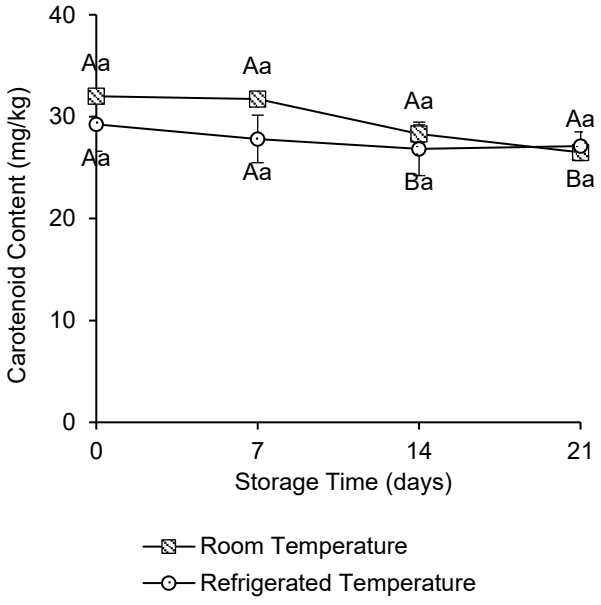
Sample	L*		a*		b*		ΔE	
Fresh	76.85±0.41^{x}		2.13±0.09^{x}		85.88±0.68^{x}		-	
Pasteurized	Room temp	Refri temp	Room temp	Refri temp	Room temp	Refri temp	Room temp	Refri temp
Day 0	78.67±1.30^{Aax}	78.67±1.30^{Aax}	1.69±0.19^{Aax}	1.69±0.19^{Aax}	85.29±2.11^{Aax}	85.29±2.11^{Aax}	3.24±0.25	
Day 7	78.66±0.86^{Aa}	78.26±1.21^{Aa}	1.10±0.56^{Aa}	1.34±0.24^{Aa}	85.06±1.53^{Aa}	83.30±1.13^{Aa}	1.95±0.02^{Aa}	2.37±1.19^{Aa}
Day 14	76.81±0.66^{Aa}	79.08±0.46^{Aa}	1.99±0.04^{Aa}	1.66±0.25^{Aa}	81.15±0.91^{Aa}	79.93±1.83^{Aa}	4.56±1.10^{Aa}	5.39±1.86^{Aa}
Day 21	77.09±0.03^{Aa}	78.35±0.10^{Aa}	2.41±0.54^{Aa}	1.89±0.06^{Aa}	82.05±0.96^{Aa}	81.74±0.67^{Aa}	3.72±0.95^{Aa}	3.57±0.68^{Aa}

Note: Different uppercase superscripts within the same column denote significant effects of storage time (p<0.05). Different lowercase superscripts within the same row denote significant effects of storage temperature (p<0.05). Same x superscripts denote insignificant effect of pasteurization process (p>0.05). ΔE value of the pasteurized sample on day 0 compared with the fresh sample. ΔE value of the pasteurized sample on day 7, day 14, and day 21 compared with the pasteurized sample on day 0. Values are expressed as means ± standard deviation.

The stable color of RPO emulsion beverage could be caused by the sample bottle packaging being covered with aluminium foil during storage, thus preventing changes in brightness due to light exposure. Yoboue *et al*. (2022) examined the damage of vitamin A of RPO samples with and without aluminium foil protection. In the samples not protected with aluminium foil, extensive vitamin A loss was observed because light exposure degraded the provitamin A carotenoid compounds.

Carotenoid content

Fresh RPO emulsion beverage contained 29.09±1.77 mg/kg carotenoid, while the pasteurized product exhibited a slightly higher concentration of 30.62±2.37 mg/kg (Figure 5). However, this difference was not statistically significant different (p>0.05). The absence of carotenoid loss could be due to emulsion matrix that protected carotenoid against thermal degradation. This protective effect can be attributed to the interfacial adsorption of emulsifiers and the presence of whey protein, which enhance droplet stability and limit exposure of carotenoids to oxygen and heat, thereby suppressing oxidative degradation during thermal processing (Mao *et al.,* 2018).



Note: Different uppercase within the same line denote significant effects of storage time (p<0.05). Different lowercase between lines denote significant effects of storage temperature (p<0.05)

Figure 5. Carotenoid content of RPO emulsion beverage during storage

During storage, carotenoid content for samples stored at refrigerator did not decrease significantly (p>0.05). Meanwhile, it decreased significantly in samples stored at room temperature on the 14th day, but remained stable until 21st day. These findings are consistent with the work of Rodriguez-Rodriguez *et al*. (2020), which tested 9 types of carotenoid compounds during storage. After being stored for 21 days at refrigerated temperature, the carotenoid content of samples was relatively stable.

Refrigerated temperature prevented carotenoid degradation during storage (Rodriguez-Rodriguez *et al*., 2020; Yoboue *et al.,* 2022). Conditions with minimum light, low temperature, and minimum oxygen exposure prevented the degradation of carotenoid compounds in RPO emulsion beverage. Meanwhile, in samples stored at room temperature, there was a decrease of around 17.22%. At room temperature, oxidative degradation of carotenoid compounds occurred more rapidly than at lower temperature (Ekpa *et al*., 2021).

From a nutritional perspective, consumption of 100 mL of the RPO emulsion beverage produced in this study can provide approximately 30–50% of the recommended daily vitamin A intake, as stipulated by the Regulation of the Minister of Health of the Republic of Indonesia Number 28 of 2019 about Recommended Nutritional Adequacy Rates for Indonesian People (Kemenkes RI, 2019). This estimate was based on the conversion of 6 μg of β-carotene equal to 1 retinol equivalent (RE) of vitamin A, while RPO was assumed to have approximately 50% of β-carotene of carotenoid total.

Furthermore, based on National Agency of Food and Drug Control Regulation Number 1 of 2022 about Supervision of Claims on Processed Food Labels and Advertisements (BPOM, 2022), the requirement for a product claim to be rich or high in vitamin A is minimum 15% of RDA per 100 mL product. Accordingly, the RPO emulsion beverage meets the criteria for a high-vitamin A functional drink and holds strong potential as a dietary strategy for improving vitamin A intake.

CONCLUSION

This study demonstrated that a red palm oil (RPO) emulsion beverage can be successfully formulated and stabilized through batch pasteurization and appropriate storage conditions. Pasteurization did not compromise the structural integrity of the emulsion, as evidenced by relatively stable particle size distribution, zeta potential, and oil globule microstructure, while significantly enhancing viscosity and centrifugal stability. During 21 days of storage, the emulsion maintained consistent physicochemical and colloidal properties at both room and refrigerated temperatures, with superior carotenoid retention observed under refrigerated conditions. Notably, the beverage retained carotenoid concen-

trations sufficient to provide approximately 30–50% of the recommended daily intake of vitamin A per 100 mL serving, supporting its classification as a pro-vitamin A-rich functional beverage. Collectively, these findings confirm that pasteurization combined with controlled storage enables the development of physically stable, nutritionally valuable RPO emulsion beverage with strong potential for functional food applications and public health nutrition strategies.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of PT. DKSH Indonesia for providing access to the Particle Size Analyzer Mastersizer 3000+ (Malvern) for analytical facility used in this study.

REFERENCES

Aji, L. P. (2012). Shaking and blending effect on microalgae concentrates size. *HAYATI Journal of Biosciences*, *19*(1), 11–17. https://doi.org/10.4308/hjb.19.1.11

Armetha, V., Hariyadi, P., Sitanggang, A. B., & Yuliani, S. (2022). The stability of whey protein-stabilized red palm oil emulsion from a rheological perspective. *The Annals of the University Dunarea de Jos of Galati. Fascicle VI - Food Technology*, *46*(2), 35–49. https://doi.org/10.35219/foodtechnology.2022.2.03

Assar, M., Simon, S., Sørland, G. H., & Grimes, B. A. (2023). A theoretical and experimental investigation of batch oil-water gravity separation. *Chemical Engineering Research and Design*, *194*, 136–150. https://doi.org/10.1016/j.cherd.2023.04.029

Baghabrishami, R. G., & Goli, S. A. H. (2023). Tomato seed oil-enriched tomato juice: Effect of oil addition type and heat treatment on lycopene bioaccessibility and oxidative stability. *Food Chemistry*, *402*, 134217. https://doi.org/10.1016/j.foodchem.2022.134217

[BPOM] Badan Pengawas Obat dan Makanan. (2022). *Peraturan Badan Pengawas Obat dan Makanan Nomor 1 Tahun 2022*. Jakarta: Badan Pengawas Obat dan Makanan.

[BPS] Badan Pusat Statistik. (2023). *Statistik kelapa sawit Indonesian oil palm statistics 2022* (Vol. 16). Jakarta: Badan Pusat Statistik.

May, C. Y. (1994). Palm oil carotenoids. *Food and Nutrition Bulletin*, *15*(2), 130–136. https://doi.org/10.1177/156482659401500212

Dari, D. W., & Junita, D. (2020). Karakteristik fisik dan sensori minuman sari buah pedada. *Jurnal Pengolahan Hasil Perikanan Indonesia*, *23*(3), 532–541. https://doi.org/10.17844/jphpi.v23i3.33219

Dekker, R. I., Kibbelaar, H. V. M., Deblais, A., & Bonn, D. (2022). Rheology of emulsions with polymer solutions as the continuous phase. *Journal of Non-Newtonian Fluid Mechanics*, *310*, 104938. https://doi.org/10.1016/j.jnnfm.2022.104938

Dewi, E. K., Mardawati, E., & Nurhasanah, S. (2023). Evaluasi perubahan warna dalam tahapan pengolahan minyak mentah sawit menjadi minyak sawit merah dan minyak goreng sawit sebagai indikator kandungan *β*-karoten minyak. *Biomass, Biorefinery, and Bioeconomy*, *1*(1), 25–29.

Dianingsih, N., Purnomo, E. H., & Muchtadi, T. R. (2016). Sifat reologi dan stabilitas fisik minuman emulsi minyak sawit. *Jurnal Teknologi dan Industri Pangan*, *27*(2), 165–174. https://doi.org/10.6066/jtip.2016.27.2.165

Domian, E., & Mańko-Jurkowska, D. (2022). The effect of homogenization and heat treatment on gelation of whey proteins in emulsions. *Journal of Food Engineering*, *319*, 110915. https://doi.org/10.1016/j.jfoodeng.2021.110915

Dongho Dongmo, F. F., Annie, N. N., Adélaide, D. M., Florian, S., & Inocent, G.(2014). Effect of heating and of short exposure to sunlight on carotenoids content of crude palm oil. *Journal of Food Processing & Technology*, *5*(4), 1000314. https://doi.org/10.4172/2157-7110.1000314

Ekpa, O., Fogliano, V., & Linnemann, A. (2021). Carotenoid stability and aroma retention during the post-harvest storage of biofortified maize. *Journal of the Science of Food and Agriculture*, *101*(10), 4042–4049. https://doi.org/10.1002/jsfa.11039

Elvira-Torales, L. I., García-Alonso, J., & Periago-Castón, M. J. (2019). Nutritional importance of carotenoids and their effect on liver health: A review. *Antioxidants*, *8*(7), 229. https://doi.org/10.3390/antiox8070229

Fadzilah, M. F., Zubairi, S. I. Z., Abidin, N. Z., Kasim, Z. M., & Lazim, A. (2020). Physico-chemical and sensory acceptance of *Carica papaya* leaves extract edible O/W emulsion as prospective natural remedies. *Arabian Journal of Chemistry*,

13(11), 7829–7842. https://doi.org/10.1016/j.arabjc.2020.09.014

Gao, Z., Zhu, Y., Jin, J., Jin, Q., & Wang, X. (2023). Chemical-physical properties of red palm oils and their application in the manufacture of aerated emulsions with improved whipping capabilities. *Foods*, *12*(21), 3933. https://doi.org/10.3390/foods12213933

Gila, A., Aguilera, M. P., Sánchez-Ortiz, A., Jiménez, A., & Beltrán, G. (2022). Effect of centrifugal force (*g*) on stability of natural emulsions (water/oil) present in fresh virgin olive oils. *Journal of Food Engineering*, *334*, 111169. https://doi.org/10.1016/j.jfoodeng.2022.111169

Hariyadi, P. (2019). *Landasan Teknik Pangan*. IPB Press.

Hasibuan, H. A., Warnoto, Magindrin, & Lubis, A. (2021). Produksi minyak sawit merah kapasitas 10 kg/batch dan produk diversifikasinya berupa shortening dan margarin kapasitas 50 kg/batch. *Warta PPKS*, *26*(1), 20–29.

Hisprastin, Y., & Nuwarda, R. F. (2018). Review: Perbedaan emulsi dan mikroemulsi pada minyak nabati. *Farmaka*, *16*(1), 133–140.

Hu, Y.-T., Ting, Y., Hu, J.-Y., & Hsieh, S.-C. (2017). Techniques and methods to study functional characteristics of emulsion systems. *Journal of Food and Drug Analysis*, *25*(1), 16–26. https://doi.org/10.1016/j.jfda.2016.10.021

[IPOA] Indonesian Palm Oil Association. (2025, November 14). *Kinerja industri sawit 2025 tumbuh lebih cepat, GAPKI soroti tantangan dan arah strategis*. Retrieved December 18, 2025, from https://gapki.id/news/2025/11/14/kinerja-industri-sawit-2025-tumbuh-lebih-cepat-gapki-soroti-tantangan-dan-arah-strategis/

Karthik, P., & Anandharamakrishnan, C. (2016). Enhancing omega-3 fatty acids nanoemulsion stability and in-vitro digestibility through emulsifiers. *Journal of Food Engineering*, *187*, 92–105. https://doi.org/10.1016/j.jfoodeng.2016.05.003

[Kemenkes RI] Kementerian Kesehatan Republik Indonesia. (2019). *Peraturan Menteri Kesehatan Republik Indonesia Nomor 28 Tahun 2019*. Jakarta: Kementerian Kesehatan Republik Indonesia.

[Kemenkes RI] Kementerian Kesehatan Republik Indonesia. (2020). *Profil Kesehatan Indonesia*. Jakarta: Kementerian Kesehatan Republik Indonesia.

[Kemenkes RI] Kementerian Kesehatan Republik Indonesia. (2023). *Profil Kesehatan Indonesia Tahun 2023*. Jakarta: Kementerian Kesehatan Republik Indonesia.

Kim, J. A., Jang, J. H., & Lee, S. Y. (2021). An updated comprehensive review on vitamin A and carotenoids in breast cancer: Mechanisms, genetics, assessment, current evidence, and future clinical implications. *Nutrients*, *13*(9), 3162. https://doi.org/10.3390/nu13093162

Kupikowska-Stobba, B., Domagała, J., & Kasprzak, M. M. (2024). Critical review of techniques for food emulsion characterization. *Applied Sciences*, *14*(3), 1069. https://doi.org/10.3390/app14031069

Li, J., Ji, W., Prince, R. C., Lee, K., Pegau, W. S., & Boufadel, M. (2025b). Impact of below-freezing air temperatures on the formation and stability of seawater-crude oil emulsion. *Marine Pollution Bulletin*, *218*, 118186. https://doi.org/10.1016/j.marpolbul.2025.118186

Li, Y., Wang, S., Liu, X., Zhao, G., Yang, L., Zhu, L., & Liu, H. (2023). Improvement in texture and color of soy protein isolate gel containing capsorubin and carotenoid emulsions following microwave heating. *Food Chemistry*, *428*, 136743. https://doi.org/10.1016/j.foodchem.2023.136743

Li, Z., Zhang, T., Zhou, R., Zhang, X., Ren, J., & Diao, M. (2025a). Effects of pasteurization on set yogurt fortified with astaxanthin-rich yolk: Evaluation of physicochemical properties, stability, and biological activity. *Journal of Dairy Science*, *108*(4), 3499–3514. https://doi.org/10.3168/jds.2024-26012

Liang, Y., Patel, H., Matia-Merino, L., Ye, A., & Golding, M. (2013). Structure and stability of heat-treated concentrated dairy-protein-stabilised oil-in-water emulsions: A stability map characterisation approach. *Food Hydrocolloids*, *33*(2), 297–308. https://doi.org/10.1016/j.foodhyd.2013.03.012

Luo, R., Dong, J., & Luo, Y. (2020). pH-responsive Pickering emulsion stabilized by polymer-coated silica nanoaggregates and applied to recyclable interfacial catalysis. *RSC Advances*, *10*(70), 42423–42431. https://doi.org/10.1039/d0ra07957j

Mafe, A. N., Edo, G. I., Makia, R. S., Joshua, O. A., Akpoghelie, P. O., Gaaz, T. S., Jikah, A. N., Yousif, E., Isoje, E. F., Igbuku, U. A., Ahmed, D. S., Essaghah, A. E. A., Umar, H. (2024). A review on food spoilage mechanisms, food

borne diseases and commercial aspects of food preservation and processing. *Food Chemistry Advances*, *5*, 100852. https://doi.org/10.1016/j.focha.2024.100852

Maheshwar, M. (2018). A review article on measurement of viscosity. *International Journal of Research in Pharmacy and Chemistry*, *8*(1), 69–77.

Mao, L., Wang, D., Liu, F., & Gao, Y. (2018). Emulsion design for the delivery of *β*-carotene in complex food systems. *Critical Reviews in Food Science and Nutrition*, *58*(5), 770–784. https://doi.org/10.1080/10408398.2016.1223599

Margono, Putri, E. N., & Gumilar, E. (2022). Pengaruh fraksi minyak dan emulsifier serta kecepatan pengadukan terhadap karakteristik emulsi minyak biji matahari (*Helianthus annuus* L.) dalam air (M/A). *Equilibrium Journal of Chemical Engineering*, *6*(2), 117–126. https://doi.org/10.20961/equilibrium.v6i2.64147

Marín-Sánchez, J., Gimeno-Ruiz, S., Berzosa, A., Raso, J., & Sánchez-Gimeno, C. (2025). Measuring viscosity and consistency in thickened liquids for dysphagia: Is there a correlation between different methods? *Foods*, *14*(13), 2384. https://doi.org/10.3390/foods14132384

Mohamad, W. A. F. W., McNaughton, D., Buckow, R., & Augustin, M. A. (2017). Stability and partitioning of *β*-carotene in whey protein emulsions during storage. *Food & Function*, *8*(11), 3917–3925. https://doi.org/10.1039/C7FO01012E

Ng, S. P., Khor, Y. P., Lim, H. K., Lai, O. M., Wang, Y., Wang, Y., Cheong, L. Z., Nehdi, I. A., Mansour, L., & Tan, C. P. (2020). Fabrication of concentrated palm olein-based diacylglycerol oil–soybean oil blend oil-in-water emulsion: In-depth study of the rheological properties and storage stability. *Foods*, *9*(7), 877. https://doi.org/10.3390/foods9070877

Niakousari, M., Damyeh, M. S., Gahruie, H. H., Bekhit, A. E.-D. A., Greiner, R., & Roohinejad, S. (2018). Conventional emulsions. In S. Roohinejad, R. Greiner, I. Oey, & J. Wen (Eds.), *Emulsion-based systems for delivery of food active compounds: Formation, application, health and safety* (pp. 1–27). John Wiley & Sons. https://doi.org/10.1002/9781119247159.ch1

Niu, B., Shao, P., Feng, S., Qiu, D., & Sun, P. (2020). Rheological aspects in fabricating pullulan-whey protein isolate emulsion suitable for electrospraying: Application in improving *β*-carotene stability. *LWT*, *129*, 109581. https://doi.org/10.1016/j.lwt.2020.109581

Normah, I., Cheow, C. S., & Chong, C. L. (2013). Crystal habit during crystallization of palm oil: Effect of time and temperature. *International Food Research Journal*, *20*(1), 417–422.

Östbring, K., Matos, M., Marefati, A., Ahlström, C., & Gutiérrez, G. (2021). The effect of pH and storage temperature on the stability of emulsions stabilized by rapeseed proteins. *Foods*, *10*(7), 1657. https://doi.org/10.3390/foods10071657

Pal, R. (2024). Non-Newtonian behavior of suspensions and emulsions: Review of different mechanisms. *Advances in Colloid and Interface Science*, *333*, 103299. https://doi.org/10.1016/j.cis.2024.103299

Pan, N., Wan, W., Du, X., Kong, B., Liu, Q., Lv, H., Xia, X., & Li, F. (2021). Mechanisms of change in emulsifying capacity induced by protein denaturation and aggregation in quick-frozen pork patties with different fat levels and freeze–thaw cycles. *Foods*, *11*(1), 44. https://doi.org/10.3390/foods11010044

Pathania, R., Khan, H., Kaushik, R., & Khan, M. A. (2018). Essential oil nanoemulsions and their antimicrobial and food applications. *Current Research in Nutrition and Food Science*, *6*(3), 626–643. https://doi.org/10.12944/CRNFSJ.6.3.05

Raval, N., Maheshwari, R., Kalyane, D., Youngren-Ortiz, S. R., Chougule, M. B., & Tekade, R. K. (2019). Importance of physicochemical characterization of nanoparticles in pharmaceutical product development. In R. K. Tekade (Ed.), *Basic Fundamentals of Drug Delivery* (pp. 369–400). Academic Press. https://doi.org/10.1016/B978-0-12-817909-3.00010-8

Rodríguez-Rodríguez, E., Sánchez-Prieto, M., & Olmedilla-Alonso, B. (2020). Assessment of carotenoid concentrations in red peppers (*Capsicum annuum*) under domestic refrigeration for three weeks as determined by HPLC-DAD. *Food Chemistry: X*, *6*, 100092. https://doi.org/10.1016/j.fochx.2020.100092

Rymaruk, M. J., Cunningham, V. J., Brown, S. L., Williams, C. N., & Armes, S. P. (2020). Oil-in-oil Pickering emulsions stabilized by diblock copolymer nanoparticles. *Journal of Colloid and Interface Science*, *580*, 354–364. https://doi.org/10.1016/j.jcis.2020.07.010

Sharma, M., Mann, B., Pothuraju, R., Sharma, R., & Kumar, R. (2022). Physico-chemical characterization of ultrasound assisted clove oil-loaded nanoemulsion: As enhanced antimicrobial potential. *Biotechnology Reports*, *34*, e00720. https://doi.org/10.1016/j.btre.2022.e00720

Soni, A., & Brightwell, G. (2022). Effect of hurdle approaches using conventional and moderate thermal processing technologies for microbial inactivation in fruit and vegetable products. *Foods*, *11*(12), 1811. https://doi.org/10.3390/foods11121811

Sridharan, S., Meinders, M. B. J., Bitter, J. H., & Nikiforidis, C. V. (2020). Pea flour as stabilizer of oil-in-water emulsions: Protein purification unnecessary. *Food Hydrocolloids*, *101*, 105533. https://doi.org/10.1016/j.foodhyd.2019.105533

Sriprablom, J., Luangpituksa, P., Wongkongkatep, J., Pongtharangkul, T., & Suphantharika, M. (2019). Influence of pH and ionic strength on the physical and rheological properties and stability of whey protein stabilized O/W emulsions containing xanthan gum. *Journal of Food Engineering*, *242*, 141–152. https://doi.org/10.1016/j.jfoodeng.2018.08.031

Sun, H., Ma, Y., Huang, X., Song, L., Guo, H., Sun, X., Li, N., & Qiao, M. (2023). Stabilization of flaxseed oil nanoemulsions based on flaxseed gum: Effects of temperature, pH and NaCl on stability. *LWT*, *176*, 114512. https://doi.org/10.1016/j.lwt.2023.114512

Szterk, A., Roszko, M., & Górnicka, E. (2013). Chemical stability of the lipid phase in concentrated beverage emulsions colored with natural β-carotene. *Journal of the American Oil Chemists' Society*, *90*(4), 483–491. https://doi.org/10.1007/s11746-012-2194-8

Szulc, K. (2022). Investigation of rheological characteristics and stability of emulsions based on pea, soy, and whey proteins. *Technological Progress in Food Processing*, *1*, 76–82.

Viñas-Ospino, A., López-Malo, D., Esteve, M. J., Frígola, A., & Blesa, J. (2023). Improving carotenoid extraction, stability, and antioxidant activity from *Citrus sinensis* peels using green solvents. *European Food Research and Technology*, *249*(9), 2349–2361. https://doi.org/10.1007/s00217-023-04302-0

Weiss, J., Gaysinsky, S., Davidson, M., & McClements, D. J. (2009). Nanostructured encapsulation systems: Food antimicrobials. In G. Barbosa-Cánovas, A. Mortimer, D. Lineback, W. Spiess, K. Buckle, & P. Colonna (Eds.), *Global Issues in Food Science and Technology* (pp. 425–479). Academic Press. https://doi.org/10.1016/B978-0-12-374124-0.00024-7

Widyasaputra, R., Bimantio, M. P., Oktavianty, H., Ruswanto, A., & Ngatirah. (2022). Karakteristik viskositas dan titik leleh pada campuran minyak sawit merah dan minyak jagung. *Prosiding Seminar Nasional INSTIPER Yogyakarta*, *1*(1), 225–232. https://doi.org/10.55180/pro.v1i1.258

Wittmus, M., Amft, J., Heyn, T. R., & Schwarz, K. (2024). Oil binding capacity and related physicochemical properties of commercial plant protein products. *Food Bioscience*, *59*, 103823. https://doi.org/10.1016/j.fbio.2024.103823

Xiao, T., Ma, X., Hu, H., Xiang, F., Zhang, X., Zheng, Y., Dong, H., Adhikari, B., Wang, Q., & Shi, A. (2025). Advances in emulsion stability: A review on mechanisms, role of emulsifiers, and applications in food. *Food Chemistry: X*, *29*, 102792. https://doi.org/10.1016/j.fochx.2025.102792

Xu, H., Huang, M., Huan, H., Cui, L., Liu, L., Xu, X., Chen, Y., Wei, W., Jin, Q., Jin, J., & Wang, X. (2025). Plant-based whipping cream: A promising sustainable alternative to dairy products. *Advances in Colloid and Interface Science*, *341*, 103494. https://doi.org/10.1016/j.cis.2025.103494

Xu, H., Yang, L., Jin, J., Zhang, J., Xie, P., Chen, Y., Shi, L., Wei, W., Jin, Q., & Wang, X. (2022). Elucidation on the destabilization mechanism of whipping creams during static storage. *Food Hydrocolloids*, *129*, 107613. https://doi.org/10.1016/j.foodhyd.2022.107613

Yadav, S., & Prabha, R. (2014). Effect of pH and temperature on carotenoid pigments produced from *Rhodotorula minuta*. *International Journal of Fermented Foods*, *3*(2), 105–113. https://doi.org/10.5958/2321-712X.2014.01312.X

Yoboué, B. A., Diallo, K., Diomandé, I., Tiahou, G. G., & Assidjo, N. E. (2022). Evaluation of the nutritional quality of red and refined palm oils marketed in Yamoussoukro (Côte d'Ivoire). *Food and Nutrition Sciences*, *13*(2), 97–107. https://doi.org/10.4236/fns.2022.132010

Yussof, N. S., Tan, C. P., Tan, T. B., Utra, U., & Ramli, M. E. (2023). Influence of soy lecithin and sodium caseinate on the stability and in vitro bioaccessibility of lycopene nanodispersion.

Food Technology and Biotechnology, *61*(1), 39–50. https://doi.org/10.17113/ftb.61.01.23.7538

Zalazar, A. L., Campos, C. A., García-González, M.-C., & Alfaro-Rodríguez, M.-C. (2025). Substitution of synthetic emulsifiers by a hemp protein in canola oil-in-water emulsions resembling salad dressing: Comparison of rheological properties and physical stability. *International Journal of Biological Macromolecules*, *334*, 148989. https://doi.org/10.1016/j.ijbiomac.2025.148989

Zhai, M., Zhou, K., Sun, Z., Xiong, Z., Du, Q., Zhang, Y., Shi, L., & Hou, J. (2023). Rheological characterization and shear viscosity prediction of heavy oil-in-water emulsions. *Journal of Molecular Liquids*, *381*, 121782. https://doi.org/10.1016/j.molliq.2023.121782

Zhang, M., Fan, L., Liu, Y., Huang, S., & Li, J. (2022). Effects of proteins on emulsion stability: The role of proteins at the oil–water interface. *Food Chemistry*, *397*, 133726. https://doi.org/10.1016/j.foodchem.2022.133726

Zhou, B., Tobin, J. T., Drusch, S., & Hogan, S. A. (2021). Dynamic adsorption and interfacial rheology of whey protein isolate at oil-water interfaces: Effects of protein concentration, pH and heat treatment. *Food Hydrocolloids*, *116*, 106640. https://doi.org/10.1016/j.foodhyd.2021.106640