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Research paper

The effect of selected hydrocolloids on the physicochemical, viscoelastic, and organoleptic properties of full-fat processed cheese sauces

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ABSTRACT

The current study investigated the effects of three polysaccharide hydrocolloids [pectin (PE), agar (AG), and guar gum (GG)] at varying concentrations (0.25, 0.50, 0.75, and 1.00 % w/w) on the physicochemical, viscoelastic, and organoleptic properties of full-fat processed cheese sauces (PCS). The hydrocolloid (HC) type and concentration affected the PCS properties. The values of emulsion stability (ES) enhanced progressively with higher HC concentrations ($P < 0.05$). Rheological analysis revealed an increase in elastic, viscous, and complex moduli, as well as in complex viscosity, gel strength, and interaction factor, with higher HC levels ($P < 0.05$). Furthermore, sensory analysis of viscosity supported rheological findings. Additionally, sensory assessors preferred sauces with AG and GG concentrations of 0.50 and 0.75 % w/w the most ($P < 0.05$). These results confirm that the tested HCs act as effective gel-forming/thickening and stabilizing agents in full-fat PCS, enhancing both ES and viscoelastic properties, while also improving texture, as demonstrated by sensory evaluation.

1. Introduction

Processed cheese sauces (PCS) represent a distinct category of cheese-based products characterized by specific compositional and functional properties. These sauces can be manufactured through various techniques, allowing for flexibility in formulation and processing. Due to the extensive variability in ingredient composition, a universally applicable block diagram delineating the production process of cheese sauce cannot be established. In recent years, cheese sauces have gained prominence not only as appealing appetizers but also as standalone culinary components serving as first courses, side dishes, or integral ingredients within meals. Their versatility enables applications such as dipping, topping, grilling, and coating (Saad et al., 2015; Szafrańska et al., 2025).

In the absence of standardized definitions or legal regulations concerning the classification of PCS and cheese sauces, a broad range of dairy-based raw materials may be utilized in their production. These include various natural cheeses, cream, quark, rework, dairy powders (e.g., cheese powder, milk protein concentrate/isolate, casein/caseinate, whey protein concentrate/isolate), each contributing distinct compositional and functional characteristics to the end-product. Although many commercially available PCS rely predominantly on cheese powders or flavoring agents, the inclusion of natural cheese as a primary ingredient remains critical for achieving superior organoleptic and functional attributes. Formulations utilizing blends of natural cheeses significantly contribute to flavor complexity, authenticity, and overall product quality. Furthermore, to achieve optimal sensory and rheological characteristics, PCS formulations typically include various non-dairy ingredients such as emulsifying salts, stabilizers, preservatives, acidity regulators, and flavor enhancers. The consistency and emulsion stability of PCS can be markedly enhanced through the strategic addition of hydrocolloids (Kůrová et al., 2022; Salek et al., 2019; Szafrańska & Sołowiej, 2020a). Table 1 summarizes commercially available PCS from various countries of origin, with a focus on fat content, type of fat used, and the type of stabilizer/hydrocolloid incorporated.

Hydrocolloids (HC) comprise a diverse group of water-dispersible biopolymers capable of forming viscous solutions and/or gels. Their inclusion in PCS formulations allows for targeted modification of texture, viscosity, and mouthfeel. In dairy applications, HCs are commonly categorized by origin into polysaccharides and proteins, with their functional behavior governed by molecular structure, concentration, and interaction with other ingredients (Alam et al., 2025; Cobbinah-Sam et al., 2025; Pirsa & Hafezi, 2023). Pectin (PE) is a plant-derived heteropolysaccharide composed predominantly of

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Table 1
Survey of hydrocolloids/stabilizers used in commercial processed cheese sauces and cheese sauces.[a]

Product	Country of origin	Fat content (% w/w)	Type of used fat	Hydrocolloid/Stabilizer
PCS_1	Australia	27.3	milkfat	sodium carboxymethylcellulose
PCS_2	Belgium	10.0	canola oil	MAG/DAG[b], xanthan gum, guar gum
PCS_3	Belgium	11.0	canola oil, coconut oil	starch, xanthan gum, guar gum
PCS_4	Czech Republic	18.0	butter	starch, xanthan gum
PCS_5	Czech Republic	11.0	butter	starch, xanthan gum
PCS_6	Czech Republic	11.0	butter	starch, xanthan gum
PCS_7	Germany	16.0	butter	starch, xanthan gum
PCS_8	Saudi Arabia	11.9	cream	starch
PCS_9	Saudi Arabia	12.0	cream	starch
PCS_10	The Netherlands	10.5	canola oil, coconut oil, butter	sodium carboxymethylcellulose, xanthan gum
PCS_11	The Netherlands	9.0	canola oil	sodium carboxymethylcellulose
PCS_12	The Netherlands	9.0	canola oil	sodium carboxymethylcellulose
PCS_13	USA	7.0	canola oil	starch, sodium alginate
PCS_14	USA	8.0	canola oil, milkfat	milk protein concentrate, sodium alginate, sodium caseinate
PCS_15	USA	26.9	canola oil, milkfat	starch, sodium alginate, whey protein concentrate
PCS_16	USA	6.0	canola oil, soybean oil, sunflower oil, anhydrous milkfat	starch, xanthan gum
PCS_17	USA	12.9	palm oil	MAG/DAG, starch
PCS_18	USA	7.2	canola oil, soybean oil, sunflower oil	MAG/DAG, starch
PCS_19	USA	7.5	cream, canola oil	starch, xanthan gum,
PCS_20	USA	30.4	cream	locust bean gum, guar gum

[a] All information is according to label declarations. Starches used include corn starch, modified starch, modified corn starch, modified food starch, modified tapioca starch, modified maize starch, and modified potato starch.
[b] MAG/DAG = monoacylglycerols and diacylglycerols.

galacturonic acid residues, with varying degrees of methyl esterification. Its structural architecture includes linear homogalacturonan regions, as well as branched domains such as rhamnogalacturonan I and II. In PCS applications, PE contributes to the development of desirable viscosity and gel strength, especially in reduced-fat formulations, where it can improve mouthfeel, diminish cavity formation, and enhance rheological performance (Freitas et al., 2021; Singhal & Swami Hulle, 2022). Agar (AG), obtained from red algae species such as *Gelidium* and *Gracilaria*, consists primarily of two components: agarose and agaropectin. Agarose is composed of alternating D-galactose and 3,6-anhydro-L-galactose units, forming linear chains responsible for its gel-forming capabilities. At the same time, agaropectin contains sulfate and pyruvate groups, contributing to water solubility but lacking gelling function. AG forms thermo-reversible gels, thereby providing heat-stable structural integrity to various food products (Kadirvel & Narayana, 2023; Liao et al., 2021). Guar gum (GG), a galactomannan polysaccharide extracted from the guar seeds, consists of a β-(1 → 4)-linked mannose backbone with α-(1 → 6)-linked galactose side chains. Its high water-binding capacity and solubility make it an effective thickening agent in PCS, improving viscosity, texture uniformity, and mouthfeel, particularly during storage of low-fat products (Sharma et al., 2018; Tahmouzi et al., 2023).

Most scientific studies on PCS focus on low-fat formulations, reflecting the market trend toward healthier options driven by consumer demand. However, fat reduction often compromises key organoleptic properties – particularly flavor – whereas using butter as the primary fat source helps preserve the rich, full-bodied flavor typically associated with traditional cheese sauces. Furthermore, despite the widespread use of HC in PCS, existing literature predominantly addresses their functionality within low-fat processed cheese/PCS systems. The aforementioned studies typically aim to compensate for reduced fat content by enhancing texture and stability through the HC addition (El-Mahdi et al., 2014; Hassan et al., 2015). However, full-fat PCS formulations – particularly those using butter as the primary fat source – remain underexposed in the food science and technology literature, presenting a clear gap in scientific research. Moreover, while AG is well known for its gelling and thermal stability properties in various food systems, a thorough review of current literature reveals no published studies specifically investigating its incorporation into PCS formulations. Additionally, to our best knowledge, no research has addressed the sensory impact of polysaccharide HCs in PCS. Most available studies focus on processed cheese or processed cheese analogues. Hence, this study aimed to evaluate the effects of three polysaccharide HCs (PE, AG, and GG) at various concentrations on the physicochemical, viscoelastic, and organoleptic properties of full-fat PCS.

2. Material and methods

2.1. Experimental design and sample preparation

All PCS samples were designed to have a dry matter (DM) content of 30 % w/w and a fat in dry matter (FDM) content of 66 % w/w. Three HCs were used, namely PE, AG, and GG, in concentrations of 0.25, 0.50, 0.75, and 1.00 % w/w. All tested HCs were applied separately. Furthermore, a control sample (CS) with no HC addition was manufactured. Therefore, a total of 39 PCS batches were manufactured: 13 variants of HC types and concentrations (including the CS) × 3 repetitions (n = 39).

For the manufacture of the PCS samples, the following raw materials were used: Edam Dutch-type cheese (7-week maturity; 52 % w/w DM content and 30 % w/w FDM content; Lacrum Ltd., Velké Meziříčí, Czech Republic), butter (84 % w/w DM content and 82 % w/w fat content; Olma, Olomouc, Czech Republic), mixture of emulsifying salts [26 % w/w disodium hydrogen phosphate (Na_2HPO_4), 30 % w/w monosodium phosphate (NaH_2PO_4), 22 % w/w tetrasodium diphosphate ($Na_4P_2O_7$), and 22 % w/w sodium salt of polyphosphate with the chain length $n \sim 20$ ($(NaPO_3)_6$; Fosfa Plc., Břeclav, Czech Republic], commercial mixture of monoacylglycerols and diacylglycerols (MAG/DAG; Brenntag CR Ltd., Prague, Czech Republic), low-methoxyl citrus PE (Classic CM 701; 39–45 % esterification; Herbstreith & Fox GmbH, Neuenbürg, Germany), AG (Ausamics Pty Ltd., Thomastown, Australia), GG (Merck KGaA, Darmstadt, Germany), and water. The formulations of the PCS are presented in Table 2.

Samples were manufactured under the same conditions (target melting temperature 90 °C, holding time 1 min, agitation rate 3100 rpm, total processing time 10–11 min) using a Vorwerk Thermomix TM6 blender cooker (Vorwerk SE & Co. KG, Wuppertal, Germany) with indirect heating. Immediately after the processing, the hot samples were poured into the laminated aluminum containers (conical shape; inner dimensions of 26.8 mm in height, 81.1 mm in diameter at the top, and 68.9 mm in diameter at the bottom; Aluflexpack Ltd., Praha, Czech Republic) and the sealing was carried out using a NovaSeal equipment (Nirosta Ltd., Chlumec nad Cydlinou, Czech Republic). The weight of the mass in one container was approximately 93 ± 3 g. After cooling to ambient temperature (25 ± 2 °C, approximately 5 h), the samples were

Table 2
Composition of raw materials (% w/w) used for manufacture of processed cheese sauces with various content of HC[a] (pectin, agar and guar gum).

Raw material (g)	Processed cheese sauce samples				
	CS[b]	HC 0.25 % w/w	HC 0.50 % w/w	HC 0.75 % w/w	HC 1.00 % w/w
Edam cheese	18.75	18.03	17.31	16.59	15.87
Butter	20.26	20.41	20.56	20.71	20.86
Emulsifying salts	2.25	2.25	2.25	2.25	2.25
MAG/DAG[c]	1.00	1.00	1.00	1.00	1.00
HC	–	0.25	0.50	0.75	1.00
Water	57.74	58.06	58.38	58.71	59.03

[a] HC = hydrocolloid.
[b] CS = control sample (with no HC).
[c] MAG/DAG = monoacylglycerols and diacylglycerols.

transferred to the refrigerator and stored at 6 ± 2 °C for one week until analyses were performed.

2.2. pH-value, dry matter content, and emulsion stability determination

The pH-values of the samples were measured using a calibrated pH meter with glass-tip electrode (Foodcare HI 99161, Hanna Instruments Czech Ltd., Prague, Czech Republic), which was inserted directly into the sample at three different (randomly selected) locations. The measurement was performed at 23 ± 1 °C. The DM content was determined gravimetrically according to ISO 5534:2004 (ISO, 2004) by drying the samples in the oven at a temperature of 102 ± 2 °C until a constant weight loss was reached.

Emulsion stability (ES) measurement was performed as described in Kůrová et al. (2022). Aliquots of PCS, each with a mass of m_1 (5 ± 1 g), were placed into 50 mL polypropylene centrifuge tubes with conical base (internal diameter: 29.1 mm; height: 114.4 mm) and closed with plastic caps. The samples were subjected to centrifugation at 6000 rpm for 20 min. Following complete removal of the supernatant, the remaining sediment was weighed (m_2). ES was determined using equation (1). All analyses were performed in nine replicates (three production batches × three repetitions; $n = 9$).

$$ES = (m_2/m_1) \times 100 \tag{1}$$

2.3. Viscoelastic properties assessment

The viscoelastic properties of PCS were determined using an oscillatory shear rheometer (HAAKE RheoStress 1, Thermo Fisher Scientific Inc., Waltham, MA, USA) equipped with a parallel plate geometry (diameter 35 mm; gap 1 mm) according to Kůrová et al. (2022). Rheological measurements were conducted at 20.0 ± 0.1 °C in oscillatory mode within the linear viscoelastic region, employing a shear stress amplitude of 5.0 Pa and a frequency range of 0.1–10.0 Hz. To delineate the boundaries of the linear viscoelastic region, stress sweep tests were performed over a stress range of 1–100 Pa at a constant frequency of 10 Hz. The elastic modulus (G', Pa), the viscous modulus (G'', Pa), and complex viscosity (η^*, Pa·s) were recorded as functions of frequency (f, Hz) using the Rheowin Job software (version 2.93, Thermo Scientific). For data presentation of η^*, a reference frequency of 1 Hz was selected. Additionally, the complex modulus (G^*, Pa) and loss tangent ($\tan \delta$, unitless) were calculated in accordance with equations (2) and (3), respectively:

$$G^* = \sqrt{(G')^2 + (G'')^2} \tag{2}$$

$$\tan \delta = G''/G' \tag{3}$$

Moreover, Winter's critical gel theory was applied using equation (4):

$$G^*(f) = A_f \times f^{1/q} \tag{4}$$

where A_f (Pa·$s^{1/q}$) is the gel strength, f (Hz) is the frequency, and q (unitless) represents the interaction factor. Rheological analysis was conducted at least nine times (three production batches × three repetitions; $n = 9$).

2.4. Sensory analysis

The PCS samples were evaluated by two different sensory panels conforming to the ISO 8586:2023 (ISO, 2023). The first panel consisted of employees from the Department of Food Technology, Faculty of Technology, Tomas Bata University (12 expert sensory assessors, 6 males and 6 females, aged between 31 and 55 years old). Each assessor received a minimum of 40 h experience with sensory analysis on a wide variety of products, including PCS. These panelists evaluated PCS samples using 7-point intensity scales (1–very low intensity, 4–medium intensity, 7–very high intensity); in particular, homogeneity, viscosity/thickness, cheese flavor and off-flavors were assessed. The second panel consisted of students and employees of the Faculty of Technology, Tomas Bata University (70 naïve sensory assessors, 32 males and 38 females, aged between 19 and 59 years old) and examined PCS samples using 7-point hedonic scales (1–excellent, 4–good, 7–unacceptable). Overall texture acceptability and overall flavor acceptability were tested by this panel. Sensory evaluation was realized according to ISO 8589:2007 (ISO, 2007) in a sensory laboratory equipped with individual testing booths at a controlled temperature of 23 ± 2 °C. PCS samples were labelled with three-digit codes and served on white plates in random order. Water and white wheat bread were provided along with samples, to neutralize the taste receptors.

2.5. Statistical analysis

The data obtained were analyzed using a nonparametric analysis of the variance of the Kruskal-Wallis and Wilcoxon tests. A correlation analysis was performed between the complex viscosity (derived from rheological analysis) and viscosity/thickness (as determined by sensory evaluation) using the Spearman correlation coefficient (Pripp, 2013). Minitab 16 (Minitab Inc., State College, PA, USA; 2010) statistical software was used to analyze the data, with a significance level of 0.05.

3. Results and discussion

3.1. pH-value, dry matter content, and emulsion stability

The results of pH-value, dry matter content, and emulsion stability of the PCS samples are presented in Table 3. The pH values of the samples, ranging from 5.83 to 5.92 ($P \geq 0.05$), indicate an optimal environment for casein interaction and uniform distribution of caseins within the PCS matrix, thereby promoting the development of a smooth PCS consistency (Kůrová et al., 2022; Lee & Klostermeyer, 2001). Moreover, the recorded pH-values corresponded to the standard pH range of PCS described in the scientific literature (Desouky et al., 2019; Salek et al., 2019). The DM content of all model PCS samples (in the range of 30.13–31.02 % w/w) was consistent with the designed value of 30 % w/w and was not affected by the type and amount of polysaccharide applied ($P \geq 0.05$). Comparable DM content among the samples is essential, as it significantly influences their rheological behavior (Weiserová et al., 2011).

ES improved with increasing HC concentration across all tested formulations ($P < 0.05$). The CS had the lowest stability (88.2 %), while the samples with GG reached the highest (99.8 %). The samples with GG demonstrated exceptional stability even at lower concentrations (≥0.50 % w/w), suggesting superior stabilization capability. Moreover, the

Table 3
Results of pH, dry matter content, emulsion stability, complex viscosity (at 1 Hz), gel strength and interaction factor in processed cheese sauces with different contents of pectin, agar and guar gum. Results are expressed as means ± SD* (n = 9).

PCS[a] samples	HC[b] (% w/w)	pH (unitless)	Dry matter (% w/w)	Emulsion stability (%)	Complex viscosity (Pa·s)	Gel strength (Pa·s$^{a/q}$)	Interaction factor (unitless)
CS[c]	0.00	5.90 ± 0.02^{a}	31.01 ± 0.09^{a}	88.2 ± 0.6^{a}	1.6 ± 0.1^{a}	9.2 ± 0.1^{a}	1.3 ± 0.2^{a}
PE[d]	0.25	5.89 ± 0.02^{a}	30.22 ± 0.37^{a}	88.8 ± 0.2^{a}	51.9 ± 0.9^{b}	361.1 ± 2.5^{b}	2.5 ± 0.1^{b}
	0.50	5.91 ± 0.08^{a}	30.75 ± 0.09^{a}	91.7 ± 0.3^{b}	65.3 ± 1.1^{c}	520.6 ± 6.8^{c}	2.7 ± 0.2^{b}
	0.75	5.92 ± 0.08^{a}	30.44 ± 0.32^{a}	95.1 ± 0.7^{c}	150.2 ± 1.5^{d}	884.1 ± 10.5^{d}	3.1 ± 0.1^{c}
	1.00	5.86 ± 0.07^{a}	30.62 ± 0.48^{a}	98.9 ± 0.1^{d}	193.0 ± 2.4^{e}	1106.4 ± 5.7^{e}	3.4 ± 0.2^{c}
AG[e]	0.25	5.83 ± 0.05^{a}	31.02 ± 0.30^{a}	90.4 ± 0.1^{a}	79.1 ± 1.3^{f}	485.1 ± 3.7^{f}	5.3 ± 0.1^{d}
	0.50	5.92 ± 0.02^{a}	30.25 ± 0.11^{a}	96.1 ± 0.3^{c}	165.6 ± 2.2^{g}	1026.7 ± 12.8^{g}	6.4 ± 0.1^{e}
	0.75	5.90 ± 0.03^{a}	30.27 ± 0.15^{a}	97.1 ± 0.9^{c}	234.5 ± 2.9^{h}	1457.8 ± 22.5^{h}	6.4 ± 0.2^{e}
	1.00	5.89 ± 0.05^{a}	30.92 ± 0.04^{a}	99.4 ± 0.1^{e}	686.8 ± 7.3^{i}	4191.9 ± 12.4^{i}	6.5 ± 0.1^{e}
GG[f]	0.25	5.87 ± 0.02^{a}	30.42 ± 0.08^{a}	94.1 ± 1.1^{c}	59.5 ± 0.8^{j}	363.6 ± 3.5^{b}	4.1 ± 0.2^{f}
	0.50	5.91 ± 0.01^{a}	30.29 ± 0.17^{a}	99.8 ± 0.1^{e}	155.9 ± 1.6^{k}	1434.1 ± 16.8^{h}	3.6 ± 0.1^{c}
	0.75	5.84 ± 0.01^{a}	30.13 ± 0.07^{a}	99.8 ± 0.1^{e}	249.6 ± 3.1^{l}	1738.9 ± 27.8^{j}	4.2 ± 0.1^{f}
	1.00	5.92 ± 0.04^{a}	30.82 ± 0.06^{a}	99.8 ± 0.1^{e}	347.5 ± 3.5^{m}	2147.9 ± 32.7^{k}	4.4 ± 0.1^{f}

*Mean values within a column (the difference between hydrocolloid type and concentration; the CS was also included) followed by different superscript letters statistically differ ($P < 0.05$).

[a] PCS = processed cheese sauce.

[b] HC = hydrocolloid.

[c] CS = control sample (with no HC).

[d] PE = pectin.

[e] AG = agar.

[f] GG = guar gum.

samples with PE and AG showed a gradual increase with increasing HC concentration, with the AG samples reaching 99.4 % at a concentration of 1.00 % w/w, indicating effective stabilization properties. PCS with PE achieved the lowest ES (maximum 98.9 % in the case of 1.00 % w/w addition). Improved stability of PCS with increasing polysaccharide addition was also reported by Kůrová et al. (2022). Additionally, Szafrańska et al. (2025) concluded that the incorporation of dietary fibers as non-typical HC replacers in PCS elevated the ES.

The enhanced stability of PCS can be attributed to the intensive water-binding capacity of the used HCs, which is facilitated by their high affinity of hydroxyl groups. Additionally, the formation of protein–polysaccharide complexes, arising from electrostatic interactions between negatively charged polysaccharides and positively charged segments of milk proteins, further contributes to the stabilization of the developed PCS matrix (Saha & Bhattacharya, 2010; Ye et al., 2008; Yousefi & Jafari, 2019).

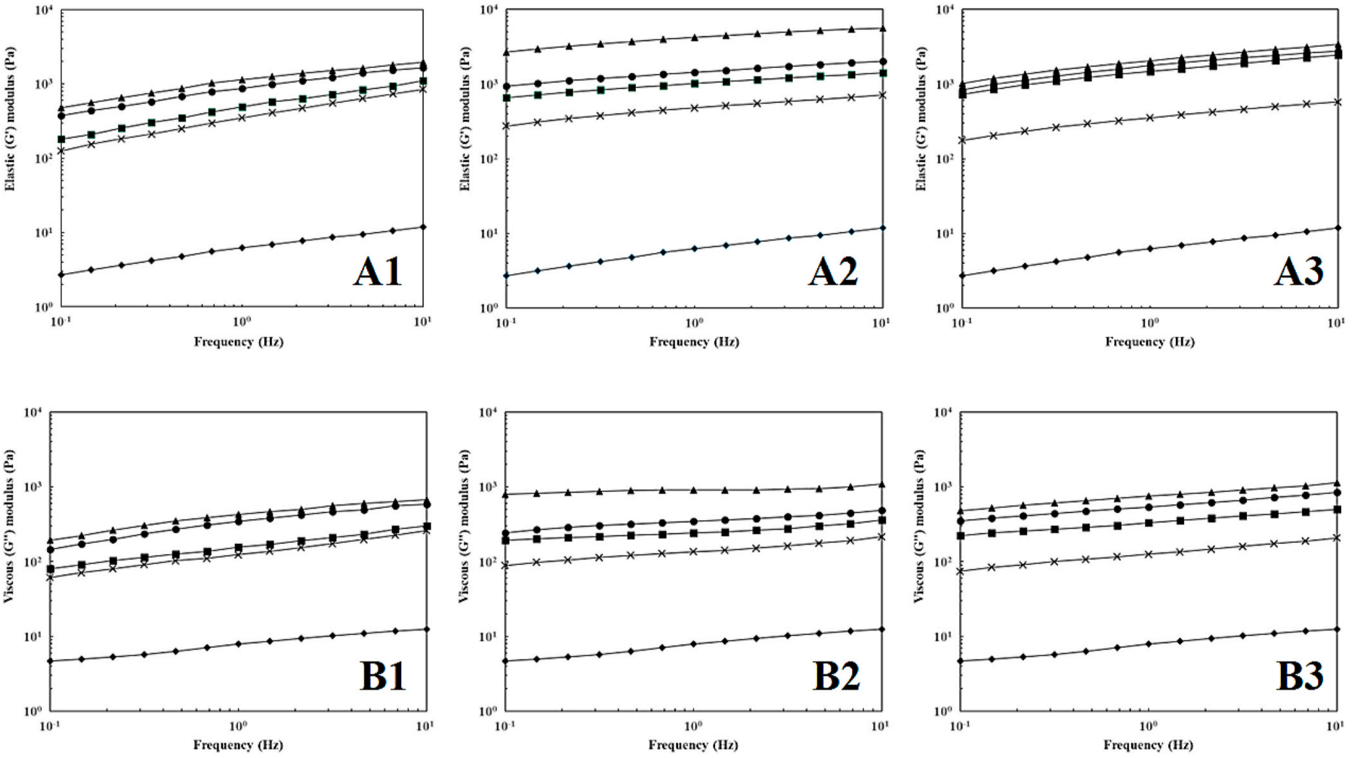

Fig. 1. The dependence of the elastic modulus (G'; Pa), and the viscous modulus (G''; Pa) of the model processed cheese sauce samples containing pectin (parts A1, B1), agar (parts A2, B2), and guar gum (parts A3, B3) in the concentrations of 0.25 (cross), 0.50 (square), 0.75 (circle), and 1.00 (triangle) % w/w on the frequency (Hz). The control sample (rhombus) without hydrocolloid addition is also included (n = 9).

3.2. Rheological analysis

Rheological analysis provides essential insights into the structural and mechanical properties of the PCS samples by evaluating the measured viscoelastic parameters (Zheng, 2019). To date, the available scientific literature contains very few studies addressing the viscoelastic properties of PCS as influenced by the concentration of polysaccharide HCs. Although some publications have investigated PE and GG, these studies typically report only viscosity. Therefore, the results obtained in this study are discussed in the context of processed cheese research, given the similarity in manufacturing processes between processed cheese and PCS. Generally, processed cheese products (including PCS) are stable oil-in-water emulsions reinforced by a gel network of hydrated and emulsified casein proteins, with their viscoelastic behavior primarily determined by this network, although additional ingredients can modify its structure (Schädle et al., 2022). Accordingly, the elastic modulus (G') quantifies the energy stored within the gel structure during time-dependent stress application, whereas the viscous modulus (G'') characterizes the material's flow response under deformation (Saha & Bhattacharya, 2010; Yousefi & Jafari, 2019).

Fig. 1 shows that in all HC-containing formulations, G' exceeded G'' across the entire frequency range, indicating predominantly elastic, solid-like behavior. This is in agreement with the findings of Kůrová et al. (2022) and Szafrańska and Sołowiej (2020b). By contrast, the CS exhibited a more viscous character. The dominant elastic response of PCS (excluding CS) increased with higher HC content, likely reflecting the molecular structure and gelling mechanisms of the respective HCs, as well as potential HC–protein matrix interactions, which collectively contribute to the observed increases in viscoelastic moduli (Imeson, 2009; Macků et al., 2008). Furthermore, both G' and G'' moduli increased with the increasing concentration of all HCs used.

Among the tested HCs, the PCS sample containing AG exhibited the highest G' and G'' values, reflecting the unique properties of AG that enhance its effectiveness (Fig. 1, Parts A2 and B2). Notably, AG forms reversible gels upon cooling hot aqueous solutions. Gelation is a thermoreversible process driven by hydrogen bonding between agarose molecules. Upon heating, AG dissolves into random coils that, below 30–40 °C, convert into single and then double helices (Imeson, 2009). These helices aggregate into higher-order structures, producing a three-dimensional network stabilized by hydrogen bonds and entrapped water (Zucca et al., 2016). In agar–milk gels, AG establishes a homogeneous network determining G', while casein micelles diffuse within the voids (Corredig et al., 2011). A further advantage is its neutral backbone and cation-independent gelation, which is beneficial in calcium-rich dairy systems, as AG neither interferes with gel performance nor interacts electrostatically with proteins. Thus, variations in milk protein quality do not markedly affect texture (Imeson, 2009; Zhang et al., 2024). Moreover, the neutral chain confers acid resistance, and the effective pH range for gelation (5–8) explains the stability of PCS gels prepared at pH ~5.8.

The addition of PE showed trends in G' and G'' comparable to those observed for AG, although the viscoelastic moduli of the PE-containing samples were generally lower (Fig. 1, Parts A1 and B1). Low-methoxyl PE is considered a suitable hydrocolloid for PCS, as it forms gels in the presence of Ca^{2+} within an optimal pH range of 2.0–6.0 (Gawkowska et al., 2018). Gelation occurs through ionic interactions between free carboxyl groups of galacturonic acid residues and divalent ions, resulting in a three-dimensional network. A low degree of methylation increases available carboxyl groups, enabling stable junction zones through the "egg-box" mechanism, with strength depending on the distribution of non-methoxylated blocks (Said et al., 2023; Yousefi & Jafari, 2019). Gelation is enhanced at higher pH values due to greater dissociation of carboxyl groups (Fraeye et al., 2010). Interactions with casein micelles also contribute to viscoelastic moduli: below pH 5, electrostatic attraction occurs, while at neutral pH, repulsion dominates (Maroziene & de Kruif, 2000; Tuinier et al., 2002). Thus, PE thickening reflects both partial gelation of the serum phase and reduced surface charge of casein particles, promoting gel network formation (Matia-Merino et al., 2004). Comparable findings in the literature indicate that the addition of low-methoxyl PE increased the elasticity of processed cheese gels over the tested concentration range of 0.2–0.8 % w/w, with higher PE content resulting in more elastic gels (Macků et al., 2008). Moreover, Szafrańska and Sołowiej (2020b) reported increased G' and G'' values in PCS formulations containing citrus fiber with high PE content.

Lastly, the viscoelastic moduli of GG-enriched PCS are presented (Fig. 1, Parts A3 and B3). Generally, GG is classified as a non-gelling agent and is primarily utilized as a thickening agent. Moreover, GG significantly increases the low-shear viscosity of aqueous systems and exhibits pronounced shear-thinning behavior (Saha & Bhattacharya, 2010). In the context of the PCS samples, the observed increase in viscoelastic moduli can be attributed to the thickening effect of GG and the resulting enhancement of system viscosity (see further η^* results). Increased viscosity of PCS with GG was also noted by El-Mahdi et al. (2014) and Hassan et al. (2015).

Beyond the viscoelastic moduli G' and G'', it is helpful to assess sample rigidity using the complex modulus G^*. This parameter highlights the effect of HC concentration on the PCS samples. Fig. 2 presents the development of G^* of the PCS samples in relation to the frequency. The data indicate that PCS samples with added HCs exhibited higher G^* values, which further increased with rising concentration. At 0.25 % w/w (Fig. 2A), only minor differences in the G^* profiles were observed among AG, PE, and GG across the entire frequency range. At 0.50 % w/w (Fig. 2B), a more pronounced increase in G^* was observed for PCS with GG and AG, whereas PE-containing samples followed a similar rising trend but with a larger offset, which decreased above approximately 1 Hz. At 0.75 % w/w (Fig. 2C), G^* values continued to increase, with the HC curves maintaining a comparable trend. At the highest tested concentration of 1.00 % w/w (Fig. 2D), the AG-enriched sample exhibited a substantially higher increase in G^*, whereas the samples with PE and GG showed a more gradual rise. The rigidity enhancement with increasing concentration of HCs used in PCS formulation was also reported by Szafrańska and Sołowiej (2020b) and Kůrová et al. (2022). Hassan et al. (2015) concluded that PCS with GG were more viscous compared to those with PE, which is in agreement with our findings (see also η^* results below).

Additionally, the loss tangent values presented in Fig. 3 further characterize the viscoelastic nature of the PCS samples. According to Murata (2012), a material with $\tan \delta = 1$ exhibits a balance between solid-like and liquid-like behavior. Values of $\tan \delta < 1$ indicate a predominantly elastic response, whereas values of $\tan \delta > 1$ reflect behavior dominated by viscous contributions. For PCS samples containing HCs at all tested concentrations, $\tan \delta$ values remained below 1 across the entire frequency range, indicating predominantly an elastic behavior. However, PE-enriched PCS exhibited a lower degree of elasticity, particularly in the 0.1–1 Hz region. In contrast, CS displayed a predominantly viscous character. These observations are consistent with the results published by Kůrová et al. (2022).

Table 3 also presents the results of η^* and Winter's critical gel theory parameters, particularly A_f and q values. The interaction factor is defined as the number of structural units interacting within a three-dimensional network. The higher interaction factor corresponds to a greater number of interactions within the sample matrix (Černíková et al., 2018). Increasing HC concentration, regardless of type, significantly increased the values of η^*, A_f, and q of PCS, whereas values observed for CS were significantly lower ($P < 0.05$). Both results of η^* and data obtained from Winter's critical gel theory were consistent with trends observed for G^*. Among the tested HCs, PE exhibited the lowest η^*, A_f, and q values, whereas the AG gel was the most developed and, at 1.00 % w/w, achieved the highest η^* and A_f values ($P < 0.05$). The effectiveness of the HCs can be attributed to more intensive interactions occurring in PCS samples, depending on the type and gelation

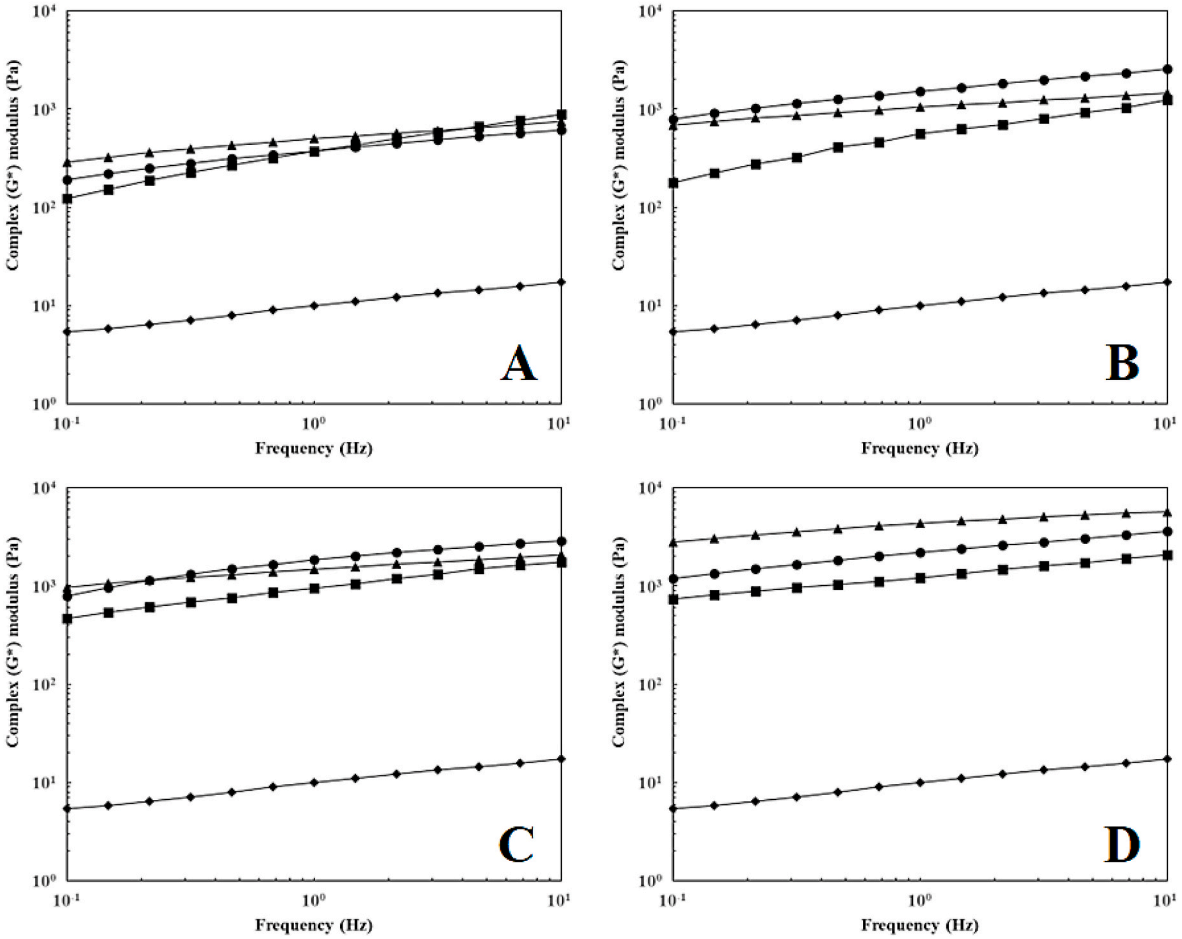

Fig. 2. The dependence of the complex modulus (G*; Pa) of the model processed cheese sauce samples in the concentrations of 0.25 (Part A), 0.50 (Part B), 0.75 (Part C), and 1.00 (Part D) % w/w containing pectin (square), agar (triangle), and guar gum (circle) on the frequency (Hz). The control sample (rhombus) without hydrocolloid addition is also included ($n = 9$).

mechanism (Saha & Bhattacharya, 2010; Vincová et al., 2023). In the matrix of processed cheese and similar products, interactions based on hydrogen bonding, hydrophobic interactions between caseins and fat, or calcium-mediated electrostatic bonds among caseins may also play a role (Salek et al., 2016). The observed findings align with those of Macků et al. (2009), confirming that higher PE concentrations increase the η^*, A_f, and q values, resulting in greater rigidity and elasticity attributable to the reinforced protein–PE network. These observations are further supported by Szafrańska and Sołowiej (2020b), who reported that systems containing higher PE content form thicker and firmer gel structures.

3.3. Sensory analysis

The sensory evaluation results of PCS with polysaccharide HCs are presented in Fig. 4. All PCS were rated as very homogeneous, and this parameter remained unaffected by either the type or concentration of the HC used ($P \geq 0.05$). The homogeneity of the samples could also be supported by the trends obtained from the ES results (see Table 3). The addition of HC led to a noticeable improvement in overall texture acceptance compared to the CS, with the most favorable texture observed in samples containing AG and GG at concentrations of 0.50–0.75 % w/w ($P < 0.05$). Samples formulated with 0.25 % w/w polysaccharides were evaluated less favorably due to their overly fluid consistency; however, they were still rated as good. Conversely, samples containing 1.00 % w/w HC exhibited a texture more reminiscent of spreadable processed cheese rather than sauce, which negatively influenced their sensory perception. Viscosity/thickness, one of the key textural parameters, was consistently higher in all HC-enriched samples compared to the control ($P < 0.05$). A direct relationship was observed between HC concentration and sample viscosity/thickness ($P < 0.05$), which aligns with the rheological data presented in Figs. 1–3 and Table 3. The correlation analysis confirmed a strong positive correlation between viscosity/thickness (sensory attribute) scores and η^* values (rheological parameter) in all tested HC systems. For PE-enriched samples, the correlation was strong ($r_s = 0.975$) and statistically significant ($P = 0.0048$), indicating a consistent increase in both sensory and rheological parameters with increasing concentration. PCS with AG and GG exhibited very strong correlations ($r_s = 0.997$, $P < 0.0001$), clearly demonstrating that higher HC concentrations led to parallel enhancements in rheological properties and sensory perception of viscosity. These findings reinforce the conclusion that sensory evaluation reliably reflects rheological behavior in PCS.

The cheese flavor intensity of all samples was rated as high, and no off-flavors were detected by the panelists ($P \geq 0.05$). Overall flavor acceptability scores were higher for HC-containing samples (≥0.50 % w/w) than for the CS. Based on the conclusions drawn from the hedonic evaluation of texture and flavor, it can be stated that the samples with AG and GG in concentrations of 0.50 and 0.75 % w/w were rated the highest ($P < 0.05$).

Our results are consistent with those published by El-Mahdi et al. (2014) and Hassan et al. (2015). El-Mahdi et al. (2014) found that samples containing GG were rated better than control sauces without HC and concluded that PCS should contain a suitable stabilizing agent.

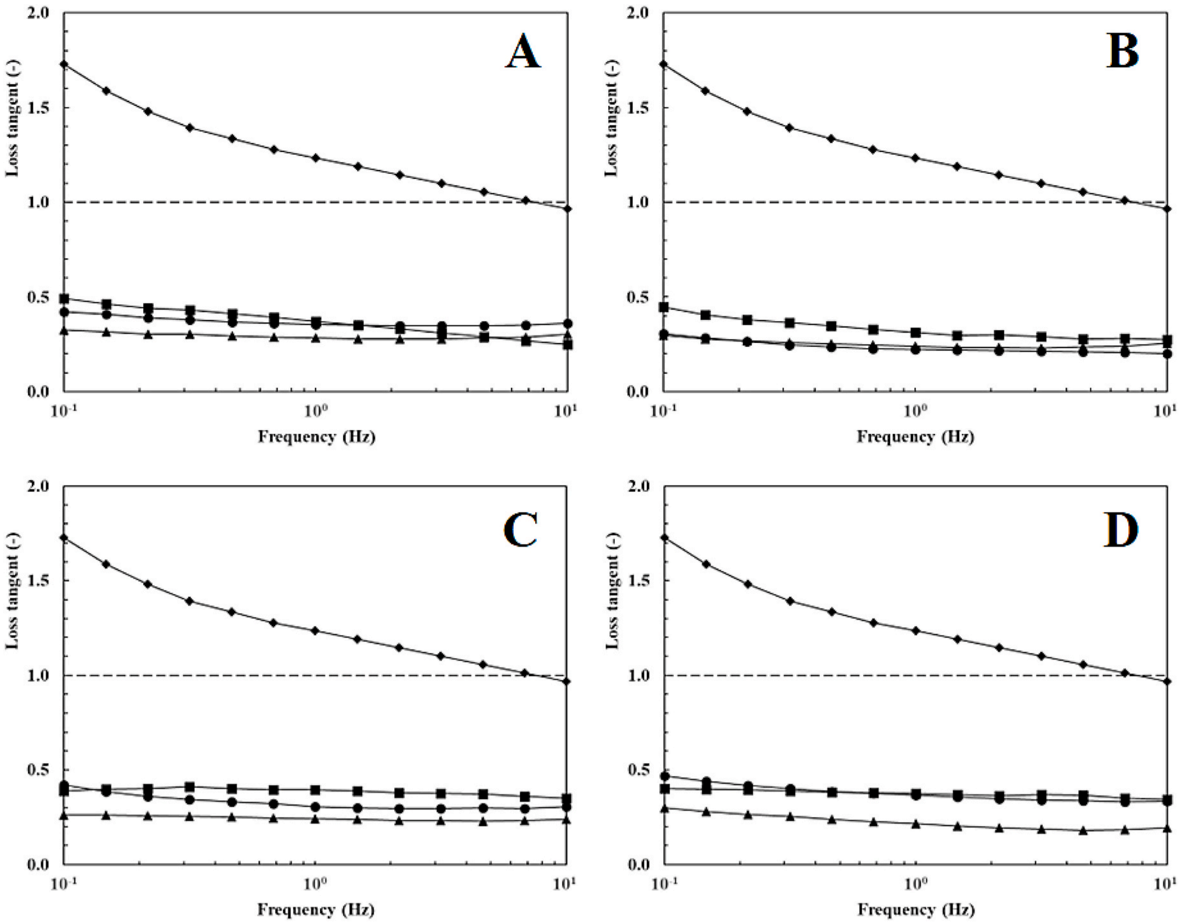

Fig. 3. The dependence of the loss tangent (tan δ) of the model processed cheese sauce samples in concentrations of 0.25 (Part A), 0.50 (Part B), 0.75 (Part C), and 1.00 (Part D) % w/w containing pectin (square), agar (triangle), and guar gum (circle) on the frequency (Hz). The control sample (rhombus) without hydrocolloid addition is also included. The dashed line indicates the boundary between the elastic and viscous regions (n = 9).

Furthermore, according to Hassan et al. (2015), the addition of stabilizers improved organoleptic properties of PCS; all PCS with added stabilizer were highly acceptable and highly preferred over the control sauce. Authors stated that PCS with GG obtained a higher total score compared to those with PE, which corresponds to our results. Moreover, Szafrańska and Sołowiej (2020b) reported that the addition of citrus fiber (containing approx. 43 % w/w of PE) significantly improved the consistency of PCS compared to the control sample. In addition, there are several publications concluding that HC addition improves sensory quality of processed cheese and/or processed cheese products (Chatziantoniou et al., 2015; Chatziantoniou & Thomareis, 2024; Macků et al., 2008; Rohani & Rashidi, 2019).

4. Conclusion

The impact of three polysaccharide HCs (PE, AG, and GG) at concentrations ranging from 0.25 to 1.00 % w/w on the physicochemical, viscoelastic, and organoleptic properties of full-fat PCS was studied. All tested HCs effectively stabilized the PCS matrix, confirming their suitability as functional stabilizers. The highest emulsion stability value was observed in samples containing 1.00 % of GG. HC-enriched samples exhibited a predominantly elastic character, in contrast to the more viscous behavior of CS without HC. Increasing HC concentration led to a progressive enhancement of all tested rheological parameters, including elastic, viscous, and complex moduli, loss tangent, complex viscosity, gel strength, and interaction factor. This trend reflected a strengthening of the PCS structure, particularly in formulations containing AG and GG, as further supported by sensory evaluation. Overall, the results demonstrate a strong correlation between sensory evaluation and rheological measurements, confirming that both approaches consistently reflect the viscosity characteristics of PCS. From a sensory perspective, HC addition improved the texture of PCS. Based on overall texture and flavor acceptability scores, the highest panelist ratings were assigned to samples formulated with 0.50 and 0.75 % of AG and GG, confirming their positive contributions to both structural integrity and consumer acceptability. The findings of this study are applicable in practice, demonstrating that all investigated HCs can be effectively employed as stabilizers in full-fat PCS, where their incorporation consistently improved textural properties.

CRediT authorship contribution statement

Zuzana Lazárková: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Tomáš Gryger:** Writing – review & editing, Methodology, Investigation. **Richardos Nikolaos Salek:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Ethical statement

This study was conducted at Tomas Bata University in Zlín, which does not have a formal institutional ethical committee for sensory analysis. However, all research was performed in accordance with the ethical principles outlined in the Declaration of Helsinki. Furthermore, all participants were informed about the purpose of the study and any

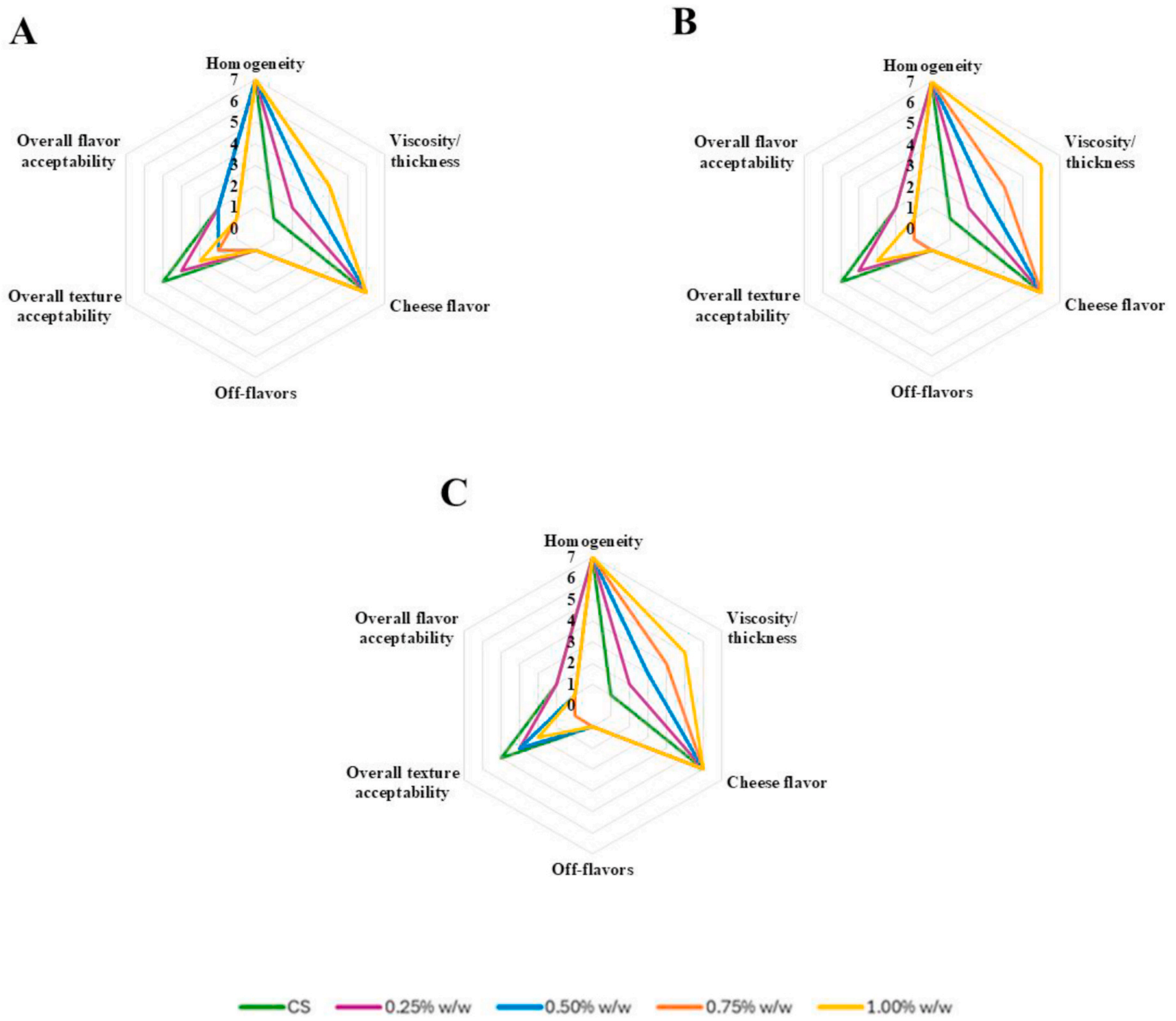

Fig. 4. The effect of hydrocolloid addition on the organoleptic parameters (homogeneity, viscosity/thickness, cheese flavor, off-flavors, overall texture acceptability, and overall flavor acceptability) of the model processed cheese sauce samples containing pectin (part A), agar (part B), and guar gum (part C) in the concentration of 0.25–1.00 % w/w. The control sample (CS) without hydrocolloid addition is also included. Results are expressed as medians. Homogeneity, viscosity/thickness, cheese flavor and off-flavors were evaluated by expert sensory panel (n = 12), whereas overall texture acceptability, and overall flavor acceptability were assessed by naïve sensory panel (n = 70).

potential risks, and they provided written consent before participation. All participants were fully aware they could withdraw from the study at any time without penalty. Participant anonymity and data confidentiality were maintained throughout the study, and no personally identifiable information was published. The risks associated with participation were minimal, and the benefits of the research outweigh any potential harm.

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Declaration of competing interest

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

Data availability

Data will be made available on request.

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