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Rheological Properties of Mayonnaise with Non-Traditional Ingredients

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Abstract.
Rheological measurements are used in the food industry to determine physical characteristics of raw materials, as well as semi-finished and finished products. We aimed to study the effects of ingredients and homogenization parameters on the rheological properties of mayonnaise prepared with pumpkin and rice oils, as well as various honeys.

Mayonnaise samples were prepared with non-traditional ingredients, namely cold-pressed pumpkin seed oil, refined rice oil, and four varieties of honey (acacia, linden, forest, and spring). The samples were made in the traditional way on an Ultra Turrax T25 IKA homogenizer (3500–24 000 rpm). The rheological properties of honey and mayonnaise were determined on a Brookfield rotational viscometer.

Forest honey had the highest viscosity, while linden honey had the lowest viscosity, compared to the other honeys. The sample of mayonnaise with forest honey had the highest effective viscosity (3.427 Pa·s) and consistency (101.26 Pa·s^n). The use of whey powder provided mayonnaise with the most optimal rheological parameters. Of all carbohydrates, inulin HD had the best effect on the consistency of mayonnaise, with effective viscosity of 2.801 ± 0.001 Pa·s and a flow index of 0.2630 ± 0.0020. Disaccharides provided mayonnaise with higher viscosity and consistency than monosaccharides. Mayonnaise with fresh egg yolk had higher viscosity (2.656 ± 0.002 Pa·s) and consistency (65.640 ± 0.004 Pa·s) than the samples with other egg products. The rheological characteristics of mayonnaise were also determined by the homogenization time and rotor speed. Increasing the time from 2 to 4 min at 10 000 rpm raised the emulsion's viscosity and consistency from 6.253 to 8.736 Pa·s and from 77.42 to 134.24 Pa·s^n, respectively, as well as reduced the flow index from 0.2628 to 0.1995. The rotor speed of 10 000–12 000 rpm was optimal for mayonnaise with pumpkin and rice oils and honey.

The studied samples of mayonnaise with pumpkin and rice oils, as well as honey, belong to non-Newtonian systems and pseudoplastic fluids. The empirical flow curves can be adequately described by the Herschel-Bulkley model. Our results can significantly increase the efficiency of mayonnaise production, improve its quality, and reduce production costs.

Keywords. Mayonnaise, rheological properties, homogenization, honey, vegetable oil, carbohydrates

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Исследование реологических свойств майонеза с нетрадиционным сырьем

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Аннотация.
Реологические измерения в пищевой промышленности играют важную роль в определении физических характеристик сырья, полуфабрикатов и готовых продуктов. Цель работы состояла в исследовании влияния ингредиентов и параметров процесса гомогенизации на реологические свойства майонеза с добавлением тыквенного и рисового масел, а также различных сортов мёда.

Для приготовления опытных образцов майонеза в качестве нетрадиционных ингредиентов использовали тыквенное масло холодного отжима и рафинированное рисовое масло, а также четыре сорта мёда (акациевый, липовый, лесной и весенний). Приготовление майонеза осуществляли традиционным способом на лабораторном гомогенизаторе Ultra Turrax T25 IKA (диапазон скоростей вращения ротора 3500–24 000 об/мин). Реологические свойства меда и опытных образцов майонеза определяли на ротационном вискозиметре Brookfield.

Сравнительный анализ реологических показателей меда показал, что высокую вязкость имеет лесной мед, а низкую – липовый. Введение в рецептуру майонеза различных сортов мёда повлияло на реологические свойства готового продукта. Образец майонеза с лесным медом имел высокие значения эффективной вязкости (3,427 Па·с) и коэффициента консистенции (101,26 Па·с^n). Использование сухой сыворотки в качестве молочного компонента при приготовлении майонеза с добавлением тыквенного и рисового масел позволило получить продукт с лучшими реологическими показателями. Также положительное влияние, по сравнению с другими углеводами, на консистенцию майонеза оказало введение инулина HD (эффективная вязкость 2,801 ± 0,001 Па·с, индекс текучести 0,2630 ± 0,0020). Используемые дисахариды обеспечивают более высокую вязкость и консистенцию майонеза, чем моносахариды. Майонез со свежим яичным желтком имел более высокую вязкость (2,656 ± 0,002 Па·с) и консистенцию (65,640 ± 0,004 Па·с) по сравнению с добавлением других яичных продуктов. Реологические характеристики майонеза также зависят от продолжительности гомогенизации и частоты вращения ротора гомогенизатора. Увеличение продолжительности гомогенизации с 2 до 4 мин при частоте вращения ротора гомогенизатора 10 000 об/мин повышало вязкость эмульсии с 6,253 до 8,736 Па·с и коэффициент консистенции – с 77,42 до 134,24 Па·с^n, а также снижало индекс текучести с 0,2628 до 0,1995. Частота вращения ротора гомогенизатора в диапазоне 10 000–12 000 об/мин является оптимальной для майонеза с добавлением тыквенного и рисового масел и меда.

Исследованные образцы майонеза с тыквенным и рисовым маслом, а также с мёдом относятся к неньютоновским системам, псевдопластическим типам жидкостей. Полученные эмпирические кривые течения с высокой степенью адекватности описываются моделью Гершеля-Балкли. Применение полученных результатов позволит повысить эффективность проектирования технологических процессов при производстве майонезов, улучшить качественные показатели готового продукта и снизить производственные издержки.

Ключевые слова. Майонез, реологические свойства, гомогенизация, мёд, растительное масло, углеводы

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Introduction

Food production processes are organized in such a way as to ensure the highest quality of the finished product. During processing, raw materials of plant origin are exposed to various mechanical stresses. In this regard, rheological analysis of food products is becoming increasingly important for assessing the quality of raw materials and finished products, as well as for predicting the behavior of semi-finished products during processing. In particular, it is used to determine the structure of the product and its characteristics in accordance with the technical regulations [1].

Mayonnaise is a multicomponent, finely dispersed water-fat emulsion of the direct oil-in-water type that is stable over a wide temperature range [2–4]. In this product, vegetable oil is an internal phase in the form of tiny drops in a dispersion medium [5].

According to the standard, high-calorie mayonnaise must contain more than 50% of edible vegetable oil, which forms its fat phase [6]. Mayonnaise is classified as a promising food product due to its composition and sensory properties. Also, it is used as a seasoning for various dishes. By enhancing the food's nutritional value and taste, mayonnaise stimulates appetite and improves digestion. It is a product of high biological and physiological value [7].

Vegetable oil is one of the main components of mayonnaise that contributes to its sensory and physicomechanical properties [8]. The oil content has a significant effect on the product's rheological properties such as yield strength, as well as storage and loss moduli. A combination of sunflower and pumpkin seed oils can provide an optimal composition of fatty acids and tocopherols, natural antioxidants that improve nutritional and sensory properties of mayonnaise. In particular, sunflower oil enriches the product with essential linoleic acid, while cold-pressed pumpkin oil is rich in oleic acid and gamma-tocopherol, contributing to longer shelf life. In addition, the latter's aroma and color can enhance the product's sensory properties.

Other main ingredients of mayonnaise are milk proteins, egg powder, stabilizers, and water. Fat-soluble vitamins, sugar, salt, mustard, and various flavor additives are present in small amounts [9].

Powdered milk, egg powder, and vegetable phospholipids are used as emulsifiers [10]. Powdered milk is also a structure-forming agent, since milk proteins swell in the presence of moisture, increasing the water-retaining capacity of mayonnaise [11].

Mustard powder is used as a flavor additive, as well as an emulsifier and a structure-forming agent due to its proteins. Mustard powder should be dry, with a sharp smell of allyl oil and a light yellow color. Mustard paste should be free of mustiness and bitterness [12].

Acetic acid improves the taste and enhances bactericidal properties of mayonnaise. Water is needed to dissolve salt and sugar, as well as to dissolve and swell milk proteins and other ingredients.

Vegetable oil contained in mayonnaise provides the human body with physiologically active (essential) fatty acids, which lower blood cholesterol and help prevent atherosclerosis. Milk and egg powder are sources of proteins and essential amino acids, while sugar is a source of carbohydrates. Organic acids (acetic and citric) improve digestion, provide the required acidity and bactericidal purity, and determine taste and aroma [11].

Mayonnaise is a direct-type emulsion that is easily absorbed by the body. This fact and the content of vegetable oil determine its nutritional value [14].

Egg yolks act as emulsifiers mainly due to the presence of phospholipids, as well as high and low density lipoproteins. Vinegar, salt, sugar, and mustard are added to mayonnaise for flavor. These ingredients play an important role in the physical stability of the emulsion [15, 16]. Lutein, phycocyanin and other compounds, as well as processed beets and fruit components provide mayonnaise with oxidation stability and contribute to its taste and color, enhancing consumer interest [10, 17–19]. Rheological properties are an important quality criterion for food products, including water-fat emulsions (mayonnaise, sauces, and margarine) [20]. They are responsible for the product's consistency and quality during production, storage, and transportation [21, 22]. The rheological characteristics of mayonnaise are mainly determined by its fat phase, as well as thickeners, stabilizers, and emulsifiers in its formulation [23]. The product's quality, stability, and viscosity depend on the homogenization process, the dispersion of fat droplets in the continuous water phase, egg yolk, the type of carbohydrates, as well as the amount and type of milk [24–27]. In this type of emulsion, fat droplets are mechanically dispersed in the continuous water phase of acetic acid, while natural emulsifiers from egg yolk (phospholipids and proteins) ensure greater stabilization of the entire system [28].

The homogenization parameters (rotor speed and time) and the choice of a rotor-stator system, which forms fat droplets of a larger or smaller diameter, determine the medium's stability and play an important role in the formation of a water-fat emulsion [29–31].

We aimed to study the rheological and textural properties of mayonnaise containing pumpkin and rice oils, as well as various types of honey. We also sought to determine the influence of process parameters and the composition of the oil phase on the rheological properties of mayonnaise.

Study objects and methods

High-calorie mayonnaise with pumpkin and rice oils was formulated from refined sunflower oil, cold-pressed pumpkin seed oil, and refined rice oil (fat phase); egg products (fresh and pasteurized egg yolks and whole egg powder); carbohydrates (glucose, fructose, lactose, sucrose, inulin HD); acetic acid; sea salt; mustard; dairy products (whole milk, skimmed milk, and whey powders); tartaric acid; distilled water; and banana puree (Table 1).

Mayonnaise with the addition of honey was formulated from refined sunflower oil (fat phase), egg yolk, honey, acetic acid, sea salt, tartaric acid, and distilled water (Table 2).

The fat phase of mayonnaise consisted of refined sunflower oil (Sloboda, Russia), cold-pressed pumpkin seed oil (Organic brand), and refined rice oil (Tayra, Thailand). Vinegar, sea salt, and mustard were bought at a local shop. Egg yolk was purchased from a private supplier and prepared both fresh and pasteurized. Four types of honey (acacia, spring, linden, and forest) were purchased from a private supplier (Moscow region). The milk component consisted of whole milk powder (26.3% proteins, 39.8% sugars, 26% fats), skimmed milk powder (1.5% fat) (Tagris), and whey powder (2% milk fat, 12–14% proteins, 74% lactose) (Vita-Max). The carbohydrates glucose, sucrose, fructose, lactose, tartaric acid, and inulin HD were purchased from Novaprodukt. Tartaric acid was added as an acidity regulator. The fruit component (banana puree) was prepared by peeling bananas, cutting them into pieces, and crushing by stirring to obtain a homogenized sample.

Table 1. Formulation of mayonnaise with pumpkin and rice oils

Таблица 1. Рецептура для приготовления майонеза с добавлением тыквенного и рисового масел

Formulation	Sample	
	Content, %	Weight, g
Refined sunflower oil	50.0	150.0
Cold-pressed pumpkin seed oil	12.5	37.5
Refined rice oil	12.5	37.5
Egg products	6.2	18.6
Dairy products	2.1	6.3
Carbohydrates	2.2	6.6
Acetic acid	3.0	9.0
Sea salt	0.9	2.7
Mustard	0.2	0.6
Tartaric acid	0.1	0.3
Distilled water	7.8	23.4
Banana puree	2.5	7.5
TOTAL	100	300

Table 2. Formulation of mayonnaise with honey

Таблица 2. Рецептура приготовления майонеза с добавлением меда

Formulation	Sample	
	Content, %	Weight, g
Refined sunflower oil	75.0	225.0
Fresh egg yolk	7.7	23.1
Honey	3.8	11.4
Acetic acid	4.0	12.0
Sea salt	0.9	2.7
Tartaric acid	0.1	0.3
Distilled water	8.5	25.5
TOTAL	100	300

Mayonnaise preparation. Mayonnaise samples (300 g) with pumpkin and rice oils were prepared in the traditional way on a T25 Ultra Turrax IKA laboratory homogenizer, using a S25 D-14 G-KS rotor-stator system with a rotor speed of 3500–24 000 rpm. For this, we pre-weighed the ingredients (fresh egg yolk, vinegar, water, and others) and mixed them with half of sunflower oil. Then, we turned on the homogenizer and slowly added the rest of sunflower oil, as well as pumpkin seed and rice oils. The mixture was homogenized for 3 min at 10 000 rpm at room temperature, followed by rheological analysis. Other samples were prepared in the same way, with varying ingredients and homogenization parameters depending on the formulation.

Rheological properties. The rheological analysis of freshly prepared mayonnaise samples with pumpkin and rice oils was performed on a Brookfield rotational viscometer with coaxial cylinders. The viscometer was connected to a computer equipped with Rheocalc 3.2 software for measurements and data processing. The measurements were taken at 25 and 10°C. The temperatures were maintained using a TC-501P Brookfield thermostat. In particular, we determined the dependence of shear stress (τ) and effective viscosity (μ) on shear rate (D) in the ranges of 2.15–136.6 1/s (increasing measurement) and 136.6–2.15 1/s (reverse measurement). We also studied the phenomenon of thixotropy, i.e. the ability to restore viscous and plastic properties after the load is removed and deformation ceases.

The experimental data showed the rheological model of mayonnaise. Particularly, the samples had non-Newtonian properties and belonged to pseudoplastic fluids. The rheological parameters of consistency coefficient (k) and flow index (n) were calculated using the linear regression method in Microsoft Excel.

Formula (1) describes the Ostwald-Reiner power law used to calculate the rheological parameters.

$$\tau = k \cdot D^n \quad (1)$$

where τ is the shear stress, Pa; D is the shear rate, 1/s; k is the consistency coefficient, Pa·s^n; n is the flow index.

Formula (2) was used to calculate effective viscosity of the mayonnaise sample:

$$\mu = k \cdot D^{n-1} \quad (2)$$

where μ is the effective viscosity, Pa·s.

Statistical analysis. All the experiments were carried out in triplicate. One-way analysis of variance (ANOVA) was used to establish the significance of differences in the experimental data. Data management and analysis was performed using SPSS software and presented as mean ± standard deviation.

Results and discussion

Rheological properties of mayonnaise with honey. We determined the influence of honey varieties and homogenization parameters on the rheological properties of mayonnaise measured at 25°C (Figs. 1 and 2, Tables 3–6). Figure 1 shows the relationship between shear stress and shear rate for spring honey.

According to the results, honey belongs to Newtonian fluids, since the line passed through the origin of the coordinate system (Fig. 1). Table 3 presents the rheological properties of the studied honey varieties expressed in terms of rheological parameters.

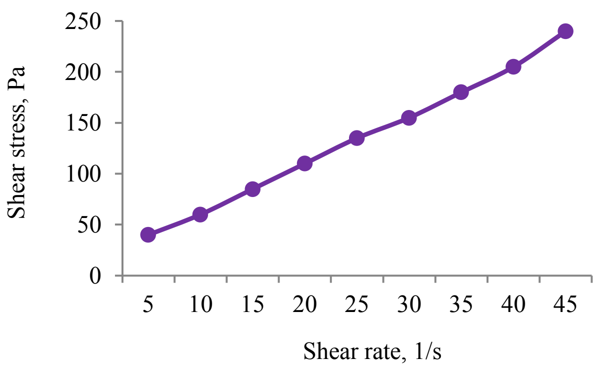

Figure 1. Relationship between shear stress and shear rate for spring honey at 25°C

Рисунок 1. Зависимость между напряжением сдвига и скоростью сдвига весеннего меда при 25 °C

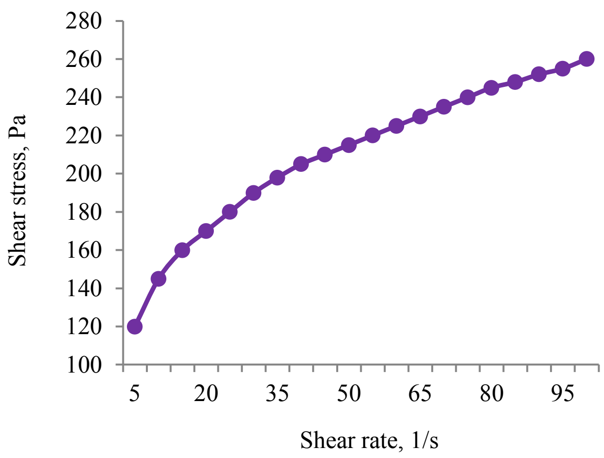

Figure 2. Relationship between shear stress and shear rate for mayonnaise with acacia honey (10 000 rpm, 2 min) at 25°C

Рисунок 2. Зависимость напряжения сдвига и скорости сдвига майонеза с акациевым медом (10 000 об/мин, 2 мин) при 25 °C

As can be seen in Table 3, forest honey had the highest viscosity and consistency coefficient, while linden honey had the lowest viscosity.

The relationship between shear stress and shear rate for mayonnaise with acacia honey indicated that the samples with honey exhibited non-Newtonian, pseudoplastic properties (Fig. 2).

Li *et al.* confirmed that mayonnaise is a non-Newtonian fluid that exhibits yield strength, pseudoplasticity, and thixotropy [32]. Sakai *et al.* reported the pseudoplastic behavior of mayonnaise with characteristics depending on the raw material [10].

Empirical flow curves with a high degree of adequacy are described by the Herschel-Bulkley model.

Table 4 shows the effect of honey on the rheological parameters of mayonnaise homogenized at 10 000 rpm for 2 min at 25°C.

The control mayonnaise with acacia honey had an effective viscosity of 3.118 ± 0.001 Pa·s, a shear rate of 77.82 1/s, a consistency coefficient of 77.420 ± 0.125 Pa·s^n, and a flow index of 0.2624 ± 0.0003 measured at 25°C. The sample with linden honey had slightly higher effective viscosity (3.294 ± 0.002 Pa·s^n) and consistency coefficient (78.460 ± 0.002 Pa·s^n) compared to the acacia honey mayonnaise. Forest honey showed higher viscosity (3.4270 ± 0.0005 Pa·s^n) and consistency (101.260 ± 0.002 Pa·s^n) but a lower flow index (0.2224 ± 0.0002) compared to the other samples.

Tables 5 and 6 show the effects of homogenization time and rotor speed on the rheological properties of mayonnaise with acacia honey measured at 25°C.

As can be seen in Table 5, the homogenization time of 2 min led to an effective viscosity of 6.253 ± 0.001 Pa·s at a shear rate of 30.36 1/s, a consistency coefficient of 77.42 ± 0.04 Pa·s^n, and a flow index of 0.2628 ± 0.0002. Increasing the time to 4 min contributed to higher viscosity (8.7360 ± 0.0005 Pa·s) and consistency (134.240 ± 0.125 Pa·s^n) but a lower flow index (0.1995 ± 0.0002).

Table 6 shows the effect of the rotor speed (10 000 and 12 000 rpm) during 2 min of homogenization on

Table 3. Rheological properties of honeys measured at 25°C

Таблица 3. Реологические свойства различных сортов меда, измеренные при 25 °C

Honey variety	μ*, Pa·s	k, Pa·s^n	n
Spring honey	4.9446	6.4789	0.8950
Forest honey	16.6509	17.3020	0.9851
Linden honey	4.7719	7.3144	0.8341
Acacia honey	5.8413	6.0930	0.9837

*Effective viscosity at shear rate of 77.82 1/s.

*Эффективная вязкость при скорости сдвига 77,82 1/с.

Table 4. Effect of honey variety on the rheological parameters of mayonnaise

Таблица 4. Влияние сорта меда на реологические параметры майонеза

Honey variety	μ*, Pa·s	k, Pa·s^n	n	R^2
Spring honey	3.083 ± 0.001	63.110 ± 0.029	0.3067 ± 0.0040	0.968
Forest honey	3.4270 ± 0.0005	101.260 ± 0.002	0.2224 ± 0.0002	0.990
Linden honey	3.294 ± 0.002	78.460 ± 0.002	0.2719 ± 0.0002	0.989
Acacia honey	3.118 ± 0.002	77.420 ± 0.125	0.2624 ± 0.0003	0.994

*Effective viscosity at shear rate of 77.82 1/s. R^2 is the coefficient of determination.

*Эффективная вязкость при скорости сдвига 77,82 1/с. R^2 – коэффициент детерминации.

Table 5. Effect of homogenization time on the rheological properties of mayonnaise with acacia honey

Таблица 5. Влияние продолжительности гомогенизации на реологические свойства майонеза с акациевым медом

Sample, min	μ*, Pa·s	k, Pa·s^n	n	R^2
2	6.253 ± 0.001	77.42 ± 0.04	0.2628 ± 0.0002	0,994
4	8.7350 ± 0.0005	134.240 ± 0.125	0.1995 ± 0.0002	0,964

*Effective viscosity at shear rate of 30.36 1/с. R^2 is the coefficient of determination.

*Эффективная вязкость при скорости сдвига 30,36 1/с. R^2 – коэффициент детерминации.

Table 6. Effect of the rotor speed on the rheological properties of mayonnaise with acacia honey

Таблица 6. Влияние частоты вращения ротора на реологические свойства майонеза с акациевым медом

Sample, rpm	μ*, Pa·s	k , Pa·s^n	n	R^2
10 000	6.253 ± 0.010	77.42 ± 0.04	0.2628 ± 0.0002	0.994
12 000	8.039 ± 0.029	102.320 ± 0.125	0.2547 ± 0.0002	0.982

*Effective viscosity at shear rate of 30.36 1/s. R^2 is the coefficient of determination.

*Эффективная вязкость при скорости сдвига 30,36 1/с. R^2 – коэффициент детерминации.

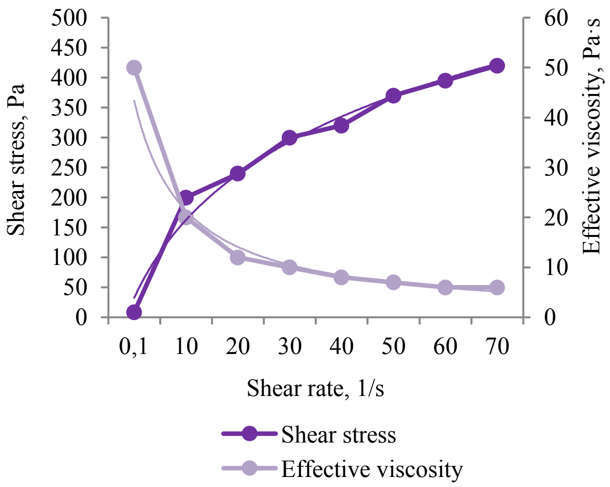

Figure 3. Flow curves for mayonnaise with pumpkin and rice oils at 25°C

Рисунок 3. Кривые течения майонеза с добавлением тыквенного и рисового масел при 25 °C

the rheological parameters of mayonnaise with acacia honey measured at 25°C.

As can be seen, the rotor speed changed the rheological properties of mayonnaise. In particular, the speed of 10 000 rpm resulted in the effective viscosity of 6.253 ± 0.001 Pa·s at a shear rate of 30.36 1/s, a consistency coefficient of 77.42 ± 0.04 Pa·s^n, and a flow index of 0.2628 ± 0.0002. Increasing the rotor speed to 12000 rpm produced a more stable emulsion with higher effective viscosity (8.039 ± 0.029 Pa·s) and consistency (102.320 ± 0.125 Pa·s^n). The emulsion's higher stability was due to finer fat droplets formed at the rotor speed of 12 000 rpm, which were finely dispersed in the water phase. Thus, this speed was more optimal than 10 000 rpm.

Rheological properties of mayonnaise with pumpkin and rice oils. Figure 3 and in Tables 7–11 show the effects of ingredients on the rheological properties of mayonnaise with pumpkin and rice oils measured at 25 and 10°C.

Figure 3 features the relationship between shear stress and shear rate measured at 25°C.

We found that the tested samples exhibited non-Newtonian, pseudoplastic properties, as well as thixotropy. The empirical flow curves are described by the Herschel-Bulkley model with a high degree of adequacy.

Table 7 shows the effect of milk components on the rheological parameters of mayonnaise homogenized for 3 min at 10 000 rpm.

Table 7. Effect of milk component on the rheological properties of mayonnaise with pumpkin and rice oils

Таблица 7. Влияние молочного компонента на реологические свойства майонеза с добавлением тыквенного и рисового масел

Sample	μ*, Pa·s	k, Pa·s^n	n	R^2	μ*, Pa·s	k, Pa·s^n	n	R^2
	25 °C				10 °C			
Skimmed milk powder	2.2290 ± 0.0002	46.870 ± 0.078	0.3005 ± 0.0030	0.998	2.7120 ± 0.0002	54.840 ± 0.029	0.3095 ± 0.0030	0.998
Whole milk powder	2.3430 ± 0.0002	55.210 ± 0.004	0.2744 ± 0.0030	0.997	2.9990 ± 0.0002	67.110 ± 0.002	0.2863 ± 0.0030	0.987
Whey powder	2.3910 ± 0.0002	57.180 ± 0.003	0.2710 ± 0.0020	0.990	3.0550 ± 0.0002	69.090 ± 0.002	0.2838 ± 0.0020	0.995

*Effective viscosity at shear rate of 77.82 1/s. R^2 is the coefficient of determination.

*Эффективная вязкость при скорости сдвига 77,82 1/с. R^2 – коэффициент детерминации.

Table 8. Effect of carbohydrate composition on the rheological properties of mayonnaise with pumpkin and rice oils

Таблица 8. Влияние углеводного состава на реологические свойства майонеза с добавлением тыквенного и рисового масел

Sample	μ*, Pa·s	k, Pa·s^n	n	R^2	μ*, Pa·s	k, Pa·s^n	n	R^2
	25 °C				10 °C			
Glucose	2.392 ± 0.004	57.160 ± 0.078	0.2712 ± 0.0010	0.990	3.052 ± 0.004	69.060 ± 0.029	0.2837 ± 0.0010	0.995
Fructose	1.997 ± 0.003	39.050 ± 0.003	0.3172 ± 0.0020	0.997	2.464 ± 0.003	55.620 ± 0.002	0.2842 ± 0.0020	0.989
Sucrose	2.425 ± 0.002	58.630 ± 0.004	0.2685 ± 0.0030	0.992	3.024 ± 0.002	70.150 ± 0.002	0.2780 ± 0.0030	0.995
Lactose	2.748 ± 0.001	68.480 ± 0.002	0.2615 ± 0.0020	0.993	3.031 ± 0.001	77.510 ± 0.001	0.2556 ± 0.0020	0.984
Inulin HD	2.801 ± 0.001	69.360 ± 0.002	0.2630 ± 0.0020	0.992	3.051 ± 0.001	78.920 ± 0.004	0.2530 ± 0.0020	0.983

*Effective viscosity at shear rate of 77.82 1/s. R^2 is the coefficient of determination.

*Эффективная вязкость при скорости сдвига 77,82 1/с. R^2 – коэффициент детерминации.

Table 9. Effect of egg products on the rheological properties of mayonnaise

Таблица 9. Влияние яичных продуктов на реологические свойства майонеза

Sample	μ*, Pa·s	k, Pa·s^n	n	R^2	μ*, Pa·s	k, Pa·s^n	n	R^2
	25 °C				10 °C			
Fresh egg yolk	2.656 ± 0.002	65.640 ± 0.004	0.2634 ± 0.0020	0.991	3.144 ± 0.001	73.520 ± 0.004	0.2761 ± 0.0020	0.998
Pasteurized egg yolk	2.391 ± 0.002	57.150 ± 0.003	0.2711 ± 0.0002	0.990	3.054 ± 0.002	69.090 ± 0.003	0.2838 ± 0.0030	0.995
Whole egg powder	2.504 ± 0.001	54.230 ± 0.002	0.2937 ± 0.0030	0.999	3.116 ± 0.002	71.240 ± 0.002	0.2813 ± 0.0020	0.997

*Effective viscosity at shear rate of 77.82 1/s. R^2 is the coefficient of determination.

*Эффективная вязкость при скорости сдвига 77,82 1/с. R^2 – коэффициент детерминации.

Table 10. Effect of homogenization time on the rheological properties of mayonnaise with pumpkin and rice oils

Таблица 10. Влияние продолжительности гомогенизации на реологические свойства майонеза с добавлением тыквенного и рисового масел

Sample, min	μ*, Pa·s	k, Pa·s^n	n	R^2	μ*, Pa·s	k, Pa·s^n	n	R^2
	25 °C				10 °C			
1	1.548 ± 0.002	42.150 ± 0.004	0.2887 ± 0.0020	0.991	2.244 ± 0.001	60.410 ± 0.004	0.2908 ± 0.0020	0.998
3	1.939 ± 0.002	57.150 ± 0.003	0.2711 ± 0.0020	0.990	2.485 ± 0.002	69.099 ± 0.003	0.2838 ± 0.0030	0.995
5	1.758 ± 0.001	53.610 ± 0.002	0.3282 ± 0.0030	0.999	2.208 ± 0.002	58.760 ± 0.002	0.3026 ± 0.0020	0.997

*Effective viscosity at shear rate of 103.8 1/s. R^2 is the coefficient of determination.

*Эффективная вязкость при скорости сдвига 103,8 1/с. R^2 – коэффициент детерминации.

Table 11. Effect of the rotor speed on the rheological properties of mayonnaise with pumpkin and rice oils

Таблица 11. Влияние частоты вращения ротора на реологические свойства майонеза с добавлением тыквенного и рисового масел

Sample, rpm	μ*, Pa·s	k, Pa·s^n	n	R^2	μ*, Pa·s	k, Pa·s^n	n	R^2
	25 °C				10 °C			
10 000	1.939 ± 0.002	57.150 ± 0.004	0.2711 ± 0.0020	0.990	2.485 ± 0.001	69.090 ± 0.004	0.2838 ± 0.0020	0.995
12 000	2.281 ± 0.002	59.880 ± 0.003	0.2242 ± 0.0020	0.999	2.515 ± 0.002	75.130 ± 0.003	0.3075 ± 0.0030	0.996
15 000	1.810 ± 0.001	38.910 ± 0.002	0.3375 ± 0.0030	0.996	2.208 ± 0.002	49.560 ± 0.002	0.3299 ± 0.0020	0.995

*Effective viscosity at shear rate of 77.82 1/s. R^2 is the coefficient of determination.

*Эффективная вязкость при скорости сдвига 77,82 1/с. R^2 – коэффициент детерминации.

The control mayonnaise made from whey powder had an effective viscosity of 2.3910 ± 0.0002 Pa·s, a consistency index of 57.180 ± 0.003 Pa·s^n, and a flow index of 0.271 ± 0.002 measured at 25°C. Using skimmed milk powder led to lower effective viscosity (2.2290 ± 0.0002 Pa·s^n) and consistency (46.870 ± 0.078 Pa·s^n) but a higher flow index (0.3005 ± 0.0030), compared to the samples with whole milk and whey powders. Thus, whey powder contributed to higher consistency and viscosity of mayonnaise with pumpkin and rice oils measured at 25°C. When measured at 10°C, the rheological parameters showed higher values than those obtained at 25°C, which confirmed the effect of temperature on the rheological properties.

Table 8 shows the effect of carbohydrate type on the rheological parameters of mayonnaise homogenized for 3 min at 10 000 rpm. The measurements were taken at 25 and 10°C.

The control mayonnaise was prepared with glucose. We found that the use of glucose and fructose monosaccharides lowered effective viscosity and consistency, compared to the use of sucrose and lactose disaccharides, inulin HD, or acacia honey. Fructose contributed to the lowest values of these parameters, while inulin HD provided the highest consistency (69.360 ± 0.002 Pa·s) and effective viscosity (2.801 ± 0.001 Pa·s), but the lowest flow index (0.2630 ± 0.0020) measured at 25°C. Alvarez-Sabatel *et al.* found that the content of vegetable oil and inulin affected the stability and rheological properties of mayonnaise homogenized in the rotor-stator system, as well as under high pressure [17]. The same effects were observed on the rheological parameters of the samples with pumpkin and rice oils at 10°C.

Table 9 shows the effects of egg products on the rheological parameters of mayonnaise with pumpkin and rice oils homogenized for 3 min at 10 000 rpm. The measurements were taken at 25 and 10°C.

The mayonnaise prepared with fresh egg yolk had higher viscosity (2.656 ± 0.002 Pa·s) and consistency (65.640 ± 0.004 Pa·s^n) but a lower flow index (0.2634 ± 0.0020). Using whole egg powder resulted in higher effective viscosity and consistency compared to pasteurized egg yolk and lower values of these parameters compared to fresh egg yolk. Higher values were obtained for the rheological properties at 10°C, compared to measurements at 25°C.

Tables 10 and 11 show the effects of homogenization time and rotor speed on the rheological properties of mayonnaise with pumpkin and rice oils. According to the flow index, the mayonnaise under study belonged to non-Newtonian fluids of the pseudoplastic type.

Table 10 shows the effect of homogenization time (1, 3 and 5 min) at 10 000 rpm on the rheological properties of mayonnaise measured at 25 and 10°C.

As can be seen, the sample homogenized for 1 min had an effective viscosity of 1.548 ± 0.002 Pa·s at a shear rate of 103.8 1/s, a consistency coefficient of 42.150 ± 0.004 Pa·s^n, and a flow index of 0.2887 ± 0.0020. Increasing homogenization time to 3 min resulted in higher viscosity (1.936 ± 0.002 Pa·s) and consistency (57.150 ± 0.003 Pa·s^n) but a lower flow index (0.2711 ± 0.0020). A further increase to 5 min destroyed the structure of mayonnaise and led to lower viscosity (1.758 ± 0.001 Pa·s) and consistency (53.610 ± 0.002 Pa·s^n) but a higher flow index (0.3282 ± 0.0030). Measurements at 10°C showed the same results, but higher values compared to those for the rheological parameters obtained at 25°C.

Table 11 shows the effects of the rotor speed (10 000, 12 000, and 15 000 rpm) on the rheological parameters of mayonnaise homogenized for 3 min. Measurements were taken at 25 and 10°C.

As can be seen, the rotor speed affected the rheological parameters of the samples. An increase from 10 000 to 12 000 rpm led to higher effective viscosity (2.281 ± 0.002 Pa·s) and consistency (59.880 ± 0.003 Pa·s), as well as a lower flow index (0.2242 ± 0.0020). This meant better stability since the system formed a large number of small fat droplets finely dispersed in the water phase of the emulsion. A further increase to 15 000 rpm resulted in an emulsion with lower effective viscosity (1.810 ± 0.001 Pa·s) and consistency

(38.910 ± 0.002 Pa·s^n), compared to the rotor speeds of 10 000 and 12 000 rpm. Thus, such a high speed destroyed the structure of the water-fat emulsion, resulting in the system's dilution. This phenomenon can be observed when measuring the rheological properties at 10°C.

Conclusion

The tested samples of mayonnaise prepared with pumpkin and rice oils, as well as various honeys, belong to non-Newtonian systems and pseudoplastic fluids. Using whey powder resulted in the highest effective viscosity and consistency, as well as the lowest flow index. We also studied the effects of carbohydrates on the rheological properties of mayonnaise with pumpkin and rice oils. Mayonnaise prepared with inulin HD had higher effective viscosity (2.801 ± 0.001 Pa·s) and consistency, as well as a lower flow index (0.2630 ± 0.0020), compared to the other sugars tested. Disaccharides contributed to higher viscosity and consistency compared to monosaccharides. Mayonnaise prepared with fresh egg yolk had higher viscosity (2.656 ± 0.002 Pa·s) and consistency (65.640 ± 0.004 Pa·s^n). Forest honey provided mayonnaise with higher effective viscosity and consistency, as well as a lower flow index, compared to spring, linden, and acacia honeys. The sample with spring honey had the lowest effective viscosity and consistency, as well as the highest flow index.

The rotor speed and homogenization time also affected the rheological properties of mayonnaise. The sample homogenized at 12 000 rpm had higher viscosity and consistency, as well as a lower flow index, compared to the sample prepared at 10 000 rpm. The same parameters were obtained for the samples homogenized for 3 min. The empirical flow curves can be adequately described by the Herschel-Bulkley model.

Our results may be useful for formulators of edible fatty products, especially mayonnaise. The rheological properties are important for mayonnaise consistency and quality control during production, storage, and transportation.

Contribution

S.A. Bredikhin supervised the research. All the authors performed the experiments, processed the data, and wrote the manuscript.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Критерии авторства

С. А. Бредихин руководил работой. Все авторы принимали участие в исследованиях, обработке данных и написании текста.

Конфликт интересов

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