Effect of encapsulated *punica granatum* peel extract on physicochemical, sensorial, and rheological properties of mayonnaise

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ABSTRACT:

Double nanoemulsions (DEs), containing pomegranate peel extract (PPE) stabilized with/without carboxymethyl cellulose (CMC), were used to prepare reduced-fat and functional mayonnaise samples. The effect of substituting oil in mayonnaise with DEs at different levels (5, 10, and 20%) was evaluated in terms of physicochemical properties, stability, color characteristics, sensory evaluation, and rheological behavior. The results revealed that the use of pomegranate peel extract encapsulated within double emulsion (PPE-DE) and PPE-DE stabilized with CMC (CMC/PPE-DE) in mayonnaise had significant effects on the physicochemical characteristics during storage. All mayonnaise samples had physical and heat stability more than 99%, and the samples containing CMC/PPE-DE exhibited higher stability than that containing PPE-DE. Regarding color attributes, replacing oil with DEs increased the lightness and decreased the yellowness and greenness of the mayonnaise samples as compared to control mayonnaise made without DEs. Furthermore, sensory evaluation of all mayonnaise formulations presented satisfactory acceptance; however, the mayonnaise with CMC/PPE-DE 10% was the best. Eventually, the rheological measurements indicated that all mayonnaise samples exhibited a non-Newtonian, shear-thinning flow behavior, making it more applicable to the food industry.

Keywords: Functional mayonnaise; Rheology; Stability; Double emulsion; Sensory evaluation

INTRODUCTION:

Recently, consumers have had an increasing awareness of consuming functional foods containing bioactive compounds that provide health benefits (Bouarab Chibane *et al.*, 2019). Bioactive compounds, mainly polyphenols, have proved its importance not only in preventing several chronic diseases but also for their role in promoting the safety and quality of foodstuffs (Shahidi and Zhong, 2010). However, there are some problems in using these valuable compounds in the food industry. The main drawbacks of using phenolic compounds directly include their conditioned solubility, low stability, unfavorable taste, and low bioavailability. Besides, their sensitivity to thermal treatments, oxygen, and light, which make them easily destroyed during processing and storage (Zhang *et al.*, 2014; Rafiee *et al.*, 2018). In addition,, the industry currently inquires proven methods that allow the use of encapsulated polyphenols, instead of free molecules for promoting the stability and bioavailability (Niknam *et al.*, 2020). Consequently, encapsulating phenolic compounds in a double nanoemulsion system is a valid strategy to overcome all the above drawbacks (Hady *et al.*, 2022).

Salad dressings and mayonnaise increasingly becoming a popular sector of the food industry, especially among the young population due to the increasing consumption of ready-to-eat foods. It is growing at a faster rate not only in developed countries but also in developing countries (Castro-Rosas *et al.*, 2012). Mayonnaise is one of the most extensively used sauces worldwide currently. It is a viscous sauce fabricated by mixing vinegar, edible vegetable oil, salt, and egg yolk via cold emulsion (Laca *et al.*, 2010). The global mayonnaise market is estimated around 11.8 billion dollars in 2021 and is expected to reach 15.1 billion dollars by 2027 (IMARC Group, 2022).

Edible vegetable oil, as one of the main ingredients, positively affects the rheological attributes and sensory properties of the final manufactured mayonnaise. It also contributes to the texture, flavor, creaminess, palatability, appearance, and shelf-life of mayonnaise (Mun *et al.*, 2009). Moreover, one of the most important properties of mayonnaise, induced mainly by oil, is the mouthfeel property. The mouthfeel of oil in a lipid-based product is called a rheological phenomenon. The sensation of fattiness is a complex phenomenon involving a food product's flow ability and viscosity properties (Mirzanajafi-Zanjani *et al.*, 2019). However, increased consumption of dietary fats has been correlated with an increased risk of obesity, high cholesterol, coronary heart disease, some cancer, and gallbladder disease, which has promoted the trend towards low-fat foods (Worrasinchai *et al.,* 2006). Thus, demand for reduced-fat mayonnaise has been increased dramatically.

Several carbohydrate/protein-based materials have already been used to reduce fat content in mayonnaise, e.g., starch, gum, gelatin, chia mucilage, whey protein, etc. (Mun *et al.,* 2009; Fernandesa and Salas-Mellado, 2018; Yang *et al.,* 2022). However, this study uses a novel approach to reduce oil content in mayonnaise by using an encapsulated phenolic-rich extract of pomegranate peel.

This study was carried out to investigate the effect of using double nanoemulsions containing phenolic-rich extract of pomegranate peel to prepare a reduced-fat and functional mayonnaise. We investigated the effects of their replacement on the physicochemical and sensory properties as well as the rheological behavior of the mayonnaise formulations during one month of storage.

MATERIAL AND METHODS:

Materials:

Fresh pomegranate fruits Sahrawy Sp. were obtained from El-Obour market, Cairo, Egypt. Corn oil without added antioxidants (TBHQ -ve) was donated by Arma Food Industries Company (Egypt). Fresh egg yolk, Cane vinegar (5% acidity), Table salt (NaCl), and sugar were purchased from the local market, Nasr city, Cairo, Egypt. Sodium carboxymethyl cellulose (CMC) was purchased from Advent Company, Navi Mumbai (India). Sodium thiosulfate, other chemicals, and solvents were purchased from El- Gamhouria Trading Chemicals and Drugs Company (Cairo, Egypt).

Methods:

Preparations of pomegranate peel extract - Double emulsions (PPE-DE):

Pomegranate peel extract was prepared according to the methods described by Hady *et al.* (2022), while pomegranate peel extract - Double emulsions (PPE-DE) were prepared by the method of Velderrain-Rodriguez *et al.* (2019) as modified by Hady *et al.* (2022). Briefly, double $W_1/O/W_2$ nanoemulsions were fabricated as follows:

In the first step, primary W_1/O emulsions are comprised of corn oil (70%, wt/wt), the internal water phase (W_1) (22%, wt/wt), glycerol (3%, wt/wt) as cosurfactant, and PGPR (5%, wt/wt) as lipophilic surfactant. Loaded W_1/O emulsions were prepared using the PPE solution (1 mg/mL) dissolved in 0.1 M NaCl solution as W_1, while non-loaded emulsion (blank, without PPE) was prepared using 0.1 M NaCl solution as W_1. Before emulsification, glycerol and PGPR were dissolved in W_1 and corn oil, respectively, using a magnetic stirrer (60 °C for 5 min). W_1 phase was dispersed in corn oil using a high-speed homogenizer (Uni-drive X1000D-CAT, USA) operated at 6000 rpm/8 min. Subsequently, to diminish the water droplets' particle size, W_1/O emulsions were sonicated with an Ultrasonic liquid processor (Vibra-cell, VCX-750, sonics & materials, Inc.) for 3 min at 24 kHz frequency and 40% amplitude.

In the second step, $W_1/O/W_2$ emulsions were comprised of 25, 73, and 2% (wt/wt) of the W_1/O emulsion, external water phase (W_2), and Tween 20 (as a hydrophilic surfactant), respectively. The W_2 of emulsions is comprised of 0.1 M NaCl solution which was used to dissolve Tween 20 and CMC (0.5% wt/wt). The final $W_1/O/W_2$ emulsions were homogenized with a high-speed homogenizer at 6000 rpm/4 min, and subsequently sonicated for 1.5 min at a frequency of 24 kHz and 30% amplitude.

Preparation of mayonnaise:

The mayonnaise samples were prepared according to the method of Raikos *et al.* (2020) and He *et al.* (2021). The full-fat and reduced-fat mayonnaise sample recipes are shown in Table 1. For this study, 300 g of each mayonnaise sample was prepared. The full-fat mayonnaise sample (MAYO-Control) was fabricated to contain (w/w), egg yolk 15%, vinegar 4% (5% acidity), salt 0.5%, sugar 0.5%, and corn oil 80%. The sample was prepared as follows: salt, sugar, vinegar, and yolk were mixed at high speed for 3- 5 mins with a hand mixer. Then the oil was added dropwise during the mixing.

The reduced-fat mayonnaise samples were prepared by replacing the corn oil with the double nanoemulsions previously prepared (with or without CMC) at replacing levels (10%, 15%, and 20%). In the case of preparing reduced-fat mayonnaise, the emulsion was mixed with the other ingredients (except the oil) till a homogeneous mixture was obtained. Then the oil was added. These samples were named MAYO-PPE-DE 10, 15, 20 % and

MAYO-CMC/PPE-DE 10, 15, 20 %, and were compared to the control sample (MAYO-Control) represented by the mayonnaise without any emulsion. The mayonnaise samples were stored at 4 °C and monitored for 28 days.

Analytical Methods:

pH measurement:

The pH values of the mayonnaise samples were determined at room temperature (25 °C) using a pH meter (JENWAY 3550 pH meter) according to Pazhvand and Khavarpour, (2019).

Acid value:

The acid values of the mayonnaise samples were estimated using the method of Horwitz (2010). The acid value is defined as the number of milligrams of potassium hydroxide required to neutralize the acids in 1 g of fatty material (mg KOH per g) using the following equation:

Acid value = (titration ml × N) / (wight of sample taken) (1)

Where **N** is the normality of potassium hydroxide (KOH) (0.1 N), and 56.1 is the molecular weight of KOH.

Peroxide value (PV):

The PV was measured using the method of Ahmed *et al*. (2015**)**. As follows, chloroform: acetic acid solution (30 mL, 70:30 v/v) and 0.5 mL potassium iodide were added to 5 g sample. After 1 min, a few drops of starch-based adhesive and 30 ml distilled water were added to the mixture. Titration was done with thiosulfate sodium solution (0.01 mol/L). Upon reaching transparency in terms of samples color, titration was stopped, and PV (meq kg^{-1}) was estimated using equation (2)

$$PV\left(\frac{meq}{kg}\right) = \frac{1000 \times normality \times titration\ volume}{sample\ volume} \quad (2)$$

Physical and heat stability test:

To determine the physical stability, freshly prepared mayonnaise samples were stored for 7 days at 25 °C. After seven days, 10 g of respective samples (F_0) were weighed into centrifuge tubes and heated at 80 °C for 30 mins. The samples were then centrifuged at 4500 rpm for 10 mins (model: K2042, made by Centurion Scientific Ltd, UK). After centrifugation, two layers were formed, the top watery transparent layer and the bottom thick opaque layer. The top layer was carefully sucked out using a syringe leaving only the bottom precipitated layer (Pazhvand and Khavarpour, 2019). The precipitated fraction (F_1) weight was measured, and storage stability (%) was determined using the following formula:

$$Stability\ (\%) = \frac{F_1}{F_0} \times 100 \quad (3)$$

F_0 = weight of the sample, F_1= weight of the precipitated fraction.

Furthermore, to measure heat stability, mayonnaise samples were kept in a water bath at 80°C for 30 mins before centrifugation. The heat stability was then characterized using equation (3).

Color measurement

Mayonnaise samples were analyzed at Cairo University Research Park (CURP), Faculty of Agriculture for the following trait: Mayonnaise color was measured by a handheld Chroma meter (Konica Minolta, model CR 410, Japan) calibrated with a white plate and light trap supplied by the manufacturer. The color was expressed using the CIE L*, a*, and b* color system (CIE, 1976). A total of three spectral readings were taken for each sample. Lightness (L*) (dark (0) to light (100)), the redness (a*) values ((+) reddish to (-) greenish). The yellowness (b*) values ((+) yellowish to (-) bluish) were estimated.

The Hue (H) and Chroma (C) were calculated according to the method of Palou *et al*. (1999) using the following equations:

$$Hue = tane^{-1}\left[\frac{b}{a}\right] \quad \textbf{(4)}$$

$$C = \sqrt{(a^2 + b^2)} \quad \textbf{(5)}$$

Sensory Evaluation

The mayonnaise samples were evaluated organoleptically (on the second day of preparation) by a panel consisting of 20 assessors. The panelists were students and members of Food Science and Technology Department, Faculty of Agriculture, Al-Azhar University, Egypt. All mayonnaise samples were coded and served at room temperature in white plastic cups with teaspoons, and water was provided for cleaning the mouth between samples. The panelists were asked to assess the color, taste, odor, texture, and overall acceptability using a 9-point hedonic scale (9=Like extremely, 8=Like very much, 7=Like moderately, 6=Like slightly, 5=Neither like nor a dislike, 4=Dislike slightly, 3=Dislike moderately, 2=Dislike very much, 1=Dislike extremely) (Khan *et al*., 2020a).

Rheological properties of mayonnaise

The rheological behavior of the mayonnaise samples was determined by Anton Paar MCR-301 Rheometer (Anton Paar GmbH, Graz, Austria). The flow behavior of the samples was evaluated using a plate-plate geometry (PP25 measurement system). The mayonnaise sample was loaded using a spatula, and the upper plate was lowered to achieve a designated gap. The experiment was conducted at a gap distance of 0.5 mm. The measurements were carried out in the shear rate range of 0.01 - 100 s^{-1} at constant temperature (25° C ± 0.5). Shear stress and apparent viscosity were recorded as a function of shear rate. Rheoplus V3.40 software was used for rheological data analysis (Kumar *et al*., 2021). The flow parameters K and n were determined using the Power-law model as in equation 6:

$$\eta = K\Upsilon^{n-1} \qquad (6)$$

where η is the apparent viscosity (Pa. s), K is the consistency coefficient (Pa s^n), Υ is the shear rate (s^{-1}) and n is flow behavior index (dimensionless).

Statistical analysis

Values are shown as mean ± SD. Statistical analyses were done using one-way analysis of variance (ANOVA) using SPSS software (Version 26); $P < 0.05$ was considered significant.

RESULTS AND DISCUSSIONS:

pH of mayonnaise samples:

The pH of mayonnaise has remarkable roles in its structure and stability (Depree and Savage, 2001). It influences the sensory properties of mayonnaise and is also vital in ensuring microbiological safety, hindering the growth of microorganisms, and enhancing food shelf life (Ghirro *et al.,* 2022). Figure 1 illustrates the pH changes of different mayonnaise samples during storage at 4° C, as affected by replacing oil with DEs. At zero time, the pH values of the control and reduced-fat mayonnaise samples were significantly different ($p < 0.05$), and the pH values varied from 4.17 to 4.42. After 28 days of storage, the pH values in all samples slightly decreased: ranged between 3.95 to 4.11. It was noted that the increasing replacement of oil by DEs resulted in a lower reduction in the pH of the mayonnaise samples after 28 days of storage. The sample MAYO-PPE-DE 20% exhibited a minimal pH reduction percentage (3.78%) compared to the other mayonnaise samples. Simultaneously, the control sample showed the highest pH reduction percentage (9.7%). These decreases were probably due to hydrolysis of triglycerides and formation of free fatty acids. These observations are in agreement with the results of (Savaghebi *et al.,* 2021) who observed a decreasing trend in pH values of mayonnaise containing different formulations of nanoliposomes loaded with brown algae extract during storage.

Acid values of mayonnaise samples:

The increase in acid value refers to the increased amount of free fatty acid in the sample caused by the hydrolysis of triglycerides, which results in hydrolytic rancidity (Jadhav *et al.,* 2022). The present findings showed that the initial acid values of the control and reduced-fat mayonnaise samples were remarkably different ($p <0.05$), as shown in figure 2. Moreover, the acid value is increased in all mayonnaise samples during the storage time, being the highest in the control sample (0.258–0.729 mg KOH g^{-1} oil), followed by MAYO-PPE-DE 10% (0.235–0.476 mg KOH g^{-1} oil) and MAYO-CMC/PPE-DE 10% (0.238–0.446 mg KOH g^{-1} oil) samples. This finding could be due to the activity of acid-tolerant microbial strains, like lactic acid bacteria, which are present in the aqueous phase in mayonnaise (Fialová *et al.,* 2008), or because of the activity of hydrolytic and oxidative enzymes in eggs (Stefanow, 1989). It is noteworthy that the increased replacement of oil by DEs in mayonnaise samples considerably ($P < 0.05$) inhibits the progress in acid value. A similar increasing trend versus storage time was also reported by (Kishk and Elsheshetawy, 2013), who found that the acid values of the mayonnaise samples gradually increased with increasing the storage time. Likewise, the mayonnaise samples with various levels of essential oils had the lowest acid value at the end of the storage period compared to the control sample (El kalyoubi *et al.,* 2021). In contrast, Karas *et al. (*2002) reported that although the acid value increased for all mayonnaise samples during storage, the standard mayonnaise had a lower acid value than the light (reduced-fat) mayonnaise.

Peroxide value of mayonnaise:

Peroxide value is the typical method used to assess peroxide and hydroperoxide concentrations during the early stage of lipid oxidation (Alizadeh *et al.,* 2019). As shown in figure 3, the initial peroxide value in the different mayonnaise formulations was considerably affected ($p < 0.05$) by the various replacements of DEs, and the values ranged from 0.497–0.869 meq kg^{-1} oil. Furthermore, the peroxide values gradually elevated as the storage period progressed, indicating that the mayonnaise gradually became rancid during storage.

On the last day of storage (day 28), the highest peroxide value was related to the control sample (6.779), followed by MAYO-CMC/PPE-DE 10% (4.559). At the same time, the lowest value corresponded to MAYO-PPE-DE 20% (3.241). Despite the control sample did not have the highest initial peroxide value, it had a higher rate of increase than the other formulations at the end of the storage period. Our results revealed that the DEs containing pomegranate peel extract significantly retard the hydroperoxide formation. Collectively, the observed data show that all peroxide values were less than 10, indicating that the mayonnaise samples were safe in refrigerated conditions. This is consistent with Yesiltas *et al.* (2021), who found that the peroxide value of mayonnaise samples enriched with high-fat fish O/W emulsions was less than 10 meq kg^{-1} at the end of storage.

Physical stability of mayonnaise:

Physical stability was considered the period during which the emulsions did not show a separation of the visual phase (Anamaria, 2019). The results of physical stability are displayed in figure 4. Physical stability greater than 99% was observed in all mayonnaise samples. The highest stability value (100%) was obtained for the control sample. At the same time, the MAYO-PPE-DE 20% sample exhibited the lowest stability (99.517%). Our results are in agreement with those of Shamooshaki *et al*. (2015), who found that the physical stability of the mayonnaise samples was above 99%.

Emulsion stability is generally concerned with preventing coalescence, flocculation, and creaming of droplets. For mayonnaise samples with a high-fat content (80%), creaming is usually not a problem because the droplets are packed so tightly together that they cannot move. However, in low-fat products, creaming is usually avoided by adding a thickening agent, such as gum or protein, to the water phase to slow the movement of the droplets (Mun *et al.,* 2009). Therefore, in our study, mayonnaise samples containing CMC/PPE-DE exhibited higher stability than mayonnaise samples containing PPE-DE. This is due to the increased viscosity caused by the addition of carboxymethyl cellulose.

Heat stability of mayonnaise:

It is generally known that the mayonnaise stability decreases at high temperatures. An oil-in-water emulsion system like mayonnaise can be broken by increasing temperature which causes oil exudation (Huang *et al.,* 2016). Here, the heat stability experiment revealed that replacing oil with DEs in mayonnaise formulations did not negatively affect its stability.

Results related to stability towards temperature are also shown in figure 4. The samples had heat stability greater than 99%. The highest stability was recorded for sample MAYO-CMC/PPE-DE 10% (99.97%) and the lowest for control (99.25%). From figure 4, it could also be observed that the heat stability was higher in mayonnaise samples prepared with CMC/PPE-DE, while the samples prepared with PPE-DE (without CMC) and the control represented lower stability. This finding is consistent with Shamooshaki *et al.* (2015), who found that the mayonnaise samples prepared using a combination of whole milk and xanthan gum as egg replacers had heat stability higher than 99 % during 30 days storage period.

Color change of mayonnaise:

Color is one of the most important quality characteristics of mayonnaise and the first criterion by which consumers decide whether to reject or accept the product (Fernandesa and Salas-Mellado, 2018). As shown in Table 2, the L* value of all mayonnaise formulations in which DEs replaced corn oil was significantly different ($P < 0.05$) from the control mayonnaise. Furthermore, with the increasing replacement of oil with DEs, the mayonnaise showed a trend of becoming brighter; in this regard, MAYO-CMC/PPE-DE 20% gave the brightest color and the highest L* value (89.59), followed by MAYO-CMC/PPE-DE 15% (89.45). Meanwhile, MAYO- Control exhibited the lowest L* value (86.72). Our findings are similar to those of Amin *et al.* (2014). They reported increased luminosity in mayonnaise samples with low-fat containing xanthan gum, guar gum, and a blend of xanthan and guar gums.

The redness (a*) values of mayonnaise are influenced by replacing oil with various percentages of DEs. The a* values exhibited negative denominations (ranging from -3.85 to - 4.51), indicating the tendency of mayonnaise to green color. As seen in Table 2, a* values of all mayonnaise formulations were significantly different (P < 0.05) compared to control mayonnaise.

In general, the intensity of the green color increased by increasing the replacement levels in PPE-DE samples, reaching - 4.51 in mayonnaise containing 20% PPE-DE; this might be attributed to the variations in moisture content of different mayonnaise samples (Sun *et al.,* 2018). In contrast, the CMC/PPE-DE samples showed a decreasing trend in the intensity of green color with increasing the replacement levels, which is linked directly to the emulsifier, CMC, included in the DEs.

The variation in the value of b* is considered a limiting factor in mayonnaise development (Khan *et al.,* 2020b). Replacing oil with DEs significantly decreased b* values, where the MAYO-Control sample exhibited the greatest b* value (37.6). In contrast, the MAYO-CMC/PPE-DE 20% sample showed the lowest value (23.01). Li *et al.* (2014) found that the b* value of mayonnaise reduced with the addition of polymers (micronized konjac).

The Hue angle value lessened with increasing oil replacement by DEs; all mayonnaise samples had Hue angle values slightly above 80, which indicates the yellow coloration. Moreover, MAYO-Control (full-fat mayonnaise) was noted with the highest value (84.1), compared to the other mayonnaise formulations, which proved that the yellow color of the oil was reduced. On the other hand, the chroma, which is an indicator of the intensity and saturation of the color, also diminished with increasing oil replacement with DEs, and it ranges from 37.45- to 23.38. Overall, these results clearly indicated that replacing oil with DEs increased the lightness and decreased the yellowness and greenness of the mayonnaise compared to control mayonnaise made without DEs.

Sensory Evaluation:

The effects of replacing oil with DEs on the sensory characteristics of mayonnaise are presented in figure 5. It could be noticed that the increment in the replacing level of oil with DEs led to a decrement in the mean value of the color score of the produced mayonnaise, except for the CMC/PPE-DE 10% sample, which had a better color score (8.64) which seems the same as the control (8.60). Meanwhile, there is no notable difference (P< 0.05) between all types of mayonnaise. Sensory evaluation of color was correlated to the color parameters (L*, a*, b*) measured by the Chroma meter (Table 2). A greater yellowness (b*) of mayonnaise resulted in better color acceptance by the panelists. These results are consistent with (Liu *et al.,* 2007), who found that full-fat mayonnaise with a dark yellow color was more receptive than off-white color.

The taste score, one of the vital organoleptic properties of mayonnaise, ranges from 8.40 to 7.50. It is noteworthy that an increase in oil replacement by DEs resulted in a decrease in the taste score of the mayonnaise produced, except for the sample PPE-DE 10%, which has the same score as the control. Mayonnaise made with high oil replacement levels had a lower taste score than the other mayonnaise samples. But there were no significant differences between the samples. Similar results were reported by Khan *et al.* (2020b) who made mayonnaise with the addition of microencapsulated vitamin D and showed no significant difference in the taste parameter.

On the other hand, the odor score was slightly increased by increasing the oil replacement levels. CMC/PPE-DE 10% sample gave the highest score for this attribute. However, there was no statistically significant difference (P< 0.05) between all types of mayonnaise. El-Bostany *et al.* (2011) found that the addition of potato powder as a substitute of fat did not significantly influence the odor attribute of mayonnaise samples.

Regarding texture, replacing oil with DEs decreased the texture score, but CMC/PPE-DE 10% was superior in texture scores. The maximum score was acquired by CMC/PPE-DE 10% (8.8), while the lowest was given to PPE-DE 20% (6.7).

These results agree with those of Rafiee *et al.* (2018) who found that mayonnaise prepared with nanoliposomes containing pistachio green hull's phenolic compounds, which had a high degree of acceptability in sensory attributes. In the present study, all mayonnaise samples showed satisfactory results for overall acceptability; however, the best results were obtained in MAYO-CMC/PPE-DE 10%.

Rheological Properties of Mayonnaise:

Figure 6 shows the flow rheogram of different mayonnaise samples relating viscosity to shear rate. From the curves, it can be concluded that the viscosity (η) of mayonnaise samples decreases with increasing shear rate (γ) from 10^{-2} to 10^{2} S^{-1}, confirming that all mayonnaise samples exhibit shear-thinning (pseudoplastic) non-Newtonian flow behavior. In more detail, the initial viscosity of all mayonnaise samples ranged from 1420 to 8790 Pa.s, while the viscosity obtained at the higher shear rate (100) ranged from 1.77 to 6.27 Pa.s. The viscosity was the highest for the control sample but decreased with increasing oil replacement level with DEs, except for the CMC/PPE- DE 10% sample, which was higher than the control sample at a high shear rate. From figure 6, the viscosity of mayonnaise samples fabricated with CMC/PPE- DE was higher than that fabricated with PPE-DE. This finding indicates that the CMC can be used as a hydrophilic emulsifier in DE to enhance the viscosity.

The shear-thinning non-Newtonian flow behavior can be explained as when the shear rate increases adequately to overcome the Brownian motion, the resistance to the flow also decreases; thus, the viscosity decreases. This flow behavior may also be due to the breakdown of the interactions between the compounds (Erçelebi and Ibanoğlu, 2009). Our results are like to those of Lorenzo *et al.* (2008) who observed the shear-thinning behavior of low-fat emulsions stabilized with xanthan/guar blends.

Figure 7 shows the flow rheogram of different mayonnaise formulations for shear stress (τ) as a function of shear rate (γ). In general, shear stress and shear rate data showed that their relationship was nonlinear for all mayonnaise formulations. Thus, non-Newtonian flow characteristic was observed. In more detail, for the control, the shear stress, after the initial rapid increase (till share rate 5.27 S^{-1}), quickly turned to a wavy curve (moves up and down) when the shear rate further increased from 5.27 - 100 S^{-1}. On the other hand, the reduced-fat mayonnaise samples showed shear-thinning behavior (pseudoplastic behavior). Increasing the shear rate and replacers percentage causes an increase in the shear stress. MAYO-CMC/PPE-DE 10% sample exhibited higher shear stress values with increasing shear rate, whereas MAYO-PPE-DE 20% exhibited lower shear stress values.

It must be noted that, at a similar shear rate, MAYO-PPE-DE sampes displayed lower shear stress values than MAYO-CMC/PPE-DE samples indicating that the CMC affects the structure of the mayonnaise. The MAYO-PPE-DE 10% and MAYO-CMC/PPE-DE, 20% samples were almost overlapping, indicating that these samples showed similar steady shear rheological properties despite the difference in oil content. This could be due to the influence of CMC. In salad dressing type emulsions, reducing oil content could change their rheological and textural behavior and profoundly influence their stability during storage (Tekin-Cakmak *et al.,* 2021). Therefore, the fact that low-fat mayonnaise with hydrocolloids (CMC) and high-fat mayonnaise show similar rheological properties is an important development for the food industry.

Our findings are similar to those of Izidoro *et al*. (2007), who found that the shear stress increased with increasing the shear rate, and the mayonnaise samples exhibited non-Newtonian pseudoplastic behavior. They also found that the control mayonnaise exhibited higher shear stress than the light (reduced-fat) mayonnaise.

Power-law model:

The flow characteristics of the mayonnaise sample were calculated according to the Power-law model to check the behavior of the mayonnaise samples. The results (Table 3) are expressed as consistency index (K) that resembles the viscosity at a particular shear rate (s^{-1}) and flow exponent (n) a dimensionless parameter that reveals deviance of the fluid from the Newtonian flow.

When the flow behavior index (n) is greater than 1, the fluid acts as a shear-thickening non-Newtonian fluid. When n is less than 1, the fluid has shear-thinning (pseudoplastic nature) non-Newtonian flow behavior (Li *et al*., 2021). In this study, the flow behavior index (n) values of mayonnaise samples ranged from 0.198 to 0.431, indicating that mayonnaise behaves as a non-Newtonian fluid with shear thinning.

The consistency index (K) of all mayonnaise samples was found to be higher than 1 and affected by the replacement of the oil. The K value is the parameter that indicates the viscous nature of the fluid. As can be observed from Table 3, the K decreased with increasing the replacement levels of the oil. MAYO-Control sample achieved the highest K (K=208.1 $Pa.s^n$). Generally, a higher value of K usually indicated that the emulsion had high viscosity, which corresponds to a stronger network structure (Worrasinchai *et al*., 2006). Consequently, the MAYO-Control sample had the highest viscosity followed by MAYO-CMC/PPE-DE 10%.

CONCLUSION

In this study, a reduced-fat and functional mayonnaise was formulated by replacing the oil with PPE-DE or CMC/PPE- DE at 5%, 10%, and 20%. The use of the encapsulated extract in the mayonnaise formulations gave better results in the parameters of pH, acidity, and peroxide compared to the control sample, consequently improving safety and extending the shelf-life of the products. In addition, the color determination showed that the lightness of the mayonnaise increased with the increasing replacement of the oil. Sensory evaluation showed satisfactory results for overall acceptability. Moreover, the rheological properties presented non-Newtonian fluid behavior with pseudoplastic characteristics, and the apparent viscosity decreased with increasing shear rate. These results suggest new approaches for formulating healthier foodstuffs and valorizing pomegranate by-products.

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Table 1: Formulations of mayonnaise samples.

Ingredients	MAYO-Control	MAYO-PPE-DE			MAYO-CMC/PPE-DE		
		10%	15%	20%	10%	15%	20%
Corn oil	80	72	68	64	72	68	64
Egg yolk	15	15	15	15	15	15	15
Cane vinegar (acidity 5%)	4	4	4	4	4	4	4
Salt	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Sugar	0.5	0.5	0.5	0.5	0.5	0.5	0.5
PPE-DE	-	8	12	16	-	-	-
CMC/PPE-DE	-	-	-	-	8	12	16
Total	100	100	100	100	100	100	100

Note: MAYO-Control, mayonnaise without double emulsion; MAYO-PPE-DE (10, 15, 20%), mayonnaise with double emulsion containing pomegranate peel extract; MAYO-CMC/PPE-DE (10, 15, 20%), mayonnaise with double emulsion containing pomegranate peel extract stabilized with carboxymethyl cellulose.

Table 2: Color parameters of mayonnaise as affected by replacing oil with different levels of double nanoemulsions containing pomegranate peel extract.

Color parameters	Control	PPE-DE			CMC/PPE-DE		
		10%	15%	20%	10%	15%	20%
L*	86.72 ± 0.25^{d}	88.91± 0.03^{bc}	89.11 ± 0.00^{b}	89.00 ± 0.13^{b}	88.68 ± 0.04^{c}	89.45 ± 0.00^{a}	89.59 ± 0.06^{a}
a*	- 3.85 ± 0.09^{e}	- 4.31 ± 0.03^{c}	- 4.42 ± 0.02^{b}	- 4.51 ± 0.01^{a}	- 4.25 ± 0.02^{c}	- 4.09 ± 0.01^{d}	- 4.16 ± 0.01^{d}
b*	37.25 ± 013^{a}	24.96 ± 0.01^{d}	24.89 ± 0.01^{d}	25.12 ± 0.01^{c}	31.00 ± 0.02^{b}	24.74 ± 0.00^{e}	23.01 ± 0.04^{f}
hue	84.10 ± 0.15^{a}	80.20 ± 0.1^{b}	82.90 ± 5.2^{ab}	79.82 ± 0.0^{b}	82.19 ± 0.05^{ab}	80.61 ± 0.0^{ab}	79.75 ± 0.05^{b}
Saturation	37.45 ± 0.12^{a}	25.33 ± 0.0^{d}	25.28 ± 0.01^{d}	25.52 ± 0.01^{c}	31.29 ± 0.02^{b}	25.08 ± 0.0^{e}	23.38 ± 0.04^{f}

Note: Values are the means ± standard deviations (n = 3). and different small letters (a, b, c ...) in the same column shows significant difference among different treatments (Tukey's test, $p<0.05$). For abbreviations see Table 1.

Table 3: power-law parameters (K, *n*) of mayonnaise as affected by replacing the oil with different levels of double nanoemulsions containing pomegranate peel extract.

Rheological parameters	MAYO-Control	MAYO-PPE-DE			MAYO-CMC/PPE-DE		
		10%	15%	20%	10%	15%	20%
Consistency Index (K) (Pa.s^n)	208.18	33.53	40.961	25.923	139.6	69.35	44.201
Flow Behavior Index (n)	0.1987	0.4312	0.4163	0.41	0.3177	0.3527	0.3607

Note: For abbreviations see Table 1.

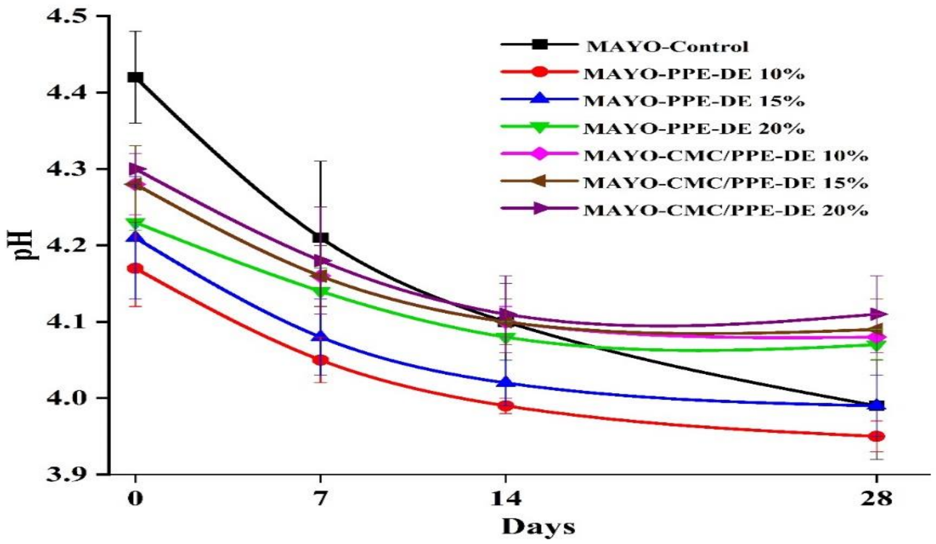

Figure 1: pH of mayonnaise samples with different formulations during storage at 4 °C. MAYO-Control, mayonnaise without double emulsion; MAYO-PPE-DE (10, 15, 20%), mayonnaise with double emulsion containing pomegranate peel extract; MAYO-CMC/PPE-DE (10, 15, 20%), mayonnaise with double emulsion containing pomegranate peel extract stabilized with carboxymethyl cellulose.

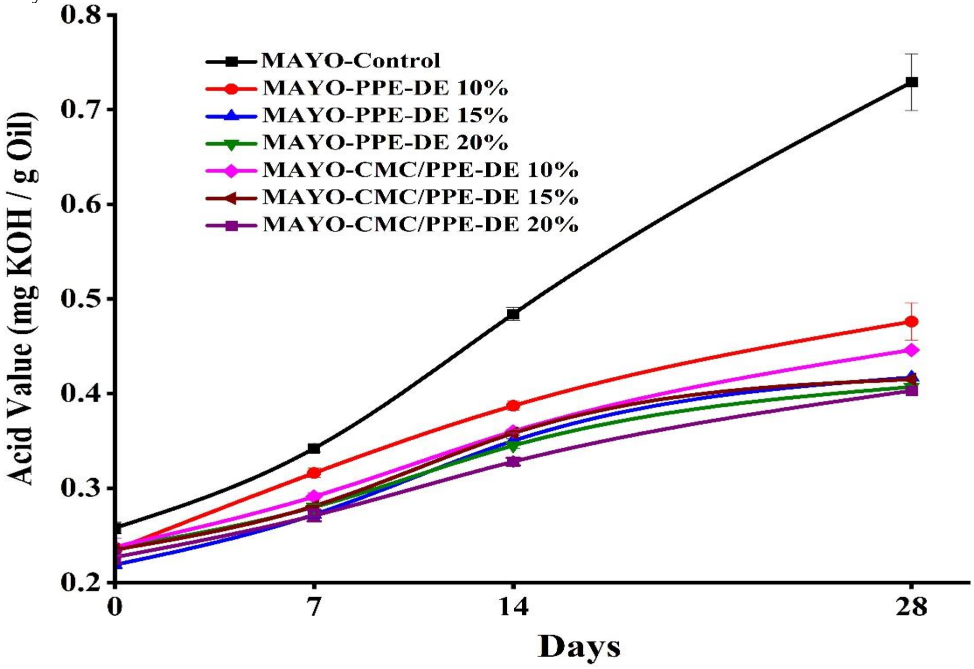

Figure 2: Acid value of mayonnaise samples with different formulations during storage at 4 °C. For abbreviations see Figure 1.

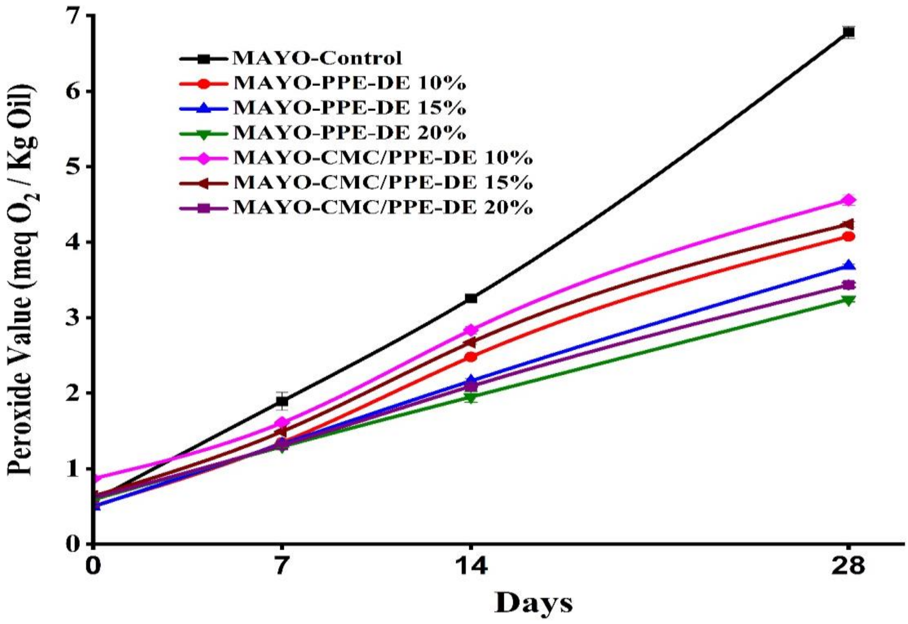

Figure 3: Peroxide value of mayonnaise samples with different formulations during storage at 4 °C. For abbreviations see Figure 1.

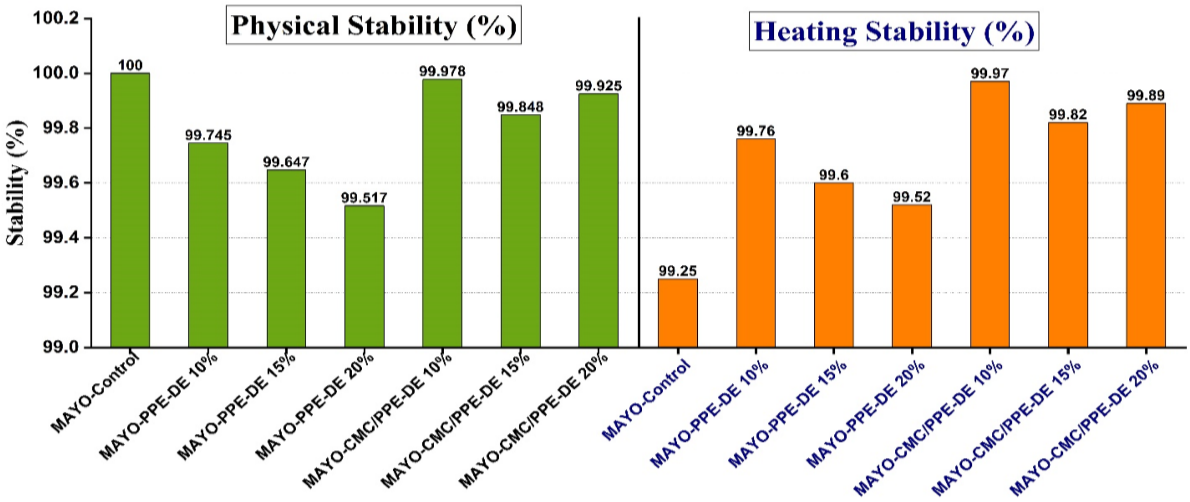

Figure 4: Stability of different formulations of mayonnaise samples. For abbreviations see Figure 1.

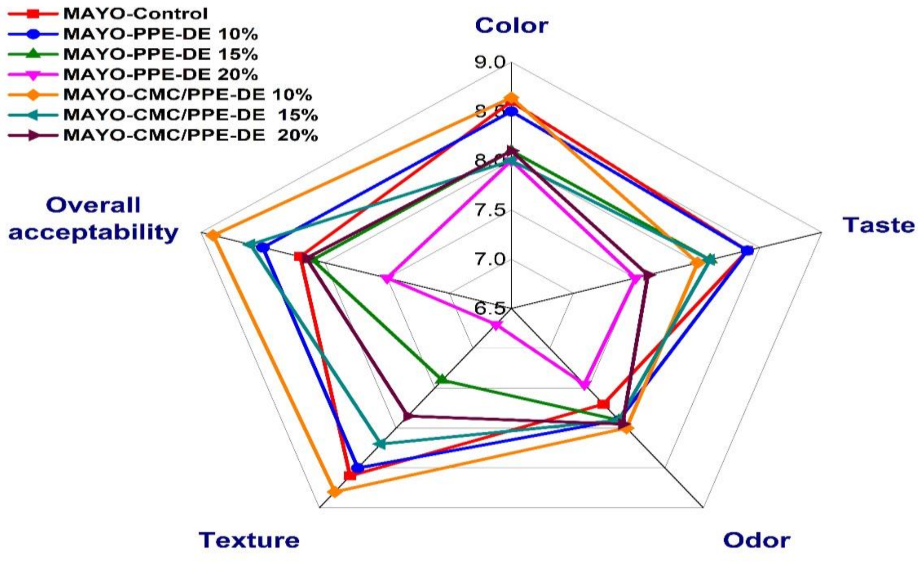

Figure 5: Sensory evaluation of different formulations of mayonnaise samples. For abbreviations see Figure 1.

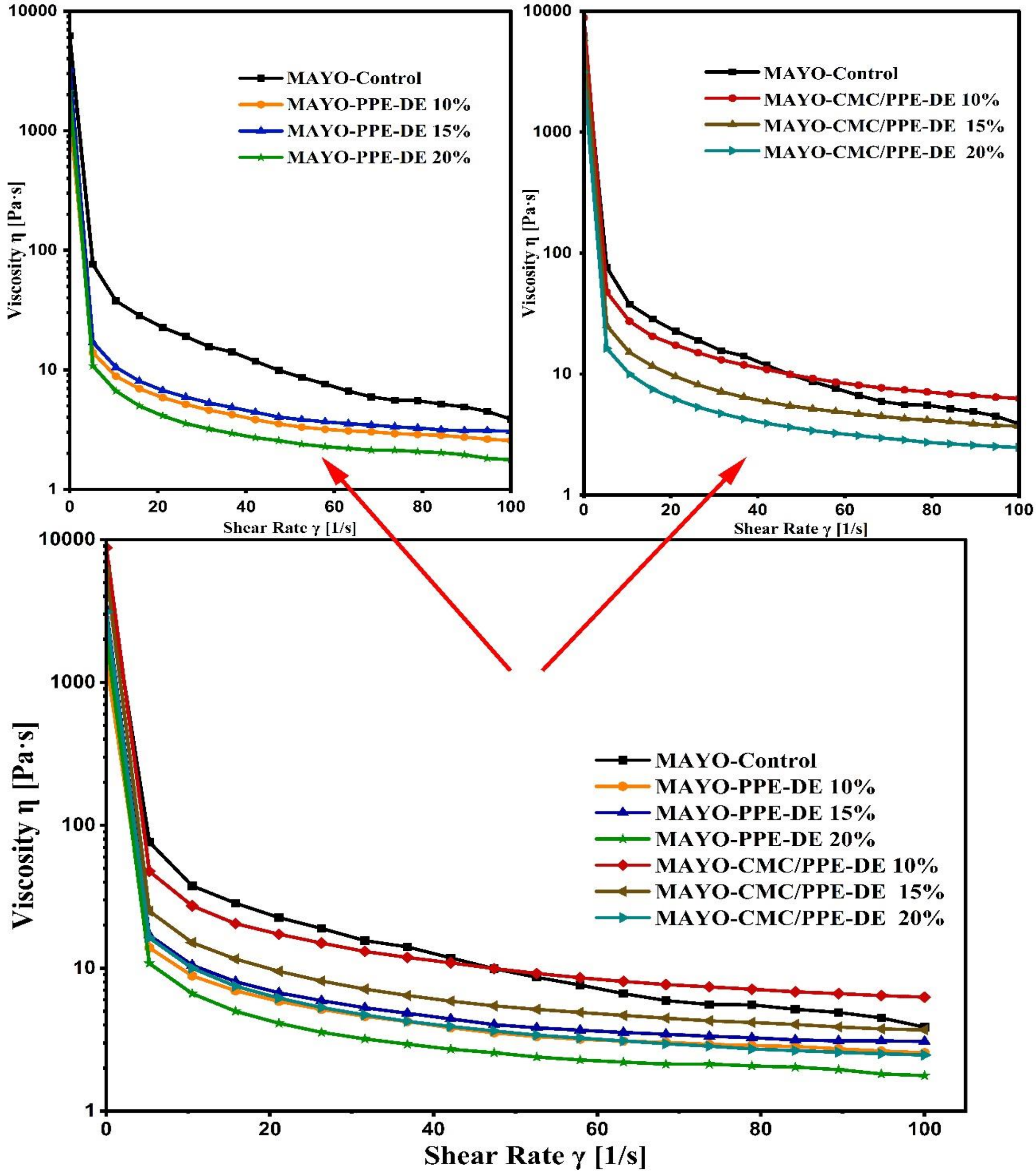

Figure 6: Apparent viscosity versus shear rate of different formulations of mayonnaise samples. For abbreviations see Figure 1.

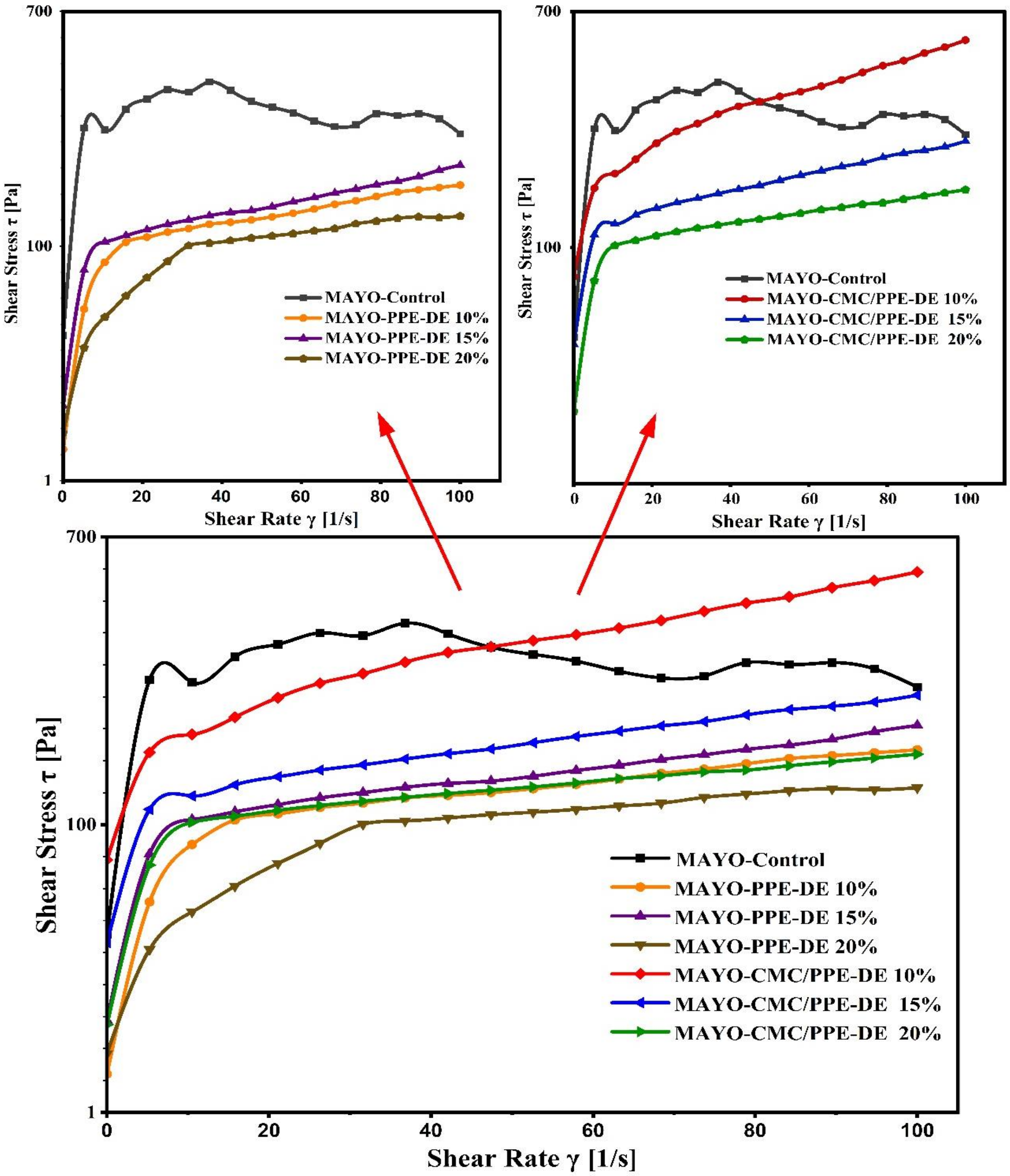

Figure 7: Shear stress versus shear rate of different formulations of mayonnaise samples. For abbreviations see Figure 1.

تأثير إستخدام مستخلص قشر الرمان المغُلف على الخواص الفيزيائية والكيميائية والحسية والريولوجية للمايونيز

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الملخص العربي

تم استخدام مستخلص قشر الرمان المغلف داخل مستحلبات النانو المزدوجة المثبتة بـ/بدون كربوكسي ميثيل السليلوز، لتحضير مايونيز وظيفي و منخفض الدهن. تم تقييم تأثيرات إستبدال الزيت في المايونيز بمستويات مختلفة (٥ و ١٠ و ٢٠٪) من المستحلبات المزدوجة على الخصائص الفيزيائية والكيميائية والثباتية وخصائص اللون والتقييم الحسي والصفات الريولوجية للمايونيز المنتج. أظهرت النتائج أن استخدام مستخلص قشر الرمان المغلف داخل المستحلب المزدوج في المايونيز كان له تأثير كبير على الخصائص الفيزيائية والكيميائية أثناء التخزين. جميع عينات المايونيزكان لها ثبات فيزيائي وحرارى أكبر من ٩٩٪ وقد أظهرت العينات التي تحتوي على مستخلص قشر الرمان المغلف والمثبت بالكربوكسي ميثيل السليلوز ثباتًا أعلى من عينات المايونيز التي تحتوي على قشر الرمان المغلف غير المثبت بالكربوكسي ميثيل السليلوز. فيما يتعلق بصفات اللون، أدي استبدال الزيت بمستحلبات النانو المزدوجة الى زيادة درجة بياض اللون للمايونيز بينما قلل من درجات الاصفرار والإخضرار له مقارنة بالمايونيز الكنترول المصنوع بدون مستحلبات مزدوجة. علاوة على ذلك، أظهر التقييم الحسي لجميع تركيبات المايونيز قبولًا مرضيًا؛ ومع ذلك كانت عينة المايونيز المحتوية على قشر الرمان المغلف والمثبت بالكربوكسي ميثيل السليلوز ١٠٪ هى الأفضل. أشارت القياسات الريولوجية إلى أن جميع عينات المايونيز أظهرت سلوكاً غير نيوتروني .

الكلمات الاسترشادية: المايونيز الوظيفى ، الصفات الريولوجية ، الثباتية ، المستحلب المزدوج ، التقييم الحسى.