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Effects of Starch Type and Concentration on the Physicochemical, Rheological and Sensory Properties of Bream (*Abramis brama* L.) Surimi-Based Gels Enriched with β-1,3/1,6-D-Glucans

Wpływ rodzaju i stężenia skrobi na właściwości fizykochemiczne, reologiczne i sensoryczne żeli przygotowanych z użyciem surimi z mięsa leszcza (*Abramis brama* L.) wzbogaconych dodatkiem β-1,3/1,6-D-glukanów

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Summary: The influence of starch type (waxy rice starch, WRS; tapioca starch, TS) and starch concentration (0-6%) on the physicochemical, rheological and sensory properties of surimi-starch gels (SSGs) enriched with β-1,3/1,6-D-Glucans was investigated. The main interactions of myofibrillar proteins were hydrophobic ones and disulfide bonds. The steady shear tests revealed that SSGs behaved as shear thinning fluids with yield stress and exhibited thixotropic properties. The SSGs showed temperature-dependent behaviour with activation energies: 27.5-9.04 kJ mol^{-1} and 27.5-6.47 kJ mol^{-1} regarding samples prepared with 0-6% WRS or TS, respectively. The structural differences between the SSGs were quantified in terms of the quality factor (Q), whose values at 10 Hz were in the following ranges: 6.64-20.3 and 6.64-29.1. The overall desirability index (ODI) values showed that the panelists most approved of the SSGs prepared with 5% TS and 6% WRS. The results presented in the work may be useful for producers and scientists involved in the design of pro-health foods.

Keywords: surimi-starch-gels, β-1,3/1,6-D-Glucans, rheology, sensory analysis.

Streszczenie: Badania dotyczyły oceny wpływu rodzaju skrobi (woskowa skrobia ryżowa, WRS; skrobia z tapioki, TS) i stężenia skrobi (0-6%) na właściwości fizykochemiczne, reologiczne i sensoryczne żeli przygotowanych z użyciem surimi (SSGs), wzbogaconych dodatkiem β-1,3/1,6-D-glukanów. Dominującą formą interakcji białek miofibrylarnych były oddziaływania hydrofobowe i wiązania disiarczkowe. SSGs wykazywały cechy płynów rozrzedzanych ścinaniem z granicą płynięcia i właściwości tiksotropowe. Wartości energii aktywacji płynięcia SSGs, będące miarą wpływu temperatury na właściwości reologiczne, mieściły się w zakresach: 27,5-9,04 kJ mol^{-1} i 27,5–6,47 kJ mol^{-1}, odpowiednio w odniesieniu do próbek przygotowanych z użyciem 0-6% WRS lub TS. Różnice strukturalne pomiędzy SSGs analizowano z użyciem współczynnika jakości (Q), którego wartości przy 10 Hz mieściły się w przedziałach: 6,64-20,3 i 6,64-29,1. Wielkości wskaźnika pożądalności (ODI) wykazały, że oceniający najbardziej aprobowali SSGs przygotowane z 5% TS i 6% WRS. Przedstawione w pracy wyniki mogą być przydatne dla producentów i naukowców zajmujących się projektowaniem prozdrowotnej żywności.

Słowa kluczowe: surimi-skrobiowe żele, β-1,3/1,6-D-glukany, reologia, analiza sensoryczna.

1. Introduction

In the food industry, many products exist in the form of gels or are essentially gels. Food gels are polymeric soft materials prepared with the polysaccharides and proteins as gelling agents. They are capable of incorporating large amounts of water in their three-dimensional networks, and are of interest in the food industry due to their unique properties, e.g. low calorie, appealing taste and satiety-enhancing property (Yang, Li, Li, Guo, and Sun, 2021).

Bream (*Abramis brama* L.) belongs to the most abundant fish species, but due to its relatively large bone fraction, the commercial use of bream fillets is generally low. The management of bream meat may enable it to be used for the production of surimi, which is a concentrate of myofibrillar proteins (MPs), produced by washing minced meat to remove sarcoplasmic proteins, lipids, blood, odorants and pigments (Kim et al., 2015).

Freshwater fish proteins (FFPs) exhibit poorer gelling capability than saltwater fish proteins and thus the systems based on FFPs required the addition of polysaccharides to improve the mechanical properties of MPs gels (Li et al., 2022). Starch is one of the most widely used ingredients in food products for textural modification and noteworthy as a component in surimi gels because it is tasteless, odourless and generally gluten-free. It contains two types of homopolysaccharides: amylose (linear polymer) and amylopectin (highly branched polymer). The amount of amylose and distribution of branched chains in amylopectin have a significant impact on the functional properties of starch, and thus the physicochemical properties of gels produced with its use (Bashir and Aggarwal, 2019). Starch granules act as fillers in the protein gel matrix and produce its reinforcement upon water absorption and swelling. Moreover, the simultaneous addition of MPs and starch may contribute to intermolecular interactions and affect the macro-properties and microstructure of the formed hydrogels (Yang et al., 2021).

In addition to improving structural properties, another important area of research into surimi is nutritional quality, with increasing attention being paid to functional exogenous supplements (Zhou et al., 2020). Among the nutrients, β-1,3/1,6-D-glucans (BGs) extracted from *Saccharomyces cerevisiae* are of great importance.

Preclinical studies have shown that BGs exhibit various pharmacological activities, such as anti-tumour and anti-infective, resulting from their immune-enhancing and immune-modulatory effects (De Marco Castro, Calder, and Roche, 2021).

The use of polysaccharides in surimi to model its textural and rheological properties has been the subject of many studies. However, the literature on the supplementation of protein-polysaccharide gels with insoluble nutrients is very scarce and no research results have been found for surimi-starch gels supplemented with insoluble β-glucans. Therefore, the objective of this study was to assess the effects of the type and concentration of starch on the physicochemical, rheological and sensory properties of bream surimi-based gels enriched with β-1,3/1,6-D-glucans.

2. Materials and methods

2.1. Materials

Bream (*Abramis brama* L.), caught in spring 2021 was purchased in the condition of *rigor mortis* from Certa-Trzebież (Poland). The native starches: tapioca starch, TS (20.4% amylose) and waxy rice starch, WRS (96.2 amylopectin), were donated by Ingredion GmbH (Hamburg, Germany). Purified *Saccharomyces cerevisiae* cell wall extract (45.1% BGs) was obtained from Ohly GmbH (Hamburg, Germany). All the chemicals were purchased from Sigma-Aldrich (Poland). Throughout this work, unless otherwise stated, the concentration is expressed in wt%.

2.2. Methods

2.2.1. Surimi-starch gels (SSGs) preparation

Surimi was prepared according to Kim et al. (2015) with a slight modification. Briefly, the fish meat was minced using a NF 13DX separator, with 5 mm diameter holes in the drum. Minced fish meat (FM) was mixed (10 min) with cold water (4°C), using FM/water ratio of 1:3. The washing process was repeated three times and 0.2% NaCl was added in the last washing step. Each washing was followed by centrifugation (2400 g, 15 min, 4°C). The SSGs were manufactured according to the procedures in Li et al. (2022), with slight modification. The mixtures of surimi, *Saccharomyces cerevisiae* cell wall extract and TS or WRS were brought to final concentrations of 6% MPs, 2% BGs and 0-6% WRS, or TS with NaCl-phosphate buffer (0.6 M NaCl, pH 7.5). The control sample (CS) was a gel system without the addition of starch. SSGs were produced by heating prepared mixtures in a water bath at 40°C for 60 minutes and then at 90°C for 30 minutes. The SSGs were stored overnight at 4°C until further analyses.

2.2.2. Determination of water-holding capacity (WHC) of SSGs, surface hydrophobicity and chemical interactions of MPs

The WHC of SSGs was determined according to Xu et al. (2022) with slight modification. The gel samples (M_1) were centrifuged (2400 g, 15 mins, 4°C) and reweighed (M_2). The WHC was calculated as WHC (%) = $M_2/M_1 \times 100$. Surface hydrophobicity (S_o) of MPs was determined according to Zhang, Yang, Tang, Chen, and You (2015) with slight modification. The fluorescence intensity of the mixture was measured using a LS-55 fluorescence spectrometer (Perkin Elmer, Waltham, USA) at an excitation wavelength of 374 nm and an emission wavelength of 485 nm. The initial slope of the plot of fluorescence intensity versus protein concentration was referred to as S_o. Chemical interactions of the MPs were determined using the method described by Zhou et al. (2020). The soluble protein contents were measured by the Kjeldahl method to quantify ionic bonds (IB), hydrogen bonds (HB), hydrophobic interactions (HI) and disulfide bonds (DB).

2.2.3. Rheological properties

The rheological characteristics of the SSGs were determined according to the previously described methods with modification using an AR-G2 rheometer (TA Instruments, New Castle, DE, USA), equipped with a cone-plate geometry (2° cone angle, diameter 60 mm, gap 62 µm) and a Peltier heating system (Bortnowska et al., 2016). Steady shear tests were performed at temperatures ranged from 5 to 40°C by shearing the samples at an increasing shear rate ($\dot{\gamma}$, s^{-1}) from 0.015 to 100 s^{-1} and in reverse sequence. Experimental data were fitted to the Herschel-Bulkley model: $\tau = \tau_0 + k\ \dot{\gamma}^n$, where τ, shear stress (Pa); τ_0, yield stress (Pa); k, consistency index (Pa s^n) and n, flow behaviour index (–). Thixotropic properties were determined by measuring hysteresis loop areas (S). The temperature dependence was evaluated using the Arrhenius equation $k = k_0 \exp(E_a/RT)$, where k_0, Arrhenius constant (Pa s^n); E_a, activation energy (J mol^{-1}); R, gas constant (J mol^{-1} K^{-1}) and T, temperature (K). Dynamic oscillatory shear tests (0.015-10 Hz) were conducted inside the linear viscoelastic region and storage modulus (G′, Pa), loss modulus (G″, Pa), complex modulus (G*, Pa), loss tangent (tan δ) and complex viscosity (η^*, Pa s) were recorded versus frequency (ω). The G′ and G″ moduli were described by a power function $G' = K'\omega^{n'}$, $G'' = K''\omega^{n''}$, where K′ and K″ were related to the strength of the intermolecular interactions, whereas n′ and n″ to the extent and stability of the network formed by proteins and polysaccharides. Quality factor was calculated from the relation: $Q = 2\pi\,(K'/K'')\,\omega^{(n'-n'')}$. Bohlin′s parameters were assessed from the equation: $G^* = A\omega^{1/z}$, where z, coordination number (dimensionless) and A, proportional coefficient (Pa $s^{1/z}$). Generalised Cox-Merz rule $\eta^*(\omega) = C\{[\eta_a(\dot{\gamma})]^{\beta}\}_{\omega=\dot{\gamma}}$, where η_a, apparent viscosity (Pa s) and C, β, constants were used to establish the relationship between dynamic and steady shear rheological properties.

2.2.4. Sensory analysis

Sensory analyses of SSGs were performed by 20 trained panelists. Coded samples (50 mL) were presented in glass cups at room temperature (~20°C). The sensory attributes, appearance, flavour, odour and texture, were evaluated on the hedonic scale ranged from 0 ('dislike') to 10 ('like extremely'). The panelists were also asked to indicate the roughness of SSGs, related to the BGs particles sensed on the palate and tongue. The determined data were transformed into desirability values (d_i) according to the general procedures in Espitia et al. (2014). The desirability score (D) for each panelist was calculated as $D = (d_1 \times d_2 \times \dots d_k)^{1/k}$, where k was the number of the evaluated attributes. The overall desirability index (ODI) of SSGs in relation to starch type (ST) and starch concentration (SC) was calculated as ODI $= (D_1 + D_2 + \dots D_n)/n$, where n was the number of panelists. The ODI values were interpreted as 0 – least desirable and 1– most desirable.

2.2.5. Statistical analysis

Statistical analyses were carried out using Statistica 8.0 software (StatSoft Inc., USA). All the experiments were performed in triplicate and the results were expressed as mean values. Tukey's test was used to determine significant ($p < 0.05$) differences between means. The effects of ST and SC on the values of measured parameters were analysed by a two-way analysis of variance (ANOVA). Pearson's correlation coefficients (r) were calculated to determine the strength of the linear relationship between the selected studied variables.

3. Results and discussion

3.1. Water-holding capacity (WHC) of SSGs, surface hydrophobicity and chemical interactions of MPs

In both sets of the samples tested (Table 1), the increasing starch concentration (SC) yielded greater values of WHC ($r \geq 0.969$, $p < 0.01$), however comparing the respective samples, significantly higher ($p < 0.05$) magnitudes of WHC were found in SSGs prepared with WRS than with TS, especially in the concentration range from 0 to 4%. This can be related to different starch molecules composition. Regarding TS, amylose most likely interacted with other components and this prevented water absorption, whereas the high content of amylopectin in the WRS, especially with short side chains, probably allowed for its relatively high hydration through hydrogen bonds (Cornejo-Ramírez et al., 2018). Irrespective of the starch type (ST), all the studied parameters, namely S_o, IB, HB, HI and DB, were negatively correlated with increasing starch concentration, SC ($r \leq -0.934$; $p < 0.01$) and according to ANOVA affected by both SC and ST [$F \geq 3.59$, $p < 0.05$] (Table 1).

This can be interpreted as a process of increased coverage of SH groups and other sites for intermolecular (IB, HB and HI) proteins interactions (Mi et al., 2019). The HI and DB demonstrated relatively high values which may suggest that both contributed mainly to the formation of the gel network. This is generally in line with the research by Zhou et al. (2020) and Li et al. (2022).

Table 1. Water-holding capacity (WHC %) of SSGs, surface hydrophobicity (S_o) and chemical interactions: ionic bonds, IB; hydrogen bonds, HB; hydrophobic interactions, HI; disulfide bonds, DB (mg mL^{-1}) of MPs
Tabela 1. Wodochłonność (WHC %) SSGs, hydrofobowość powierzchniowa (S_o) oraz oddziaływania chemiczne: wiązania jonowe, IB; wiązania wodorowe, HB; oddziaływania hydrofobowe, HI; wiązania disiarczkowe, DB (mg mL^{-1}) MPs

Starch concentration (%)		Parameter					
		WHC	S_o	IB	HB	HI	DB
CS*	0	59.8a	765.2f	0.319e	0.942f	2.961f	2.423f
WRS	2	70.1c	753.7e	0.312d	0.939f	2.943f	2.365e
	3	82.9e	735.1c	0.308d	0.928d	2.911e	2.229d
	4	94.3g	724.5b	0.294c	0.916c	2.848c	2.137c
	5	100h	716.4b	0.286b	0.902b	2.825b	2.069b
	6	100h	687.9a	0.272a	0.893a	2.804a	2.015a
TS	2	65.6b	754.1e	0.314d	0.941f	2.956f	2.412e
	3	75.7d	751.3e	0.311d	0.936e	2.938f	2.357e
	4	89.4f	741.2d	0.298c	0.921c	2.907e	2.239d
	5	98.6h	734.7c	0.289b	0.911b	2.861d	2.141c
	6	100h	726.8b	0.276a	0.904b	2.843c	2.106b

* CS, control sample. Within the columns, values followed by different letters are significantly different ($p < 0.05$).

* CS, próbka kontrolna. W kolumnach wartości średnie oznaczone tymi samymi literami nie różnią się statystycznie istotnie ($p < 0,05$).

Source/Źródło: own study/opracowanie własne.

This explanation can be related to the fact that in response to heat treatment, MPs undergo a gelation reaction consisting of unfolding (denaturation), exposure of reactive (hydrophobic) groups and sulfur-containing amino acids, association (aggregation) through hydrophobic interactions and the formation of new disulfide bonds (Wu et al., 2019).

3.2. Rheological properties of surimi-starch gels (SSGs)

3.2.1. Steady-shear behaviour

The flow behaviour of SSGs was determined at temperatures ranging from 5 to 40°C, and the flow curves found at 20°C in relation to ST and SC are demonstrated in Figure 1A and B. All the investigated SSGs exhibited a non-Newtonian shear-thinning flow with yield stress and time-dependent features. Increasing the SC contributed to an upward shift in the flow curves of samples prepared with both TS and WRS. This can be generally considered in terms that as the polysaccharide concentration became higher, individual molecules began to overlap making the intermolecular connections or forming 'junction zones', which limited polymer chains movement and stretching in the aqueous system (Hao et al., 2018). The shear thinning behaviour can be explained by the fact that the increased shear of the SSGs caused a progressive deformation of the aggregated particles and entangled polymers, and the disruption and alignment with the flow field, which decreased flow resistance and reduced viscosity over time during the flow test. The Herschel-Bulkley model was used to describe the flow behaviour of the SSGs, and the identified parameters are presented in Table 2.

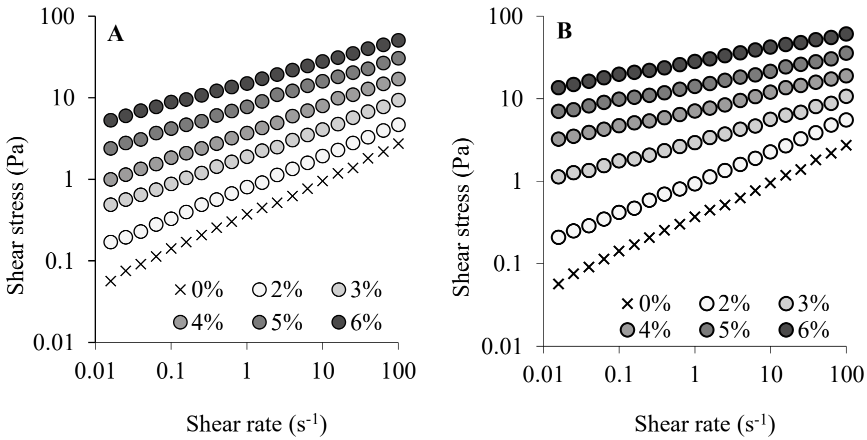

Fig. 1. Shear stress versus shear rate plots for SSGs, prepared with WRS (A) and TS (B) at 20°C
Rys. 1. Krzywe płynięcia SSGs, przygotowanych z WRS (A) i TS (B) w 20°C

Source/Źródło: own study/opracowanie własne.

Both the values of τ_0 and k demonstrated an ascending trend with increasing SC ($r \geq 0.861$, $p < 0.05$), while the n values were negatively correlated with the increase in SC ($r \leq -0.962$, $p < 0.01$), and this can be interpreted as a development of the gel structure (Bortnowska et al., 2016). Parameter τ_0 determines the minimum shear stress to trigger the flow, and the systems with increasing its value are becoming more compact and allow for the remaining of the suspended insoluble particles, whereas parameter k indicates the viscous nature and flowability of the system.

Table 2. Parameters of the Herschel-Bulkley (τ_0, k, n), Arrhenius (E_a, k_0) equations and hysteresis loop areas (S)
Tabela 2. Parametry równań Herschela-Bulkleya (τ_0, k, n) i Arrheniusa (E_a, k_0) oraz pola powierzchni pętli histerezy (S)

Starch concentration (%)		Parameter					
		τ_0 (Pa)	k (Pa s^n)	n (-)	S × 10^{-2} (Pa s^{-1})	E_a (kJ mol^{-1})	k_0 × 10^2 (Pa s^n)
CS*	0	0.07a	0.32a	0.43e	0.36a	27.5g	0.01a
WRS	2	0.12b	0.79b	0.38d	1.21b	21.4f	0.02a
	3	0.86c	1.93c	0.32c	2.24c	17.9e	0.12b
	4	1.24d	3.61e	0.31c	4.37e	14.4d	0.37b
	5	4.32e	7.94g	0.28c	9.32f	10.5c	11.2c
	6	6.81f	14.3h	0.25b	14.9h	9.04b	35.1d
TS	2	0.26b	0.83b	0.37d	1.12b	18.1e	0.05a
	3	0.97c	2.75d	0.26b	2.09c	14.2d	0.83b
	4	4.27e	6.72f	0.21a	3.87d	10.4c	9.61c
	5	7.28f	13.2h	0.18a	7.81e	7.53a	60.4e
	6	11.5g	27.1i	0.17a	13.4g	6.47a	191f

*CS, control sample. Within the columns, values followed by different letters are significantly different ($p < 0.05$).

*CS, próbka kontrolna. W kolumnach wartości średnie oznaczone tymi samymi literami nie różnią się statystycznie istotnie ($p < 0,05$).

Source/Źródło: own study/opracowanie własne.

The increase in the values of k and τ_0 parameters can be attributed to the fact that starch granules were entrapped within the protein matrix and acted as fillers. The expansion of the starch granules during SSGs heating most likely resulted in a reinforcing or pressuring effect on the gel matrix and contributed to gel strength formation (Mi et al., 2019). The found differences between samples composed of WRS and TS can be interpreted in terms that TS contained more amylose than WRS and this component leached during gelatinisation has the capacity to form a three-dimensional network stabilised by hydrogen bonds. Consequently this contributed to the increase in viscosity, whereas the ability of swollen starch granules, composed mainly of amylopectin to form a network was generally weak (Lu et al., 2009). SSGs subjected to increasing and decreasing shear rates showed characteristic hysteresis loop areas indicating their thixotropic behaviour (Table 2). In both examined sets of samples the S values were positively correlated with increasing SC ($r \geq 0.898$, $p < 0.05$). The clockwise hysteresis loop can be attributed to structural changes in three-dimensional networks of SSGs caused by the generated hydrodynamic forces, whereas the newly developed SSGs texture was less resistant to shear, which resulted in a decrease in apparent viscosity as demonstrated by the down curves, data not shown (Hao et al., 2018). The relationships between consistency index (k) and temperature (5-40°C) in relation to ST and SC are shown in Figure 2A and B.

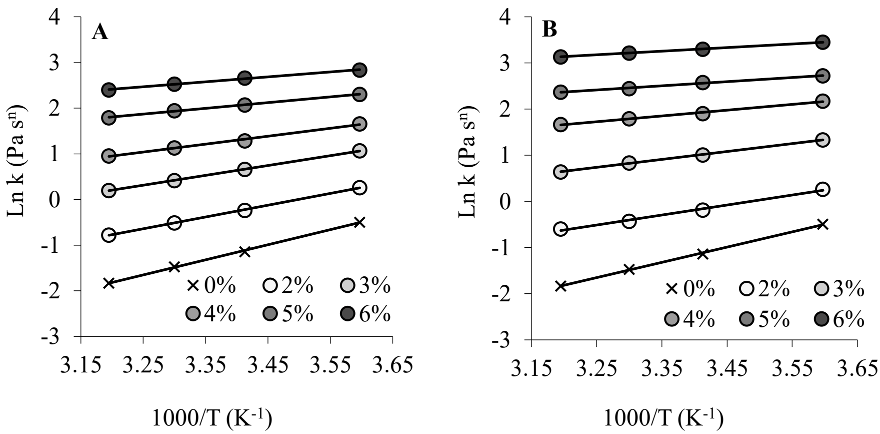

Fig. 2. Consistency index (k) as a function of temperature (T) of SSGs prepared with WRS (A) and TS (B)

Rys. 2. Wpływ temperatury (T) na wartości współczynnika konsystencji (k) dla SSGs przygotowanych z WRS (A) i TS (B)

Source/Źródło: own study/opracowanie własne.

It was found that with the temperature increase, the k values showed a decreasing tendency which was dependent on ST and SC. The explanation can be related to the fact that the thermal energy of the molecules increases with increasing temperature. This enhances the mobility of the molecules and increases the intermolecular spacing as well as decreases the intermolecular interactions. Consequently, the resistance to flow of the fluid and its viscosity are reduced. Data obtained from experimental studies were fitted to an Arrhenius equation and thus the derived values of activation energy (E_a) and Arrhenius constant (k_0) are depicted in Table 2. In both the studied sets of samples the E_a values were negatively correlated with increasing SC ($r \leq -0.984$, $p < 0.001$) and according to ANOVA affected by both SC and ST ($F \geq 13.2$, $p < 0.01$), whilst k_0 values were positively correlated with increasing SC ($r \geq 0.739$, $p < 0.05$). These results can be interpreted in terms that the higher E_a, the greater is the impact of the temperature on the viscosity (Bortnowska et al., 2016).

3.2.2. Viscoelastic behaviour

Dynamic oscillatory shear tests were used to determine the viscoelastic properties and model the structural changes in gels during processing and storage. The G′ and G″ moduli of SSGs manufactured with WRS and TS are shown in Figure 3A-D. It was found that both tested moduli showed an increasing tendency with the increase of oscillation frequency and SC, higher in samples prepared with TS than with WRS. A similar trend regarding the increase of G′ with increasing SC in the system was reported by Macias-Rodriguez and Velikov (2022). With regard to oscillation frequency, the values of tan δ, followed the behaviour of the studied moduli, which may suggest variations in interactive forces maintaining the gel network (Bortnowska et al., 2016). Regardless of ST and shear rate, the tan δ values were < 1 and decreased with increasing SC, which indicates an increase in the elastic properties of SSGs with higher SC, especially in the samples prepared with TS (Hao et al., 2018). The values of tan δ, determined at 1 Hz and those of K′, K″, n′, n″ and A, z, related to G′, G″ and G* moduli, are depicted in Tables 3 and 4. K′, K″, A, and z were positively correlated with the increase in SC ($r \geq 0.812$, $p < 0.05$), whereas n′, n″ negatively ($r \leq -0.954$, $p < 0.01$) and as revealed by ANOVA, were mostly affected by SC [$F \geq 16.2$, $p < 0.001$]. The corresponding samples demonstrated higher ($p < 0.05$) values of K′ in SSGs prepared with TS than with WRS, and in the majority the opposite effects were found with respect to K″ In addition to the reasons discussed above, the content of amylose, which retrogrades faster than amylopectin, most likely contributed to the differences found (Bortnowska et al., 2016). Greater values of n′, than the corresponding n″ may suggest the development of the viscous behaviour of the SSGs with increasing oscillation frequency. The SSGs prepared with TS in their majority yielded higher than those with WRS ($p < 0.05$) values of z and A, related to the number of rheological units correlated with one another in a three-dimensional structure and strength of interactions between these units, respectively (Table 4).

This may be related to the differences in intermolecular interactions (between biopolymers) induced by changes in the SSGs' composition (Table 1). The Q parameter defined as 2π times the ratio of stored energy to the average energy loss per period was used to determine the structural characteristics (Table 3). Based on the obtained results, it seems reasonable to conclude that the intermolecular interactions in the SSGs increased with increasing SC, contributing to higher Q values and a more coherent structure, especially in samples prepared with TS. The C and β parameters derived from the generalised Cox-Merz rule are presented in Table 4. Both were positively correlated with the increase in SC ($r \geq 0.956$, $p < 0.01$). Hence, the obtained results can be interpreted as the starch-induced development of the bonds' density between biopolymers in the SSGs (Bortnowska et al., 2016).

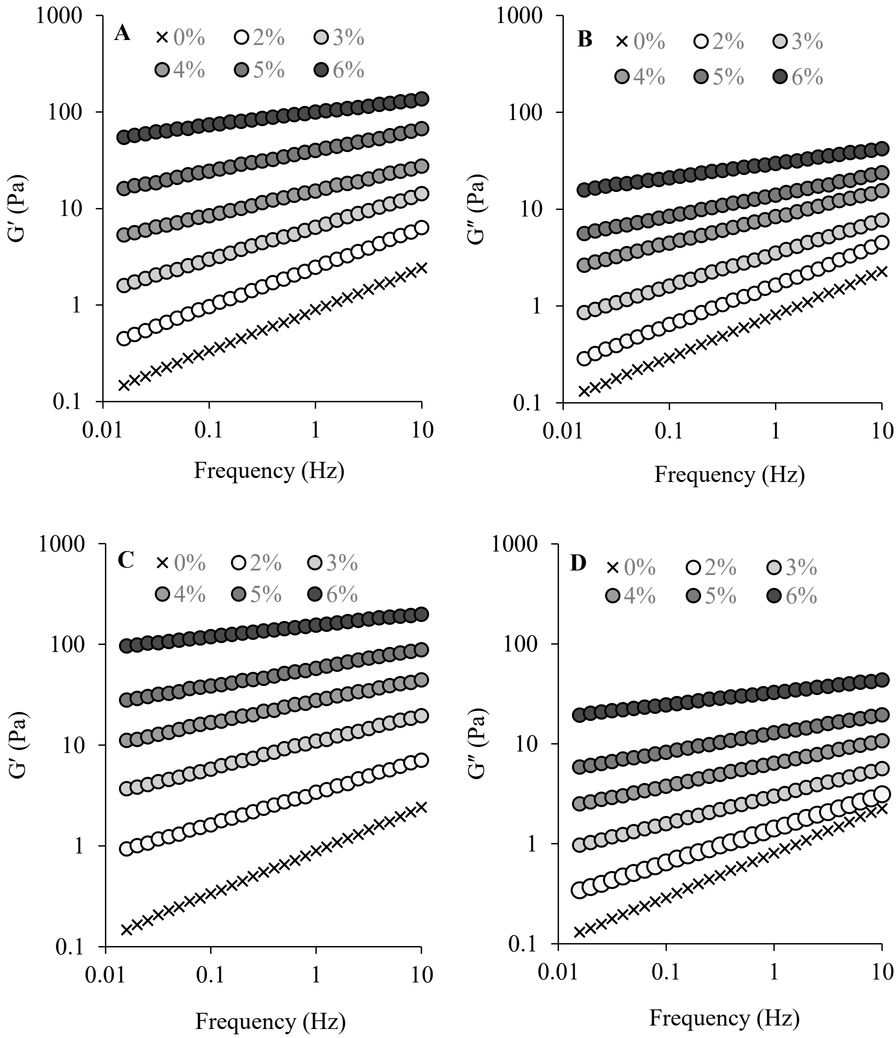

Fig. 3. Storage modulus (G′) and loss modulus (G″) rheograms versus frequency for SSGs, prepared with WRS (A, B) and TS (C, D)
Rys. 3. Wartości modułu zachowawczego (G′) i modułu stratności (G″) w zależności od częstotliwości oscylacji dla SSGs, przygotowanych z WRS (A, B) i TS (C, D)

Source/Źródło: own study/opracowanie własne.

Table 3. Loss tangent (tan δ, 1 Hz), dynamic shear parameters of power function (K′, n′, K″, n″) and quality factor (Q, 10 Hz) of SSGs prepared with WRS or TS
Tabela 3. Tangens kąta przesunięcia fazowego (tg δ, 1 Hz), parametry równań potęgowych wyznaczane w ścinaniu dynamicznym (K′, n′, K″, n″) oraz współczynnik jakości (Q, 10 Hz) dla SSGs przygotowanych z WRS lub TS

Starch concentration (%)		Parameter					
		tan δ (–)	K′ (Pa $s^{n'}$)	n′ (–)	K″ (Pa $s^{n''}$)	n″ (–)	Q (–)
CS*	0	0.89a	0.87a	0.42g	0.81a	0.44f	6.64a
WRS	2	0.67b	2.47b	0.41g	1.67b	0.42f	9.03b
	3	0.55c	6.46c	0.34f	3.53d	0.35e	11.4c
	4	0.53c	15.3e	0.25e	8.31f	0.26c	10.9c
	5	0.35e	40.1g	0.22d	14.1h	0.22b	17.8e
	6	0.30f	99.4i	0.14b	29.8i	0.15a	20.3f
TS	2	0.42d	3.42b	0.32f	1.42b	0.34e	14.3d
	3	0.27g	10.8d	0.26e	3.01c	0.27d	22.1g
	4	0.23h	27.5f	0.22d	6.42e	0.23c	26.3h
	5	0.22h	58.6h	0.18c	12.8g	0.19b	28.2i
	6	0.21h	155j	0.11a	32.9j	0.12a	29.1i

* CS, control sample. Within the columns, values followed by different letters are significantly different ($p < 0.05$) / *CS, próbka kontrolna. W kolumnach wartości średnie oznaczone tymi samymi literami nie różnią się statystycznie istotnie ($p < 0,05$).

Source/Źródło: own study/opracowanie własne.

Table 4. Bohlin's parameters (A, z) and Cox-Merz rule coefficients (C, β) of SSGs prepared with WRS or TS
Tabela 4. Parametry Bohlina (A, z) i współczynniki równania Coxa-Merza (C, β) dla SSGs przygotowanych z WRS lub TS

Starch concentration (%)		Parameter			
		A (Pa $s^{1/z}$)	z (–)	C (–)	β (–)
CS*	0	1.21a	2.30a	3.25a	0.88a
WRS	2	2.98b	2.43b	3.63b	1.02b
	3	7.37c	2.96c	3.86c	1.06b
	4	17.4e	3.87d	4.12d	1.14c
	5	42.5g	4.59e	4.39e	1.19d
	6	103i	7.27g	4.48f	1.24e
TS	2	3.71b	3.12c	3.91c	1.04b
	3	11.3d	3.77d	4.05c	1.13c
	4	28.2f	4.58e	4.19d	1.21d
	5	59.8h	5.56f	4.31e	1.26e
	6	158j	8.77h	4.37e	1.32f

* CS, control sample. Within the columns, values followed by different letters are significantly different ($p < 0.05$) / *CS, próbka kontrolna. W kolumnach wartości średnie oznaczone tymi samymi literami nie różnią się statystycznie istotnie ($p < 0,05$).

Source/Źródło: own study/opracowanie własne.

3.3. Sensory properties of surimi-starch gels (SSGs)

Sensory analyses were performed in order to to quantify hedonic responses regarding appearance, flavour, odour and texture of the SSGs in relation to starch type (ST, WRS or TS) and starch concentration (SC) ranging from 0% to 6% (Figure 4A-D).

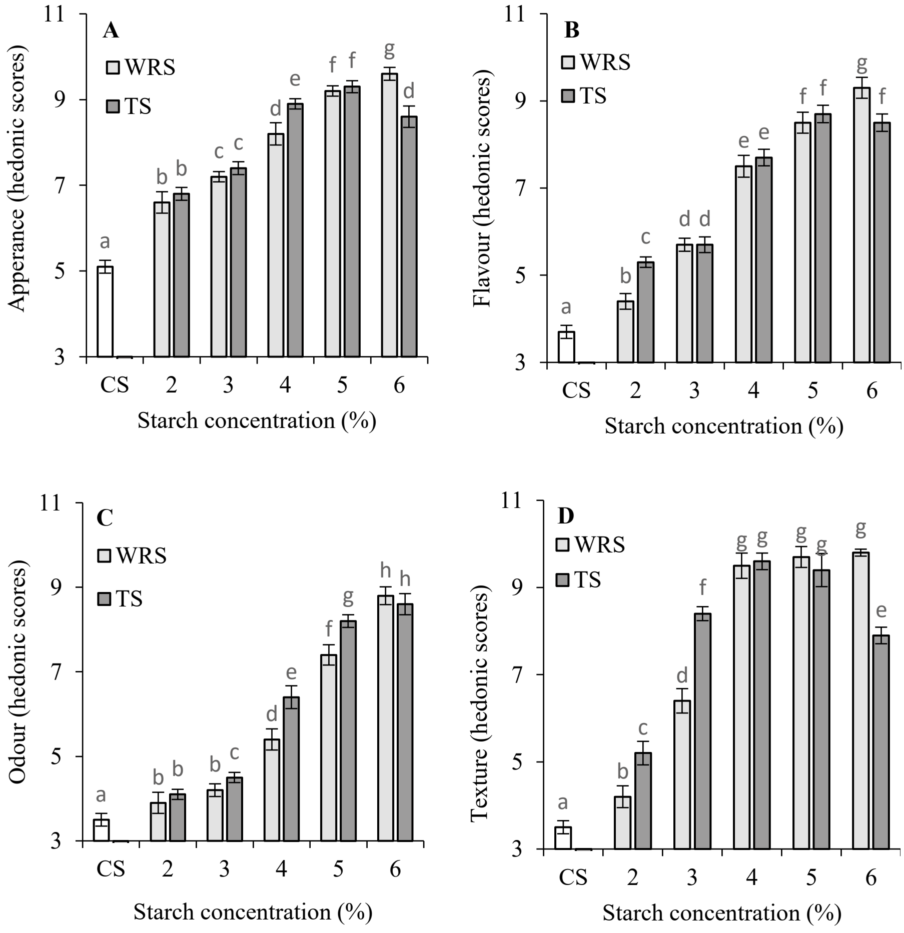

Fig. 4. Results of the sensory analysis of surimi-starch gels (SSGs) prepared with WRS or TS. Mean values marked with no common letters are significantly different ($p < 0.05$)

Rys. 4. Wyniki analizy sensorycznej żeli (SSGs) przygotowanych na bazie surimi i skrobi (WRS, TS). Wartości średnie oznaczone tymi samymi literami nie różnią się statystycznie istotnie ($p < 0,05$)

Source/Źródło: own study/opracowanie własne.

ANOVA revealed that generally all the evaluated sensory attributes were affected by both SC and ST [$F \geq 5.62$, $p < 0.05$]. Greater correlation values (r) between SC and sensory parameters studied were found in SSGs containing WRS ($r \geq 0.917$, $p < 0.01$) than in those prepared with TS ($r \geq 0.819$, $p < 0.05$). As compared to the control sample, the hedonic scores of: appearance, flavour, odour and texture increased by 46.9%, 60.2%, 61.3%, 64.2%, or by 40.7%, 56.5%, 59.2%, 55.7%, regarding samples prepared with 6% WRS or 6% TS, respectively. This can be interpreted in terms that the gels prepared with WRS were softer than those made with TS and therefore more acceptable for the panelists (Bortnowska et al., 2016). It should also be emphasised that in both tested sets of samples, at the starch concentration ≥ 4%, the panelists did not sense the presence of β-1,3/1,6-D-glucans (BGs) particles. This can be attributed to the significant increase in the values of rheological parameters (consistency, yield stress) and the development of the three-dimensional spatial network formed by myofibrillar proteins and starches (Tables 2 and 4). The overall desirability index (ODI) was used to summarise the hedonic sensory scores of: appearance, flavour, odor and texture (Figure 5). A steady progressive increase in the ODI values ($r = 0.972$, $p < 0.01$) was observed regarding SSGs prepared with WRS. However, regarding the sample prepared with 6% TS, the ODI value decreased, mainly because the texture was less accepted (Figure 4D).

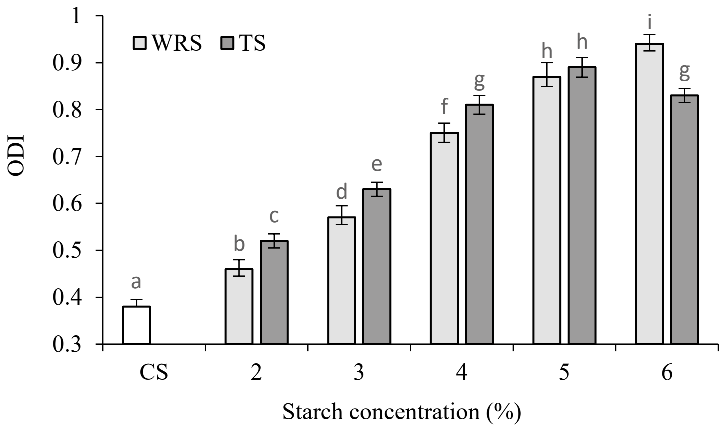

Fig. 5. Overall desirability index (ODI) of SSGs prepared with WRS or TS.
Mean values marked with no common letters are significantly different ($p < 0.05$)
Rys. 5. Ogólny wskaźnik pożądalności (ODI) dla SSGs przygotowanych z WRS lub TS.
Wartości średnie oznaczone tymi samymi literami nie różnią się statystycznie istotnie ($p < 0,05$)

Source/Źródło: own study/opracowanie własne.

This outcome may be attributed to the fact that with increasing amylose content the gels were more rigid and stronger (Bortnowska et al., 2016), which probably was not accepted by the panelists.

4. Conclusions

Increasing starch concentration (SC) contributed to the decrease of surface hydrophobicity and chemical interactions of myofibrillar proteins, including hydrogen bonds, hydrophobic interactions, ionic bonds, and disulfide bonds, to a greater extent in surimi-starch gels (SSGs) prepared with waxy rice starch (WRS) than with tapioca starch (TS). Steady shear stress-growth and oscillatory shear sweeps studies revealed that SSGs exhibited pseudoplastic behaviour with yield stress and thixotropic properties; consistency index, and quality factor increased with increasing SC, more so in the samples prepared with TS than with WRS; the values of the flow behaviour index and loss tangent decreased with greater starch amount, indicating the development of the gel-like structure. The activation energy values were greater in the SSGs prepared with WRS than with TS. The generalised Cox-Merz rule was applicable ($R^2 \geq 0.978$) to establish the relationships between the apparent and complex viscosities. Increasing SC contributed to greater values of overall desirability index, more pronounced in samples prepared with WRS than with TS. The results of these studies can help food technologists in designing gels prepared with surimi derived from bream meat, and enriched with β-1,3/1,6--D-glucans.

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