



The effect of sodium- or potassium-based emulsifying salts on the physicochemical, mechanical, thermal, and sensory properties of processed cheese: A comparative study

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ABSTRACT

Reducing the sodium content in processed cheese (PC) is a major nutritional goal, whereas maintaining its functional and sensory quality remains challenging. The current study evaluated the impact of potassium-based emulsifying salts (ES; dipotassium hydrogen phosphate, DKP; tetrapotassium pyrophosphate, TKPP; pentapotassium triphosphate, KTPP) at different concentrations (2.0%, 2.5%, and 3.0% wt/wt) on the physicochemical, mechanical (viscoelastic, textural, and mechanical vibration damping), thermal, and sensory properties of model PC samples (40% wt/wt DM and 50% wt/wt fat in DM contents) during a 60-d storage period at 6°C ± 2°C. Selected types of sodium-based ES (disodium hydrogen phosphate, DSP; tetrasodium pyrophosphate, TSPP; pentasodium triphosphate, STPP) were also prepared for comparison reasons. All tested samples exhibited a gel-like, predominantly elastic behavior, with functional responses dependent on ES type and concentration. Hardness increased with longer (potassium or sodium) phosphate chains: DKP (or DSP) < TKPP (or TSPP) < KTPP (or STPP), with KTPP producing the firmest PC samples. Mechanical vibration damping measurements were consistent with hardness and complex modulus (G*) results. In addition, storage period slightly decreased samples' pH and yellowness. The results of the differential scanning calorimetry indicated enhanced water binding with higher potassium content. Furthermore, the use of potassium-based ES significantly lowered sodium levels in the resultant PC without compromising sensory quality. The obtained results highlighted that potassium-based ES could be considered as a beneficial alternative to sodium-based ES, offering an effective strategy to

reduce dietary sodium intake while preserving key functional and sensory properties of PC.

Key words: processed cheese, sodium-based emulsifying salts, potassium-based emulsifying salts, rheological properties, organoleptic properties

INTRODUCTION

The term processed cheese (PC) refers to a multicomponent dairy complex system that is also characterized as a stable oil in water emulsion from a physicochemical perspective (Kapoor and Metzger, 2008; Fox et al., 2017). In general, PC is obtained by mixing various ingredients of dairy or nondairy origin. In particular, natural cheeses (of different types and varying maturity degrees), anhydrous milk fat, butter, cream, buttermilk, dairy powders (milk, casein products, whey, whey protein products), as well as water, different types of emulsifying salts (ES), stabilizers, preservatives, flavoring agents, and hydrocolloids are commonly used, according to the final product desired properties. The addition of individual ingredients can affect numerous essential functional properties (physicochemical and technological) of PC (Kapoor and Metzger, 2008; Nagyová et al., 2014; Salek et al., 2017). Furthermore, heating natural cheese in the presence of ES, under constant shear and partial vacuum, leads to the development of a PC with homogeneous and smooth consistency (Johnson et al., 2009; Salek et al., 2016; Pluta-Kubica et al., 2021).

The structure of PC represents a continuous network (consisting of proteins, water, dissolved solids), which is disrupted by dispersed fat globules (Brighenti et al., 2008). Caseins present in ripened natural cheeses exhibit excellent emulsifying properties, which ensure the necessary fat emulsification and water stabilization in PC. However, in the system of natural cheese, the caseins are organized into a 3-dimensional network through calcium bridges. These are considered the main attractive force

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responsible for the linkage of caseins in the form of a gel, which literally immobilizes them and prevents them from performing their natural emulsifying functions. These “cross-links,” also referred to as “calcium bridges,” are formed by calcium ions binding directly to aspartate and glutamate groups or to nanoclusters of calcium phosphate attached to serine-phosphate groups on the casein molecules (Brighenti et al., 2008; Fox et al., 2017). As a result, to enhance the emulsifying capability of caseins, ES are used in the manufacture of PC (Nagyová et al., 2014). Particularly, ES enhance the emulsifying properties of caseins through the ion exchange of calcium ions present in the natural cheese’s casein matrix for sodium or potassium ions from the used ES. This phenomenon is also referred as calcium sequestration, whereby this chemical reaction leads to the transformation of the less soluble calcium paracaseinate into the more soluble sodium or potassium paracaseinate, which can possess the desired emulsifying and stabilizing properties. Moreover, this conversion ensures the reinforcement of casein molecules, thereby increasing the stability of the product without undesirable water expulsion from the system (Nagyová et al., 2014; Fox et al., 2017; Šantová et al., 2024). Nevertheless, not all ES exhibit the same ion-exchange ability. Generally, the ability to support ion exchange occurs in the following order (with respect to the type of sodium-based ES): citrates $\approx$ monophosphates < diphosphates < triphosphates < short polyphosphates (<10 phosphorus atoms per molecule) < long polyphosphates (>10 phosphorus atoms per molecule; Nagyová et al., 2014; Salek et al., 2015, 2016).

In industrial practice, sodium-based ES such as phosphates, diphosphates, polyphosphates, and their various mixtures are more widely applied. The exchange of sodium ions for calcium ions and the hydration of casein typically results in better functional and sensory properties of the final PC product compared with the exchange of potassium ions for calcium ions, even though both are monovalent cations of alkali metals. Monovalent cations (sodium) and polyvalent anions (phosphate, citrate) are the 2 main components of sodium-based ES (Buňka et al., 2024). However, their use significantly contributes to the increase in the overall sodium content in PC (Johnson et al., 2009; Hoffmann et al., 2012; Chavhan et al., 2015). The main reason for using potassium-based ES or partially replacing sodium chloride (NaCl) with potassium chloride (KCl) in natural cheese (the main ingredient for PC manufacture) is the desire to reduce the sodium content in the resultant PC product (Cruz et al., 2019). Excessive dietary sodium intake combined with inadequate potassium intake may contribute to the potential development of cardiovascular diseases such as hypertension, heart failure, and among others, chronic kidney disease (Stambolliu et al., 2025). Processed

cheeses have a relatively high sodium content (typically >1% wt/wt). One promising approach involves the partial or complete substitution of sodium-based ES with potassium-based ones. Potassium phosphates exhibit similar emulsifying and buffering capacities but contribute less dietary sodium and more potassium, which is beneficial for cardiovascular health. However, replacing sodium with potassium ions can influence casein hydration, protein–protein interactions, and mineral equilibria within the cheese matrix, potentially affecting viscoelastic textural properties, meltability, and overall product quality. Furthermore, ES are typically applied in amounts of 2.0% to 3.0% (wt/wt) of the total ingredient composition. The selection of the appropriate concentration and type of ES can significantly influence several PC functional properties, particularly textural and sensory characteristics. However, excessively high concentrations of potassium-based ES in PC can result in a bitter or metallic aftertaste (Agarwal et al., 2011; Hoffmann et al., 2012; Buňka et al., 2014; Chavhan et al., 2015). However, few studies have described the potential effects of potassium-based ES on the functional and sensory properties of PC. Therefore, the appropriate selection of both the concentration and the type of potassium-based ES is crucial (Šantová et al., 2024).

On the whole, sodium-based ES have been examined extensively for their influence on the physicochemical and functional properties of PC (Shirashoji et al., 2010; Weiserová et al., 2011; Chen and Liu, 2012; Nagyová et al., 2014; Salek et al., 2015, 2016, 2017). The substitution of sodium-based ES with potassium-based alternatives in PC formulations remains a significant technological challenge, primarily due to their potential adverse effects on sensory quality and product acceptability (Khetra et al., 2015; Chavhan et al., 2015; Nogueira et al., 2018; Šantová et al., 2024). The current study is unique because it provides a direct comparison between sodium-based and potassium-based ES, offering insights into their differential effects on PC properties and addressing the growing demand for reduced-sodium PC formulations. Therefore, the objective of this study was to evaluate and compare the effects of potassium-based (dipotassium hydrogen phosphate [K_2HPO_4 ; **DKP**], tetrapotassium pyrophosphate [$K_4P_2O_7$; **TKPP**], and pentapotassium triphosphate [$K_5P_3O_{10}$; **KTPP**]) and sodium-based (disodium hydrogen phosphate [Na_2HPO_4 ; **DSP**], tetrasodium pyrophosphate [$Na_4P_2O_7$; **TSPP**], pentasodium triphosphate [$Na_5P_3O_{10}$; **STPP**]) emulsifying salts with different phosphate chain lengths on the physicochemical, mechanical (viscoelastic, textural, and mechanical vibration damping), thermal, and sensory properties of PC during a 60-d storage period ($6^\circ C \pm 2^\circ C$). The examined ES were applied in concentrations ranging from 2.0% to 3.0% (wt/wt), with incremental steps of 0.5% (wt/wt; 3

Table 1. Formulation of the processed cheese samples manufactured with different potassium-based emulsifying salts and with target values: 40% wt/wt in DM content, 50% wt/wt fat in DM content, and 14% wt/wt in protein content

Ingredient	DM content (% wt/wt)	Treatment A (% wt/wt)	Treatment B (% wt/wt)	Treatment C (% wt/wt)
Edam cheese ¹	52.08	50.81	50.56	50.30
Butter	84.56	15.25	15.17	15.09
Water	0	31.94	31.77	31.61
Emulsifying salts ²		2.00	2.50	3.00
Processing parameter				
Agitation speed (rpm)		3,000	3,000	3,000
Holding time at the target temperature (min)		1	1	1
Target temperature (°C)		90	90	90
Total time (min)		12	12	12

¹Dutch-type semihard cheese, 7-wk maturity.

²Emulsifying salts used: DKP, K₂HPO₄ = dipotassium hydrogen phosphate; TKPP, K₄P₂O₇ = tetrapotassium pyrophosphate; KTPP, K₅P₃O₁₀ = pentapotassium triphosphate; DSP, Na₂HPO₄ = disodium hydrogen phosphate; TSPP, Na₄P₂O₇ = tetrasodium pyrophosphate; STPP, Na₅P₃O₁₀ = pentasodium triphosphate.

concentrations for each tested ES). The study aimed to determine whether potassium-based ES can lead to the manufacturing of PC with high-quality sensory and functional properties with reduced sodium content.

MATERIALS AND METHODS

Raw Materials for the Manufacture of the PC Samples

The PC were manufactured using the following ingredients: Edam cheese blocks (52% wt/wt DM content, 30% wt/wt fat in DM, a Dutch-type semihard cheese; 7-wk maturity; Lacrum Velké Meziříčí s.r.o., Velké Meziříčí, Czech Republic); butter (83% wt/wt fat content, 85% wt/wt DM content; Lacrum Velké Meziříčí s.r.o., Velké Meziříčí, Czech Republic), water, and ES (supplied by Fosfa a.s., Břeclav, Czech Republic). The model PC samples were designed to have target values of DM content and fat in DM content of 40% and 50% (wt/wt), respectively. Three diverse types of sodium-based ES (DSP, TSPP, and STPP) and 3 types of potassium-based ES (DKP, TKPP, and KTPP) were applied. In particular, 2 groups of model PC samples were prepared: (1) PC samples with sodium-based ES addition; and (2) PC samples with the potassium-based ES addition. For each ES type, concentrations ranging from 2.0% to 3.0% (wt/wt) were used, with incremental steps of 0.5% (wt/wt; 3 concentrations in total for each ES). Additionally, each PC sample was manufactured in triplicate, resulting in 54 batches of PC (54 batches of PC = 6 types of ES [3 types of potassium-based ES and 3 types of sodium-based ES] × 3 ES concentrations × 3 repetitions). The PC samples were tested on d 1, 14, 30, and 60 of storage (6°C ± 2°C; d 1 was the day of manufacturing). Ingredient composition is presented in Table 1.

Manufacturing of the Model Processed Cheese Samples

The PC samples were manufactured using the Niromix mixer (Nirosta s.r.o., Chlumec nad Cidlinou, Czech Republic). The first step involved cutting the ingredients (Edam cheese and butter) into the desired size (20 mm × 20 mm × 20 mm). Thereafter, the Edam cheese was placed into the device for disintegration (1 min at 3,000 rpm). Subsequently, butter, ES, and water were added into the equipment. The processing was conducted at a target temperature of 90°C ± 1°C and a holding time of 3 min at 3,000 rpm. The total processing time for one sample was ~11 to 12 min. Afterward, the hot melt was poured into 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) and sealed with aluminum lids using the NovaSeal equipment (Nirosta s.r.o., Chlumec nad Cidlinou, Czech Republic). The weight of the sample in one container was ~95 ± 2 g (from each manufacturing batch ~27 containers were obtained). The samples were left to cool at 25°C ± 2°C and then were stored at 6°C ± 2°C until subsequent analyses were performed.

Proximate Analysis and Water Activity Determination

The contents of DM, fat, and protein were determined according to ISO 8968–1:2014 (ISO, 2014), ISO 23319:2022 (ISO, 2022), and ISO 5534:2004 (ISO, 2004), respectively. For each PC sample tested, the analyses were performed at least 6 times (n = 6). In addition, the pH of the samples was determined using the Foodcare pH-meter (HI-99161, Hanna Instruments Inc., Woonsocket, RI) with a combined glass tip electrode (at 25°C ± 1°C).

Water activity (a_w) was determined using the Meter AquaLab 4TE (AquaLab, Decagon, USA). The apparatus was calibrated using an appropriate solution ($a_w = 0.92$ NaCl, 2.33 M in H₂O [Qi Analytical s.r.o., Prague, Czech Republic]) just before every measurement. The analyses were performed at least 3 times ($n = 3$; Kůrová et al., 2022).

Determination of Viscoelastic Properties

Viscoelastic properties measurements were performed according to Kůrová et al. (2022). A dynamic oscillatory shear rheometer (Thermo Scientific RheoStress 1, Haake, Bremen, Germany) with a plate-plate geometry (35 mm in diameter; gap of 1 mm) at $20.0^\circ\text{C} \pm 0.1^\circ\text{C}$ was used to determine the viscoelastic characteristics of the PC samples. A gap height of 1 mm and a shear stress amplitude set at 20 Pa (in the region of linear viscoelasticity) were selected. Each PC sample was measured in the control stress mode at a frequency range of 0.01 to 100.00 Hz. All measurements were conducted within the region of linear viscoelasticity. A thin layer of silicon oil was used to cover the exposed edges of the plate-plate geometry to avoid sample dehydration. The monitored parameters included the storage (G' ; Pa) and loss (G'' ; Pa) moduli (determined as a function of frequency), which were used for complex modulus (G^* ; Pa) calculation according to the following (Equation 1):

$$G^* = \sqrt{(G')^2 + (G'')^2}. \quad [1]$$

Furthermore, the loss tangent ($\tan \delta = G''/G'$) was also calculated (Andreadis and Moschakis, 2023). A reference frequency of 1 Hz was used to express the values of G^* and $\tan \delta$. The analyses were carried out in triplicate ($n = 3$).

Texture Profile Analysis

The texture profile analysis (TPA) of the PC samples was performed using the TA.Xtplus texture analyzer (Stable Micro Systems Ltd., Godalming, UK). Moreover, the tests were carried out at $6^\circ\text{C} \pm 2^\circ\text{C}$ (the samples measurement was performed immediately after removing them from a refrigerator where they were stored) after 1, 14, 30, and 60 d of storage. The TPA was implemented by 2 successive penetrations with a 20-mm-diameter stainless-steel cylindrical probe (P20) directly into the sample. The trigger force was equivalent to 5 g, and the probe penetration depth was set at 10 mm at a speed rate of $2 \text{ mm} \cdot \text{s}^{-1}$. Using the “texture profile” feature of the Texture Exponent Lite software version 4 (Stable Micro Systems Ltd., Godalming, UK), the force data as a function of time for the 2 penetration cycles were acquired, along with values for the following parameters: hardness, relative adhesiveness,

and cohesiveness (Bayarri et al., 2012; Nagyová et al., 2014; Salek et al., 2017, 2019, 2020). All tested samples were measured at least 6 times ($n = 6$).

Instrumental Color and Computer Vision Analyses

The color of each PC sample was first analyzed using a spectrophotometer, followed immediately by analysis with a computer vision system. Instrumental color analysis of the PC samples was performed using the HunterLab UltraScan VIS Pro spectrophotometer (Hunter Associates Laboratory Inc., Reston, VA) at $25^\circ\text{C} \pm 1^\circ\text{C}$ with a 10-mm glass cuvette. The CIELAB color scale ($L^*a^*b^*$) was employed with D65 illumination (average daylight) at a 10° angle. Color is defined as a point in a 3-dimensional space using the coordinates L^* , a^* , and b^* . L^* indicates the lightness of the color positioned on the vertical axis, ranging from 0 (black) to 100 (white). The other 2 parameters (a^* , b^*) represent values from which color saturation [$C^* = (a^{*2} + b^{*2})^{0.5}$] and hue [$^\circ\text{h} = \tan^{-1}(a^*/b^*)$] can be calculated; they are positioned on the horizontal axis. The a^* parameter corresponds to the spectral wavelengths associated with colors from green ($-a^*$) to red ($+a^*$). In contrast, the b^* parameter corresponds to colors from blue ($-b^*$) to yellow ($+b^*$). Moreover, the samples whiteness index $\{WI = [(100 - L^*)^2 + a^{*2} + b^{*2}]^{0.5}\}$ was also calculated. The instrument was calibrated in the reflectance mode, excluding mirror reflection, using a white ($L^* = 100$) and black ($L^* = 0$) reference plate. Each sample was measured in triplicate ($n = 3$; Chen and Liu, 2012; Šantová et al., 2024).

Colorimetric properties (computer vision analysis) were derived from RAW RGB images by sampling the digital image of the specimen using Photoshop's Average Color Sampler Tool (Adobe Inc., San Jose, CA). A digital camera (Coolpix P6000, Nikon, Tokyo, Japan; 13.5-Mpx resolution, equipped with a Nikkor glass lens) was mounted on a copy stand. Illumination was provided by two 70-W lamps (5,500 K) positioned 60 cm above the base and spaced ~30 cm apart on opposite sides of the stand. The camera was placed directly above the samples to ensure consistent imaging geometry. Before photographing, PC samples were removed individually from refrigerated storage and placed on a black cardboard base to maximize contrast. Each sample was positioned at a fixed distance of 40 cm from the camera, and a steel ruler was included within the frame for image calibration.

Determination of Potassium, Sodium, Calcium, and Magnesium Content by Atomic Emission Spectrometry

An atomic absorption spectrometer contrAA 800D (Analytik Jena, Jena, Germany) was used to determine

the amount concentrations of potassium, sodium, calcium, and magnesium in the tested model PC samples. First, the PC samples (0.25 g of sample) were mineralized by adding 6 mL of concentrated nitric acid (65% vol/vol) and 2 mL of hydrogen peroxide (30% vol/vol). The mineralization process was then performed using an Ethos SEL Microwave Labstation (Milestone, Sorisole, Italy) at 200°C for 30 min. The amount of potassium was determined at wavelengths of 588 and 766 nm using flame emission spectrometry with an air-acetylene flame composition. Additionally, calcium and magnesium concentrations were determined by absorption at wavelengths of 422.7 and 285.2 nm, respectively. All measurements were performed at least 3 times ($n = 3$). Furthermore, the obtained data were processed using the Aspect CS software (ver. 2.2.1.0, Analytik Jena, Jena, Germany), resulting in one final value for each sample (batch of product; Šantová et al., 2024).

Differential Scanning Calorimetry

Thermal analysis was performed on differential scanning calorimetry (DSC) 250 Discovery (TA Instruments) with Tzero patented technology. Each sample (10.0 ± 1.1 mg) was filled in Tzero aluminum pin hole hermetic pans (with a hole of 1 mm), and empty aluminum pan was used as a reference. A thermogram was obtained by scanning from 25°C to -80°C using a cooling step of $10^\circ\text{C}\cdot\text{min}^{-1}$, subsequently an isothermal step at -80°C for 1 min, and then a heating cycle in a temperature range from -80 to +80°C with a heating rate of $5^\circ\text{C}\cdot\text{min}^{-1}$. The measurement was carried out under nitrogen atmosphere at a flow rate of $50\text{ mL}\cdot\text{min}^{-1}$. The DSC instrument was calibrated by indium standard. The state of water in PC was evaluated by parameters of temperature peaks and relevant enthalpies: $T_{p,\text{cryst}}$ = exothermal crystallization peak temperature, T_{onset} = onset melting temperature, $T_{p,m}$ = endothermal melting peak temperature, ΔH_{cryst} = freezing enthalpy, and ΔH_{fus} = melting fusion enthalpy, respectively. Enthalpies were calculated as an integral area below thermograms and expressed as normalized enthalpy ($\text{J}\cdot\text{g}^{-1}$). Freezable water (i.e., freezable free and freezable bound water) content in PC was calculated (Equation 2) as the ratio of sample endothermic peak area (ΔH_s) to endothermic heat flow of pure water ($333.5\text{ J}\cdot\text{g}^{-1}$):

$$W_{f,s} (\%) = \frac{\Delta H_s}{\Delta H_{m,H_2O}} \times 100, \quad [2]$$

where $W_{f,s}$ is the freezable free and freezable bound water content, ΔH_s is the enthalpy of freezable water,

$\Delta H_{m,H_2O} = 333.5\text{ J}\cdot\text{g}^{-1}$ represents the melting enthalpy of pure water (Yudianti et al., 2009; Yang and Mather, 2022).

Mechanical Vibration Damping Properties

The ability of the studied cheese samples to dampen mechanical vibrations, and consequently their mechanical stiffness, was evaluated under harmonic dynamic loading using the displacement transmissibility T_d (-), which is defined for a linear single degree of freedom system by the following formula (Equation 3; Rao, 2005; Carrella et al., 2012):

$$T_d = \frac{X}{Y} = \frac{A_x}{A_y} = \frac{\sqrt{k^2 + (c\omega)^2}}{\sqrt{(k - m\omega^2)^2 + (c\omega)^2}} = \frac{\sqrt{1 + (2\zeta r)^2}}{\sqrt{(1 - r^2)^2 + (2\zeta r)^2}}, \quad [3]$$

where X (m) is the displacement amplitude on the output side of the investigated sample, Y (m) is the displacement amplitude on the input side of the investigated sample, A_x and A_y ($\text{m}\cdot\text{s}^{-2}$) are the acceleration amplitudes on the output and input sides of the investigated sample, k ($\text{N}\cdot\text{m}^{-1}$) is the sample stiffness, c ($\text{N}\cdot\text{s}\cdot\text{m}^{-1}$) is the viscous damping coefficient, ω ($\text{rad}\cdot\text{s}^{-1}$) is the angular velocity, m (kg) is the mass, ζ (-) is the damping ratio, and r (-) is the frequency ratio.

Mechanical vibrations can generally be classified into 3 types based on displacement transmissibility: damped ($T_d < 1$), undamped ($T_d = 1$), and resonance ($T_d > 1$) vibrations. By applying the condition $dT_d/d\zeta = 0$ in Equation 3, the displacement transmissibility T_d reaches a local extremum (i.e., its maximum value $T_{d,\text{max}}$ at the first resonance frequency f_{R1}), specifically at the frequency ratio r_0 (Rao, 2005):

$$r_0 = \frac{\sqrt{\sqrt{1 + 8\zeta^2} - 1}}{2\zeta}. \quad [4]$$

Equation 4 also shows that the frequency ratio r_0 generally decreases as the damping ratio ζ increases (or as the mechanical stiffness k decreases; Li et al., 2023).

Experimental measurements of the displacement transmissibility of the investigated cheese specimens were performed using the method of harmonically excited mechanical vibrations within the frequency range of 2 to 800 Hz. The measuring apparatus (Brüel & Kjær, Nærum, Denmark) consisted of a mini-shaker (BK 4810), a signal PULSE multi-analyzer (BK 3560-B-030), and a power amplifier (BK 2706). The displacement transmissibility

was determined from Equation 3 based on the measured acceleration amplitudes A_x and A_y , recorded using BK 4393 piezoelectric accelerometers (Brüel & Kjær, Nærum, Denmark). The tested block specimens measured 60 mm $\times$ 60 mm $\times$ 20 mm (length $\times$ width $\times$ thickness) and were loaded with an inertial mass of 90 g placed on the top surface of the harmonically loaded cheese samples. Each measurement was repeated 4 times ($n = 4$) under ambient conditions at a temperature of 23°C.

Sensory Analysis

The sensory evaluation of the PC samples was conducted with 16 trained assessors (9 women, 7 men, aged between 25 and 46 yr) in a sensory laboratory with sensory booths under standard lighting conditions and at a temperature of 20°C $\pm$ 2°C (ISO, 2007, 2012). Samples were served at a temperature of 6°C $\pm$ 2°C on white plates. The evaluation used a 5-point hedonic scale (1 = excellent; 3 = good; 5 = unacceptable) for the following attributes: appearance, consistency, spreadability, bitterness, and off-flavors. The overall evaluation of the PC samples was assessed using a 7-point hedonic scale (1 = extremely good; 7 = very bad).

Statistical Analysis

The collected data were analyzed to assess normality using the Shapiro–Wilk test (significance level: 0.05) using Minitab 16 software (Minitab Ltd., Coventry, UK). According to ISO 5479 (ISO, 1997), the Shapiro–Wilk test is recommended for evaluating the normality of small datasets. However, because normal distribution was not confirmed for all data ($P < 0.05$), the application of standard parametric tests was deemed inappropriate. The results were analyzed using nonparametrical ANOVA of Kruskal–Wallis and Wilcoxon tests (Minitab 16 software, Minitab Ltd., Coventry, UK).

RESULTS AND DISCUSSION

Proximate Analysis and Water Activity

The DM content of the model PC samples ranged from 40.48% to 41.23% (wt/wt) when potassium-based ES were used, and values ranging from 40.16% to 42.86% (wt/wt) were observed in PC samples with the addition of sodium-based ES. In all tested PC samples, no significant changes in DM content were observed ($P > 0.05$). The similarity in DM values is essential for ensuring the comparability of individual model samples, as this parameter significantly affects the textural properties of the analyzed samples (Weiserová et al., 2011; Nagyová et al., 2014; Salek et al., 2019).

The results of pH for the model samples are shown in Figure 1. The pH ranged from 5.57 $\pm$ 0.01 to 6.78

$\pm$ 0.01 for model PC samples with potassium-based ES and from 5.67 $\pm$ 0.01 to 6.53 $\pm$ 0.01 for samples with sodium-based ES. Overall, as the number of phosphorus atoms in the phosphate molecule of potassium-based ES increased, the pH values of the PC also increased ($P < 0.05$), except for KTPP and STPP. Furthermore, the samples containing KTPP exhibited the lowest pH values compared with all other samples ($P < 0.05$). In general, the PC samples presented significantly higher pH values ($P < 0.05$) compared with the reported optimal pH range (5.5–5.8) for spreadable PC (Šantová et al., 2024). Additionally, similar pH values were also observed in the studies of Hoffmann et al. (2012) and Mozuraityte et al. (2019). In particular, the latter phenomenon could primarily be attributed to the ES buffering capacity, or due to the fact that the samples were produced using “real” ingredients (Nagyová et al., 2014; Šantová et al., 2024). Furthermore, based on the obtained results, it can be clearly stated that, with increasing storage time, a slight decrease in pH values occurred in all tested PC samples, regardless of the type of ES used. A similar decreasing trend with respect to prolonging storage time was also observed in studies of Weiserová et al. (2011), Khetra et al. (2015), Salek et al. (2015), and Šantová et al. (2024). This trend could be primarily attributed to the potential hydrolysis of phosphate salts (containing 2 or more phosphorus atoms in the molecule), or the potential alteration of the bonds of the present salts, leading to a subsequent change in their degree of dissociation. A growing trend can also be observed in all PC samples, depending on the amount of ES used, with the pH parameter consistently increasing as the amount of ES in the sample increased. Based on all these facts, it can be concluded that the final pH is always dependent on the type of ES used (Guinee, 2011; Weiserová et al., 2011). In general, pH plays a critical role in determining the functional properties of PC by affecting protein interactions and the emulsification process. In particular, lower pH values reduce electrostatic repulsion and promote protein aggregation, resulting in firmer products. Conversely, higher pH values enhance casein solubilization and calcium chelation, leading to softer PC consistency. Therefore, pH control is essential for achieving desired functional and sensory characteristics in PC formulations (Awad et al., 2002; Sołowiej et al., 2016; Bulut-Solak and Akin, 2019).

Moreover, the tested PC samples showed no significant variations in a_w values ($P > 0.05$). The PC samples with the addition of potassium-based ES exhibited a_w values ranging from 0.972 $\pm$ 0.001 to 0.985 $\pm$ 0.001. In contrast, PC samples containing sodium-based ES presented pH values, ranging from 0.969 $\pm$ 0.001 to 0.986 $\pm$ 0.001. The a_w of all model PC samples remained relatively unaffected by storage time ($P > 0.05$). In general,

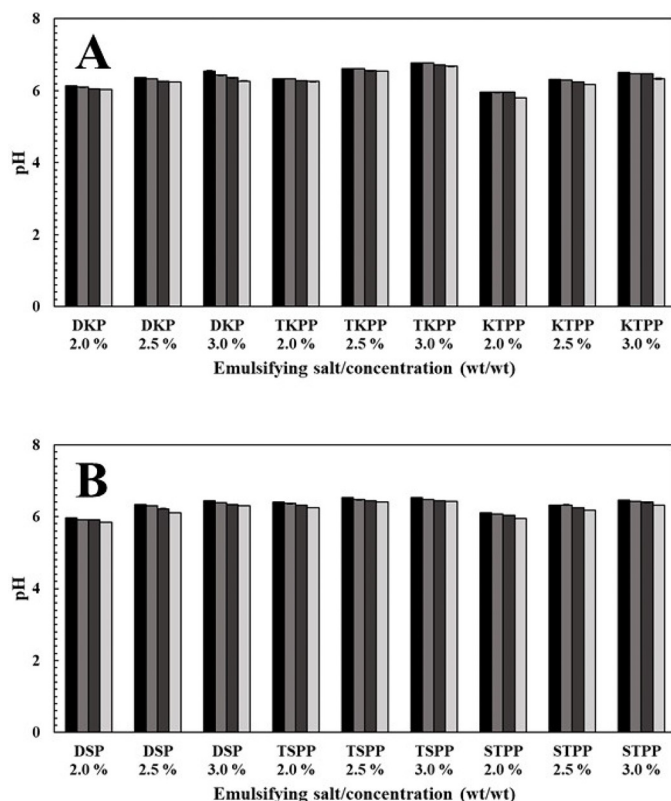


Figure 1. The development of processed cheese pH on the type of the applied potassium-based (dipotassium hydrogen phosphate [K_2HPO_4 , DKP; part A], tetrapotassium pyrophosphate [$K_4P_2O_7$, TKPP; part A], pentapotassium triphosphate [$K_5P_3O_{10}$, KTPP; part A]) and sodium-based (disodium hydrogen phosphate [Na_2HPO_4 , DSP; part B], tetrasodium pyrophosphate [$Na_4P_2O_7$, TSPP; part B], pentasodium triphosphate [$Na_5P_3O_{10}$, STPP; part B]) emulsifying salts and concentration (2.00%–3.00% wt/wt; with a concentration shift of 0.5) during a 60-d storage period at $6^\circ C \pm 2^\circ C$ ($n = 18$; the results were expressed as means [columns] and SD [bars]; processed cheeses were sampled after 1 [black], 14 [light gray], 30 [dark gray], 60 [silver] d of storage).

a_w is crucial in assessing the risk of microbial growth in food products, as a high-water content creates more favorable conditions for the development of molds and fungi, thereby influencing bacterial proliferation. A food product with a $pH > 4.6$ can be considered stable only if its a_w is 0.85 or lower. In the model PC samples, a $pH > 5.57$ and $a_w > 0.969$ were observed, which provides conditions for the growth of undesirable microorganisms. This risk becomes particularly significant if the product is not stored at refrigerated temperatures ($6^\circ C \pm 2^\circ C$; Szafrńska et al., 2020).

Viscoelastic Properties

The results of the viscoelastic properties for PC samples with different types of potassium-based and sodium-based ES (at concentrations of 2.0%–3.0% wt/wt, with a concentration shift of 0.5% wt/wt) are presented in Fig-

ures 2 and 3. In particular, the figures illustrate the dependence of the complex modulus (G^*) on the frequency (ranging from 0.01 to 100.00 Hz) for selected PC samples stored for 1, 14, 30, and 60 d (at $6^\circ C \pm 2^\circ C$). Based on the obtained results, it can be stated that the type of ES and concentration used significantly influenced the viscoelastic properties of the PC samples ($P < 0.05$). All PC samples, regardless of whether potassium- or sodium-based ES were used during manufacturing, exhibited an elastic behavior, as the elastic component predominated over the viscous one ($\tan \delta < 1$) across the entire frequency range (0.1–100.0 Hz). Additionally, the values of G^* modulus increased with frequency, indicating the typical behavior of a weak gel. This finding aligns with the conclusions of Ningtyas et al. (2017). In general, with an increasing number of phosphate units in sodium-based ES, the stiffness of the investigated samples increased, which aligns with the results obtained in the study of Nagyová et al. (2014). Furthermore, this trend was also confirmed for potassium-based ES, as well as in the study performed by Šantová et al. (2024). Additionally, as it was observed that with increasing concentrations of ES, regardless of the applied type of ES, there was a corresponding increase in the G^* values of the tested PC sample. This increasing trend can be explained by more intensive ion exchange within the PC sample, where calcium ions from the natural cheese matrix are exchanged for potassium or sodium ions from the ES during the melting process. As a result, a PC with a much denser final structure is formed, leading to higher stiffness. It is important to note that each ES type has a different intensity of ion exchange. Therefore, the appropriate selection of the type of ES can be considered a key factor in achieving a product with desired viscoelastic properties. Similar findings were reported by Salek et al. (2020), who attributed the differing results of stiffness between the PC samples to the varying quantities and types of ES used during the production of the PC. Another factor that may potentially influence the viscoelastic properties of PC is the possible hydrolysis of polyphosphates, which can result in higher G^* values, indicative of increased stiffness of the PC samples. The ratio between the viscous and elastic components in PC is significantly influenced not only by the degree of casein hydration and aggregation but also by the concentration of ES and the pH of the system. The pH value directly affects the chemical modifications occurring within the protein network of the cheese matrix, with higher pH levels promoting stronger protein–protein interactions. Similarly, increased levels of ES in PC formulations tend to produce a firmer cheese matrix and lower degree of casein hydration (Guinee et al., 2004; Agarwal et al., 2011). Furthermore, it was observed that the stiffness of all PC samples increased with increasing storage time. The PC samples with the addition of KTPP exhibited

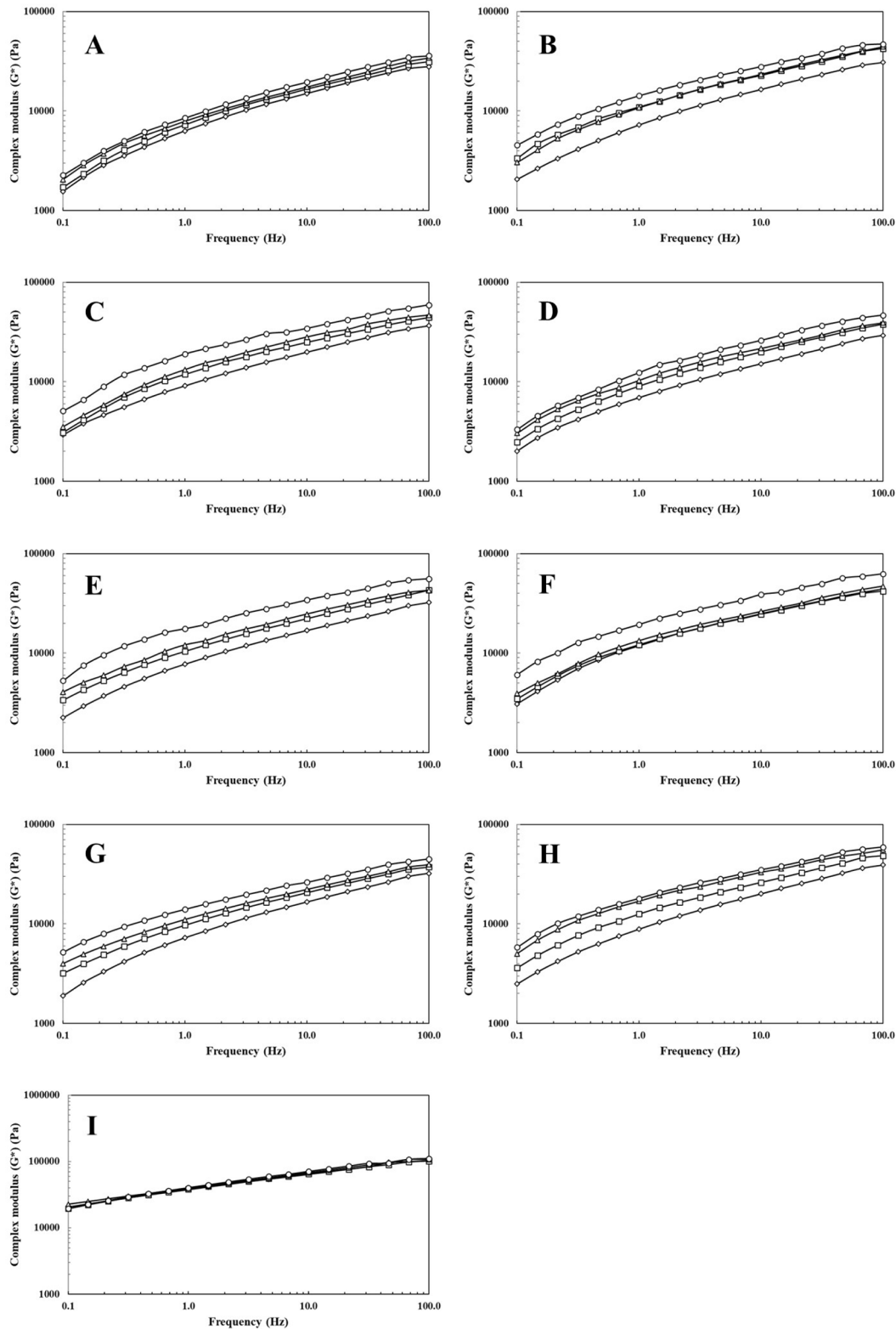


Figure 2. The dependence of complex modulus (G^*) of the processed cheese samples manufactured with different types of potassium-based emulsifying salts (dipotassium hydrogen phosphate [K_2HPO_4 , DKP; parts A–C], tetrapotassium pyrophosphate [$K_4P_2O_7$, TKPP; parts D–F], pentapotassium triphosphate [$K_5P_3O_{10}$, KTPP; parts G–I]) with various concentrations of emulsifying salts (2.00%–3.00% wt/wt; with a concentration shift of 0.5), on the frequency (in the range of 0.1–100.0 Hz) after 1 d (rhombus), 14 d (square), 30 d (triangle), and 60 d (circle) of storage ($6^\circ C \pm 1^\circ C$; $n = 18$).

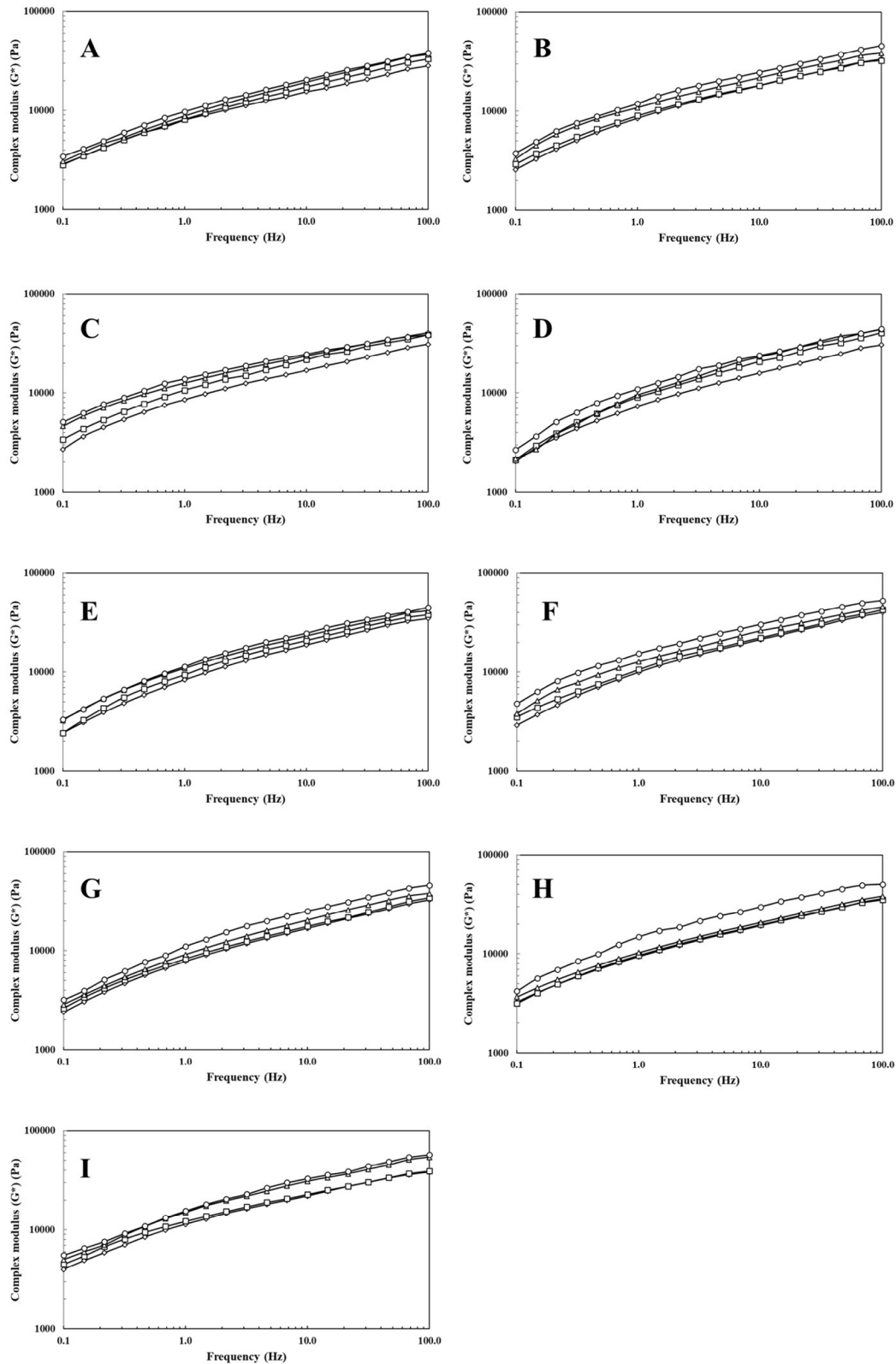


Figure 3. The dependence of complex modulus (G^*) of the processed cheese samples manufactured with different types of sodium-based emulsifying salts (disodium hydrogen phosphate [Na_2HPO_4 , DSP; parts A–C], tetrasodium pyrophosphate [$\text{Na}_4\text{P}_2\text{O}_7$, TSPP; parts D–F], pentasodium triphosphate [$\text{Na}_5\text{P}_3\text{O}_{10}$, STPP; parts G–I]) with various concentrations of emulsifying salts (2.00%–3.00% wt/wt; with a concentration shift of 0.5), on the frequency (range of 0.1–100.0 Hz) after 1 d (rhombus), 14 d (square), 30 d (triangle), and 60 d (circle) of storage ($6^\circ\text{C} \pm 1^\circ\text{C}$; $n = 18$).

Table 2. Values of $\tan \delta$ (tangent of the phase angle) at the frequencies of 0.1, 1.0, 10.0, and 100.0 Hz in processed cheese samples with the addition of potassium- and sodium-based emulsifying salts at various concentrations during a 60-d storage period ($6^{\circ}\text{C} \pm 2^{\circ}\text{C}$)

Sample ¹	Concentration (% wt/wt)	Parameter (Hz)			
		0.1	1.0	10.0	100.0
Time (d) 1					
DKP	2.0	1.2 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	1.3 ± 0.1 ^{a,A}	0.8 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.3 ± 0.1 ^{a,B}
	3.0	0.8 ± 0.1 ^{b,A}	0.5 ± 0.1 ^{a,A}	0.4 ± 0.1 ^{a,A}	0.4 ± 0.1 ^{a,A}
TKPP	2.0	1.2 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	1.1 ± 0.1 ^{a,A}	0.9 ± 0.1 ^{a,B}	0.6 ± 0.1 ^{a,C}	0.4 ± 0.1 ^{a,C}
	3.0	0.9 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
KTPP	2.0	0.7 ± 0.1 ^{a,A}	0.4 ± 0.1 ^{a,B}	0.3 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	0.9 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	1.0 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
DSP	2.0	1.1 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}
	2.5	0.9 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	0.8 ± 0.1 ^{a,A}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
TSPP	2.0	1.1 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}
	2.5	1.1 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}
	3.0	1.2 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}
STPP	2.0	0.8 ± 0.1 ^{a,A}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	1.1 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	1.1 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
Time (d) 14					
DKP	2.0	0.8 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	1.1 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	1.1 ± 0.1 ^{a,B}	0.6 ± 0.1 ^{a,A}	0.5 ± 0.1 ^{a,A}	0.4 ± 0.1 ^{a,A}
TKPP	2.0	1.0 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	1.1 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,C}	0.5 ± 0.1 ^{a,C}	0.4 ± 0.1 ^{a,C}
	3.0	1.0 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.3 ± 0.1 ^{a,B}
KTPP	2.0	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.3 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	1.3 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.2 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	1.3 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
DSP	2.0	1.1 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	0.9 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	0.9 ± 0.1 ^{a,A}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
TSPP	2.0	1.3 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	1.1 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	1.2 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
STPP	2.0	1.3 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}
	2.5	1.1 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}
	3.0	1.2 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
Time (d) 30					
DKP	2.0	1.2 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.2 ^{a,B}
	2.5	1.0 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	1.0 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
TKPP	2.0	0.9 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}
	2.5	1.2 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	1.0 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
KTPP	2.0	0.4 ± 0.1 ^{a,A}	0.3 ± 0.1 ^{a,A}	0.3 ± 0.1 ^{a,A}	0.4 ± 0.1 ^{a,A}
	2.5	1.0 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	0.7 ± 0.1 ^{a,A}	0.5 ± 0.1 ^{a,A}	0.4 ± 0.1 ^{a,A}	0.4 ± 0.1 ^{a,A}
DSP	2.0	0.9 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	0.9 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	0.9 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
TSPP	2.0	1.1 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	1.3 ± 0.1 ^{a,A}	0.8 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	1.2 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
STPP	2.0	0.7 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,A}	0.4 ± 0.1 ^{a,A}	0.5 ± 0.1 ^{a,A}
	2.5	1.1 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	0.9 ± 0.1 ^{a,A}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}

Continued

Table 2 (Continued). Values of $\tan \delta$ (tangent of the phase angle) at the frequencies of 0.1, 1.0, 10.0, and 100.0 Hz in processed cheese samples with the addition of potassium- and sodium-based emulsifying salts at various concentrations during a 60-d storage period ($6^\circ\text{C} \pm 2^\circ\text{C}$)

Sample ¹	Concentration (% wt/wt)	Parameter (Hz)			
		0.1	1.0	10.0	100.0
Time (d) 60					
DKP	2.0	0.9 ± 0.1 ^{a,B}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	1.1 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}
	3.0	1.0 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
TKPP	2.0	1.3 ± 0.1 ^{a,A}	0.8 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	1.0 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	0.9 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
KTPP	2.0	0.7 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,A}	0.3 ± 0.1 ^{a,A}	0.4 ± 0.1 ^{a,A}
	2.5	1.5 ± 0.1 ^{a,C}	0.9 ± 0.1 ^{a,A}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	1.3 ± 0.1 ^{a,B}	0.7 ± 0.3 ^{a,A}	0.5 ± 0.1 ^{a,A}	0.4 ± 0.1 ^{a,A}
DSP	2.0	0.9 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.2 ± 0.1 ^{a,B}	0.3 ± 0.1 ^{a,B}
	2.5	0.9 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	0.9 ± 0.1 ^{a,A}	0.6 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.3 ± 0.1 ^{a,B}
TSPP	2.0	1.3 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	2.5	1.4 ± 0.1 ^{a,A}	0.8 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	1.3 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
STPP	2.0	1.2 ± 0.1 ^{a,B}	0.7 ± 0.1 ^{a,A}	0.5 ± 0.1 ^{a,A}	0.4 ± 0.1 ^{a,A}
	2.5	1.1 ± 0.1 ^{a,A}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}
	3.0	1.2 ± 0.1 ^{a,C}	0.7 ± 0.1 ^{a,B}	0.5 ± 0.1 ^{a,B}	0.4 ± 0.1 ^{a,B}

^aMeans within a column do not differ significantly ($P < 0.05$).^{A-C}Mean values within a row followed by different uppercase superscripts differ significantly ($P < 0.05$).¹Emulsifying salts used: DKP, K_2HPO_4 = dipotassium hydrogen phosphate; TKPP, $\text{K}_4\text{P}_2\text{O}_7$ = tetrapotassium pyrophosphate; KTPP, $\text{K}_5\text{P}_3\text{O}_{10}$ = pentapotassium triphosphate; DSP, Na_2HPO_4 = disodium hydrogen phosphate; TSPP, $\text{Na}_4\text{P}_2\text{O}_7$ = tetrasodium pyrophosphate; STPP, $\text{Na}_5\text{P}_3\text{O}_{10}$ = pentasodium triphosphate.

the highest G^* value during the 60-d storage period ($P < 0.05$). These higher G^* values can be explained not only by more intensive ion exchange but also by stronger interactions within the PC samples, such as hydrogen or disulfide bridges, calcium bridges, hydrophobic interactions, or electrostatic interactions. These interactions play a crucial role in developing a “denser” final PC structure, thereby enhancing the product’s stiffness.

Moreover, the $\tan \delta$ values exhibited a proportional decrease throughout the storage period across the tested frequency range (Table 2), from 0.1 to 100.0 Hz ($\tan \delta < 1$), further validating that the behavior of the PC resembled that of an elastic gel ($P < 0.05$). Our results are consistent with findings of Weiserová et al. (2011), Salek et al. (2016), and Šantová et al. (2024). The stiffness of PC samples exhibits a similar relationship to hardness of TPA; the higher the hardness of the sample, the more rigid the final product is expected to be (Salek et al., 2016).

Texture Profile Analysis

Figure 4 shows the development of hardness of the PC samples manufactured with different types of ES (potassium- and sodium-based ES) at concentrations of 2.0% to 3.0% (wt/wt), with a concentration shift of 0.5% (wt/wt) during a 60-d storage period (at $6^\circ\text{C} \pm 2^\circ\text{C}$). The results

of the hardness of the analyzed samples exhibited a similar trend to that previously reported for the rheological analysis.

Based on the obtained results, it can be inferred that both the type and concentration of the used ES had a significant impact on the hardness of the examined PC samples ($P < 0.05$). In terms of the application of individual potassium-based ES, the samples prepared with KTPP exhibited the highest hardness ($P < 0.05$). Each type of ES significantly influenced the hardness of the PC, with the hardness of all PC samples consistently increasing with the length of the applied phosphate ES chain in the following order: DKP(DSP) < TKPP(TSPP) < KTPP(STPP) ($P < 0.05$). The ongoing decomposition reactions (hydrolysis) of polyphosphate ES, which lead to the formation of primary phosphates during storage, have a direct impact on textural properties. Hydrolysis of the ES occurs over time and involves gradual changes in the structure due to small variations in pH values (Shirashoji et al., 2010; Weiserová et al., 2011; Nagyová et al., 2014; Bulut-Solak and Akin, 2019). As a result of hydrolysis, phosphates contain progressively fewer phosphate groups, which initially exhibited a high affinity for calcium ions. The reduction of these groups leads to a decrease in this affinity, ultimately causing the spontaneous release of calcium ions from the ES and their gradual incorporation into the protein network. Consequently, this process contrib-

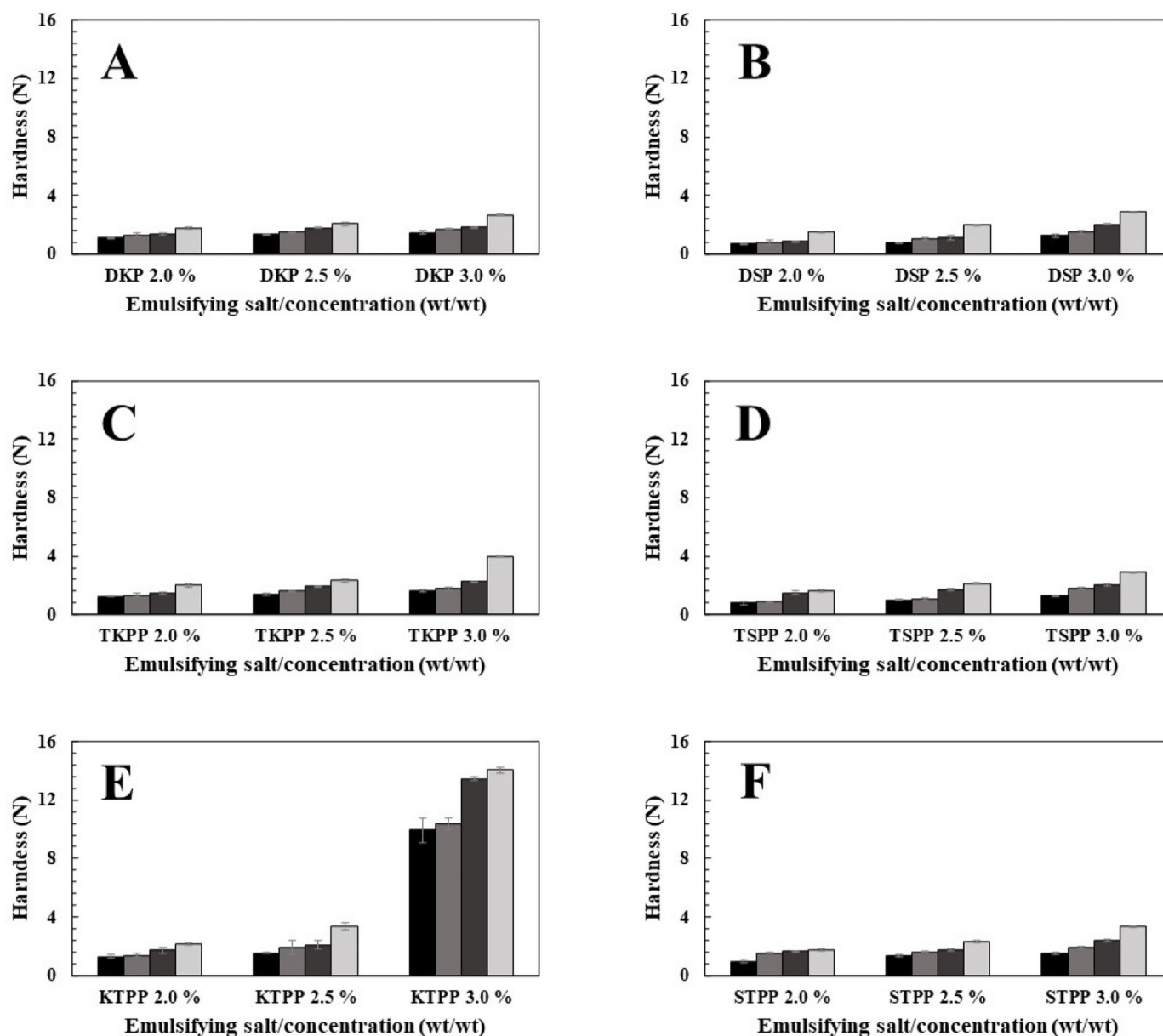


Figure 4. The development of processed cheese hardness (N) on the type of the applied potassium-based (dipotassium hydrogen phosphate [K_2HPO_4 , DKP, part A], tetrapotassium pyrophosphate [$K_4P_2O_7$, TKPP, part C], pentapotassium triphosphate [$K_5P_3O_{10}$, KTPP, part E]) and sodium-based (disodium hydrogen phosphate [Na_2HPO_4 , DSP; part B], tetrasodium pyrophosphate [$Na_4P_2O_7$, TSPP; part D], pentasodium triphosphate [$Na_5P_3O_{10}$, STPP; part F]) emulsifying salts and concentration (2.00%–3.00% wt/wt; with a concentration shift of 0.5) during a 60-d storage period at $6^\circ C \pm 2^\circ C$ ($n = 18$; the results were expressed as means [columns] and SD [bars]; processed cheeses were sampled after 1 [black], 14 [light gray], 30 [dark gray], and 60 [silver] d of storage).

utes to the increasing hardness of the final product during storage (Mulsow et al., 2007). In general, as the length of the sodium-based phosphate ES chains increases, the ability for ion exchange probably also increases, leading to a more intense dispersion of casein fractions. As the processes of protein hydration and fat emulsification progress, the intensity of interactions within the melt also increases, thus intensifying the cross-linking of caseins.

Therefore, the higher the degree of cross-linking within the product matrix, the firmer the PC can be expected to be. The hardness of the samples increases with the addition of salts in the following order: monophosphates < diphosphates < triphosphates < polyphosphates (Mizuno and Lucey, 2005). The same trend was observed by Weiserová et al. (2011), Nagyová et al. (2014), and Salek et al. (2015, 2016, 2019), but using only sodium-based ES.

Table 3. Values of lightness (L^*), chromaticity coordinates (a^* , b^*), hue (h), chroma (C^*), and whiteness index in processed cheese samples with the addition of potassium- and sodium-based emulsifying salts at various concentrations

Sample ¹	Concentration (% wt/wt)	L^*	a^*	b^*	h (°)	C^*	WI
DKP	2.0	92.12 ± 1.10 ^a	0.29 ± 0.09 ^a	15.02 ± 0.71 ^a	88.88 ± 0.30 ^a	15.03 ± 0.71 ^a	82.90 ± 1.09 ^a
	2.5	91.92 ± 0.52 ^a	0.38 ± 0.09 ^a	14.88 ± 0.24 ^a	88.52 ± 0.33 ^a	14.89 ± 0.24 ^a	83.07 ± 0.52 ^a
	3.0	91.84 ± 0.57 ^a	0.33 ± 0.90 ^a	14.46 ± 0.69 ^a	88.71 ± 0.29 ^a	14.46 ± 0.69 ^a	83.53 ± 0.57 ^a
TKPP	2.0	91.62 ± 0.48 ^a	0.28 ± 0.01 ^a	13.91 ± 0.40 ^a	88.86 ± 0.08 ^a	13.92 ± 0.40 ^a	83.76 ± 0.48 ^a
	2.5	92.27 ± 0.74 ^a	0.37 ± 0.12 ^a	13.92 ± 0.18 ^a	88.48 ± 0.45 ^a	13.92 ± 0.18 ^a	84.08 ± 0.74 ^a
	3.0	92.07 ± 0.03 ^a	0.28 ± 0.02 ^a	13.22 ± 0.13 ^a	88.77 ± 0.05 ^a	13.23 ± 0.13 ^a	84.58 ± 0.03 ^a
KTPP	2.0	91.33 ± 0.30 ^a	0.36 ± 0.05 ^a	13.83 ± 0.08 ^a	88.52 ± 0.21 ^a	13.83 ± 0.08 ^a	83.68 ± 0.30 ^a
	2.5	92.06 ± 0.14 ^a	0.26 ± 0.03 ^a	13.73 ± 0.14 ^a	88.90 ± 0.11 ^a	13.74 ± 0.14 ^a	84.13 ± 0.14 ^a
	3.0	92.01 ± 0.14 ^a	0.18 ± 0.03 ^a	13.28 ± 0.12 ^a	89.21 ± 0.14 ^a	13.28 ± 0.12 ^a	84.51 ± 0.14 ^a
DSP	2.0	90.89 ± 0.12 ^a	0.19 ± 0.03 ^a	14.62 ± 0.13 ^a	89.24 ± 0.11 ^a	14.62 ± 0.13 ^a	82.77 ± 0.11 ^a
	2.5	91.09 ± 0.16 ^a	0.16 ± 0.02 ^a	14.36 ± 0.14 ^a	89.35 ± 0.08 ^a	14.36 ± 0.14 ^a	83.10 ± 0.16 ^a
	3.0	90.76 ± 0.42 ^a	0.21 ± 0.11 ^a	15.45 ± 0.81 ^a	89.21 ± 0.35 ^a	15.46 ± 0.81 ^a	81.99 ± 0.41 ^a
TSPP	2.0	91.11 ± 0.12 ^a	0.26 ± 0.02 ^a	14.46 ± 0.22 ^a	88.98 ± 0.08 ^a	14.46 ± 0.22 ^a	83.02 ± 0.12 ^a
	2.5	91.44 ± 0.17 ^a	0.27 ± 0.01 ^a	14.20 ± 0.04 ^a	88.90 ± 0.02 ^a	14.20 ± 0.04 ^a	83.42 ± 0.17 ^a
	3.0	91.65 ± 0.09 ^a	0.11 ± 0.02 ^b	13.76 ± 0.19 ^a	89.53 ± 0.09 ^a	13.76 ± 0.19 ^a	83.90 ± 0.09 ^a
STPP	2.0	91.50 ± 0.01 ^a	0.14 ± 0.02 ^b	13.86 ± 0.08 ^a	89.42 ± 0.07 ^a	13.86 ± 0.08 ^a	83.74 ± 0.01 ^a
	2.5	91.23 ± 0.92 ^a	0.21 ± 0.10 ^a	14.39 ± 0.60 ^a	89.18 ± 0.35 ^a	14.39 ± 0.60 ^a	83.15 ± 0.92 ^a
	3.0	91.80 ± 1.14 ^a	0.20 ± 0.09 ^a	14.78 ± 0.71 ^a	89.24 ± 0.31 ^a	14.78 ± 0.71 ^a	83.10 ± 1.14 ^a

^{a,b}Mean values within a column followed by different superscripts differ significantly ($P < 0.05$).

¹Emulsifying salts used: DKP, K_2HPO_4 = dipotassium hydrogen phosphate; TKPP, $K_4P_2O_7$ = tetrapotassium pyrophosphate; KTPP, $K_5P_3O_{10}$ = pentapotassium triphosphate; DSP, Na_2HPO_4 = disodium hydrogen phosphate; TSPP, $Na_4P_2O_7$ = tetrasodium pyrophosphate; STPP, $Na_5P_3O_{10}$ = pentasodium triphosphate. L^* = luminosity (0 for black, 100 for white); a^* = chromaticity on a green (negative values) to red/magenta (positive values) axis; b^* = chromaticity on a blue (negative values) to yellow (positive values) axis; chroma (C^*), represents color saturation (i.e., the proportions in which the color is mixed with white, black, or gray); h (°) = the hue angle, expressed in degrees, with 0° being a location on the + a^* axis, then continuing to 90° for the + b^* axis, 180° for - a^* , 270° for - b^* , and 360° = 0°; WI = whiteness index.

In our study, this trend was also confirmed for the group of potassium-based ES. Additionally, the hardness of all examined samples increased with the rising of the storage period ($P < 0.05$). For all model samples of PC, the lowest hardness values were observed on d 1 of storage, with a gradual increase in hardness as the storage period extended up to 60 d ($P < 0.05$). The highest hardness value was recorded for the sample with KTPP addition on d 60 (14.07 N; $P < 0.05$), whereas the lowest value (0.72 N) was observed for the sample with DSP on d 1 ($P < 0.05$). The significantly lower hardness values observed for sodium-based ES compared with potassium-based ES can be attributed to the reduced ion-exchange activity, which is related to pH changes in the melt. When the pH deviates bidirectionally from the optimal pH range (5.5–5.8), the ion-exchange capacity decreases, leading to a reduction in the dispersion intensity of caseins in the melt and, consequently, a decline in the hardness values of PC samples. Therefore, achieving the optimal pH of the melt is crucial for ensuring proper textural properties of PC (Mizuno and Lucey, 2007; Nagyová et al., 2014; Šantová et al., 2024).

Instrumental Color Analysis

The results of the PC instrumental analysis of color are shown in Table 3. The L^* values for the PC samples with the addition of potassium-based ES ranged from 91.33 ± 0.30 to 92.27 ± 0.74, whereas those with sodium-based ES

ranged from 90.76 ± 0.42 to 91.80 ± 1.14. The L^* results for all PC samples were close to 100, indicating products with high lightness (Figures 5 and 6). All PC samples, regardless of the type of applied ES, can be characterized as light yellow with a slight red tint (positive a^* values indicated a red hue, and positive b^* values indicated a yellow hue). A similar conclusion was also drawn by Šantová et al. (2024) and Kůrová et al. (2022) in their studies. The weakest red tone was observed in the PC samples with the addition of 3.0% (wt/wt) KTPP (0.18) and with the addition of 3.0% (wt/wt) TSPP (0.11). In general, the application of ES with a longer phosphate chain results in a reduction of the yellow tone in the PC samples. This was confirmed in our study for all types of applied ES. The type and concentration of potassium- and sodium-based ES used had no significant effect ($P > 0.05$) on the PC color. The color and appearance of food play a significant role in shaping consumers' expectations, which in turn influence their preferences and ability to identify the food. Therefore, it is important for products to have the expected color, as consumers associate certain colors with specific flavors (Kůrová et al., 2022; Šantová et al., 2024).

Potassium, Sodium, Calcium, and Magnesium Content

The detection of elements (potassium, sodium, calcium, magnesium) in PC with the addition of potassium-

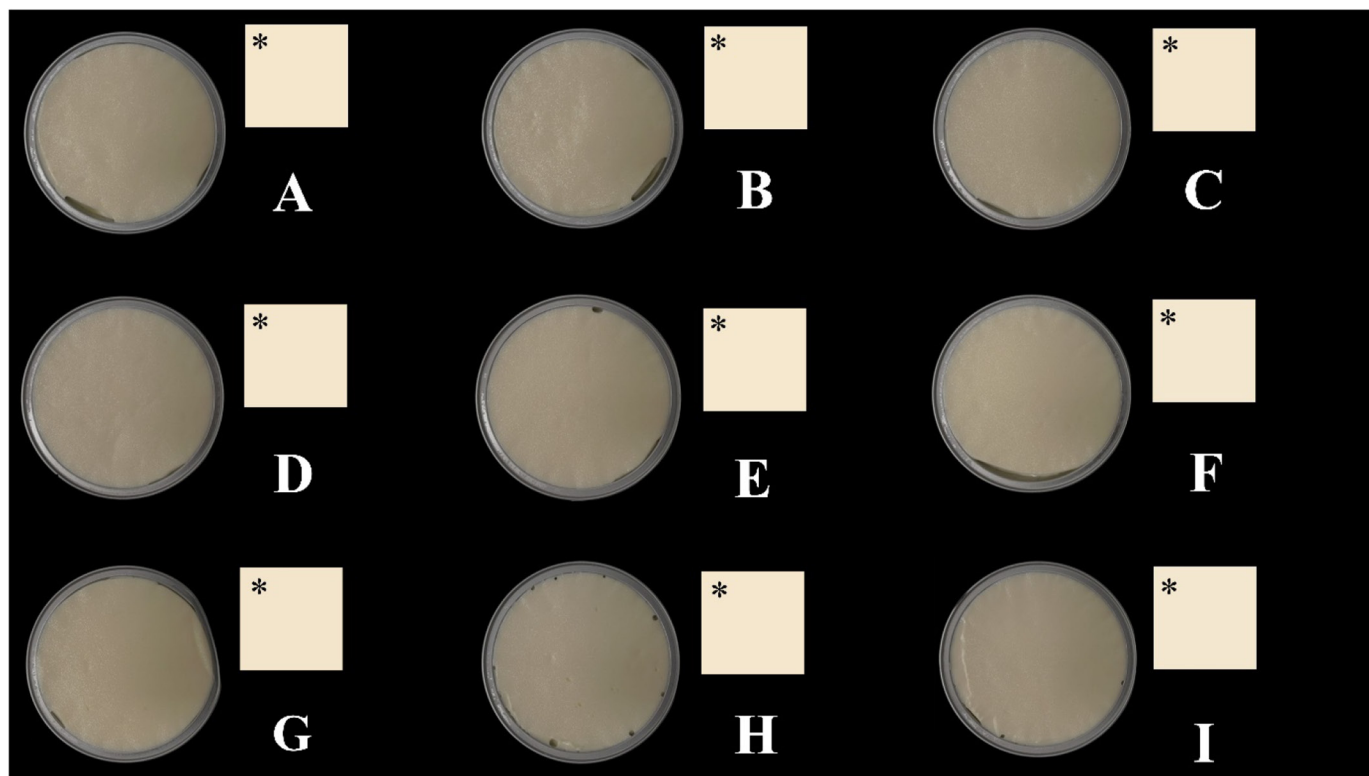


Figure 5. Images of the processed cheese samples manufactured with different types of potassium-based emulsifying salts (dipotassium hydrogen phosphate [K_2HPO_4 , DKP; parts A–C], tetrapotassium pyrophosphate [$\text{K}_4\text{P}_2\text{O}_7$, TKPP; parts D–F], pentapotassium triphosphate [$\text{K}_5\text{P}_3\text{O}_{10}$, KTPP; parts G–I]) with various concentrations of emulsifying salts (2.00%–3.00% wt/wt; with a concentration shift of 0.5) after 30 d of storage ($6^\circ\text{C} \pm 2^\circ\text{C}$). The squares with an asterisk represent the mean color (RGB space) of each processed cheese sample.

based ES was carried out by flame atomic emission spectrometry. The results are shown in Table 4. The PC sample containing TKPP generally reported the highest sodium content (particularly the 2.0% wt/wt sample: $9,087.0 \pm 53.5 \text{ mg}\cdot\text{kg}^{-1}$) among all PC samples prepared with potassium-based ES. In contrast, the greatest reduction in sodium content, resulting from the use of potassium-based ES (Na: $4,495.1 \pm 17.8 \text{ mg}\cdot\text{kg}^{-1}$; K: $20,603.5 \pm 28.3 \text{ mg}\cdot\text{kg}^{-1}$), was observed in the PC sample with 2.0% (wt/wt) DKP addition, without any negative impact on the viscoelastic or sensory properties of the product. This sample also showed the highest potassium level among all PC samples with the addition of potassium-based ES. This pronounced reduction in sodium content in the PC sample can also be confirmed by comparison with the samples prepared using the corresponding sodium-based ES, in which the sodium content in the final product was significantly higher (Na: $16,214.7 \pm 602.9 \text{ mg}\cdot\text{kg}^{-1}$; $P < 0.05$).

The relationship between ES type, concentration, and mineral composition in PC is evident from the results. Potassium-based ES significantly increased potassium content ($P < 0.05$) while reducing sodium levels ($P <$

0.05) compared with sodium-based ES, confirming their potential for sodium reduction strategies. Moreover, as ES concentration increased from 2.0% to 3.0% (wt/wt), potassium levels increased markedly, whereas calcium content remained moderate ($6,096.0$ – $7,520.0 \text{ mg}\cdot\text{kg}^{-1}$; $P < 0.05$), indicating partial calcium sequestration. In particular, DKP promoted greater calcium removal, probably enhancing protein solubilization and resulting in softer PC consistencies, whereas KTPP and TKPP maintained higher residual calcium, leading to firmer PC samples. However, sodium-based ES (DSP, TSPP, STPP) exhibited the highest sodium concentrations and calcium levels in the range of $7,316.0$ to $8,324 \text{ mg}\cdot\text{kg}^{-1}$, suggesting less intensive calcium sequestration and possible stronger protein cross-linking, which could explain the samples increased firmness (Deshwal et al., 2023). These findings confirm that ES type and concentration govern mineral balance and calcium chelation efficiency, thus influencing emulsification, water binding, and textural properties of PC.

Reducing the sodium content in PC represents a major challenge for the dairy industry. In PC, sodium can be introduced from various sources—sodium-based ES (ac-

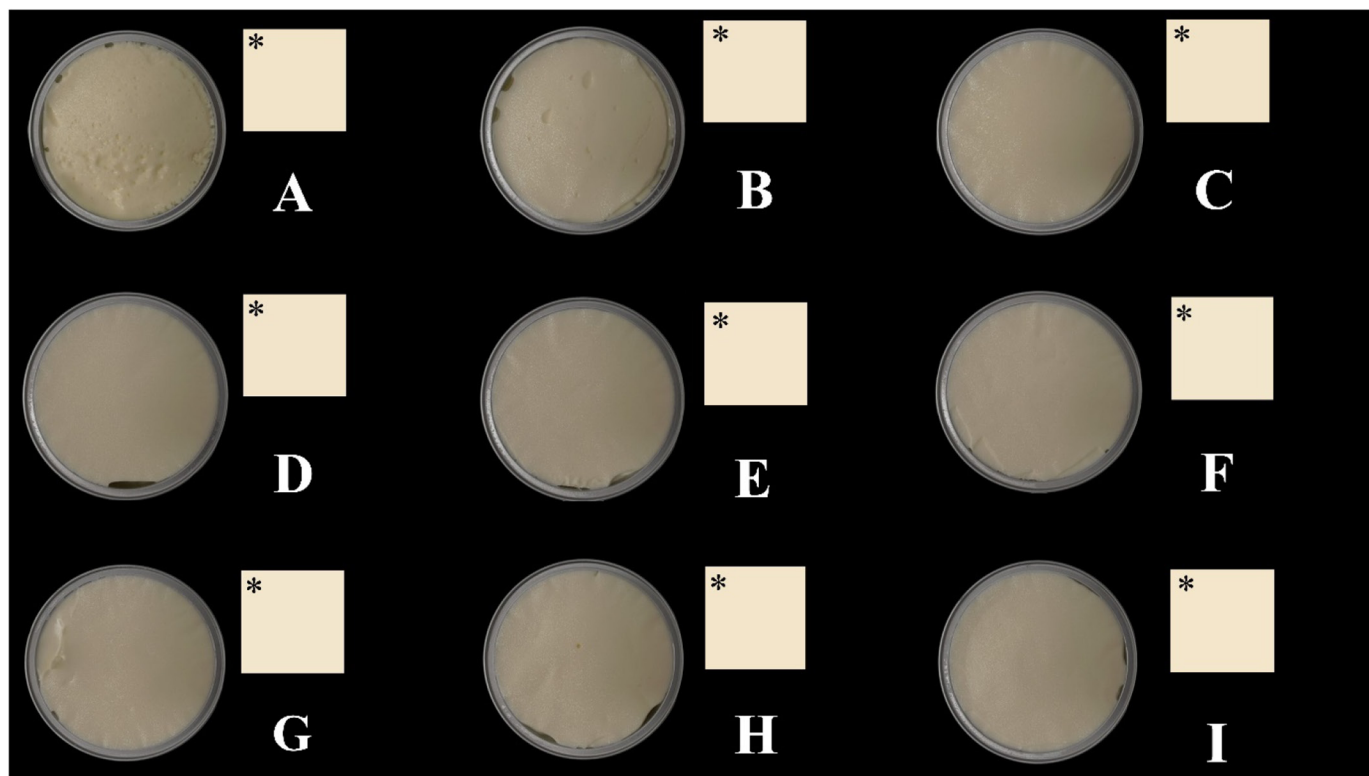


Figure 6. Images of the processed cheese samples manufactured with different types of sodium-based emulsifying salts (disodium hydrogen phosphate [Na_2HPO_4 , DSP; parts A–C], tetrasodium pyrophosphate [$\text{Na}_4\text{P}_2\text{O}_7$, TSPP; parts D–F], pentasodium triphosphate [$\text{Na}_5\text{P}_3\text{O}_{10}$, STPP; parts G–I]) with various concentrations of emulsifying salts (2.00%–3.00% wt/wt; with a concentration shift of 0.5) after 30 d of storage ($6^\circ\text{C} \pm 2^\circ\text{C}$). The squares with an asterisk represent the mean color (RGB space) of each processed cheese sample.

counting for 30%–48% wt/wt), natural cheese (25%–37% wt/wt), and added NaCl (15%–35% wt/wt; Johnson et al., 2009; Kommineni et al., 2010). Several approaches have been proposed to reduce the sodium content in PC, such as the use of natural cheeses with reduced sodium content, potassium-based ES, or other salt replacers and flavor enhancers (Gupta and Reuter, 1993; Kapoor and Metzger, 2008; Johnson et al., 2009). Kommineni et al. (2010) produced PC with varying fat and sodium contents and conducted triangle tests along with functional analyses to compare the samples. The PC with a 50% sodium reduction exhibited functional properties comparable to those of the regular sodium controls.

The typical sodium content for PC can vary according to the manufacturer and label claims, but in general the average content is $\sim 14,880 \text{ mg}\cdot\text{kg}^{-1}$ (Agarwal et al., 2011). From the results obtained, it can be stated that a reduction of sodium content in the developed PC products occurred ($P < 0.05$). In the study of Agarwal et al. (2011), the sodium content in PC from various manufacturers was investigated, revealing a range from 7,500 to $15,200 \text{ mg}\cdot\text{kg}^{-1}$. Moreover, Johnson et al. (2009) further reported that the sodium content in reduced-sodium

PC may range from 4,800 to $12,000 \text{ mg}\cdot\text{kg}^{-1}$. In their study, DKP was used as the ES at a concentration of 2.2% (wt/wt), resulting in a final PC containing $6,140 \text{ mg}\cdot\text{kg}^{-1}$ of sodium. In our study, a similar range for reduced-sodium PC was reported, as the samples with potassium-based ES contained sodium in the range of 7,801 to $9,087.0 \text{ mg}\cdot\text{kg}^{-1}$ ($P < 0.05$).

Differential Scanning Calorimetry

Using DSC measurement, freezable water was classified as free and bound water based on melting peak of PC (Yang and Mather, 2022). As evident from Table 5, fluctuated values of melting enthalpy change (ΔH_{fus}) and onset melting temperature (T_{onset}) were determined in dependence of ES concentration. It can be assumed that ES type as well as concentration in PC can affect formation of protein aggregates and fat clusters (Felix da Silva et al., 2021), and thus influence thermal parameters of the samples. In general, obvious shift of T_{onset} to lower temperatures with increasing ES content was observed. In the whole concentration region, 3.0% (wt/wt) salt content provided the most distinguished thermal behavior in

Table 4. Summary of macromineral (sodium, potassium, magnesium, and calcium) values in processed cheese with the addition of different types and concentrations of potassium- and sodium-based emulsifying salts after 30 d of storage ($6^{\circ}\text{C} \pm 1^{\circ}\text{C}$; results were expressed as mean $\pm$ SD; $n = 18$)

Sample ¹	Concentration (% wt/wt)	Na content ($\text{mg}\cdot\text{kg}^{-1}$)	K content ($\text{mg}\cdot\text{kg}^{-1}$)	Mg content ($\text{mg}\cdot\text{kg}^{-1}$)	Ca content ($\text{mg}\cdot\text{kg}^{-1}$)
DKP	2.0	$8,495.1 \pm 17.8^a$	$20,603.5 \pm 28.3^a$	472.1 ± 5.8^a	$6,861.4 \pm 30.3^a$
	2.5	$8,568.7 \pm 44.1^a$	$19,640 \pm 46.7^b$	398.0 ± 14.4^b	$6,096.0 \pm 104.9^b$
	3.0	$7,801.0 \pm 198.7^a$	$22,199.3 \pm 321.3^c$	478.0 ± 21.7^a	$6,447.0 \pm 249.7^b$
TKPP	2.0	$9,087.0 \pm 53.5^a$	$21,899.4 \pm 206.1^d$	402.1 ± 7.7^c	$7,066.5 \pm 39.7^c$
	2.5	$8,884.7 \pm 93.8^a$	$29,340.3 \pm 293.5^e$	412.7 ± 8.1^c	$7,091.0 \pm 79.8^c$
	3.0	$8,875.0 \pm 289.8^a$	$29,560.3 \pm 1,081.8^e$	341.0 ± 13.5^d	$6,222.0 \pm 76.7^b$
KTPP	2.0	$8,869.0 \pm 244.3^a$	$19,551.0 \pm 882.5^b$	415.8 ± 7.7^c	$7,189.6 \pm 235.4^c$
	2.5	$8,830.3 \pm 12.5^a$	$24,687.0 \pm 241.3^f$	391.3 ± 2.2^b	$6,624.0 \pm 199.3^b$
	3.0	$8,986.7 \pm 59.4^a$	$29,737.0 \pm 326.4^c$	428.3 ± 12.8^c	$7,520.0 \pm 78.8^c$
DSP	2.0	$16,214.7 \pm 602.9^c$	860.0 ± 45.1^h	435.7 ± 14.9^c	$7,785.7 \pm 280.3^c$
	2.5	$20,214.3 \pm 1,497.3^f$	$1,106.0 \pm 256.4^i$	457.0 ± 52.7^c	$8,324.3 \pm 653.4^d$
	3.0	$22,005.0 \pm 632.1^g$	$1,001.0 \pm 57.4^i$	472.0 ± 15.6^c	$8,293.7 \pm 183.2^d$
TSPP	2.0	$15,255.3 \pm 72.7^h$	793.0 ± 29.4^j	387.0 ± 17.6^b	$7,764.7 \pm 190.0^c$
	2.5	$17,571.0 \pm 20.7^i$	772.3 ± 49.5^j	367.3 ± 1.4^b	$7,318.7 \pm 63.4^c$
	3.0	$19,671.7 \pm 185.4^j$	860.0 ± 13.1^h	392.7 ± 20.1^b	$7,856.0 \pm 305.0^c$
STPP	2.0	$16,254.7 \pm 108.4^k$	$1,444.0 \pm 285.3^i$	457.3 ± 74.7^b	$7,578.3 \pm 91.4^c$
	2.5	$17,537.0 \pm 143.7^i$	772.3 ± 41.1^j	425.7 ± 1.2^b	$6,845.7 \pm 69.1^a$
	3.0	$21,401.0 \pm 931.6^f$	$1,694.0 \pm 58.9^j$	414.3 ± 25.7^b	$7,316.0 \pm 175.6^c$

^{a-k}Mean values within a column followed by different superscripts differ significantly ($P < 0.05$).

¹Emulsifying salts used: DKP, K_2HPO_4 = dipotassium hydrogen phosphate; TKPP, $\text{K}_4\text{P}_2\text{O}_7$ = tetrapotassium pyrophosphate; KTPP, $\text{K}_5\text{P}_3\text{O}_{10}$ = pentapotassium triphosphate; DSP, Na_2HPO_4 = disodium hydrogen phosphate; TSPP, $\text{Na}_4\text{P}_2\text{O}_7$ = tetrasodium pyrophosphate; STPP, $\text{Na}_5\text{P}_3\text{O}_{10}$ = pentasodium triphosphate.

terms of enthalpy change as well as melting temperature. For that reason, 3.0% (wt/wt) concentration can be estimated as optimal concentration for preparation of PC. The number of Na and K ions in salts plays a key role in terms of emulsifying ability with increasing number of ions. $W_{f,s}$ calculated from Equation 2 decreased with increasing ES content due to the fact that water was incorporated in sample matrix to a higher degree (Table 5).

Dependent on the different ES types, we observed decreasing values of ΔH_{fus} with increasing number of ions in ES compounds ($P < 0.05$). The amount of freezable free and freezable bound water ($W_{f,s}$) was calculated from Equation 2, and for 3.0% (wt/wt) KTPP was equal to $9.59 \pm 0.07\%$, corresponding to the lowest ice crystal formation determined. In the case of sodium-based ES, a similar trend was observed, but the enthalpy values were higher compared with potassium-based ES, for example, for STPP the $W_{f,s} = 13.96\% \pm 0.77\%$ ($P < 0.05$).

As noted previously, PC with potassium-based ES exhibited a mild shift of onset and peak melting temperatures to lower values with increasing potassium content, as evident from Table 4 (e.g., $T_{onset} = -21.84^{\circ}\text{C}$ and $T_{p,m} = -9.43^{\circ}\text{C}$ for the KTPP sample [3.0% wt/wt], compared with $T_{onset} = -9.79^{\circ}\text{C}$ and $T_{p,m} = -3.21^{\circ}\text{C}$ for the DKP sample; $P < 0.05$). This behavior can indicate that crystal melting is influenced by action of K ions, creating less stable ice crystals. Therefore, the melting process is detected at lower temperatures by applying salts of higher potassium content. The differences between samples with potassium- and sodium-based ES could be

related to specific character of K^+ (chaotropic) and Na^+ (kosmotropic) ions. Chaotropic ions of potassium-based ES can suppress electrostatic repulsion effect on cheese sauce polymer chains and enhance dissolution of colloidal aggregates (Wang et al., 2015). Kosmotropic ions of sodium-based ES can promote interactions between water molecules in cheese matrix, and thus stabilize intramolecular interactions in protein macromolecules (Moelbert et al., 2004). Ion actions may have an influence on thermal behavior of our samples, characterized by the relevant thermal parameters.

In addition, the presence of fat and proteins plays a significant role for water behavior in sample matrix (Noronha et al., 2008; Baranowska, 2011; Urgu-Öztürk et al., 2021). Within PC, bulk (free) water fraction is the part of water-in-fat emulsion (Thanasukarn et al., 2004). In contrast to this, bound water fraction is constituted by hydrogen-bonded or ion-associated water molecules (or both) bound to other large molecules, particularly proteins (Anedda, 2015). Thermal behavior of PC can be affected by the presence and proportion of protein and fat components, as well as preparation procedure.

Results of our study can be compared with the values determined by Tomaszewska-Gras et al. (2019), who investigated different types of goat cheeses. In agreement with the findings of this study, a decrease of melting fusion enthalpy (ΔH_{fus}) with decreasing freezable free and freezable bound water content ($W_{f,s}$) was observed, as evident in Table 4. By measuring DSC freezing/melting process, a distinct sharp narrow peak in temperature range around

Table 5. Differential scanning calorimetry parameters ($T_{p,cryst}$ = water crystallization peak temperature; ΔH_{cryst} = freezing enthalpy; T_{onset} = onset melting temperature; $T_{p,m}$ = ice melting peak temperature; ΔH_{fus} = melting fusion enthalpy; W_{fs} = freezable free and freezable bound water content) and first resonance frequency f_{R1} (Hz) under harmonic mechanical loading of processed cheese manufactured with different types and concentrations of potassium- and sodium-based emulsifying salts after 30 d of storage ($6^{\circ}\text{C} \pm 2^{\circ}\text{C}$; results were expressed as mean $\pm$ SD; $n = 36$)

Sample ¹	Cooling cycle				Heating cycle			
	Concentration (% wt/wt)	$T_{p,cryst}$ ($^{\circ}\text{C}$)	ΔH_{cryst} (J g^{-1})	T_{onset} ($^{\circ}\text{C}$)	$T_{p,m}$ ($^{\circ}\text{C}$)	ΔH_{fus} (J g^{-1})	W_{fs} (%)	First resonance frequency (f_{R1} ; Hz)
DKP	2.0	-17.38 $\pm$ 0.55 ^{a,A}	110.59 $\pm$ 1.32 ^{a,A}	-5.60 $\pm$ 1.18 ^{a,A}	-1.17 $\pm$ 0.22 ^{a,A}	118.03 $\pm$ 2.10 ^{a,A}	35.39 $\pm$ 0.33 ^{a,A}	98 $\pm$ 4 ^{a,A}
	2.5	-17.85 $\pm$ 1.17 ^{a,A}	68.67 $\pm$ 1.55 ^{b,A}	-6.29 $\pm$ 0.08 ^{a,A}	-2.39 $\pm$ 0.61 ^{b,A}	71.64 $\pm$ 1.37 ^{b,A}	21.48 $\pm$ 0.31 ^{b,A}	104 $\pm$ 5 ^{b,A}
	3.0	-18.52 $\pm$ 1.36 ^{a,A}	56.90 $\pm$ 1.28 ^{c,A}	-9.79 $\pm$ 0.45 ^{b,A}	-3.21 $\pm$ 0.38 ^{b,A}	58.77 $\pm$ 1.12 ^{c,A}	17.62 $\pm$ 0.46 ^{c,A}	116 $\pm$ 5 ^{b,A}
TKPP	2.0	-19.68 $\pm$ 1.21 ^{a,A}	95.81 $\pm$ 1.25 ^{d,B}	-7.22 $\pm$ 0.43 ^{b,B}	-2.40 $\pm$ 0.33 ^{b,B}	99.43 $\pm$ 1.18 ^{d,B}	29.82 $\pm$ 0.13 ^{d,B}	118 $\pm$ 6 ^{b,B}
	2.5	-16.27 $\pm$ 1.44 ^{a,A}	69.68 $\pm$ 1.31 ^{b,A}	-8.52 $\pm$ 0.68 ^{b,B}	-3.19 $\pm$ 0.23 ^{b,B}	83.24 $\pm$ 1.03 ^{c,B}	24.96 $\pm$ 0.19 ^{c,B}	132 $\pm$ 6 ^{c,B}
	3.0	-20.67 $\pm$ 1.20 ^{a,A}	66.87 $\pm$ 1.44 ^{b,B}	-10.14 $\pm$ 1.06 ^{b,A}	-3.69 $\pm$ 0.64 ^{b,A}	72.28 $\pm$ 1.02 ^{b,B}	21.67 $\pm$ 0.27 ^{b,B}	142 $\pm$ 7 ^{b,B}
KTPP	2.0	-26.36 $\pm$ 1.24 ^{b,B}	67.32 $\pm$ 1.16 ^{b,C}	-8.28 $\pm$ 0.65 ^{b,B}	-4.66 $\pm$ 0.31 ^{c,C}	76.32 $\pm$ 1.59 ^{b,C}	22.88 $\pm$ 0.18 ^{b,C}	122 $\pm$ 5 ^{c,B}
	2.5	-20.97 $\pm$ 1.18 ^{b,A}	64.14 $\pm$ 1.33 ^{b,A}	-11.72 $\pm$ 1.30 ^{b,C}	-6.20 $\pm$ 0.74 ^{d,C}	67.29 $\pm$ 1.15 ^{c,C}	20.18 $\pm$ 0.29 ^{b,C}	132 $\pm$ 6 ^{b,B}
	3.0	-23.56 $\pm$ 1.06 ^{b,B}	33.78 $\pm$ 1.07 ^{d,C}	-21.84 $\pm$ 1.09 ^{d,B}	-9.43 $\pm$ 0.47 ^{e,B}	31.97 $\pm$ 1.36 ^{g,C}	9.59 $\pm$ 0.07 ^{f,C}	164 $\pm$ 8 ^{d,C}
DSP	2.0	-16.65 $\pm$ 0.25 ^{a,A}	97.91 $\pm$ 1.38 ^{d,B}	-5.75 $\pm$ 0.24 ^{a,A}	-1.89 $\pm$ 0.11 ^{a,A}	99.09 $\pm$ 1.01 ^{d,B}	29.71 $\pm$ 0.48 ^{d,B}	74 $\pm$ 4 ^{c,C}
	2.5	-17.87 $\pm$ 0.67 ^{a,A}	75.05 $\pm$ 1.21 ^{e,B}	-7.11 $\pm$ 0.20 ^{b,A}	-3.12 $\pm$ 0.47 ^{b,B}	70.99 $\pm$ 1.42 ^{b,A}	21.29 $\pm$ 0.12 ^{b,A}	88 $\pm$ 5 ^{a,C}
	3.0	-18.23 $\pm$ 0.42 ^{a,A}	62.42 $\pm$ 1.29 ^{b,B}	-9.25 $\pm$ 0.18 ^{b,A}	-3.32 $\pm$ 1.01 ^{b,A}	65.71 $\pm$ 2.01 ^{f,D}	19.70 $\pm$ 0.53 ^{b,D}	128 $\pm$ 6 ^{a,A}
TSPP	2.0	-18.72 $\pm$ 0.33 ^{a,A}	70.93 $\pm$ 1.18 ^{b,D}	-9.69 $\pm$ 0.24 ^{b,C}	-3.55 $\pm$ 0.24 ^{b,D}	67.53 $\pm$ 0.78 ^{f,D}	20.25 $\pm$ 0.76 ^{b,D}	101 $\pm$ 5 ^{b,A}
	2.5	-19.43 $\pm$ 0.61 ^{a,A}	54.10 $\pm$ 1.42 ^{f,C}	-10.27 $\pm$ 0.31 ^{b,C}	-5.34 $\pm$ 0.06 ^{d,D}	51.61 $\pm$ 1.26 ^{h,D}	15.47 $\pm$ 0.09 ^{g,D}	116 $\pm$ 6 ^{a,A}
	3.0	-22.94 $\pm$ 0.16 ^{b,B}	39.79 $\pm$ 1.67 ^{g,D}	-11.80 $\pm$ 0.27 ^{b,B}	-9.57 $\pm$ 0.09 ^{e,B}	40.64 $\pm$ 2.22 ^{i,E}	12.19 $\pm$ 0.75 ^{h,E}	130 $\pm$ 6 ^{c,B}
STPP	2.0	-19.23 $\pm$ 0.39 ^{a,A}	94.07 $\pm$ 1.17 ^{d,B}	-7.5 $\pm$ 0.22 ^{b,B}	-1.97 $\pm$ 0.21 ^{a,A}	109.87 $\pm$ 2.11 ^{j,E}	32.95 $\pm$ 0.98 ^{d,E}	106 $\pm$ 4 ^{a,A}
	2.5	-20.19 $\pm$ 0.98 ^{a,A}	81.49 $\pm$ 1.89 ^{h,D}	-9.83 $\pm$ 0.29 ^{b,C}	-3.73 $\pm$ 0.09 ^{b,B}	103.34 $\pm$ 1.59 ^{d,E}	30.99 $\pm$ 1.03 ^{d,E}	119 $\pm$ 5 ^{c,A}
	3.0	-23.71 $\pm$ 1.03 ^{b,B}	40.40 $\pm$ 1.31 ^{g,D}	-10.83 $\pm$ 0.25 ^{b,A}	-4.41 $\pm$ 0.17 ^{b,C}	46.54 $\pm$ 0.47 ^{k,F}	13.96 $\pm$ 0.77 ^{h,E}	133 $\pm$ 7 ^{b,B}

^{a-k}Mean values within a column followed by different lowercase superscripts differ significantly ($P < 0.05$).

^{A-F}Mean values within a row followed by different uppercase superscripts differ significantly ($P < 0.05$).

¹Emulsifying salts used: DKP, K_2HPO_4 = dipotassium hydrogen phosphate; TKPP, $\text{K}_4\text{P}_2\text{O}_7$ = tetrapotassium pyrophosphate; KTPP, $\text{K}_3\text{P}_3\text{O}_{10}$ = pentapotassium triphosphate; DSP, Na_2HPO_4 = disodium hydrogen phosphate; TSPP, $\text{Na}_4\text{P}_2\text{O}_7$ = tetrasodium pyrophosphate; STPP, $\text{Na}_5\text{P}_3\text{O}_{10}$ = pentasodium triphosphate.

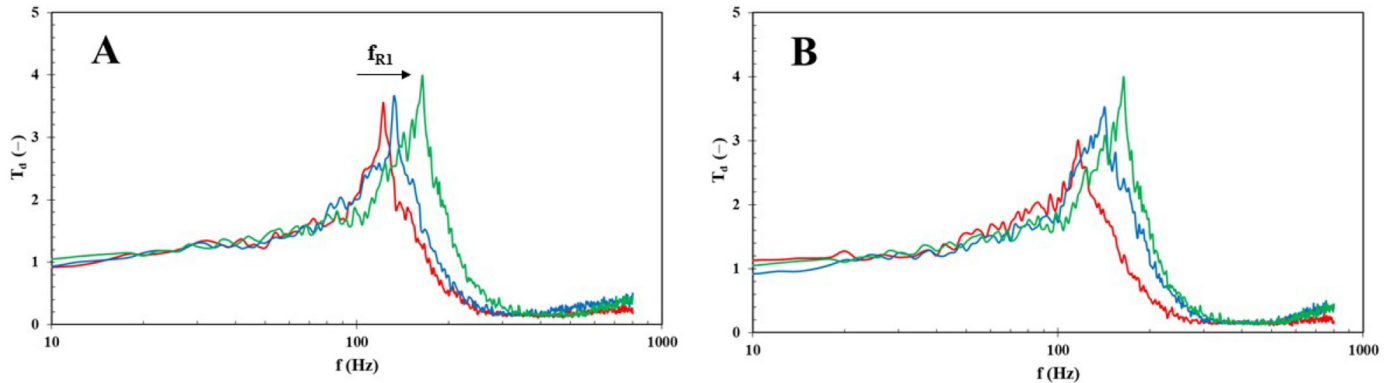


Figure 7. Frequency (f) dependencies of the displacement transmissibility (T_d) of the tested processed cheese samples containing potassium-based emulsifying salts. Part A: effect of emulsifying salt concentration in pentapotassium triphosphate (KTPP) processed cheese specimen (2.0% wt/wt, red line; 2.5% wt/wt, blue line; 3.0% wt/wt, green line); part B: effect of emulsifying salt type (dipotassium hydrogen phosphate [DKP], red line; tetrapotassium pyrophosphate [TKPP], blue line; pentapotassium triphosphate [KTPP], green line) at a salt concentration of 3.0% wt/wt; f_{R1} is the first resonance frequency.

-15°C to -25°C was detected, corresponding to water crystallization phase transition. Ice formation at temperatures much lower than 0°C relates to the phenomenon of supercooling, which is typical for water-oil emulsions (Clausse, 2010), for example, for PC in our study.

Mechanical Vibration Damping Properties

Examples of measured frequency dependencies of the displacement transmissibility of cheese samples containing potassium and sodium-based ES are shown in Figures 7 and 8. It is obvious that resonant mechanical vibration (i.e., for $T_d > 1$) was generally found at low excitation frequencies. In contrast, mechanical vibration damping (i.e., for $T_d < 1$) was observed at higher excitation frequencies depending on the type and concentration of ES in the studied cheese specimens ($P < 0.05$).

The effect of the sodium-based ES concentration on the displacement transmissibility of the tested DSP cheese samples is illustrated in Figure 7 (part A). It is evident that an increase in ES concentration generally led to a rise in the first resonance frequency f_{R1} (i.e., from 74 to 128 Hz) and, consequently, an increase in the dynamic mechanical stiffness of the investigated specimens. Similar results regarding the influence of sodium-based ES concentration on displacement transmissibility were also observed for the other cheese specimens (i.e., TSPP and STPP). The influence of the sodium-based ES type, at a constant concentration of 2.0% (wt/wt), on the displacement transmissibility of the tested cheese samples is depicted in Figure 8 (part B). It is evident that the first resonance frequency increased from 74 Hz (DSP) to 106 Hz (STPP). Consequently, the highest mechanical stiffness was observed for the STPP cheese sample, followed by the TSPP and DSP cheese samples, which exhibited

higher internal damping during harmonic loading compared with the STPP sample ($P < 0.05$). Similar results were observed for other sodium-based ES concentrations. The average values of the first resonance frequency for all investigated cheese types with various sodium-based ES concentrations are presented in Table 5.

The effect of the potassium-based ES concentration in the studied KTPP cheese samples on displacement transmissibility is shown in Figure 7 (part A). As in the case of cheese samples containing sodium-based ES, an increasing concentration of potassium-based ES generally leads to a rise in the first resonance frequency from 122 Hz (at a salt concentration of 2.0% wt/wt) to 164 Hz (at a salt concentration of 3.0% wt/wt) in the investigated PC samples, which was accompanied by an increase in their dynamic mechanical stiffness ($P < 0.05$). The same trend was observed for other emulsifying salt types (i.e., DKP and KTPP), as presented in Table 5. Frequency dependencies of the displacement transmissibility for the studied cheese samples containing 3.0% (wt/wt) of different potassium-based ES types are shown in Figure 7 (part B). It is evident that the highest first resonance frequency (164 Hz) and, thus, the highest dynamic mechanical stiffness, was observed for the KTPP cheese specimen. In contrast, the lowest mechanical stiffness was found for the DKP cheese sample, which exhibited a first resonance frequency of 116 Hz (Table 5) at the same salt concentration.

It can be concluded that the mechanical vibration damping measurements are in good agreement with the hardness measurements. It was found that a higher concentration of sodium-based or potassium-based ES in PC samples generally leads to a shift of the first resonance frequency to higher values, and thus to increased dynamic mechanical stiffness of the investigated samples. This is

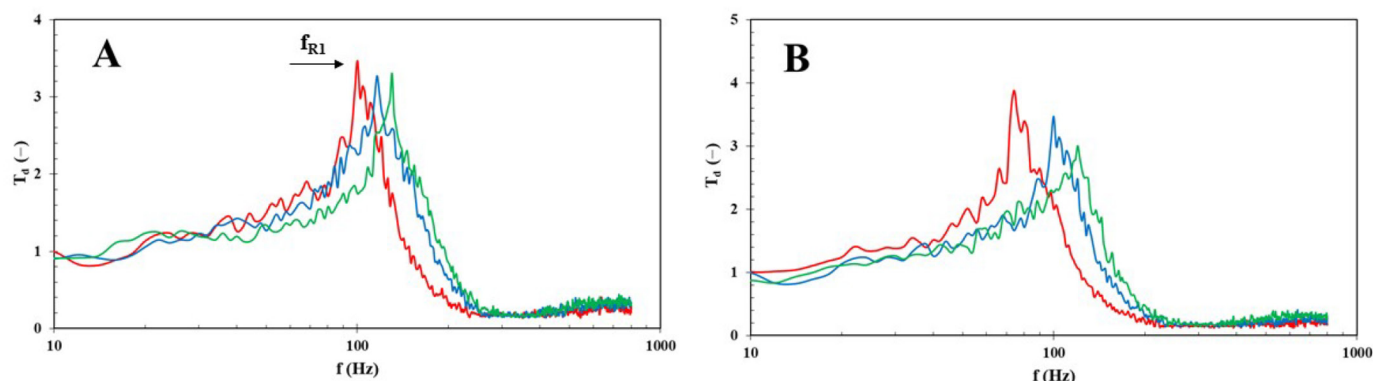


Figure 8. Frequency (f) dependencies of the displacement transmissibility (T_d) of the tested cheese samples containing sodium-based emulsifying salts. Part A: effect of emulsifying salt concentration in disodium hydrogen phosphate (DSP) processed cheese specimen (2.0% wt/wt, red line; 2.5% wt/wt, blue line; 3.0% wt/wt, green line); part B: effect of emulsifying salt type (disodium hydrogen phosphate [DSP], red line; tetrasodium pyrophosphate [TSPP], blue line; pentasodium triphosphate [STPP], green line) at a salt concentration of 2.0% wt/wt; f_{R1} is the first resonance frequency ($n = 18$).

accompanied by a lower transformation of input mechanical energy into heat during harmonic dynamic loading. Additionally, it has been established that PC specimens containing potassium-based ES exhibited higher mechanical stiffness (like hardness) compared with those containing sodium-based ES. Furthermore, the highest mechanical stiffness was observed in triphosphate (i.e., STPP and KTPP) containing PC samples regardless of the ES concentration. In contrast, the tested hydrogen phosphate (i.e., DSP and DKP) specimens exhibited the lowest mechanical stiffness compared with the studied pyrophosphates (i.e., TSPP and TKPP) and triphosphate (i.e., STPP and KTPP) containing PC samples.

Sensory Analysis

The sensory evaluation of the model PC samples was conducted on all sampling days during storage ($6^\circ\text{C} \pm 2^\circ\text{C}$), specifically on d 1, 14, 30, and 60 postmanufacturing. The sensory analysis results indicated that the inclusion of both potassium-based and sodium-based ES in the PC products did not significantly influence ($P > 0.05$) the overall appearance, nor did it affect the development of a bitter taste (Table 6). These results are highly satisfactory, as the main issue when using potassium-based ES in practice is the potential development of a bitter or chemically metallic aftertaste in PC during storage (Chavhan et al., 2015; Šantová et al., 2024). This is often caused by an incorrectly chosen concentration of ES, which, in our study, was not confirmed. However, the metallic and chemical sensitivities can vary from region to region, country to country, or population to population. For all PC samples, regardless of the type of ES applied, a gradual increase in product stiffness was observed with extended storage time. In terms of spreadability, all samples with

the addition of sodium-based ES were rated as products with optimal hardness and spreadability. In contrast, potassium-based PC samples maintained optimal hardness or slightly firmer consistency throughout most of the storage period; however, by the end of the storage time, some samples were difficult to spread (PC with the addition of 3.0% wt/wt DKP; 2.0% wt/wt KTPP; $P < 0.05$). Moreover, some model PC samples (2.0% wt/wt and 2.5% wt/wt TSPP) exhibited structural changes during consuming, specifically the presence of small crystals. The formation of these crystals can be attributed to several factors, as also mentioned in the study by Guinee (2017). One of the possible causes is the formation of insoluble calcium phosphate crystals or the incomplete dissolution of the applied ES (Guinee, 2017; El-Bakry and Mehta, 2022). Based on the overall evaluation, the PC products with potassium-based ES were ranked in the following order, from best to worst: DKP, TKPP, and KTPP. Similarly, for sodium-based ES, the ranking followed the same pattern: STPP, DSP, and TSPP. However, according to the obtained results, all tested PC samples, regardless of the type of applied ES, can be characterized as very good to excellent. The only exception was the PC product with the addition of the sodium-based ES (TSPP), which was rated by the evaluators as good to moderately good. Images of the PC samples were also captured (Figures 5 and 6).

CONCLUSIONS

This study demonstrated that potassium-based ES can effectively reduce sodium content in PC. The type and concentration of the potassium-based ES affected texture and viscoelastic properties. Furthermore, mechanical vibration damping measurements provided similar results

Table 6. Organoleptic attributes (appearance, hardness, spreadability, bitterness, off-flavor, and overall rating)¹ of processed cheese samples evaluated by an expert panel (n = 16; values are expressed as the median)

Sample ²	Concentration (% wt/wt)	Appearance	Hardness	Spreadability	Bitterness	Off-flavor	Overall rating
Time (d) 1							
DKP	2.0	1 ^a	3 ^a	3 ^a	1 ^a	1 ^a	1 ^a
	2.5	1 ^a	3 ^a	3 ^a	1 ^a	1 ^a	1 ^a
	3.0	1 ^a	3 ^a	3 ^a	2 ^b	1 ^a	3 ^b
TKPP	2.0	1 ^a	3 ^a	1 ^b	2 ^b	1 ^a	3 ^b
	2.5	1 ^a	3 ^a	3 ^a	2 ^b	1 ^a	3 ^b
	3.0	1 ^a	3 ^a	3 ^a	2 ^b	1 ^a	4 ^c
KTPP	2.0	1 ^a	4 ^b	4 ^c	1 ^a	1 ^a	3 ^b
	2.5	1 ^a	3 ^a	3 ^a	2 ^b	1 ^a	3 ^b
	3.0	1 ^a	3 ^a	3 ^a	2 ^b	1 ^a	3 ^b
DSP	2.0	1 ^a	4 ^b	3 ^a	1 ^a	2 ^b	1 ^a
	2.5	1 ^a	3 ^a	4 ^c	1 ^a	2 ^b	2 ^d
	3.0	1 ^a	4 ^b	4 ^c	1 ^a	2 ^b	3 ^b
TSPP	2.0	1 ^a	4 ^b	3 ^a	1 ^a	1 ^a	5 ^e
	2.5	1 ^a	3 ^a	3 ^a	1 ^a	2 ^b	4 ^c
	3.0	1 ^a	3 ^a	3 ^a	2 ^b	2 ^b	4 ^c
STPP	2.0	1 ^a	4 ^b	4 ^c	1 ^a	1 ^a	2 ^d
	2.5	1 ^a	4 ^b	4 ^c	2 ^b	1 ^a	1 ^a
	3.0	1 ^a	4 ^b	4 ^c	2 ^b	1 ^a	2 ^d
Time (d) 14							
DKP	2.0	1 ^a	3 ^a	3 ^a	1 ^a	2 ^b	2 ^d
	2.5	1 ^a	3 ^a	3 ^a	1 ^a	3 ^c	3 ^b
	3.0	1 ^a	4 ^b	3 ^a	2 ^b	3 ^c	3 ^b
TKPP	2.0	1 ^a	1 ^c	3 ^a	1 ^a	2 ^b	3 ^b
	2.5	1 ^a	1 ^c	1 ^b	1 ^a	2 ^b	4 ^c
	3.0	1 ^a	3 ^a	3 ^a	1 ^a	2 ^b	4 ^c
KTPP	2.0	1 ^a	4 ^b	4 ^c	2 ^b	3 ^c	4 ^c
	2.5	1 ^a	4 ^b	3 ^a	1 ^a	1 ^a	3 ^b
	3.0	1 ^a	3 ^a	3 ^a	2 ^b	2 ^b	3 ^b
DSP	2.0	1 ^a	1 ^c	3 ^a	1 ^a	1 ^a	1 ^a
	2.5	1 ^a	3 ^a	4 ^c	1 ^a	1 ^a	1 ^a
	3.0	1 ^a	4 ^b	4 ^c	1 ^a	1 ^a	1 ^a
TSPP	2.0	1 ^a	4 ^b	3 ^a	1 ^a	1 ^a	2 ^d
	2.5	1 ^a	4 ^b	4 ^c	1 ^a	1 ^a	2 ^d
	3.0	1 ^a	3 ^a	3 ^a	1 ^a	1 ^a	1 ^a
STPP	2.0	1 ^a	1 ^c	3 ^a	1 ^a	1 ^a	1 ^a
	2.5	1 ^a	3 ^a	3 ^a	1 ^a	1 ^a	1 ^a
	3.0	1 ^a	4 ^b	3 ^a	1 ^a	1 ^a	1 ^a
Time (d) 30							
DKP	2.0	1 ^a	3 ^a	4 ^c	1 ^a	1 ^a	1 ^a
	2.5	1 ^a	3 ^a	4 ^c	1 ^a	1 ^a	3 ^b
	3.0	1 ^a	3 ^a	3 ^a	2 ^b	1 ^a	3 ^b
TKPP	2.0	1 ^a	2 ^d	2 ^d	1 ^a	1 ^a	5 ^e
	2.5	1 ^a	2 ^d	1 ^b	1 ^a	1 ^a	5 ^e
	3.0	1 ^a	2 ^d	1 ^b	2 ^b	1 ^a	5 ^e
KTPP	2.0	1 ^a	4 ^b	4 ^c	1 ^a	1 ^a	2 ^d
	2.5	1 ^a	2 ^d	3 ^a	1 ^a	2 ^b	3 ^b
	3.0	1 ^a	1 ^c	1 ^b	2 ^b	2 ^b	3 ^b
DSP	2.0	1 ^a	3 ^a	1 ^b	1 ^a	1 ^a	2 ^d
	2.5	1 ^a	1 ^c	1 ^b	1 ^a	1 ^a	2 ^d
	3.0	1 ^a	4 ^b	3 ^a	1 ^a	1 ^a	3 ^b
TSPP	2.0	1 ^a	3 ^a	4 ^c	1 ^a	1 ^a	3 ^b
	2.5	1 ^a	3 ^a	3 ^a	1 ^a	1 ^a	4 ^c
	3.0	1 ^a	3 ^a	3 ^a	1 ^a	1 ^a	4 ^c
STPP	2.0	1 ^a	1 ^c	1 ^b	1 ^a	1 ^a	1 ^a
	2.5	1 ^a	1 ^c	1 ^b	1 ^a	1 ^a	1 ^a
	3.0	1 ^a	3 ^a	3 ^a	1 ^a	1 ^a	1 ^a
Time (d) 60							
DKP	2.0	1 ^a	3 ^a	1 ^b	1 ^a	1 ^a	1 ^a
	2.5	1 ^a	1 ^c	1 ^b	1 ^a	1 ^a	2 ^d
	3.0	1 ^a	4 ^b	3 ^a	1 ^a	1 ^a	1 ^a
TKPP	2.0	1 ^a	2 ^d	2 ^d	2 ^b	1 ^a	4 ^c
	2.5	1 ^a	3 ^a	1 ^b	1 ^a	1 ^a	3 ^b
	3.0	1 ^a	2 ^d	1 ^b	2 ^b	1 ^a	3 ^b

Continued

Table 6 (Continued). Organoleptic attributes (appearance, hardness, spreadability, bitterness, off-flavor, and overall rating)¹ of processed cheese samples evaluated by an expert panel (n = 16; values are expressed as the median)

Sample ²	Concentration (% wt/wt)	Appearance	Hardness	Spreadability	Bitterness	Off-flavor	Overall rating
KTPP	2.0	1 ^a	5 ^c	5 ^c	1 ^a	1 ^a	2 ^d
	2.5	1 ^a	1 ^c	1 ^b	1 ^a	1 ^a	3 ^b
	3.0	1 ^a	1 ^c	1 ^b	1 ^a	1 ^a	4 ^c
DSP	2.0	1 ^a	2 ^d	1 ^b	1 ^a	1 ^a	1 ^a
	2.5	1 ^a	3 ^a	1 ^b	1 ^a	1 ^a	2 ^d
	3.0	1 ^a	3 ^a	3 ^a	1 ^a	1 ^a	3 ^b
TSPP	2.0	1 ^a	3 ^a	3 ^a	1 ^a	1 ^a	5 ^e
	2.5	1 ^a	1 ^c	3 ^a	1 ^a	1 ^a	4 ^c
	3.0	1 ^a	1 ^c	2 ^d	1 ^a	1 ^a	4 ^c
STPP	2.0	1 ^a	1 ^c	3 ^a	1 ^a	1 ^a	2 ^d
	2.5	1 ^a	3 ^a	1 ^b	1 ^a	1 ^a	1 ^a
	3.0	1 ^a	3 ^a	2 ^d	1 ^a	1 ^a	2 ^d

^{a–e}Median values within a column followed by different superscript letters differ significantly ($P < 0.05$).

¹Appearance, hardness, spreadability, bitterness, off-flavor: 1 = excellent; 3 = good; 5 = unacceptable. Overall rating: 1 = extraordinarily good; 7 = extremely bad.

²Emulsifying salts used: DKP, K_2HPO_4 = dipotassium hydrogen phosphate; TKPP, $K_4P_2O_7$ = tetrapotassium pyrophosphate; KTPP, $K_5P_3O_{10}$ = pentapotassium triphosphate; DSP, Na_2HPO_4 = disodium hydrogen phosphate; TSPP, $Na_4P_2O_7$ = tetrasodium pyrophosphate; STPP, $Na_5P_3O_{10}$ = pentasodium triphosphate.

to that of hardness and G*. The increased ES concentrations in PC samples raised the first resonance frequency, enhancing samples' mechanical stiffness. Moreover, increasing potassium content improved water binding and structural stability, accompanied by only minor pH and color changes during storage. However, metallic and chemical sensitivities can differ across regions, countries, and populations. Importantly, no bitterness or other negative sensory effects were detected when potassium-based ES were used. Our findings confirmed that potassium-based ES can serve as a nutritionally beneficial and technologically viable alternative to conventional sodium-based ES. To build on these findings, a future study could investigate consumer sensory perception and acceptance of PC formulated with potassium-based ES across different demographic and cultural groups.

NOTES

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Nonstandard abbreviations used: a_w = water activity; DKP = dipotassium hydrogen phosphate; DSC = differential scanning calorimetry; DSP = disodium hydrogen phosphate; ES = emulsifying salts; G* = complex modulus; G' = storage modulus; G'' = loss modulus; KTPP = pentapotassium triphosphate; PC = processed cheese;

STPP = pentasodium triphosphate; TKPP = tetrapotassium pyrophosphate; TPA = texture profile analysis; TSPP = tetrasodium pyrophosphate; WI = whiteness index.

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