THESIS OF THE PHD DISSERTATION

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Techno-Functional and Sensory Properties of Nutritionally Enhanced Liquid Eggs

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1. INTRODUCTION AND OBJECTIVES

Eggs are among the most versatile and nutritionally valuable ingredients in the food industry, widely used for their unique functional properties such as emulsification, foaming, coagulation, and gelation. Liquid whole egg, which combines both yolk and albumen in a standardized, pasteurized form, is especially valued in commercial food manufacturing for its consistent quality and ease of use . It plays a critical role in bakery products, emulsified sauces, dairy analogs, ready meals, and confectionery, offering emulsifying, foaming, gelling, thickening, and binding properties that are difficult to replicate with synthetic or single-function additives.

Despite these advantages, the functional performance of liquid whole egg can be variable and is often affected by multiple factors such as pasteurization temperature, storage time, and protein denaturation. Additionally, there is an increasing demand from the food industry for egg-based ingredients that not only retain their traditional roles but also perform optimally under modern processing conditions, including high-shear mixing, heat treatment, and prolonged storage. These challenges create a need for the enhancement of liquid egg systems in a way that preserves their natural composition while improving functional reliability and product quality.

Techno-functional enhancement refers to the targeted improvement of physical and functional properties of food ingredients to better meet specific technological and sensory requirements . In case of liquid egg, this may include increasing viscosity, strengthening gelation or foaming capacity, stabilizing emulsions, or improving thermal stability. Such enhancements are often achieved through the addition of natural biopolymers, proteins, or hydrocolloids, or by modifying processing parameters (Mine, 1995). Recent trends in food science encourage the use of natural, clean-label fortifiers such as plant-based proteins, dietary fibers, or food-grade gums which align with consumer preferences for minimally processed and health-conscious foods.

Protein fortification is a particularly promising approach for enhancing the techno-functional behavior of liquid egg. Proteins, both animal and plant-based, can interact with egg proteins to form new structural networks that improve viscosity, emulsion stability, and gel strength. When incorporated into liquid egg systems, these proteins may contribute to enhanced water-binding capacity, improved emulsification, and more stable foam formation, depending on their structure, solubility, and interaction with endogenous egg proteins.

However, introducing external proteins or hydrocolloids into the liquid egg matrix can also alter its rheological and sensory properties. Thus, it is essential to study the impact of these modifications systematically considering not only their functional benefits but also their influence on product appearance, mouthfeel, and consumer acceptance. Moreover, understanding how these additives interact with egg proteins under different thermal treatments and over storage time is key to optimizing the formulation for industrial use.

This research aims to explore the techno-functional enhancement of liquid whole egg through the incorporation of selected protein fortifiers, focusing on their impact on pH, color and rheological behavior, over time and under varying storage and pasteurization conditions. It also aims to determine the optimal conditions under which these enhancements can be maximized without compromising the natural structure or sensory profile of the liquid egg.

The research is relevant not only from a technological standpoint but also in terms of sustainability and innovation. The development of improved egg-based formulations with different proteins could provide a competitive advantage in the food market. Furthermore, this work contributes to the broader scientific understanding of protein-protein interactions in mixed systems and offers insights into how formulation strategies can be used to tailor food textures and functionalities.

In summary, this thesis aims to address the growing need for improved functional performance in liquid egg products by applying protein and oils fortification strategies and analyzing their impact through a multidisciplinary lens. By doing so, it seeks to develop a liquid egg system with enhanced techno-functional properties that can meet the evolving demands of food manufacturing, while supporting innovation, nutritional value, and consumer appeal.

Objectives

The overall aim of this research is to develop functionally enhanced and sensory-acceptable fortified liquid egg products by systematically exploring the combined effects of protein or oil additives and pasteurization, with a focus on rheological behavior, pH, color and customer acceptance. The study also aims to assess how these modifications are influenced by pasteurization temperatures and storage duration. To achieve this, the following specific objectives have been identified:

- To investigate the effect of different concentrations of different protein powders and different oils on the techno-functional properties of liquid egg products, including viscosity, yield stress, flow behavior, and gelation characteristics.
- To investigate the influence of pasteurization at different temperatures (50°C, 55°C, and 60°C for egg white and 60°C, 65°C, 70°C for whole egg) on the structure-function relationships of fortified liquid egg systems, especially in terms of protein interactions, and stability.
- To perform sensory analysis on the most promising formulations to evaluate potential changes in texture, mouthfeel, or appearance that may affect consumer acceptance.
- To determine the optimal combination of protein concentration and processing conditions that achieves significant improvement in functional properties while maintaining the natural characteristics of liquid whole egg.

2. MATERIALS AND METHODS

2.1. Materials

Pasteurized homogenized liquid egg products were obtained from a liquid egg plant (Capriovus Ltd., Szigetcsép, Hungary). Powdered egg white protein was obtained from the same company as well. All essential oils were obtained from RASP GmbH (Austria). Ascorbic acid was obtained from Chem-lab NV (Belgium), both citric acid 99% and phosphoric acid 99% were obtained from Sigma-Aldrich (Germany). Whey protein isolate (WPI90) was obtained from Buda family kft (Hungary). Olive oil was obtained from Uncle Chris company (Athena, Greece). Sunflower oil was obtained from floriol (Hungary). As for Coconut oil and Palm oil both were obtained from Szekszard (Hungary). In the preparation of Patal De Nata, a dough was purchased form "Tante Fanny, Friss Linzertészta" (Austria), 2.8% fat milk was purchased from Mizo (Hungary), corn starch was purchased from Dr.Oetker (Germany), sugar was purchased from Koronás Cukor (Hungary), liquid vanilla was purchased from Dr.Oetker (Germany).

3.2 Preparation of liquid eggs samples

Fresh liquid egg products were obtained from Capriovus Ltd., Szigetcsép, Hungary and transported to the laboratories at the Department of Refrigeration and Livestock Product Technology (Faculty of Food Science, Mate University- Hungary) within 24 hours of production. It was produced from fresh, medium size, class "A", enriched cages hens following the registration of EU. Eggs are disinfected, then the shells are removed to create the liquid eggs. In case of liquid egg yolk and white separation take a place at this step. Homogenization and pasteurization are followed, in case of liquid egg yolk pasteurization occur at 65 °C for 10 minutes, on the other hand liquid egg white is pasteurized at 56 °C for 3 minutes. As for liquid whole egg it is pasteurized at 70 °C for 3 minutes. With these rates 600 kg of liquid egg yolk per hour, while 2000 kg of liquid whole egg and liquid egg white per hour were produced. The product then is filled in 1 liter PET (Polyethylene Terephthalate) bottles and refrigerated at 0-4 ± 0.5 °C. Experiments were conducted at room temperatures between 22 and 25 °C at the same day of sample arrival.

In some of the experiments shell eggs was used to create liquid whole eggs or liquid egg white in the laboratories at the Department of Refrigeration and Livestock Product Technology (Faculty of Food Science, Mate University- Hungary). In this case medium size, cage free shell eggs following the EU regulation of egg production, were obtained from Capriovus Ltd., Szigetcsép, then cracked and homogenized at 10000 rpm for 3 minutes using IKA T-18 Ultra Turrax Digital Homogenizer (Germany), then heat treated at $60 \pm 0.2°C$, with holding time of 3.5 minutes in water bath, then cooled down immediately to $4°C \pm 0.1$ using an ice bath.

3.3 Experimental design and liquid egg product treatments

Experiments were performed to enhance the nutritional value of liquid egg products by fortifying, enriching or supplementing them with different ingredient. Different proteins were chosen to increase protein content while different essential oils and vegetable oils were added to enhance bioactive benefits. Several studies have extensively analyzed the physicochemical, functional, and rheological properties of liquid eggs, focusing on their stability, viscosity, emulsification, and processing characteristics. However, limited research has been conducted on enhancing the nutritional value of liquid eggs through fortification or supplementation with additional proteins, oils, or bioactive compounds. While existing literature primarily examines the structural behavior and processing effects, there remains a gap in understanding how nutritional enrichment impacts the overall quality, sensory attributes, and functional performance of liquid egg formulations. All experiments were conducted in a fully randomized design to minimize bias. Measurements and sensory evaluations were performed in separate sessions to avoid carry-over effects. Each treatment was replicated a statistically enough times to ensure repeatability. Repeatability was verified through independent repetitions under identical conditions, and variability was monitored to confirm data reliability

3.3.1 Egg white proteins addition to liquid whole eggs

In the first experiment the aim was to investigate the effects of fortifying raw unpasteurized liquid whole eggs and liquid egg white with powdered egg white protein at different concentrations (0%, 3%, 5%, and 10% W/W) and subjecting them to heat treatment at various temperatures, 60°C, 65°C, and 70°C for liquid whole egg and 50°C, 55°C, and 60°C for liquid egg white, for 15 minutes in a water bath, followed by rapid cooling to 4°C using an ice bath. every 500 ml of the sample was stored in sterilized glass bottles prior to heat treatment then after cooling down samples were immediately stored at 4°C. The experiment evaluated how protein fortification and heat treatment influence the physical and chemical properties of liquid egg products. The untreated samples serve as control groups to compare the effects of these modifications. There is a limited understanding of how protein enrichment interacts with heat processing to alter the structural and functional properties of liquid egg products. While thermal treatments are commonly used for pasteurization and safety enhancement, their effects in combination with protein fortification have not been fully explored. The experiment provides insights into optimizing processing conditions for enhanced nutritional value, texture, and stability in liquid egg-based formulations.

3.3.2 Egg white proteins addition to liquid whole eggs with storage

In the second experiment, a storage condition of the previously made samples was addressed, samples which were made in the first experiment were stored for 21 days in 4°C condition. Measurements to check quality changes were made at the day of the production, day 7, day 14, day 21. The purpose of the experiment is to evaluate the effect of refrigerated storage 4°C over 21 days on the quality and stability of liquid egg products fortified with powdered egg white protein and subjected to different heat treatments in the fifth experiment.

3.3.3 Whey proteins addition to liquid whole eggs

The third experiment was designed to evaluate the effects of fortifying liquid whole eggs with whey protein at different concentrations (1%, 2%, and 3% W/W) on their physicochemical properties. The liquid whole egg samples were mixed with whey protein and homogenized using a Robot Coupe MiniMP160 mixer (France) before undergoing analytical measurements. The purpose of this experiment is to investigate how whey protein supplementation influences the functional characteristics of liquid whole eggs, such as viscosity, pH, and color. Whey protein was selected due to its high solubility, emulsification properties, and ability to enhance protein content while improving the structural and thermal stability of food products. Understanding these effects could provide valuable insights into developing high-protein egg formulations with improved texture, nutritional value, and processing performance for use in various food applications.

3.3.4 Different proteins addition to liquid whole eggs

The fourth experiment was conducted to evaluate the effects of fortifying liquid whole eggs with powdered egg white protein and whey protein at varying concentrations (3%, 5%, and 10% W/W) on their physicochemical properties. A total of 1400 g of raw liquid whole eggs were divided into seven beakers, each containing 200 g of sample. Three samples were fortified with powdered egg white protein at 3%, 5%, and 10% W/W, while another three samples were fortified with whey protein at the same concentrations. The seventh sample served as the control group. All samples were homogenized at 10,000 rpm for 3 minutes using an IKA T-18 Ultra Turrax Digital Homogenizer (Germany), followed by heat treatment at 60 ± 0.2°C with a holding time of 3.5 minutes in a water bath, and then rapidly cooled to 4°C using an ice bath. a second batch of 1400 g of liquid whole eggs was processed in the same conditions, with protein addition occurring after heat treatment and subsequent homogenization at 10,000 rpm for 3 minutes.

Both powdered egg white protein and whey protein were selected due to their high digestibility and complete essential amino acid profile, with a protein digestibility-corrected amino acid score (PDCAAS) of 1, indicating their optimal nutritional value for human consumption. This experiment provides insights into the formulation of enriched liquid egg products for functional food applications, catering to health-conscious consumers and athletes seeking high-protein dietary options.

3.3.5 Increasing the egg yolk content of liquid whole eggs

The fifth experiment was conducted to investigate the effect of varying egg yolk ratios on the physicochemical and sensory properties of liquid whole eggs and their application in a custard tart (Pastel de Nata). Five different samples were prepared, including pure egg yolk, liquid whole egg, and three samples with 20%, 50%, and 80% additional yolk content. The samples were homogenized to ensure uniformity before further analysis. Following the physicochemical analysis, the liquid egg samples were used to prepare custard tart fillings, following a standardized recipe that included sugar, milk, and other ingredients. The tarts were baked under controlled temperature conditions to ensure uniformity. The final product was then evaluated through sensory analysis. A trained sensory panel assessed the samples for appearance, color, texture, creaminess, and aftertaste using a structured sensory evaluation form in the sensory lab of the Hungarian university of agriculture and life sciences. The results from both physicochemical and sensory analyses were statistically analyzed to determine how yolk ratio influenced the liquid egg properties and the final quality of the custard tart.

3.3.6 Adding essential oils to liquid whole eggs

In the sixth experiment, homogenized and pasteurized liquid whole egg samples were mixed with different percentages (1,2,3% W/W) of different essential oils (basil, garlic, rosemary) then homogenized using robot coupe MiniMP160 mixer and samples for each parameter were then placed in bakers to go through measurements, samples that didn't receive any treatment acted as reference sample. By comparing treated samples to untreated reference sample, the study aimed to assess the potential of these essential oils as natural additives to enhance nutritional value and functionality of liquid egg products. pH, color, viscosity and antioxidant activity were done to evaluate the effect.

3.3.7 Adding cooking oils to liquid whole eggs

The seventh experiment was designed to evaluate the effects of different types of oils (olive, sunflower, palm, and coconut oil) at varying concentrations (2.5%, 5%, and 7.5% V/V) on the physicochemical properties like pH, color, and viscosity, of homogenized and pasteurized liquid whole eggs. Sensory attributes of the cooked scrambled eggs are assessed by 12 trained panelists to determine the impact of oil addition on the taste, texture, and overall acceptability of the final product. While the functional and nutritional benefits of oils in various food systems are well-documented, there is limited research on their specific impact on the physicochemical properties and sensory qualities of liquid egg products and their cooked version. This experiment investigated how different oils, and their concentrations influence both the processing characteristics and consumer acceptability of scrambled eggs, providing insights for improving the formulation of enriched egg-based products.

3.4 Procedures and measurements

3.4.1 Measurement of pH

The pH value of liquid egg products samples was measured in different experiments, and the readings were recorded in triplicate, using a portable pH meter by immersing a pH electrode (Testo 206; Testo-AG, Germany) about 1 cm into the liquid samples.

3.4.2 Color measurement

The color values of liquid whole eggs were measured using CIELAB (CIE, 1986) scoring system. The following parameters were obtained: *L** (lightness), *a** redness (+*a*, red; –*a*, green), and *b** yellowness (+*b*, yellow; –*b*, blue) by using Konica Minolta CR-400 colourimeter (Konica Minolta Sensing Inc., Japan) making sure calibration was carried out before taking a reading. Results from *L**, *a**, and *b** were recorded as the mean of five random readings.

The CIELAB color space, also known as the CIE L*a*b* system, provides a quantitative framework for characterizing colors based on three orthogonal axes. The L* parameter represents lightness and is measured along a vertical axis ranging from 0 (black) to 100 (white). The a*

coordinate defines the red-green chromatic component, where positive values (+a*) indicate redness and negative values (−a*) indicate greenness. Similarly, the **b*** coordinate represents the yellow-blue chromatic component, with positive values (+b*) corresponding to yellow and negative values (−b*) to blue. The intersection of the a* and b* axes provide the neutral or achromatic point. In this color space, chroma (C*), or the saturation of a color, is determined by the radial distance from the neutral axis, while hue (h°) is represented by the angular position on the chromaticity plane. The CIELAB system is widely used in various scientific disciplines.
The CIELAB system was developed by the Commission Internationale de l'Éclairage (CIE) and remains a standardized model for color representation in scientific and industrial applications.

3.4.3 Determination of the rheological properties of liquid egg products samples

At the day of production samples were used to examine the rheological behavior of liquid whole egg, it was done using MCR 92 rheometer (Anton Paar, Les Ulis, France) in rotational mode equipped with a concentric cylinder with a concentric cylinder (cup diameter 28.920 mm, bob diameter 26.651 mm, bob length 40.003 mm, active length 120.2 mm, positioning length 72.5 mm). To control the equipment, Anton Paar RheoCompass software was used. A constant temperature of 15 °C was kept throughout the rheological measurements, shear stress was measured by logarithmically increasing and decreasing shear rate between 1 and 1000 1/s for 32 measurement points and in triplicates for each sample.
Following the literature this study chose Herschel Bulkley model to describe the rheological behavior of liquid whole egg (Atılgan & Unluturk, 2008; Kumbár, Strnková, et al., 2015; Uysal et al., 2019). Herschel Bulkley model is often chosen for liquid egg products because it exhibits a yield stress and shear thinning behavior and this model takes into consideration these factors
Equation (1) was used to analyze the flow curves (shear rate-shear stress diagrams).

$$\tau = \tau 0 + K\dot{\gamma} n \quad (1)$$

Where:

τ = shear stress (Pa)

τ_0 = the yield stress (Pa)

$\dot{\gamma}$ = the shear rate (1/s)

K = the consistency coefficient (Pas^n)

n = is the flow behavior index. (-)

3.4.4 Determination of total antioxidant capacity

The total antioxidant capacity was measured using Ferric reducing antioxidant power (FRAP) method described by Benzie and Strain, 1996 (Benzie & Strain, 1996). The FRAP reagent was freshly prepared as a mixture of acetate buffer (300 mM, pH = 3.6), TPTZ (10 mM), and ferric chloride (20 mM) at a 10:1:1 (v/v/v) ratio, respectively. For sample preparation, 2 mL of homogenized sample was centrifuged at 10000 rpm for 20 mins, then the clear supernatant was used for measurements. Then, 1.5 mL of the FRAP reagent, 10 µL of the sample and 40 µL of distilled water, were mixed and put to rest for 5 minutes. The absorbance was determined at 593 nm using Hitachi U-2900 spectrophotometer and against a blank sample containing all the reagents. A calibration was carried out using ascorbic acid solutions between 0.01 and 0.1- mM concentrations. The results were expressed as kg ascorbic acid equivalent/m^3 liquid whole egg. Measurements were made in triplicate.

3.4.5 Sensory evaluation of scrambled eggs preparation

Using a non-stick pan a scrambled eggs were fried on medium heat without any extra oil addition for 3 minutes then samples were added to plates for sensory evaluation. Sensory evaluation of scrambled liquid egg and different oils mixture samples were conducted for sensory attributes: the intensity of color, aroma, appearance, and acceptability to buy. The panel consisted of 10 researchers, teachers, and technicians of MATE University (50 % male/female, aged between 25 and 57 years) they were familiar with scrambled egg consumption. The assessment was conducted using a 9-point hedonic scale (Meilgaard et al.,1999): 1, dislike extremely; 2, dislike very much; 3, dislike moderately; 4, dislike slightly; 5, neither like nor dislike; 6, like slightly; 7, like moderately; 8, like very much; 9, like extremely. All samples were coded with 3-digit random codes and offered to the individuals in the random order. The sequence in which treatments were offered to each individual was randomized.

3.4.6 Preparing Pastel De Nata

To prepare the Portuguese pastry "Pastel de Nata," the original recipe was followed for the custard filling, while the dough was purchased from "Tante Fanny, Friss Linzertészta" to optimize the crust. Each pastry was made using 25 g of dough and 30 mL of liquid custard. For a batch of 12 pieces, the custard was prepared using 120 g of liquid egg samples, combined with 280 g of milk, 100 g of sugar, 56 g of starch, and 1 g of vanilla. All ingredients were thoroughly mixed using a Robot Coupe MiniMP160 mixer (France) to achieve a smooth consistency. The dough was placed in a cupcake tray, and the custard was strained through a fine sieve in each cup cake. The pastries were then baked at 180°C for 20 minutes. After baking, the samples were left to cool in the tray for 20 minutes before being stored in a refrigerator at 4°C for sensory evaluation the following day.

3.4.7 Sensory evaluation of Pastel De Nata

On the day of the experiment, samples were transferred to the sensory lab which is designed following ISO 8589:2007 at the department of postharvest and sensory analysis, for thirteen panelists to test. Panelists were selected based on their prior experience in descriptive sensory analysis. Prior to the test day, an expert panel evaluated the products to define reference values for each attribute, after which the panel leader designed the score sheet in consultation with the panel. Sample codes and a presentation order are generated for each assessor, to provide a balanced test environment. Assessors work separately in the sensory booths. The personalized score sheets are copied to the booth PC's. Panelists evaluate the samples according to the defined terminology following ISO 6658:2017 standards. Color of surface, inner color, egg odor intensity, texture of the custard, creaminess, sweet taste intensity, and aftertaste were the attributes to be tested. Data were recorded digitally and analyzed quantitatively.

3.4.8 Statistical analysis

To analyze data statistically the statistical package for social science (SPSS, version 27.0, 2020, Chicago, IL) was used. A one way and two-ways analysis of variance (ANOVA) test was performed to test the difference between the treatments. Followed by mean separation using Tukey HSD Analysis. Means with different letters differ significantly at $p < 0.05$.

3. RESULTS AND DISSCUSION

3.1 The effect of egg white protein additions on liquid whole egg properties.

The experiment investigated the effect of adding egg white powder percentages (3,5,10%) to unpasteurized liquid whole egg, followed by homogenization and pasteurization at 60°C, 65°C, and 70°C. Results showed that increasing egg white powder decreased pH at all temperatures, with the largest drop at 60°C due to higher enzymatic activity, particularly glucose oxidase, which produces acidic byproducts. At higher pasteurization temperatures, heat denaturation reduced enzyme activity and stabilized pH. Protein–lipid interactions and changes in buffering capacity also influenced the final pH, with higher temperatures limiting protein reactivity and maintaining slightly higher pH values. Color variation in liquid whole egg is mainly driven by yolk pigment content, processing temperature, and pH changes during storage. Pasteurization can darken color through protein denaturation and Maillard reactions, with higher temperatures enhancing these effects. Storage-related pH rise alters protein structure and light scattering, reducing L* and shifting a* and b* values toward a duller appearance. Even under identical production conditions, natural variability in pigments and protein interactions causes differences in L*a*b* parameters between batches, so each experiment included its own control group for accurate comparison.

As for the rheological properties, adding egg white powder (3%, 5%, and 10%) to liquid whole egg, pasteurized at 60°C, 65°C, or 70°C, and stored at 4°C for 21 days, on rheological properties including yield stress (τ_0), consistency index (K), and flow index (n). Overall, higher protein concentrations increased τ_0 and K while lowering n, indicating stronger structure, higher viscosity, and more pronounced shear-thinning behavior. At 60°C, control samples started near-Newtonian, while added protein increased structure; the 10% sample reached gel-like consistency by day 7 but weakened by day 21, whereas 3% and 5% retained moderate stability. At 65°C, 3% and 5% protein lowered τ_0 but increased K initially, with all protein-added samples developing strong shear-thinning over time; by day 21, 3% had the highest τ_0 and all fortified samples maintained structure better than the control. At 70°C, higher protein greatly increased K and structure initially, but 10% protein became extremely viscous and gel-like by day 7 before destabilizing by day 14; 3% and 5% formed semi-gel-like textures, and by day 21 all samples weakened somewhat. Across all conditions, protein addition enhanced initial viscosity and structure, but excessive protein (10%)

sometimes led to over-aggregation and later breakdown, with shear-thinning behavior dominating most fortified samples over storage.

3.2 The effect of egg whey protein additions on liquid whole egg properties.

The addition of whey protein to liquid whole eggs caused measurable changes in pH, color, and rheological properties. Increasing whey protein concentration slightly but significantly lowered pH due to the acidic nature of whey and its interaction with egg proteins' buffering systems. Color measurements showed that higher whey levels darkened the mixture (lower L*), increased redness (a*), and slightly altered yellowness (b*), likely from protein interactions affecting light scattering and pigment dispersion. From a rheological point of view, whey protein reduced yield stress at low concentrations but increased viscosity (K value) with higher additions, while maintaining near-Newtonian flow behavior. Compared to egg white protein, whey had a milder effect on viscosity and shear-thinning; egg white protein caused stronger thickening and more pronounced pseudoplastic behavior, especially when heat treatment followed protein addition, due to higher water-binding and partial gel network formation.

3.3 The effect of adding different percentages of liquid egg yolk to liquid whole egg.

The study on adding varying percentages of liquid egg yolk to liquid whole egg showed that increasing yolk content consistently lowered pH, with values decreasing from 7.43±0.19 in standard whole egg to 6.70±0.13 at 80% added yolk, approaching the pH of pure yolk (6.40±0.23). This trend reflects yolk's naturally more acidic composition, containing phospholipids, free fatty acids, and acidic amino acids that buffer against the alkalinity of egg white. Color measurements (L*, a*, b*) revealed that decreasing yolk content produced lighter, less red, and less yellow mixtures due to dilution of carotenoids and lipids by the higher-reflectance egg white. For example, pure yolk exhibited strong yellow-orange coloration (L* = 63.0, a* = 3.2, b* = 49.9), while whole egg samples with minimal yolk showed the lowest yellowness (b* = 31.4) and even shifted toward green (a* = –2.7). Rheologically, pure yolk displayed high viscosity (K = 0.176 $Pa \cdot s^n$) and pseudoplastic behavior (n = 0.915), but as yolk percentage decreased, viscosity dropped markedly, yield stress increased slightly, and flow behavior moved toward Newtonian ($n \approx 1$), indicating a thinner, more uniform liquid dominated by egg white properties.

Sensory evaluation of pastel de nata custards made with these formulations showed that yolk percentage had a strong impact on consumer-perceived quality. Color intensity, both on the surface and inside the custard, decreased noticeably in samples with 20% and 50% yolk compared to the 100% yolk control ($p < 0.01$), while the 80% yolk sample matched the control visually, confirming the role of yolk pigments in maintaining the traditional golden hue. Odor analysis revealed that low-yolk samples (20% and whole egg) had significantly stronger egg odors ($p < 0.05$), linked to sulfur compounds from egg white, while 50% and 80% yolk samples retained a milder aroma closer to the control. Texture ratings reflected yolk's structural contribution: the control was firmest, with firmness decreasing as yolk content dropped, especially in the 20% sample, due to reduced lipid-protein network formation and higher water content. Creaminess followed a similar pattern, with the control rated creamiest, 80% yolk slightly less creamy ($p < 0.05$), and 20% and 50% yolk significantly less creamy ($p < 0.01$), reflecting the emulsifying role of yolk lipids and lecithin. Sweetness was largely unaffected, though whole egg samples were perceived as slightly sweeter, possibly due to reduced fat masking. Aftertaste duration was longest in the control, slightly reduced at 80% yolk ($p < 0.05$), and unchanged in lower-yolk formulations. Overall, results showed that yolk concentration influences pH, color, and viscosity, but its sensory effects—especially on color, aroma, texture, and creaminess—are most pronounced when reduced below ~80%, making that level an optimal compromise between functionality and partial yolk reduction.

3.4 Effect of Essential oils on liquid whole eggs properties and antioxidant activity

The addition of basil, rosemary, and garlic essential oils (1,2,3%) to liquid whole eggs caused slight, statistically insignificant decreases in pH due to the mild acidity of their bioactive compounds and minor protein–oil interactions, with the egg's strong protein buffering system preventing major shifts. Color changes (L*, a*, b*) were also insignificant, as the small oil amounts lacked strong pigments to override yolk carotenoids, though basil and rosemary slightly enhanced yellowness (b*), and garlic increased lightness (L*) at higher levels. In a Rheological point of view, rosemary oil had negligible effects on yield stress (τ_0), viscosity (K), and flow behavior index (n), basil induced small increases in τ_0 and n at higher concentrations due to moderate protein interactions, and garlic had the strongest impact, significantly increasing τ_0 and n at 2–3% via protein cross-linking and network strengthening. Antioxidant activity (FRAP) improved in all oil-treated samples in a concentration-dependent manner, with rosemary showing the highest enhancement due to its phenolic content, followed by basil and garlic. Overall, essential oils minimally altered pH, color, and viscosity but enhanced antioxidant capacity, with garlic exerting the greatest structural impact on the egg matrix and rosemary delivering the strongest antioxidant boost.

3.5 Effect of cooking oils on liquid whole eggs properties.

The addition of olive, sunflower, coconut, and palm oils at varying concentrations (2.5%, 5%, and 7.5% v/v) to liquid whole eggs caused notable changes across multiple physicochemical, rheological, and sensory properties. Regarding pH, all oil-treated samples exhibited a slight increase compared to the control (pH 5.93±0.1), with the effect becoming more pronounced as oil concentration increased. Palm oil at 7.5% resulted in the highest pH value of 6.16±0.1, attributed to its higher saturated fat content and stronger interaction with egg proteins, which altered their charge balance. Coconut oil, also rich in saturated fats, produced similar but slightly lower pH shifts, while olive and sunflower oils, which are richer in mono- and polyunsaturated fats, caused more moderate pH increases. These changes are linked to dilution of acidic egg components and modifications in protein-lipid interactions that affect the ionization of amino acids, ultimately impacting protein functionality, emulsification, stability, and microbial resistance in the egg matrix.

Color parameters were also significantly affected by oil addition and concentration. The L* values, representing lightness, increased with all oils, especially at higher concentrations, indicating a lighter egg appearance due to increased light scattering caused by lipid incorporation. At 7.5%, palm oil reached the highest L* value (63.16±0.09), followed by coconut oil (61.29±0.01) and olive oil (67.12±0.08), while sunflower oil showed more variable results with a lower L* at 7.5% (50.2±0.01). The a* values, indicating red-green color shifts, showed reductions in the green intensity for most oil treatments; notably, palm oil at 5% was the only sample to shift toward a slight red hue, likely from its carotenoid content. Sunflower oil at 2.5% and 7.5% caused the most significant neutralization of the green tint, while coconut and olive oils at varying concentrations also shifted color toward less green but with smaller magnitude. For b* values, measuring yellowness, all oils except olive oil at 7.5% increased yellowness substantially, with palm oil at 5% (24.38±0.41) and coconut oil at 2.5% (24.10±0.41) showing the greatest increases, attributed to the enhanced visibility of xanthophyll pigments and carotenoids. Olive oil at 7.5% decreased yellowness, possibly due to its own greenish tint counteracting natural egg pigments.

Rheological properties changed markedly with oil type and concentration. The control eggs exhibited low yield stress (τ_0 = 0.073±0.001 Pa) and near-Newtonian flow behavior ($n \approx 0.97$). Olive oil treatments from 2.5% to 7.5% increased yield stress moderately (up to 0.124±0.001 Pa at 5%) and induced shear-thickening behavior ($n > 1$), though consistency index K remained low, indicating minor thickening likely due to incomplete emulsification. Sunflower oil at 2.5% had the highest yield stress (0.140±0.001 Pa), also showing shear-thickening with stable low K values, implying similar interaction patterns as olive oil. In contrast, coconut oil significantly increased yield stress and viscosity, with τ_0 rising to 20.99±0.90 Pa and K to over 2 $Pa{\cdot}s^n$ at 7.5%, and exhibited strong shear-thinning ($n \approx 0.32$), indicating a highly structured, gel-like network formed by its saturated fats and fat-protein aggregation. Palm oil moderately raised yield stress (0.560±0.021 Pa at 7.5%) with minor viscosity changes and nearly Newtonian to slight shear-thickening flow, reflecting stable fat dispersions without extreme thickening. These rheological alterations highlight how saturated fats like coconut and palm oils reinforce structure and viscosity more than unsaturated oils. Sensory evaluation of scrambled eggs cooked with these oils revealed that sunflower oil at 5% and coconut oil at 2.5% received the highest overall acceptance, combining favorable color, taste, texture, and aroma profiles. Sunflower oil's mild flavor and unsaturated fats contributed to smooth texture and natural flavor enhancement, while coconut oil's medium-chain triglycerides imparted a creamy mouthfeel and subtle buttery aroma. Aroma was rated highest for coconut and palm oils at 5%, linked to volatile compounds like lactones and carotenoids that enhance sensory appeal. The results suggest that moderate concentrations of oils, particularly sunflower at 5% and coconut at 2.5%, optimize sensory attributes without compromising structural integrity, whereas higher concentrations or certain oils affect texture and color in ways that could be tailored for specific food product requirements. Overall, the type and concentration of added oils significantly influence the physicochemical characteristics—such as pH, color, and rheology—and sensory qualities of liquid whole eggs. Saturated fat-rich oils like coconut and palm produce greater effects on pH, viscosity, and color shifts, while unsaturated oils like olive and sunflower tend to moderate these changes. These findings provide valuable insights for food formulation and processing, allowing optimization of egg-based products with targeted functional and sensory properties through precise oil selection and dosage.

4. CONCLUSIONS AND RECOMMENDATIONS

This study investigated the effects of fortifying liquid whole eggs with functional ingredients such as egg white powder, whey protein isolate, essential oils, and different vegetable oils, on their techno-functional, rheological, and sensorial properties. The findings provide valuable insights into how these modifications influence product quality, stability, and consumer acceptability, with implications for both industrial processing and functional food development.

The incorporation of egg white powder or whey isolate at concentrations of 3%, 5%, and 10%, combined with pasteurization at 60°C, 65°C, and 70°C, revealed that both protein content and thermal treatment played significant roles in determining the rheological behavior of liquid egg products over a 21-day refrigerated storage period. Higher protein concentrations led to increased yield stress and consistency index while reducing the flow behavior index, indicating a shift toward a more structured and viscous system. This effect was particularly evident in the 10% protein sample, which demonstrated gel-like behavior by Day 7. However, prolonged storage and elevated pasteurization temperatures accelerated protein aggregation. These results underscore the importance of optimizing both formulation and processing parameters to achieve stability in protein-enriched egg products.

The addition of 20% liquid whole to liquid egg yolk did not affect the techno-functional and sensory characteristics when compared to those of samples containing 100% yolk. This similarity was observed not only in instrumental analyses but also in sensory evaluations, where trained panelists reported minimal perceptible differences in texture, taste, and overall acceptability between the two formulations. These findings carry significant implications for the egg processing industry. By utilizing formulations with 80% yolk instead of 100%, manufacturers have the potential to reduce production costs, optimize ingredient utilization, and improve sustainability without compromising product quality or consumer satisfaction. Such an approach can be especially valuable in large-scale production. However, further studies should assess the long-term stability, and nutritional impact of this change.

The addition of essential oils primarily enhanced antioxidant activity, contributing to the product's functional value without negatively affecting other physicochemical or rheological properties. This selective enhancement suggests essential oils may serve as natural antioxidants that extend shelf life and health appeal without compromising structural integrity or negatively effecting the sensory attributes.

The incorporation of different vegetable oils had diverse impacts on the rheological properties of liquid eggs. Coconut oil induced the most pronounced changes, significantly increasing yield stress and consistency due to strong fat-protein interactions and network formation, while also producing a strong shear-thinning behavior. In contrast, olive and sunflower oils caused mild shear-thickening effects, with minimal contributions to consistency, likely due to limited emulsification or weaker interactions with egg proteins. Palm oil exhibited a more balanced profile, modestly increasing viscosity and displaying near-Newtonian flow characteristics.

Sensorial evaluations of cooked scrambled egg formulations enriched with these oils revealed that sunflower oil at 5% and coconut oil at 2.5% provided the most favorable sensory profiles, particularly in terms of color, texture, and overall acceptability. These effects were attributed to the fatty acid composition and aromatic profiles of the oils, which improved mouthfeel, flavor balance, and aroma. Additionally, coconut and palm oils at 5% enhanced aroma due to their volatile compound profiles. While this study primarily focused on rheological, techno-functional, and sensory attributes, it is critical to conduct microbiological testing and shelf-life assessments, as the incorporation of proteins, changing yolk percentages in liquid whole egg, adding essential oils, and various types of oils along with different pasteurization treatments, can significantly influence the microbiological safety and stability of the product. Evaluating microbial load over time under various storage conditions will ensure consumer safety and regulatory compliance. Expanding research to include different storage conditions and packaging technologies, such as modified atmosphere packaging or room temperature storage, will help determine product stability in varying distribution environments, thereby supporting commercial scalability and extended shelf life. Additionally, the antioxidant benefits observed from essential oil inclusion suggest potential for further exploration of natural bioactive compounds or dietary fibers to enhance nutritional value. In summary, the fortification of liquid whole eggs with carefully selected proteins, essential oils, and lipid sources presents a promising strategy to develop nutritionally enhanced, functionally stable, and sensorially appealing egg-based products. These results emphasize the necessity of understanding ingredient-function interactions and highlight the potential of customized formulations to meet consumer demand for high-quality, functional food products.

5. NEW SCIENTIFIC RESULTS

1. I found that 5 and 10 percentages (w/w) of both egg white and whey isolate proteins combined with pasteurization temperature of 65°C and 70°C in liquid whole egg, and 55°C and 60 °C in liquid egg white, increased protein aggregation and accelerated early gelation. With the 10-percentage added proteins, sample showed the most significant viscosity changes, including potential destabilization with storage time, in case of liquid whole egg, and mid-storage breakdown in case of liquid egg white at 55 °C.
2. I found that 21-day storage at 4°C affected the stability of liquid whole egg and liquid egg white, especially with 10% W/W added egg and whey proteins and at pasteurization temperature of 60–70°C. In liquid whole egg, 10% W/W egg white protein with 70°C pasteurization increased viscosity early on but showed gel weakening and phase separation after 14 days. Liquid egg white was more stable when pasteurized at 60°C for both proteins, meanwhile at 55°C it showed some degradation after two weeks. liquid egg white with 5%W/W egg white protein pasteurized at 60°C retained structural over the full storage period, indicating it as the most favorable condition.
3. I found that the addition of whey isolates and egg white proteins into liquid whole egg after pasteurization on 60 ± 0.2°C with 3.5 minutes of holding time, showed minimal impact on liquid whole egg viscosity parameters. This indicates that these protein sources do not significantly disrupt the rheological behavior of liquid whole eggs.
4. I found that across all measured parameters, the percentages of yolk were the primary contributor to techno-functional properties. At measured parameters and sensory testing, samples with 80% (w/w) yolk scored close results to those with 100% yolk. This finding suggests that manufacturers can utilize formulations with 80% yolk to reduce production costs without causing noticeable changes in product quality.
5. I found that the addition of any percentage of essential oils significantly increased antioxidant activity in liquid whole egg samples but did not affect other rheological or structural parameters. Meanwhile, the addition of oils significantly affected the rheology of liquid whole eggs. coconut oil caused the greatest increase in yield stress with strong shear-thinning behavior at all added concentrations, while olive and sunflower oils

induced mild shear-thickening behavior, and palm oil moderately enhanced viscosity with near-Newtonian flow. The increase in antioxidant activity with the addition of essential oils suggests that they can be incorporated as natural functional additives to improve nutritional value without compromising processing characteristics.

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