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Investigation on physicochemical properties, sensory quality and storage stability of mayonnaise prepared from lactic acid fermented egg yolk

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ABSTRACT

In this research, the physicochemical properties, sensory quality, and storage stability of mayonnaise prepared from egg yolk fermented for different times (0, 3, 6, and 9 h) have been investigated. Compared with control mayonnaise (3.50 μm and 92.88%), mayonnaise prepared from fermented egg yolk possessed significantly lower particle size (3.32–3.41 μm) and higher emulsion stability (97.26–98.72%). Meanwhile, texture, color, and gas chromatography-mass spectrometry (GC–MS) analysis revealed that the fermented egg yolk significantly enhanced the firmness, consistency and cohesiveness, lightness and redness, and flavor profile of mayonnaise. Sensory evaluation showed that mayonnaise with 3 h-fermented egg yolk exhibited the highest sensory scores. And the microscopic and appearance characteristics revealed that fermented egg yolk endowed mayonnaise with a more stable appearance after 30 days of storage. These results indicated that lactic acid fermentation of egg yolk is a feasible way to improve consumer acceptability and shelf life of mayonnaise.

1. Introduction

Mayonnaise is a semi-solid emulsion generally composed of egg yolk, vegetable oil, vinegar, and other seasonings. Due to its special flavor and creamy mouthfeel, mayonnaise is a traditional condiment that is widely used in the world (Sun et al., 2018). The flavor of mayonnaise is mainly governed by egg yolk and oil (Yu et al., 2021). Depending on the high oil content, mayonnaise is vulnerable to oxidation and generates off-flavor, decreasing flavor quality and consumer acceptance (Ozdemir, Kantekin-Erdogan, Tat, & Tekin, 2018). In addition. egg yolk is an important emulsifier in mayonnaise and prevents the flocculation of components (Mirzanajafi-Zanjani, Yousefi, & Ehsani, 2019). However, during the long-term storage of mayonnaise, phase separation would occur, and oil droplets would coalesce. This induces the poor storage stability of mayonnaise. Thus, improving the flavor and storage stability of mayonnaise is crucial to enhance market competition and economic benefits.

In general, some food additives, such as flavors and preservatives, are used in mayonnaise to improve flavor and storage stability. And recent investigations have improved the flavor or storage stability of mayonnaise by adding natural flavoring ingredients or food gum (Chatterjee & Bhattacharjee, 2015; Li, Wang, Jin, Zhou, & Li, 2014b; Mozafari, Hosseini, Hojjatoleslamy, Mohebbi, & Jannati, 2017; Teneva et al., 2021). For example, Chatterjee et al. (2015) used eugenol-lean clove extract as flavor ingredient and bio preservatives, improving flavor score and shelf-life in mayonnaise. Mozafari et al. (2017) revealed that mayonnaise containing zodo gum and xanthan gum showed better texture and stability. Nevertheless, the isolation of natural food additives is still complex and costly. These days, to keep pace with the trends of health, naturalness, and sustainability, searching for a natural and green way to improve the flavor quality and prolong the storage stability of mayonnaise is meaningful and interesting.

Lactic acid fermentation is an old method to naturally improve the flavor and storage stability of foods (Dhundale, Hemke, Desai, & Dhundale, 2018; Li et al., 2014a; Liu et al., 2022; Tian et al., 2021). Li et al., (2014a) demonstrated that compared with raw soymilk, the soymilk fermented by *Lactobacillus plantarum* has lower off-flavor and better texture. Liu et al. (2022) reported that walnut milk fermented by *Lactobacillus plantarum* exhibits an improved aroma quality resulting from the decreased aldehydes and the increased alcohols, acids, esters, and ketones. Dhundale et al. (2018) reported that lactic acid bacteria were used as antibacterial agents to extend the shelf life of fruit. Our

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recent study (Tian et al., 2021) revealed that egg yolk fermented by commercial lactic acid bacteria possesses better emulsifying properties, which may contribute to the storage stability of mayonnaise. Here, we have the hypothesis that lactic acid fermentation of egg yolk is a potential method to improve the flavor quality and prolong the storage stability of mayonnaise.

In this research, egg yolk was fermented by *Streptococcus thermophilus* and *Lactobacillus delbrueckii* ssp. *Bulgaricus*, which promote each other's growth by exchanging metabolites (Sieuwerts et al., 2010) and are widely used in fermented foods such as yogurts and eggs (Jia et al., 2021; Jiang et al., 2020; Peng et al., 2022; Tian et al., 2021). The objective of this work was to (1) determine the effects of egg yolk under different fermentation time points (0, 3, 6, and 9 h) on the physicochemical properties and flavor quality of mayonnaise, and (2) evaluate the effect of fermented egg yolk on the stability of mayonnaise during 30 days of storage. The results will provide a reference for the utilization of fermentation technology to improve consumer acceptability and shelf life of mayonnaise.

2. Material and methods

2.1. Material

Fresh hen eggs, lemon, mustard, vinegar, salt, and sugar were food-grade and supplied by Jiafu Supermarket (Yangling, China). Golden dragon fish brand corn oil was food-grade and purchased from Yihai Kerry Cereals, Oils and Foodstuffs Co., Ltd. (Shanghai, China). *Streptococcus thermophilus* JYST-26 and *Lactobacillus delbruekii* ssp. *bulgaricus* JLBB-131 were supplied by Shandong Zhongkejiayi Biological Engineering Co., Ltd. (Qingzhou, China). The C_6-C_{26} *n*-alkanes were acquired from Sigma-Aldrich Co., Ltd. (St. Louis, USA). Sodium dodecyl sulfate (SDS, 190522) was purchased from MP Biomedicals, LLC. (Santa Ana, USA). Nile red (HPLC purity ≥ 98%) was purchased from Macklin Inc. (Shanghai, China).

2.2. Fermentation of egg yolk

The fermentation treatment was according to our previous study (Tian et al., 2021). Firstly, egg yolk was carefully separated from egg white, collected in sterilized bottles, and pasteurized. Subsequently, *Streptococcus thermophilus* JYST-26 and *Lactobacillus delbrueckii* ssp. *Bulgaricus* JYLB-19 powders were added into egg yolk (1%, w/v egg yolk), separately, followed by fermenting at 42 °C in Thermostatic Incubator (DNP-9162, Shanghai Jing Hong Laboratory Instrument Co., Ltd., Shanghai, China) for 3, 6, and 9 h. The native egg yolk was used as a control.

2.3. Mayonnaise preparation

The mayonnaise was prepared according to Shen et al. (2011) with some modifications of formula and mixing times. Based on the total volume of ingredients, the mayonnaise recipe contained 76% of corn oil, 12% of egg yolk, 3.4% of water, 3% of lemon juice, 3% of sugar, 1% of vinegar, 1% of salt, and 0.6% of mustard. All ingredients except corn oil were mixed using a hand mixer (HMP30, Kenwood Ltd., Havant, UK) at speed 1 for 5 min. Then, corn oil was added slowly within 15 min and mixed at speed 2. The mixture was mixed at speed 3 for 5 min. The obtained mayonnaise (containing native, 3 h, 6 h, and 9 h-fermented egg yolk, respectively) was stored at 4 °C for 24 h until determination.

2.4. Particle size

After 1 day, 7 days, 15 days, and 30 days of storage, the particle size of mayonnaise samples was analyzed based on Flamminii et al. (2020) using a nanometer particle size and zeta potentiometer (ZEN3600, Malvern Instruments Ltd., Worcestershire, UK). 0.2 g mayonnaise samples were diluted with 20 mL 1% (w/v) SDS solution and mixed using a magnetic stirrer (99–1, Changzhou guohua electric appliance Co., Ltd., Changzhou, Jiangsu). The refractive index was set at 1.46, and the absorption was 0.00. Particle size represents the volume mean diameter ($D_{4,3}$).

2.5. Rheological properties

The rheological properties of mayonnaise were measured using a rheometer (Discovery DHR-1, TA, Waters, UK) according to previous literature (Li et al., 2014b). The mayonnaise sample was loaded onto the parallel plate and removed the excess sample. Then, the exposed periphery of the mayonnaise was covered with silicone oil to prevent moisture loss. The measurement was carried out at 25 °C. The apparent viscosity of mayonnaise was detected with a shear scan (0.1–100 s^{-1}). The viscoelasticity was determined under 0.5% of strain (within the linear viscoelastic region) with an angular frequency scan (0.1–100 rad/s). The data were represented as storage modulus (G') and loss modulus (G'').

2.6. Emulsion stability

The emulsion stability of mayonnaise samples was detected based on Park, Olawuyi, & Lee (2020). Briefly, 15 g of mayonnaise samples were placed into centrifuge tubes and heated in an electrothermal constant-temperature water tank (HH-2A, Beijing kewei yongxing Instrument Co., Ltd, Beijing, China) at 60 °C for 30 min. After centrifugation (4000 rpm, 4 °C, 20 min) in a high-speed refrigerated centrifuge (HC-3018R, ANHUI USTC Zonkia Scientific Instruments Co., Ltd., Hefei, China), the separated oil was weighed. The emulsion stability was calculated as follows:

$$\text{Emulsion stability } (\%) = [\,(F_0 - F_1) / F_0] \times 100$$

Here, F_0 is the sample weight (g) and F_1 is the weight of separated oil (g).

2.7. Texture

According to Rojas et al. (2019), mayonnaise samples were measured by a texture analyzer (TA. XT Plus, Stable Microsystems Ltd, Godalming, UK) with a cylindrical probe (35 mm diameter) and 10 kg load cell. Briefly, the mayonnaise was loaded into a cylindrical container (50 mm diameter and 75 mm height) and compressed to half of the initial height at 1 mm/s speed. The firmness, consistency, cohesiveness, and cohesion work were calculated using the previous method (Rojas et al., 2019).

2.8. Volatile compounds

Volatile compounds of mayonnaise were extracted by headspace solid-phase microextraction (HS-SPME) using the previous method (Jia et al., 2022). Firstly, the mayonnaise (5 g) was placed into a 20 mL headspace vial. A 50/30 μm SPME fiber coated with divinylbenzene/carboxen/polydimethylsiloxane (CAR/PDMS/DVB; Supelco, Bellefonte, USA) was used to extract volatile compounds of mayonnaise (60 °C, 30 min). Then, the fiber was inserted into a GC injector to desorb (3 min).

The extracted volatile compounds of mayonnaise were analyzed by gas chromatography-mass spectrometry (GC–MS; Pegasus HRT 4D Plus; LECO Corp., St. Joseph, USA) with a DB-WAX column (30 m × 0.25 mm × 0.25 μm; Agilent Technologies, Santa Clara, USA). Helium gas was used as a carrier and its flow rate was set at 1.0 mL/min. The temperature program was: 40 °C (3 min) to 230 °C at 10 °C/min (6 min). The temperatures of the ion source and injector were 210 °C and 250 °C, respectively.

The identification of volatile compounds in mayonnaise was based on the NIST MS library, and compared the retention indices (RIs) calculated by C_6-C_{26} *n*-alkanes with those reported in literatures.

2.9. Color

The color of the mayonnaise samples was measured by a Colorimeter Ci7600 (X-rite color technology Co., Ltd, Shanghai, China). Color values were evaluated based on the CIELAB color system defined by the International Commission on Illumination (CIE). Before measurement, the instrument was calibrated with the white and black standard plate.

2.10. Sensory evaluation

The sensory evaluation of mayonnaise was executed according to Teneva et al. (2021). After 1 day of storage, mayonnaise samples were evaluated by 24 semi-trained panelists (ranging from 20 to 35 years of age) who consume mayonnaise in their diets and have previous experience in sensory evaluation. Before the sensory evaluation, a preliminary and specific training session was arranged for the sensory panelists to focus attention on the texture, flavor, color, taste, and overall acceptability of mayonnaise, and each panelist could carefully clarify each attribute. All mayonnaise samples were randomly coded with three digits and presented disorderly. The sensory evaluation was based on a 9-point hedonic scale with the following indicators, texture, flavor, color, taste, and overall acceptability. After each sample test, warm water and cracker were used to neutralize the taste.

2.11. Appearance

The appearance of the mayonnaise samples was measured by following Heggset et al. (2020). The mayonnaise samples were stored in vertically placed 25 mL measuring cylinders and sealed with plastic wrap. After 1 day, 7 days, 15 days, and 30 days of storage, mayonnaise samples were captured by a digital camera. The change of color and phase separation was recorded.

2.12. Optical microstructure

The optical microstructure of mayonnaise was determined based on Chang et al. (2017). After storage for 1 day, 7 days, 15 days, and 30 days, to visualize the distribution of oil droplets in the mayonnaise systems, the mayonnaise samples (1 g) were dyed with 0.1% lipophilic fluorescence dye Nile red (2 mL). After 30 min of standing, the dyed samples were loaded onto the glass slides and covered with cover slips, individually. The images were captured by an optical microscope (Olympus IX71, Olympus, Tokyo, Japan) with 40 magnifications, and the representative images were chosen from more than five similar images. The green and black area represents the oil droplets and unstained areas respectively.

2.13. Statistical analysis

Except for the sensory evaluation was carried out with 24 panelists, all the experiments were carried out in triplicate. Results were shown as mean ± standard deviation (SD). The data of particle size, emulsion stability, texture, volatile compounds, color, and sensory evaluation were assessed by one-way analysis of variance (ANOVA) followed by Duncan's multiple range tests.

3. Results and discussion

3.1. Physicochemical properties of mayonnaise prepared from egg yolk fermented for different times

3.1.1. Particle size

Particle size is a crucial index that influences the appearance, texture, color, and flavor of mayonnaise (McClements, 2016). The particle size of mayonnaise was detected by nanometer particle size and zeta potentiometer and presented in Fig. 1(a). Generally, the particle size of mayonnaise ranges from 1 to 9 μm (Laca, Saenz, Paredes, & Diaz, 2010). In this work, the particle size of mayonnaise made from native egg yolk was 3.50 μm, which was similar to values reported by Laca et al. (2010) and Patil et al. (2019). After 3 h, 6 h, and 9 h fermentation of egg yolk, the particle size of mayonnaise was significantly decreased to 3.32, 3.39, and 3.41 μm respectively ($p < 0.05$). Based on our previous studies (Tian et al., 2022), after lactic acid fermentation, egg yolk proteins are degraded to peptides, which prevents the formation of aggregates through electrostatic interaction and thus reduces the particle size of egg yolk. It was probably responsible for the lower particle size of mayonnaise prepared from fermented egg yolk. And for mayonnaise, the lower particle size could contribute to the more delicate taste (Yildirim, Sumnu, & Sahin, 2016). In addition, the decreased particle size of mayonnaise reflects the transformation of protein structure, such as the exposure of buried hydrophobic amino acids, which may lead to the reduction of interfacial tension (Tian et al., 2022). Thus, the decrease in particle size of mayonnaise samples with fermented egg yolk was beneficial to their emulsion stability and may lead to a more delicate taste. This would be demonstrated in emulsion stability and sensory evaluation.

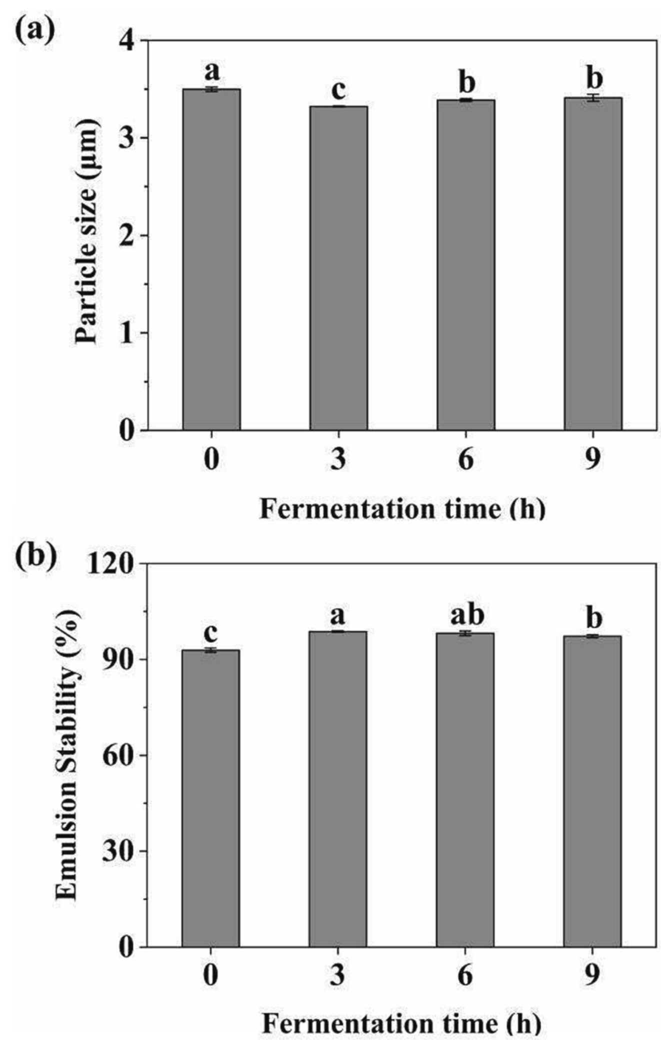

Fig. 1. Particle size (a) and emulsion stability (b) of mayonnaise prepared from egg yolks with 0, 3, 6, and 9 h of lactic acid fermentation, respectively. Superscripts (a-c) represent significant differences at the $p < 0.05$ level.

3.1.2. Rheological property

Rheological measurement sensitively detects the formation of composite gel matrix in a non-destructive way (Zhao et al., 2014). As shown in Fig. 2(a), the apparent viscosity of mayonnaise was decreased with the increase in shear rate, showing pseudoplastic behavior. This observation was synchronous with previous studies on mayonnaise (Chang et al., 2017; Patil et al., 2019; Sun et al., 2018), due to their aggregated droplets in solid-like emulsions being deformed and disrupted as the shear rate increased. Compared with mayonnaise containing native egg yolk, the apparent viscosity of mayonnaise prepared from 3 h and 6 h-fermented egg yolk was gradually decreased. Similar results were demonstrated in our recent study, reporting that the apparent viscosity of fermented egg yolk is lower than native egg yolk (Tian et al., 2021). This was mainly attributed to the degradation of proteins into peptides during lactic acid fermentation (Tian et al., 2022). The lower viscosity enhanced the migration rate of protein molecules to adsorb on the interface and further promoted the incorporation between oil and water.

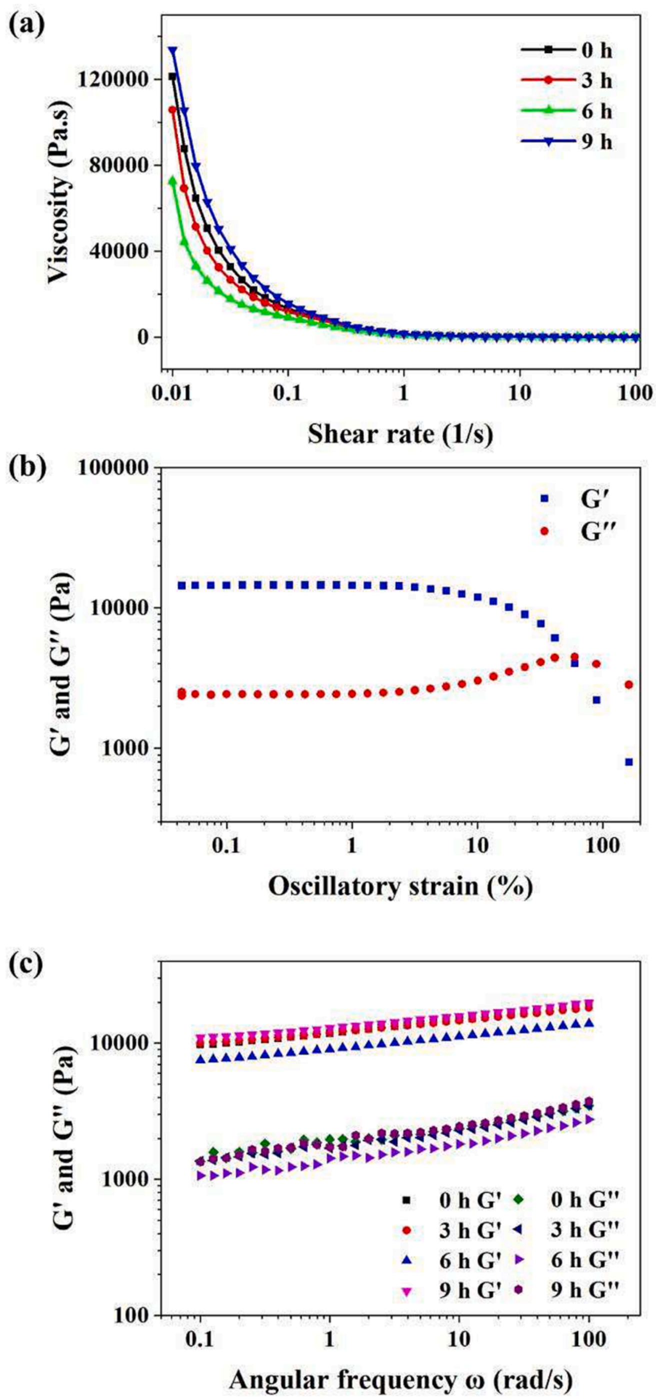

Fig. 2. Rheological properties of mayonnaise prepared from egg yolks with 0, 3, 6, and 9 h of lactic acid fermentation, respectively. (a) The apparent viscosity of mayonnaise samples; (b) Linear viscoelastic region of mayonnaise samples; (c) Storage and loss modulus of mayonnaise samples.

As shown in Fig. 2(b), the strain dependency of viscoelastic was determined under a dynamic strain sweep with the linear viscous region (LVR). Under the constant strain of 0.5% (within the LVR), G′ values of all mayonnaise samples were higher than those of G″ values throughout the test range (Fig. 2c), meaning that mayonnaise exhibited more gel-like behavior. With the increase in angular frequency, the G′ and G″ of all mayonnaise samples gradually increased. These behaviors were also reported by Laca et al. (2010) and Li et al. (2014b). Mayonnaise is a gel matrix, and its high viscosity and viscoelasticity inhibit protein migration to the oil–water interface. When mayonnaise was prepared from 6 h-fermented egg yolk, the G′ and G″ values were lower than other mayonnaise samples. This was accorded with the above viscosity result. One reason was that the smaller particle size (Fig. 1a) of fermented yolk protein molecules was easier to migrate to the oil–water interface (Tian et al., 2021). Another explanation was that the structure of egg yolk protein was changed during lactic acid fermentation. This could also lead to the change in the viscoelasticity of mayonnaise samples with fermented egg yolk (Tian et al., 2021). The decreased viscoelasticity enhanced the migration rate of protein to adsorb on the oil–water interface and may endow mayonnaise with a more stable structure.

3.1.3. Emulsion stability

The emulsion stability of mayonnaise and was evaluated under heating conditions. The density differences between dispersed and continuous phases rising the fat globules and thus phase separation (Sethi, Chauhan, & Anurag, 2017). As shown in Fig. 1(b), mayonnaise with native egg yolk maintained high emulsion stability (92.88%) after heating and centrifugation, attributing to the good emulsifying property of native egg yolk. As shown in Fig. 1(b), the emulsion stability of mayonnaise with native egg yolk was 92.88%, which was much higher than the value (65.48%) reported by Park et al. (2020) using the same method. This variation could result from the difference in the mayonnaise formula. And the emulsion stability was significantly improved in mayonnaise prepared from fermented egg yolk, reaching 98.72%, 98.17%, and 97.26%, respectively ($p < 0.05$). It may be due to the smaller particle size (Fig. 1a) of mayonnaise with fermented egg yolk, which led to stronger electrostatic repulsion among protein molecules, thus slowing the movement of oil droplets and inhibiting their aggregation. Another reason was related to the mayonnaise with fermented egg yolk possessing lower apparent viscosity and lower viscoelasticity (Fig. 2), resulting in the faster migration rate of protein molecules to adsorb on the oil–water interface. Therefore, it can be concluded that after using fermented egg yolk, the emulsion stability of mayonnaise samples under heating conditions increased significantly and peaked at 3 h. The improvement in the emulsion stability of mayonnaise samples inhibited phase separation and may positively affect their storage stability.

3.2. Sensory quality of mayonnaise prepared from egg yolk fermented for different times

The texture, flavor, and color of mayonnaise samples are the key factors that affect consumers' decisions (Sun et al., 2018). Therefore, the sensory quality of mayonnaise prepared from different fermentation times of egg yolk was evaluated based on their textural property, volatile profiles, color, and sensory acceptability, and the obtained results were discussed in detail.

3.2.1. Textural property

Firmness is an important parameter of the maximum force measured by equipment, influencing both sensory characteristics and the applicability of mayonnaise. And consistency represents the peak force area. As shown in Table 1, with the prolonged fermentation time of egg yolk, the firmness and consistency of mayonnaise gradually increased and peaked at 9 h of fermentation ($p < 0.05$). This meant the strong interaction between protein molecules and oil droplets led to a more compact three-dimensional gel structure. According to Olsson, Håkansson, Purhagen, & Wendin (2018), the significantly firmer mayonnaise is mainly caused by the smaller particle size (Fig. 1a). The compact three-dimensional gel structure in mayonnaise samples made from fermented egg yolk could restrict the movement of droplets, which is crucial to their stability during storage. Cohesiveness is the index indicating the degree of structure deforms before breaking when extended. Compared with the control mayonnaise, the mayonnaise prepared from 9 h-fermented egg yolk exhibited a higher cohesiveness ($p < 0.05$). This was related to the increasing extent of three-dimensional networks formed between proteins and hydrocolloid molecules (Werlang et al., 2021). In this study, the cohesion work of mayonnaise samples did not significantly change when prepared from egg yolk with different fermentation times. Overall, the higher firmness, consistency, and cohesiveness contribute to the textural property of mayonnaise samples prepared from fermented egg yolk, which promoted consumer acceptance.

3.2.2. Volatile profiles

The flavor of mayonnaise is a crucial indicator that could affect consumer acceptability. Volatile compounds in mayonnaise samples were detected by GC–MS and shown in Table 2. A total of 20 qualitative odor-active compounds were identified and classified into 5 chemical classes, including 3 sulfur compounds, 7 aldehydes, 3 acids, 3 terpenes, 1 ketone, and 3 other compounds. Among these volatile compounds, sulfur compounds were the dominant compounds in mayonnaise (approximately 50% relative abundance) and mainly contained 2-propenyl isothiocyanate (mustard oil). Mustard oil is the pungent compound in mustard, horseradish, and wasabi, involving garlic and pungent odor and low odor threshold (Gemert, 2011). Among these mayonnaise samples made from different fermentation times of egg yolk, no significant difference was observed in the relative abundance of sulfur compounds. Acids account for about 30% of the peak area of all compounds and were the second major type of compound detected in mayonnaise. Acetic acid was the most abundant acid in mayonnaise and involves sour and pungent aroma. It has a high odor threshold (Gemert, 2011) and contributes most of the sour flavor of mayonnaise. Instead, hexanoic acid possesses a low odor threshold (Gemert, 2011). And comparing with mayonnaise prepared from native egg yolk, the relative abundance of hexanoic acid was significantly decreased in mayonnaise containing fermented egg yolk ($p < 0.05$). Formic acid was at low levels in mayonnaise, which has a high odor threshold (Gemert, 2011), and was significantly increased in mayonnaise with 6 h and 9 h fermented egg yolk ($p < 0.05$). Terpenes were the third most abundant class in mayonnaise prepared from egg yolk with different fermentation times. It has low odor thresholds (Gemert, 2011) and involves citrus, fruit, and mint flavor. Among these terpenes, D-limonene was the dominant component, and α-terpineol was newly generated in mayonnaise made from fermented egg yolk. Aldehydes were the most varied volatile compounds but only account for a small proportion of total compounds. Among these aldehydes, phenylacetaldehyde and heptaldehyde were newly generated in mayonnaise with 6 h and 9 h fermented egg yolk, respectively. They have low odor thresholds (Gemert, 2011) and are associated with nut flavor. There was only one ketone (1-octen-3-one) detected in the mayonnaise, having an extremely low odor threshold (Gemert, 2011) and earth and mushroom aroma. Compared with the control mayonnaise, the mayonnaise made from 6 h-fermented egg yolk involved the higher 1-octen-3-one ($p < 0.05$). 2-pentylfuran has low odor thresholds (Gemert, 2011) and was described with butter and floral notes. It was newly generated in mayonnaise samples prepared from fermented egg yolk. Overall, 2-propenyl isothiocyanate, acetic acid, and D-limonene were the major components of the mayonnaise flavor, contributing to garlic, pungent, and mint aroma. Compared with control mayonnaise, the mayonnaise prepared from fermented egg yolk reduced the abundance of hexanoic acid (sour) and enhanced the abundance of formic acid (savory), phenylacetaldehyde (honey and nut), 1-octen-3-one (earth and mushroom), and heptaldehyde (citrus and nut) (Table 3).

3.2.3. Color analyses

Color is the major parameter in the appearance of mayonnaise and can influence consumers' choices (Chang et al., 2017; Teneva et al., 2021). Generally, the pale-yellow color of mayonnaise mainly stems from egg yolks and oil, and is also affected by lemon juice and mustards (Flamminii et al., 2020). The color of mayonnaise was presented as a three-dimensional color space with L^*, a^*, and b^*. L^* represents the ability of mayonnaise to reflect and scatter light (Chang et al., 2017), which has a major influence on the perceived appearance of the mayonnaise by consumers (Park et al., 2020; Shen et al., 2011). As shown in Table 1, compared with control mayonnaise, the L^* value of mayonnaise prepared from 3 h fermentation of egg yolk was markedly increased ($p < 0.05$). This was primarily because, after 3 h fermentation of egg yolk, mayonnaise has the smallest particle size (Fig. 1a), inducing an increase in light scattering. This phenomenon has been illustrated in other mayonnaise samples (Olsson et al., 2018). Similarly, the a^* value of mayonnaise prepared from 3 h-fermented egg yolk was significantly higher than that in control mayonnaise ($p < 0.05$). a^* is a parameter reflecting the green-redness of samples (Patil et al., 2019). This observation indicated that the 3 h fermentation of egg yolk might enhance the lightness and redness of mayonnaise.

3.2.4. Sensory evaluation

The consumers' decisions about mayonnaise are affected by their preference for food characteristics such as aroma, appearance, and texture (Teneva et al., 2021; Yildirim et al., 2016). Thus, the texture, flavor, color, taste, and overall acceptability of mayonnaise were assessed by sensory evaluation. As shown in Fig. 3, compared with control mayonnaise, mayonnaise samples prepared from fermented egg yolk possessed a more acceptable texture, which could be mainly dominated by their higher firmness, consistency, and cohesiveness (Table 1). Mayonnaise made from 3 h and 6 h-fermented egg yolk exhibited the most pleasant aroma, which may be due to their lower sour and higher mint and butter odor (Table 2). Noticeably, due to the

Table 1
Textural characteristics and color parameters of mayonnaise samples prepared from egg yolk with 0, 3, 6, and 9 h of lactic acid fermentation, respectively.

Fermentation time (h)	Textural characteristics				Color parameters		
	Firmness (N)	Consistency (N.s)	Cohesiveness (N)	Cohesion work (N.s)	L^*	a^*	b^*
0	1.43 ± 0.03^{c}	29.01 ± 0.92^{b}	0.64 ± 0.02^{a}	13.80 ± 1.92	71.66 ± 0.13^{b}	0.19 ± 0.14^{b}	23.19 ± 0.50
3	1.51 ± 0.03^{b}	30.29 ± 0.52^{ab}	0.71 ± 0.01^{ab}	15.17 ± 0.37	72.74 ± 0.09^{a}	0.44 ± 0.02^{a}	23.11 ± 0.19
6	1.52 ± 0.06^{b}	31.18 ± 1.78^{a}	0.71 ± 0.03^{ab}	15.54 ± 0.68	70.32 ± 0.13^{c}	0.28 ± 0.10^{ab}	22.66 ± 0.30
9	1.65 ± 0.01^{a}	32.01 ± 0.13^{a}	0.76 ± 0.06^{b}	16.14 ± 1.24	71.56 ± 0.07^{b}	0.16 ± 0.05^{b}	23.08 ± 0.12

Values are presented as means ± SD (n = 3). Different letters (a-c) within the same column indicated significant differences ($p < 0.05$).

Table 2
Main volatile compounds of mayonnaise prepared from egg yolk with 0, 3, 6, and 9 h of lactic acid fermentation, respectively.

Class	Compound [1]	CAS No.	Area % [2] 0 h	3 h	6 h	9 h	Odor description [3]
Sulfur Compounds							
	2-Propenyl isothiocyanate	57–06-7	48.41 ± 1.93	49.94 ± 1.26	50.46 ± 2.42	50.41 ± 3.43	Garlic, pungent
	Diallyl sulfide	592–88-1	0.05 ± 0.01	0.05 ± 0.00	0.06 ± 0.01	0.05 ± 0.00	Savory
	Diallyl Disulfide	2179–57-9	0.02 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.02 ± 0.01	Garlic
	∑Sulfur Compounds		48.48	50.02	50.55	50.48	
Acids							
	Acetic acid	64–19-7	30.43 ± 0.94	32.47 ± 0.91	31.63 ± 2.51	30.78 ± 1.51	Vinegary, pungent
	Hexanoic acid	142–62-1	0.13 ± 0.02^a	0.10 ± 0.01^b	0.10 ± 0.01^b	0.08 ± 0.01^b	Pungent, sour
	Formic acid	64–18-6	0.02 ± 0.00^b	0.02 ± 0.00^b	0.03 ± 0.00^a	0.03 ± 0.00^a	Savory
	∑Acids		30.58	32.59	31.76	30.89	
Terpenes							
	D-Limonene	5989–27-5	11.52 ± 0.27	11.74 ± 0.90	11.63 ± 0.71	11.11 ± 0.48	Citrus, mint
	γ-Terpinen	99–85-4	0.97 ± 0.05	0.90 ± 0.05	0.93 ± 0.06	0.91 ± 0.05	Bitter, citrus
	Myrcene	123–35-3	0.11 ± 0.01	0.10 ± 0.00	0.10 ± 0.1	0.10 ± 0.00	Fruit
	α-Terpineol	98–55-5	–	0.03 ± 0.00	0.08 ± 0.01	0.11 ± 0.01	Fresh, mint
	∑Terpenes		12.60	12.77	12.74	12.23	
Aldehydes							
	Hexanal	66–25-1	0.52 ± 0.02	0.48 ± 0.02	0.46 ± 0.10	0.45 ± 0.06	Fat, oil
	Nonanal	124–19-6	0.18 ± 0.03	0.14 ± 0.01	0.17 ± 0.02	0.17 ± 0.02	Fat, lemon
	Octanal	124–13-0	0.07 ± 0.00	0.05 ± 0.01	0.06 ± 0.01	0.06 ± 0.01	Fat, oil
	(E)-2-Octenal	2548–87-0	0.12 ± 0.04	0.11 ± 0.01	0.17 ± 0.05	0.16 ± 0.01	Fruit, grass
	(E)-2-Nonenal	18829–56-6	0.03 ± 0.00	0.04 ± 0.00	–	0.03 ± 0.00	Paper
	Phenylacetaldehyde	122–78-1	–	–	0.05 ± 0.00	0.04 ± 0.00	Honey, nut
	Heptaldehyde	111–71-7	–	–	–	0.03 ± 0.01	Citrus, nut
	∑Aldehydes		0.92	0.82	0.91	0.94	
Ketone							
	1-Octen-3-one	4312–99-6	0.33 ± 0.00^b	0.36 ± 0.01^b	0.49 ± 0.04^a	0.37 ± 0.01^b	Earth, mushroom
Other compounds							
	α-Humulene	6753–98-6	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.00	0.03 ± 0.00	N
	2-Pentylfuran	3777–69-3	–	0.08 ± 0.03	0.07 ± 0.00	0.06 ± 0.01	Butter, floral

Values are presented as means ± SD (n = 3). Different letters (a-b) within the same row indicated significant differences ($p < 0.05$). N: not found; -: not detected.
[1] All these volatile compounds had the MS fragments matching with the result of searching NIST MS library and their calculated RI matched with the RI found in literatures.
[2] Each volatile compound was expressed as relative percentage of the GC peak area (%) on the total peak areas.
[3] The odour description was obtained from Flavor & Extract Manufacturers Association.

Table 3
Sensory evaluation analysis of commercial mayonnaise and mayonnaise prepared from egg yolks with 0, 3, 6, and 9 h of lactic acid fermentation, respectively.

Fermentation time (h)	Sensory characteristics Color	Flavor	Taste	Texture	Overall acceptability
0	6.92 ± 1.28	5.79 ± 1.77	5.71 ± 1.63^b	7.42 ± 1.35	6.17 ± 1.37^b
3	7.04 ± 1.33	6.33 ± 1.63	6.63 ± 1.44^a	7.71 ± 1.23	6.88 ± 1.14^a
6	6.79 ± 1.28	6.33 ± 1.34	6.04 ± 1.68^{ab}	7.46 ± 1.35	6.42 ± 1.38^{ab}
9	6.67 ± 1.49	5.88 ± 1.36	6.50 ± 1.84^{ab}	7.25 ± 1.45	6.13 ± 1.24^b
Commercial	6.46 ± 1.22	6.33 ± 1.63	6.25 ± 1.59^{ab}	7.83 ± 1.09	6.63 ± 1.24^{ab}

Values are presented as means ± SD (n = 24). Different letters (a-b) within the same column indicated significant differences ($p < 0.1$).

advanced homogenization equipment of manufacturers and the addition of fragrance, commercial mayonnaise also had high texture and flavor scores. Generally, mayonnaise made from natural egg yolk possesses pale-yellow color. After 3 h fermentation of egg yolk, the color scores of mayonnaise were increased, resulting from more lightness and redness (Table 1). Compared with control mayonnaise, the mayonnaise samples prepared from fermented egg yolk (especially 3 h-fermented egg yolk) involved significantly higher taste scores ($p < 0.1$), which were mainly caused by their lower particle size (Fig. 1a) (Yildirim et al., 2016). In conclusion, compared with native egg yolk, 3 h-fermented egg yolk endowed mayonnaise with higher texture, flavor, color, and taste scores, and more acceptability by consumers ($p < 0.1$).

3.3. Storage stability of mayonnaise prepared from egg yolk fermented for different periods of time

Storage stability is the important index in mayonnaise products that decides their shelf life. After 1 day, 7 days, 15 days, and 30 days of storage, the stability of mayonnaise samples prepared from native and 3, 6, and 9 h-fermented egg yolks was evaluated based on their particle size, microscopic and appearance characteristics. As shown in Fig. 3, based on the macro photos captured by an inverted optical microscope, all mayonnaise samples comprise smaller oil droplets dispersed in a continuous phase, showing homogenous and compact microstructures. However, the particle size of mayonnaise samples prepared from native and fermented egg yolk was significantly increased ($p < 0.05$) after 30 days of storage. A similar observation was reported in previous studies (Patil et al., 2019; Sun et al., 2018), meaning that the oil droplets tend to coalesce or flocculate during 30 days of storage. Notably, mayonnaise prepared from 3 h-fermented egg yolk still exhibited significantly lower particle size ($p < 0.05$) than control mayonnaise. Subsequently, the mayonnaise samples in the sealed measuring cylinders were captured by a digital camera, and the phase separation were observed. Fig. 3 showed that all mayonnaise samples exhibited semisolid behavior because of their high oil content. During 15 days of storage, no visible separation of oil and water was observed among these samples. However, after 30 days of storage, a few oil droplets coalesced on the surface of mayonnaise made from native egg yolk, whereas the mayonnaise samples with fermented egg yolk remained emulsified. One reason was that the smaller particle size could improve the emulsion stability of mayonnaise with fermented egg yolk (Fig. 1 and Fig. 3). And on the other side,

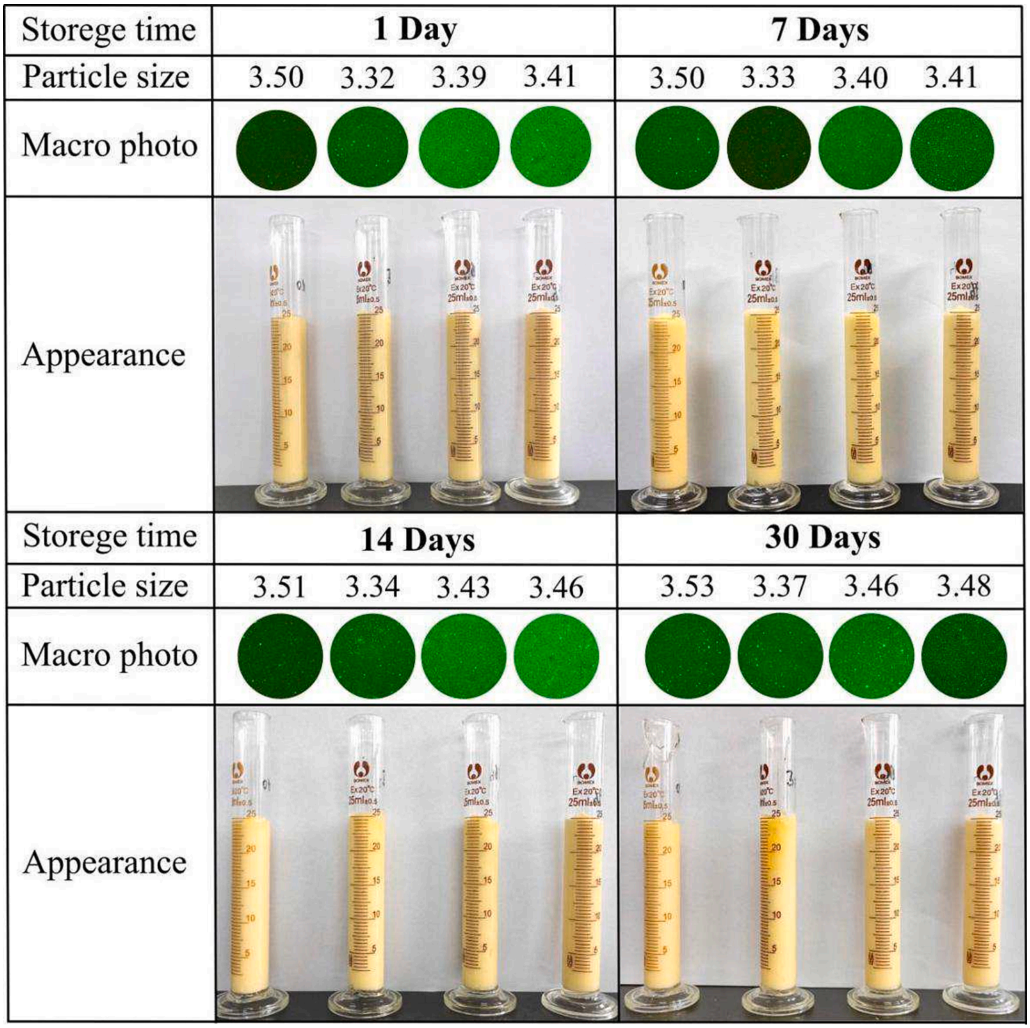

Fig. 3. After 1 day, 7 days, 15 days, and 30 days of storage, particle size, microscopic, and appearance characteristics of mayonnaise prepared from egg yolks fermented for different times. From left to right on the same day are samples of mayonnaise prepared from egg yolks with 0, 3, 6, and 9 h of lactic acid fermentation, respectively.

considering the above texture result (Table 1), the improved storage stability of mayonnaise with fermented egg yolk was mainly attributed to its network structure which restricted the movement of droplets (Atarian et al., 2019; Chevalier & Bolzinger, 2013). Therefore, according to the above observations, the fermented egg yolk improved the storage stability of mayonnaise and endowed mayonnaise with longer shelf life.

4. Conclusion

In this research, mayonnaise samples were made from egg yolk with 0, 3, 6, and 9 h of fermentation, and their physicochemical properties, sensory quality, and storage stability were studied. Results proved that compared with native egg yolk, the fermented egg yolk significantly decreased particle size, apparent viscosity, and viscoelasticity, and thus significantly improved the emulsion stability of mayonnaise from 92.88% to 98.72%, 98.17%, and 97.26%, respectively. Meanwhile, the mayonnaise made from fermented egg yolk possessed significantly higher firmness, consistency and cohesiveness texture, more lightness and redness, and better flavor through decreasing the abundance of hexanoic acid and increasing the abundance of formic acid, phenylacetaldehyde, 1-octen-3-one, and heptaldehyde. Sensory evaluation showed that 3 h-fermented egg yolk endowed mayonnaise with higher texture, flavor, color, and taste scores, and significantly more acceptability by consumers. After 1 day, 7 days, 15 days, and 30 days of storage, mayonnaise samples prepared from fermented egg yolk exhibited lower particle size and more stable appearance, which benefited their shelf life. In conclusion, these results confirmed our hypothesis that lactic acid fermentation is a natural, sustainable, and green method to improve the sensory quality and storage stability of mayonnaise. This work supplied a basis regarding the application of fermentation to improve consumer acceptability and shelf life in food manufacturing.

CRediT authorship contribution statement

Jie Jia: Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Liangjie Tian:** Investigation, Data curation, Validation. **Qi Song:** Writing - review & editing. **Xuebo Liu:** Resources. **Josep Rubert:** Writing - review & editing. **Mei Li:** Conceptualization, Supervision, Project administration. **Xiang Duan:** Conceptualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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