Food Structure 49 (2026) 100545

Contents lists available at ScienceDirect

Food Structure

journal homepage: www.elsevier.com/locate/foostr

Pressure-induced structural and rheological changes in homogenized agar and agar-collagen fluid gels for dysphagia diets

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ARTICLE INFO

Keywords:
Fluid gel
High-pressure homogenization
Dysphagia
Swallowing behavior
High protein

ABSTRACT

This study investigated the potential of high-pressure homogenization as a post-production modification to reduce particle size and enhance swallow-related properties of agar-based fluid gels. The effects of pressures ranging from 10 to 60 MPa on the stability, structural changes, and swallow-related rheological characteristics of dysphagia-oriented pre-prepared agar (1.5%) and agar-collagen (20%) fluid gels were examined. High-pressure homogenization reduced agar particle size, enhancing interactions among new agar domains. Droplet size and microstructural analyses showed that higher pressures produced smaller particles, which then re-aggregated after reaching a critical concentration. However, adding collagen prevented this re-aggregation, with particle size decreasing from 182.76 to 65.82 μm as pressure increased from 0 to 60 MPa. All treated fluid gels exhibited viscoelastic behavior, with pressure increasing viscosity—up to 4.5 in agar and twice as much in agar-collagen fluid gels—and samples transitioned from Level 2 to Level 3, according to the International Dysphagia Diet Standardization Initiative (IDDSI) testing. Furthermore, pressure-induced structural changes enhanced fluid gel stability under dynamic conditions, increasing it from 74.11% to 84.98% in agar and from 48.85% to 68.08% in agar-collagen fluid gels. These findings offer valuable insights into how post-processing high-pressure homogenization can reduce droplet size, enhance palatability, and preserve swallowing safety, influencing the properties of formulated fluid gels without requiring additional thickeners.

1. Introduction

The global population is aging rapidly, and it is estimated that by 2054, individuals over 65 will comprise 33% of the total population (United Nations, 2024). As individuals age, physiological changes—including reduced chewing ability, weakened tongue muscle strength, and delayed epiglottic closure—may contribute to the development of dysphagia (Wang et al., 2024). Dysphagia is a condition that causes chewing and oropharyngeal difficulties, leading to serious complications such as aspiration-induced choking during eating or drinking, dehydration, and malnutrition (Forster et al., 2011; Sungsinchai et al., 2019). Thickened liquids or texture-modified foods with optimized rheological properties are essential to ensure safe swallowing whilst maintaining adequate hydration and nutrition in dysphagia patients (Wei et al., 2021). The term "dysphagia foods" often refers to the use of thickeners, as well as food formulations in the form of gel, paste or puree (Hadde et al., 2021; Xu et al., 2023). The use of powdered thickeners is no longer considered an appropriate solution for the development of future diets tailored to older people. Although regulating the viscosity and stickiness of such foods may prolong the time food spends in the oral cavity and esophagus, it may also cause undesirable post-deglutitive residues (especially for starch-based thickeners), increasing the risk of choking (Liu et al., 2025; Baixauli et al., 2023). Commercial thickeners are often used only under medical or nursing staff supervision (to avoid dosing errors), which makes it challenging to eat independently (Hadde et al., 2021). Furthermore, thickened liquids are perceived as significantly less palatable than their unthickened counterparts (Munialo et al., 2020; Yver et al., 2018). Additionally, gum-based thickeners could provide greater satiety, which could be uncomfortable for the undernourished patient (Baixauli et al., 2023).

Given the information above, it is evident that new techniques and concepts, which differ substantially from traditional methods, should be

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https://doi.org/10.1016/j.foostr.2026.100545
Received 2 March 2026; Received in revised form 12 May 2026; Accepted 16 June 2026
Available online 19 June 2026

used initially to prepare pre-thickened dysphagia foods. It is becoming clear that a change in strategy is needed—specifically, thickening not by raising the thickener concentration, but by developing a structure suitable for swallowing—must be implemented.

Therefore, due to the tunable rheological properties and lubricating capacity, fluid gels appear to be a promising approach for developing dysphagia-friendly foods (Chouhan et al., 2019; Mills et al., 2013). Fluid gel, also known as sheared gel, exist in a form of microgel-particulate suspensions with very weak interactions between the densely packed gel particles. This uniqueness of structure allows particles to "squeeze" past each other after shear force in the oral phase of swallowing is applied and then re-establish weak interactions in the pharyngeal phase, preventing aspiration (Yu et al., 2024). Despite these advantages, only a few studies have examined the use of the fluid gel in dysphagia diets, tailoring their consistency by adjusting the biopolymer concentration and the mixing rate during their formation (Zhang et al., 2023; Dyglė et al., 2026; Yu et al., 2024). However, the fluid gels prepared in the studies mentioned earlier using this shearing method during gelation had several issues that need to be resolved. One of them is the formation of large particles, that could not be reduced even after applying a higher shear rate during the gelation process. When consumed, it can cause negative sensations that are incompatible with a dysphagia diet and can also lead to destabilization of systems during long-term storage (Zhang et al., 2023; Dyglė et al., 2026). As previously reported, only high-viscosity dysphagia-oriented solutions without particles (no sandy texture) were preferred by evaluators (Baixauli et al., 2023). Another one - current studies focus solely on altering fluid gel properties during preparation, which cannot be adjusted afterward.

To address this issue, we decided to pass the prepared gels through a high-pressure homogenizer. High-pressure homogenization is a continuous processing method that applies intense mechanical forces to liquid systems, resulting in droplet size reduction, enhanced stability, and modification of phase behavior (Masbernat et al., 2026; Turitich et al., 2026; Zhai et al., 2026). The only study conducted by Zhu et al. (2024) involved pre-treating egg white solutions with ultra-high pressure homogenization prior to the fluid gel manufacturing process (Zhu et al., 2024). While, to the best of our knowledge, such an approach of modifying the physicochemical and swallow-related properties of fluid gels after post-processing has not yet been described in the literature. We strongly believe that this innovative structuring approach allows for preparing a pre-thickened system with the targeted consistency for a dysphagia diet. This method allows increasing the formulation's viscosity without adding additional thickeners. Post-processing modifications allow customization for each patient's needs. Since patients with dysphagia often require different consistency levels, adjusting the fluid gel enables healthcare providers or manufacturers to tailor products without producing entirely separate formulations. It is also believed that this method helps improve sensory quality and palatability by adjusting lubrication, reducing particle size, and making fluid gels more appealing.

In this way, the aim of the study was to investigate how different pressures, applied during homogenization, can tailor properties of agar and agar-collagen fluid gels intended for dysphagia diet. The resulting fluid gel systems were investigated by monitoring appearance, microstructure, droplet size, rheology behavior, and dynamic stability. IDDSI tests were performed to evaluate the application of fluid gels for patients with dysphagia.

2. Materials and methods

2.1. Materials

Agar powder, with a composition of 0.3% fat, 3% carbohydrates, 0.4% protein, and 0.1% sodium chloride, was sourced from a local retailer (Alvo, Kaunas, Lithuania) and used directly without further treatment. A bovine collagen hydrolysate, consisting of a type I and III collagen in a ratio 50:50 with a degree of hydrolysis of 20% and 90% protein content was purchased from My Protein (Manchester, UK). Sodium azide (CAS No. 26628–22–8) was purchased from Euro chemicals (Vilnius, Lithuania).

2.2. Fluid gel preparation

In this experiment, two types of control fluid gels were prepared and subsequently homogenized: agar-only and a blend of agar and collagen. Agar powder with concentration 1.5% (w/w) was dissolved in distilled water until fully hydrated and heated in a water bath at 95 °C for 20 min. Sample was subjected to shear at 300 rpm for 60 min at room temperature (25 °C) and subsequently for 60 min under ice–water bath conditions (0–2 °C) using an overhead stirrer (HT-DX, Witeg, Wertheim, Germany). Sample with agar (1.5%) and collagen addition (20% (w/w)) was prepared following the identical procedure. Sodium azide (0.02%) was added to avoid microbiological growth. The collagen concentration was selected based on preliminary experiments. Increasing collagen hydrolysate levels caused an unpleasant aftertaste and more stickiness, which decreased the overall acceptability of the developed systems.

Prepared samples were homogenized using two-stages homogenizer (HP203-A, Omve, Schalkwilk, The Netherlands), with the first stage operated at varying pressure levels (10 MPa, 20 MPa, 30 MPa, 40 MPa, 50 MPa and 60 MPa). The second stage of homogenization was not applied and maintained the plunger in an open position, thereby ensuring that first-stage homogenization effects were applied to the samples. Samples without homogenization were identified as controls. Prior to analysis, all samples were stored in a refrigerated environment at + 4 °C for 24 h.

2.3. Methods

2.3.1. Particle size

Particle size distribution, span and mean diameter d_{43} was determined by laser diffraction using a Mastersizer 2000 (Malvern, Worcestershire, UK) particle size analyzer operated at a measurement speed of 1400 rpm. The refractive indexes of the dispersed phase and solvent were set to 1.42 and 1.33, respectively, with a droplet absorption value of 0.01 and an obscuration range of 10–15%.

2.3.2. Microstructure

Phase-contrast images of fluid gels were captured using an Olympus IX73 inverted microscope (Olympus Europe Holding GmbH, Hamburg, Germany). Random fields of the coverslips were photographed with a 20x lens right after sample preparation for imaging. The diameter of selected particles was measured using ImageJ version 1.53 t (National Institutes of Health, Bethesda, MD, USA).

2.3.3. Rheological properties

Rheological characterization of the agar-based fluid gels was evaluated with a MCR 92 rheometer (Anton Paar, Graz, Austria) using a parallel plate configuration (PP25; 25 mm diameter) set at a 1 mm measuring gap. Measurements were conducted at a constant temperature of 25 °C.

2.3.3.1. Viscosity 50 s^{-1}. Viscosity measurements were conducted at a fixed shear rate of 50 s^{-1} , and samples were subsequently categorized into four consistency classes: thin (1–50 mPa·s), nectar-like (51–350 mPa·s), honey-like (351–1750 mPa·s), and spoon-thick or pudding-like (>1750 mPa·s). This approach served as the reference method in accordance with the National Dysphagia Diet Task Force (NDD) guidelines (American Dietetic Association, 2002).

2.3.3.2. Shear yield stress. The yield stress of the samples was evaluated by means of flow sweep experiments conducted over a shear rate range of 0.001–0.1 s^{-1} . The yield point was defined as the initial peak in shear stress recorded as the shear rate increased.

2.3.3.3. Shear-dependent viscosity. Flow characteristics were determined through rheological testing conducted at shear rates between 0.1 and 400 s^{-1} . The relationship between shear stress and shear rate was modeled using the Ostwald–de Waele Eq. 1, with parameters κ and n representing consistency index and flow behavior, respectively:

$$\sigma = \kappa\gamma^{n} \quad (1)$$

2.3.3.4. Shear recovery behavior. The test consisted of three consecutive shear rate intervals. In the first stage, samples were subjected to a low shear rate of 0.1 s^{-1} for 3 min to establish the initial structural state. This was followed by the application of a high shear rate of 50 s^{-1} for 1 min to induce structural breakdown. In the final stage, the shear rate was reduced back to 0.1 s^{-1} and maintained for an additional 3 min to evaluate structural recovery.

2.3.3.5. Small amplitude oscillatory shear (SAOS) rheology. To characterize viscoelastic behavior, samples were subjected to oscillatory frequency sweeps under linear viscoelastic conditions using a strain amplitude of 0.05%, while the oscillation frequency was varied between 1 and 100 rad/s.

2.3.3.6. Large amplitude oscillatory shear (LAOS) rheology. Strain sweep measurements were carried out at a constant frequency of 1 Hz, with the strain amplitude varied from 0.01% to 1000%.

2.3.4. International dysphagia diet standardization initiative (IDDSI) tests

The flow characteristics and appropriateness of the prepared fluid gels for dysphagia management were evaluated in accordance with the IDDSI guidelines (2019) using a syringe-based flow assessment. A reference syringe was used (Amedi+plus Luer slip 21 G × 1½″; Jiangyin Nanquan Macromolecule Product Co., Ltd., Jiangsu, China), fitted with a Luer-Lok tip. The linear distance corresponding to the 0–10 mL volume interval was determined to be 61.5 mm.

Syringe test was used to evaluate applicability of the fluid gels for patients with dysphagia. A nozzle was covered with finger, and a syringe was filled with 10 mL of fluid gels. The nozzle was released and stopped after 10 s. The level of remaining fluid gel was checked, and the level of dysphagia was determinated according to IDDSI: thin (less than 1 mL remaining), slightly thick (1–4 mL remaining), mildly thick (4–8 mL remaining), moderately thick (8–10 mL remaining), extremely thick (10 mL remaining).

For samples classified as Level 3 (moderately thick) by the syringe test, a fork drip test was also performed by scooping the fluid gel with a fork. The flow behavior was then observed at the fork tip. According to the IDDSI method description, the gaps between the prongs of a standard metal fork were 2 mm (IDDSI, 2019).

2.3.5. Stability at the static conditions

Samples were transferred into 50 mL glass tubes, sealed, and stored at 25 ∘C. Over 8 weeks, visual changes were monitored by observing particle sedimentation.

2.3.6. Dynamic stability

To determine the resistance to phase separation under gravitational forces of fluid gel, centrifugal stability was measured. Samples (20 g) were centrifuged at 2500 rpm for 10 min, and the separated phase was quantified to evaluate retained phase. The stability was evaluated by calculating the percentage of the retained fluid gel phase after centrifugation, with higher retained mass indicating greater stability.

2.3.7. Statistical analysis

All experiments were conducted at least three times, unless otherwise stated, with results presented as mean ± standard deviation. Significant differences in means were identified using a p-value of < 0.05, determined through analysis of variance (ANOVA) with Statistica 12.0 (StatSoft Inc., Oklahoma, AK, USA, 2013).

3. Results

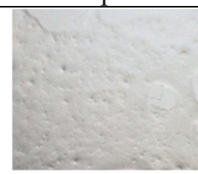
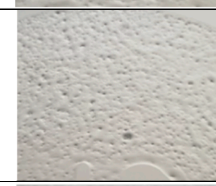
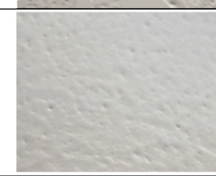
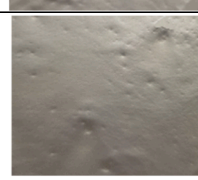
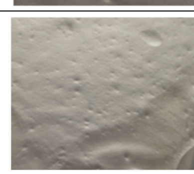
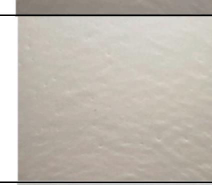
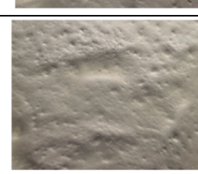
3.1. Visual appearance

When visually comparing the systems, the first noticeable difference is the color of the samples: the agar-only fluid gel had a whitish, cloudy appearance, whereas collagen was clearly yellow. For the structural confirmation, the bakers with formulated agar-based fluid gels were inverted and visually observed, and close-up photographs were taken to visually present the size of the formed particles. When the test tubes were turned upside down, the samples began to flow, indicating the formation of a fluid gel structure caused by weak aggregation of agar helices through the "hairy" structure of smaller agar domains formed as a result of shear-induced agar network disruption (Ghebremedhin et al., 2021; Zhang et al., 2023). This tendency remained consistent regardless of the type of fluid gels (agar or agar-collagen combination) and the applied pressure (Table 1). Meanwhile, the effect of pressure was clearly visible in the reduction of particle size, which was one of the most important aspects of this study. However, when pressure increased, both fluid gels behaved differently. More predictable behavior was observed in the agar-collagen fluid gels, as the particles decreased with increasing pressure and became almost invisible to the naked eye after a pressure of 60 MPa was applied. In contrast, the fluid gels with agar only showed a different pattern, with particle size decreasing at 10 MPa and 20 MPa, then increasing again as pressure grew, particularly evident at the maximum pressure of 60 MPa (Table 1). The mechanisms behind this will be explained in later sections.

3.2. Particle size and microstructure

The particle size distribution was consistent with the visual appearance of particles presented in Table 2. The agar fluid gel sample before homogenization showed a monomodal particle size distribution, with an average droplet size of 216.82 μm and a span index of 2.582, indicating moderate polydispersity. Upon application of pressure up to 20 MPa, a reduction in particle size was observed, accompanied by decreases in both mean size and span index, suggesting particle fragmentation and narrowing of the size distribution. In agarose-based fluid gels, a progressive increase in sucrose concentration was shown to slightly reduce the mean particle size, decreasing from approximately 150 μm to 100 μm at 30 wt% sucrose (Ghebremedhin et al., 2024). In contrast to our case, the authors reduced particle size during production, whereas our method allows the particle size to be adjusted after the fluid gel structure has fully formed, both immediately after production and after a period of storage (at the post-processing stage). Further increases in pressure from 30 MPa to 60 MPa resulted in a gradual increase in particle size, with mean values approaching those of the control sample. This phenomenon can be explained by the fact that increased pressure further reduces the size of particles, resulting in the formation of many more agar domains with "hairy" areas in the system that begin to interact with each other without any hindrance through weak forces, promoting the aggregation of individual particles and increasing the polydispersity of the system (Fig. 1). It has been previously reported that shear-driven formation of microgel particles can generate a high number of small nuclei, which may subsequently undergo secondary aggregation to form larger particle populations, leading to unimodal distributions with minor secondary size populations (Ren et al., 2026). The observed trends in particle size changes are consistent with the microscopic images presented in Fig. 2. A distinct reduction in agar particle size is evident at 20 MPa, followed by particle aggregation at the maximum applied pressure. The observed anisotropic morphology of the

Table 1
Visual appearance of the formulated agar and agar-collagen fluid gels (fluid gel structure confirmation) and the particles formed.

Sample	*Agar fluid gel*		*Agar-collagen fluid gel*	
	Visual appearance	Visualization of visible particles	Visual appearance	Visualization of visible particles
Control				
10 MPa				
20 MPa				
30 MPa				
40 MPa				
50 MPa				
60 MPa				

formulated fibrous agar particle aligns with findings reported in previous studies (Anderton et al., 2026; Ellis et al., 2019).

In contrast, agar–collagen fluid gel systems showed a markedly different response to pressure treatment. Increasing pressure caused a continuous decrease in average particle size, from 182.76 μm in the control sample to 65.82 μm at 60 MPa, along with a reduction in span index from 2.915 to 1.861, indicating a narrower particle size distribution and less polydispersity. Notably, while the agar–collagen control sample exhibited a bimodal particle size distribution, all pressure-treated samples displayed monomodal distributions, suggesting pressure-induced homogenization of particle populations. Microstructure images confirmed a clear pressure-driven trend in particle reduction (Fig. 2). A proposed mechanism for what happens to particles under pressure in both systems is shown in Fig. 1. The variations in particle size reduction may be attributed to collagen's presence, which prevents particles from further interacting to form aggregates. Previous research reports that collagen forms randomly distributed, interpenetrating aggregates within starch-based gel matrices (Lin et al., 2025a). The results show that not only the use of homogenization but also additional components like collagen hydrolysate, included in our formulation, influence the properties of the fluid gels.

One of the primary objectives of this study was to reduce particle size to improve suitability for dysphagia-oriented food applications. In this context, pressures exceeding 30 MPa were not beneficial for agar fluid gels, as particle sizes reverted toward pre-treatment values. Conversely, the continued particle size reduction observed in agar–collagen systems with increasing pressure is advantageous for dysphagia management, as smaller and more uniform particles are associated with a more pleasant

Table 2
Particle size distribution parameters – span index and volume-weighted mean diameter (d_{43}) of agar and agar-collagen fluid gels subjected to different pressures.

Sample	*Agar fluid gel*		*Agar-collagen fluid gel*	
	d_{43}	Span	d_{43}	Span
Control	216.82 ± 3.72^{gB}	2.582	182.76 ± 1.77^{fA}	2.915
10 MPa	100.52 ± 2.06^{bA}	2.533	155.61 ± 2.96^{eB}	2.482
20 MPa	91.90 ± 4.20 ^{aA}	2.006	114.66 ± 2.23 ^{dB}	2.503
30 MPa	117.75 ± 3.62^{cB}	1.896	84.24 ± 1.82^{cA}	2.537
40 MPa	163.88 ± 1.89 ^{dB}	2.195	68.91 ± 1.21^{bA}	2.161
50 MPa	174.75 ± 1.58^{eB}	2.159	66.46 ± 2.17 ^{aA}	1.885
60 MPa	204.07 ± 2.29^{fB}	2.436	65.82 ± 2.19 ^{aA}	1.861

Note: values are reported as means±standard deviation; data labeled with different lowercase letters (a–d) showed statistically significant differences ($p < 0.05$) between different pressures for individual fluid gel formulation; data labeled with different uppercase letters (A–B) showed statistically significant differences ($p < 0.05$) between different fluid gel formulations.

sensation when consuming (Satheeshkanth et al., 2024; Lin et al., 2025b), improved bolus cohesion, and reduced aspiration risk.

Furthermore, although the control agar-structured gel systems remained stable for 8 weeks, the presence of larger particles during long-term storage may cause destabilization of systems with anisotropic morphology, as shown in studies by other authors (Pissia et al., 2024; Yu et al., 2024; Young et al., 2021). Therefore, it is likely that reducing particle size through homogenization will also help stabilize the fluid gel systems.

3.3. Rheological properties

Numerous studies highlight the importance of rheological properties in the development of texture-modified foods for dysphagia management (Gallegos et al., 2023; Zargaraan et al., 2013). Detailed rheological characterization is essential because various parameters capture different aspects of material structure and flow under different shear conditions. This is especially critical for oral processing and swallowing, where understanding viscosity, viscoelasticity, and flow behavior is vital for ensuring bolus stability and safe swallowing of texture-modified foods (Zargaraan et al., 2013; Gamonpilas et al., 2023). Therefore, multiple rheological measurements are needed to precisely evaluate material behavior related to bolus formation, passage to the throat, and safe swallowing. Accordingly, measurements were conducted for shear-dependent viscosity, frequency- and strain-dependent viscoelasticity, shear yield stress, and shear recovery behavior.

3.3.1. Shear-dependent viscosity

Both tested systems exhibited clear shear-thinning behavior, with a flow behavior index below 1 (Table 3). Shear-thinning behavior is vital for dysphagia-friendly foods because it decreases apparent viscosity

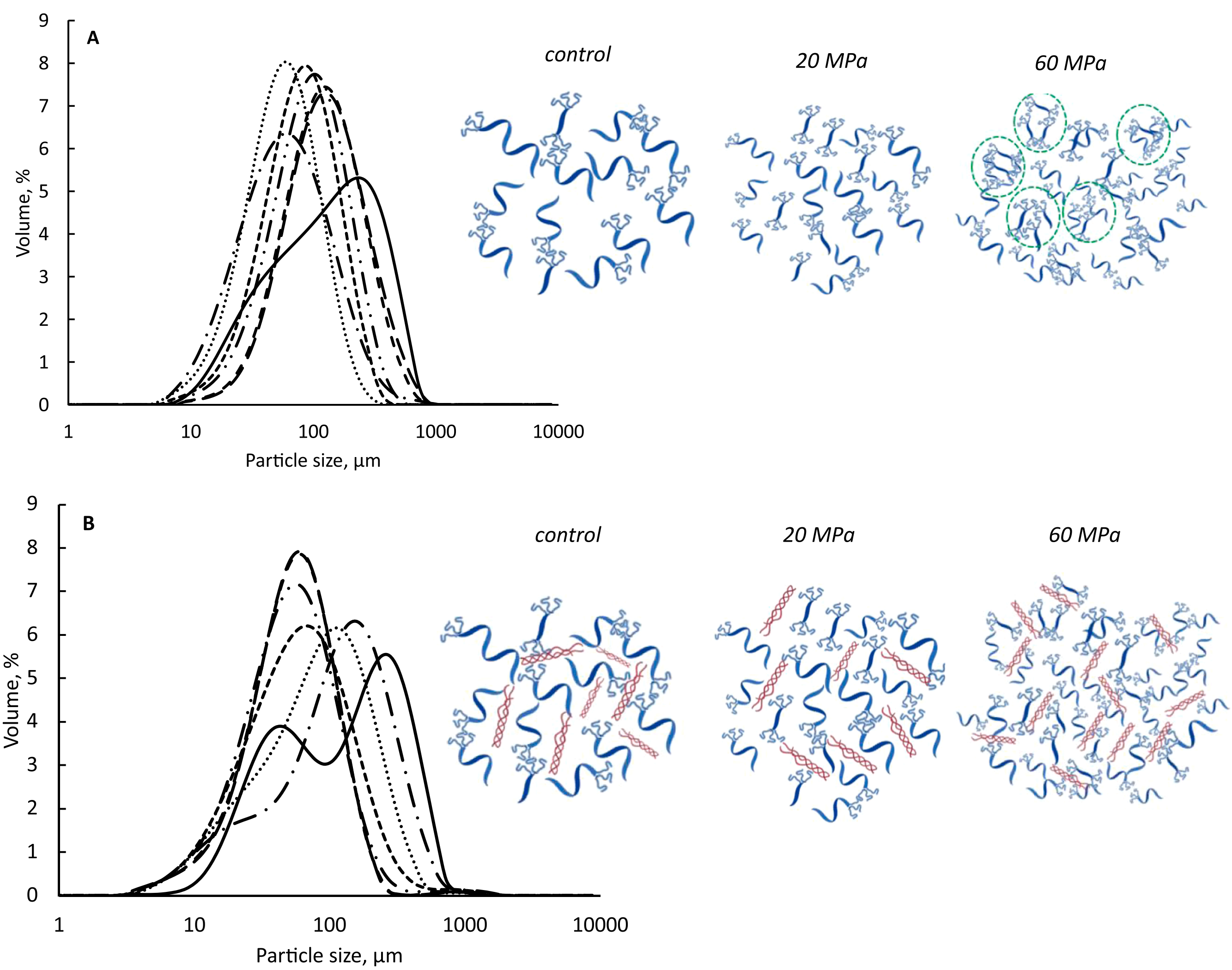


Fig. 1. Particle size distribution and structure (Created with BioGDP.com) of agar (A) and agar-collagen (B) fluid gels under different pressures: control (——), 10 MPa (– · –), 20 MPa (······), 30 MPa (– – –), 40 MPa (— · —), 50 MPa (– – –), 60 MPa (— —).

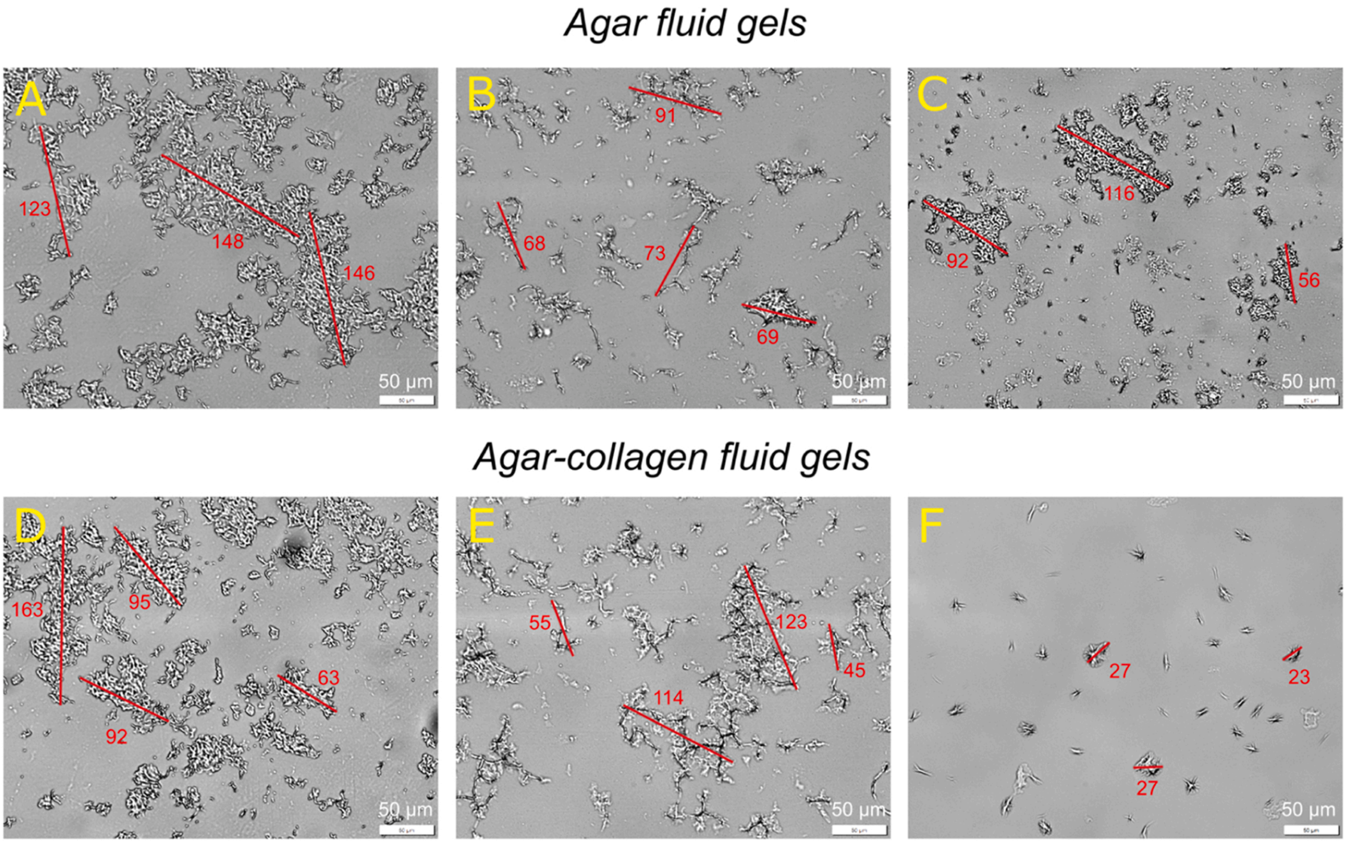


Fig. 2. Phase-contrast images of the agar and agar-collagen fluid gels before homogenization (A, D), after homogenization at 20 MPa (B, E) and 60 MPa (C, F). Red lines indicate particle size.

under high shear during mastication and swallowing, helping to facilitate bolus transport, while maintaining enough viscosity at low shear for bolus control. This improves swallow efficiency, reduces stickiness, and enhances sensory acceptance (Shay et al., 2025; Liu et al., 2025).

The consistency index increased with pressure in both agar and agar–collagen fluid gels, with a more statistically significant ($p < 0.05$) change observed in agar systems (5-fold) (Table 3). Considering that a comparable increase was observed in thickened liquids for dysphagia treatment by combining guar gum and xanthan gum at different ratios (Xu et al., 2025), this demonstrates the effectiveness of the homogenization process applied. The gradual decrease in flow index with rising pressure indicates enhanced shear-thinning behavior, which was more evident in agar fluid gels. A lower flow index indicates improved flowability at high shear rates, which is particularly beneficial for dysphagia management, as it promotes smooth bolus passage, reduces oral and pharyngeal residue, and decreases the risk of choking, thereby supporting a safer and more comfortable eating experience (Bao et al., 2026).

Table 3
Consistency, flow behavior indexes and coefficient of determination of agar and agar-collagen fluid gels after application of different pressures.

Sample	Agar fluid gel			Agar-collagen fluid gel		
	κ	n	R^2	κ	n	R^2
Control	3.404 ± 1.137^a	0.418 ± 0.060^d	0.986	1.648 ± 0.011^c	0.492 ± 0.000^e	0.964
10 MPa	6.685 ± 0.196^b	0.275 ± 0.008^c	0.981	0.962 ± 0.042^a	0.494 ± 0.042^e	0.945
20 MPa	9.424 ± 0.352^c	0.243 ± 0.009^{bc}	0.979	1.402 ± 0.015^b	0.444 ± 0.001^c	0.952
30 MPa	11.583 ± 0.115^d	0.222 ± 0.001^{ab}	0.982	1.852 ± 0.001^d	0.420 ± 0.002^{bc}	0.962
40 MPa	12.114 ± 1.030^d	0.232 ± 0.007^{ab}	0.978	2.295 ± 0.081^e	0.394 ± 0.003^b	0.964
50 MPa	14.708 ± 1.535^e	0.199 ± 0.019^a	0.961	3.236 ± 0.175^f	0.353 ± 0.004^a	0.961
60 MPa	15.533 ± 0.216^e	0.205 ± 0.002^{ab}	0.966	3.415 ± 0.044^g	0.356 ± 0.000^a	0.969

Note: values are reported as means±standard deviation; data labeled with different lowercase letters (a–d) showed statistically significant differences ($p < 0.05$) between different pressures for individual fluid gel formulation

Table 4 shows the apparent viscosity values of agar-collagen fluid gels at shear rates of 10 s^{-1} , 50 s^{-1} , and 400 s^{-1} under increasing pressure. The selected low and high shear rates represent different mechanical conditions experienced during oral processing and swallowing, where 10 s^{-1} corresponds to the oral phase and 400 s^{-1} to the pharyngeal phase. Meanwhile, viscosity measured at a shear rate of 50 s^{-1} was used to classify the samples according to standardized thickness levels (American Dietetic Association, 2002).

Assessing the apparent viscosity at 50 s^{-1} reveals that applying just 10 MPa of pressure transformed the agar fluid gel's thickness from Level 2 (nectar-like) to Level 3 (honey-like), demonstrating noticeable viscosity change. Conversely, the viscosity of agar-collagen fluid gels showed only slight increases, staying at Level 3 (honey-like) regardless of the applied pressure. Iman-Salihae et al. (2026) reported a similar effect, where pressures of 200–600 MPa transformed coconut water thickened with a commercial thickener and xanthan gum solutions from nectar-like to honey-like consistency. While xanthan gum–coconut water remained within the honey-like range despite a notable viscosity increase.

Similar pressure-induced patterns appeared in the apparent viscosity at a low shear rate (10 s^{-1}), reflecting food bolus cohesiveness in the mouth (Ross et al., 2019). As shown in Table 4, the agar fluid gels exhibited a significant pressure-induced increase from 861.55 mPa·s to 2437.40 mPa·s, nearly tripling. Higher viscosity values (η_{10}) indicate a

Table 4
Shear-dependent apparent viscosity values of agar and agar-collagen fluid gels under different pressures.

	Agar fluid gel			*Agar-collagen fluid gel*		
	η_{10} (mPa·s)	η_{50} (mPa·s)	η_{400} (mPa·s)	η_{10} (mPa·s)	η_{50} (mPa·s)	η_{400} (mPa·s)
Control	861.55 ± 26.23^{a}	$310.75 \pm 1.66^{*a}$	105.60 ± 2.97^{b}	467.80 ± 3.82^{d}	$197.01 \pm 1.37^{*e}$	88.20 ± 0.71^{g}
10 MPa	1348.55 ± 26.09^{b}	386.51 ± 28.45^{b}	90.95 ± 0.92^{a}	271.10 ± 10.04^{a}	$103.97 \pm 2.11^{*a}$	54.05 ± 0.49^{a}
20 MPa	1733.25 ± 17.18^{c}	477.94 ± 38.09^{c}	104.80 ± 0.99^{b}	352.55 ± 8.27^{b}	$131.37 \pm 3.71^{*b}$	57.30 ± 0.85^{b}
30 MPa	2010.0 ± 19.83^{d}	576.97 ± 49.73^{d}	112.15 ± 3.32^{c}	432.60 ± 6.36^{c}	$162.57 \pm 4.51^{*c}$	64.25 ± 0.35^{c}
40 MPa	2130.40 ± 18.46^{e}	613.16 ± 66.14^{d}	124.40 ± 4.67^{d}	506.15 ± 10.54^{e}	$177.95 \pm 6.02^{*d}$	67.70 ± 1.27^{d}
50 MPa	2369.55 ± 13.14^{f}	668.50 ± 73.41^{e}	124.80 ± 2.83^{d}	669.40 ± 31.68^{f}	$211.53 \pm 10.78^{*f}$	74.70 ± 2.26^{e}
60 MPa	2437.40 ± 15.24^{g}	687.28 ± 68.57^{e}	135.15 ± 5.87^{e}	704.25 ± 11.10^{g}	$233.81 \pm 9.83^{*g}$	79.30 ± 1.27^{f}

Values are reported as means±standard deviation; data labeled with different lowercase letters (a–d) showed statistically significant differences ($p < 0.05$) between different pressures for individual fluid gel formulation * Nectar-like, other fluid gel samples, honey-like.

greater ability to form and maintain a food bolus when oral manipulation is impaired, which is especially important in severe dysphagia cases (Ross et al., 2019; Xu et al., 2026a,b). Additionally, clinical studies offer further support that higher viscosity provides more time for the epiglottis to close and is associated with a lower risk of airway penetration during swallowing (Gallegos et al., 2023).

A minimal pressure effect was observed when assessing viscosity under high shear (η_{400}) conditions, which corresponds to the force needed for the food bolus to pass to the epiglottis.

3.3.2. SAOS

Frequency sweep analysis was performed within the linear viscoelastic region to characterize the fluid gels viscoelastic behavior, which indirectly indicates ease and safety of swallowing (Wang et al., 2025a,b; Cheng et al., 2025; Hou et al., 2025a,b). The results of agar and agar-collagen samples under different pressures are shown in Figs. 3A and 3B. The dominance of elastic modulus (G′) over viscous modulus (G″), along with low tan δ values (< 1) for all fluid gel samples, confirms elastic, solid-like gel behavior regardless of the applied pressure. Research has demonstrated that food systems exhibiting weak gel properties, defined by a tanδ range of 0.1–1, are able to maintain their structure and transit smoothly through the pharynx and esophagus during swallowing (Li et al., 2024). Agar fluid gel samples exhibit ($p < 0.05$) significantly higher absolute G′ values than agar–collagen gels, indicating a stronger network structure that helps reduce food bolus stickiness during swallowing (Hou et al., 2025a,b). Additionally, fluid gels containing collagen showed a more noticeable frequency dependence, with G′ and G″ increasing at higher frequencies. This is related to the molecular mobility of the particles and non-covalent interactions in the matrix (Yoo et al., 1994; Xie et al., 2023).

3.3.3. LAOS

During swallowing, the food bolus experiences rapid, nonlinear, and significant deformations over very short timescales (Xu et al., 2026a,b). Large-amplitude oscillatory shear simulates conditions that reflect the sample's ability to be squeezed, which is particularly important for

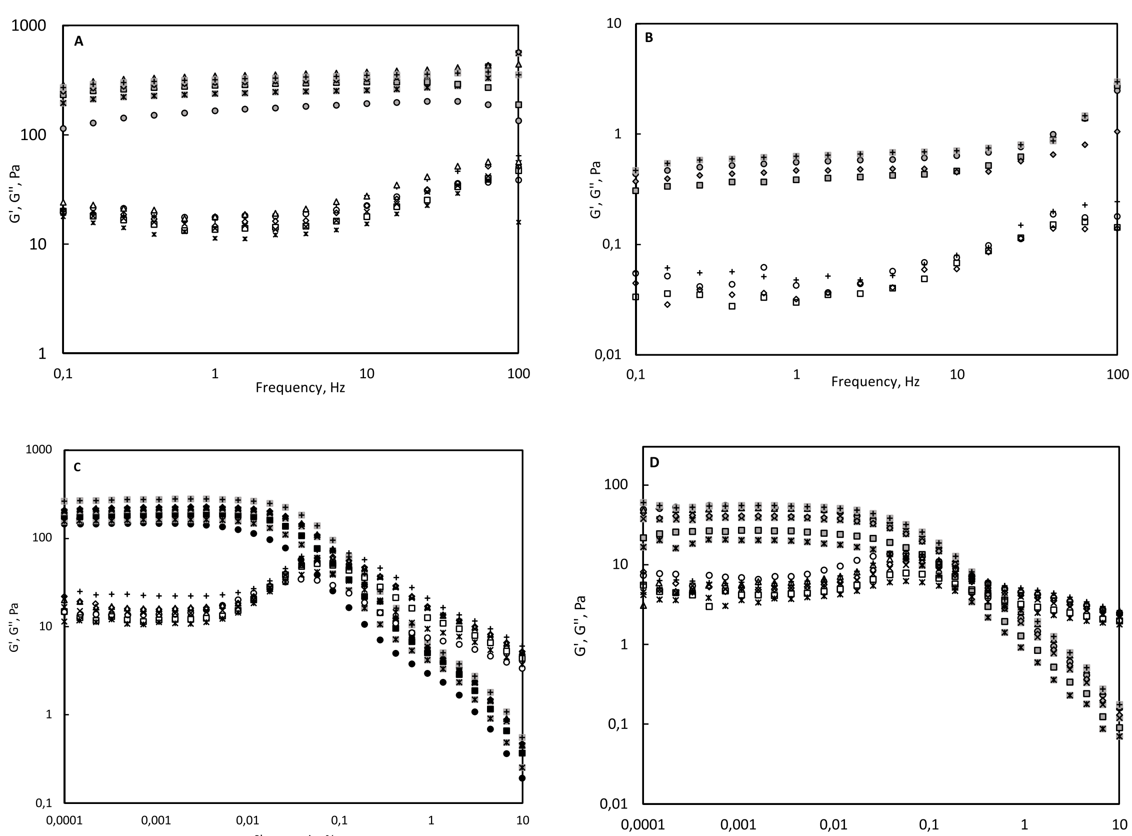


Fig. 3. Small and large amplitudes oscillatory shear of agar (A, C) and agar-collagen (B, D) fluid gels after application of different pressure: control (○), 10 MPa (✱), 20 MPa (□), 30 MPa (×), 40 MPa (⋄), 50 MPa (△), 60 MPa (+). G′ and G″ are plotted as closed and open symbols, respectively.

patients with dysphagia, who often rely on tongue pressure due to reduced tooth or muscle strength (Yu et al., 2024).

Initially, the storage modulus (G′) and loss modulus (G") of all tested fluid gels show a consistent plateau, with G' higher than G" at lower strains (Figs. 3C and 3D). This suggests that the fluid gels behave more like solids, maintaining their structure despite the applied strain. At a critical strain ($\leq$0.1%), a progressive decrease in G′ is observed, accompanied by a crossover with G″, marking the start of structural breakdown, where fluid gels show the loss of elastic dominance under large deformation (Li et al., 2024). This indicates that fluid gels formulated in this way would be easier to swallow and process orally. Homogenization at varying pressures does not alter the curve pattern or the length of the linear viscoelastic region (LVR).

A slight increase in G" modulus was also observed before the crossover with G′, consistent with behavior of agarose fluid gels (Ghebremedhin et al., 2021) or xanthan gum solution (Hyun et al., 2002). This phenomenon was previously explained by the relative movement of molecules on the surface of the "hairy" agar particles and the formation of long network bridges (Hyun et al., 2002).

3.3.4. *Yield stress and shear recovery behavior*

Yield stress and shear recovery are used as test indicators to simulate pharyngeal phase behaviors (Zhang et al., 2026a,b). Yield stress shows the initiation of bolus flow under low pharyngeal pressure (Zhao et al., 2025), while shear recovery behavior is related with the stable transit of food through the esophagus (Xu et al., 2026a,b).

Yield stress in agar systems increased with pressure up to 50 MPa. Pressures exceeding this value did not result in additional changes in yield stress (Figs. 4A and 4C). This behavior is directly linked to the reduction in particle size, which leads to increased weak intermolecular interactions between agar particles as well as secondary aggregation. The addition of collagen reduces these agar-agar interactions, as was previously confirmed by lower viscosity values. This observation may account for the less pronounced effect of pressure on agar-collagen fluid gels compared to agar fluid gels. Overall, fluid gels demonstrated very low shear yield stress across all pressure conditions, with agar fluid gels falling below 10 Pa and agar-collagen below 2 Pa. These findings are favorable, as foods formulated for individuals with dysphagia should possess relatively low yield stress, which is essential given the documented decline in muscle strength (Hadde & Chen, 2019; Marconati et al., 2019). Compared with other studies on dysphagia-oriented food systems, significantly higher yield stress values have been reported, ranging from 111.92 to 286.95 Pa in pea protein isolate gels (Liang et al., 2026), 400–800 Pa in food inks based on various carbohydrates and proteins (Yellapantula et al., 2025), and 254.89 Pa in high internal phase emulsions (Hou et al., 2025a,b). While in oleogel-in-hydrogel Pickering emulsion fluid gels, the yield stress varied from very low (10.7 Pa) to much higher (200.8 Pa) by adjusting the high acyl gellan gum (HAG) concentration and mixing process (Yu et al., 2024). Our measured yield stress values were similar to those of liquids thickened with guar gum and xanthan gum at various ratios used in dysphagia management (0.0–7.26 Pa) (Xu et al., 2025). Although these yield stress values are relatively low and might appear insufficient for forming a food bolus, our previous clinical study demonstrated that fluid gels with such low yield stress values are safe to swallow and pose no risk of aspiration (Dyglė et al., 2026).

In terms of shear recovery behavior, all agar and agar–collagen samples exhibited a marked decrease in viscosity at high shear rates. Upon returning to low shear rates, viscosity recovery varied according to the applied pressure. The shear recovery percentage of agar fluid gels decreased from 119% to 85% with increasing pressure (Figs. 4B and 4D). A distinct behavior was observed in agar-collagen systems. In these gels, initial homogenization at 10 MPa reduced structure recovery from 115% to 74%. Further increases in pressure led to a consistent rise in structure recovery, ultimately reaching 125%. This phenomenon is attributed to the rearrangement of the weak "hairy" agar structure

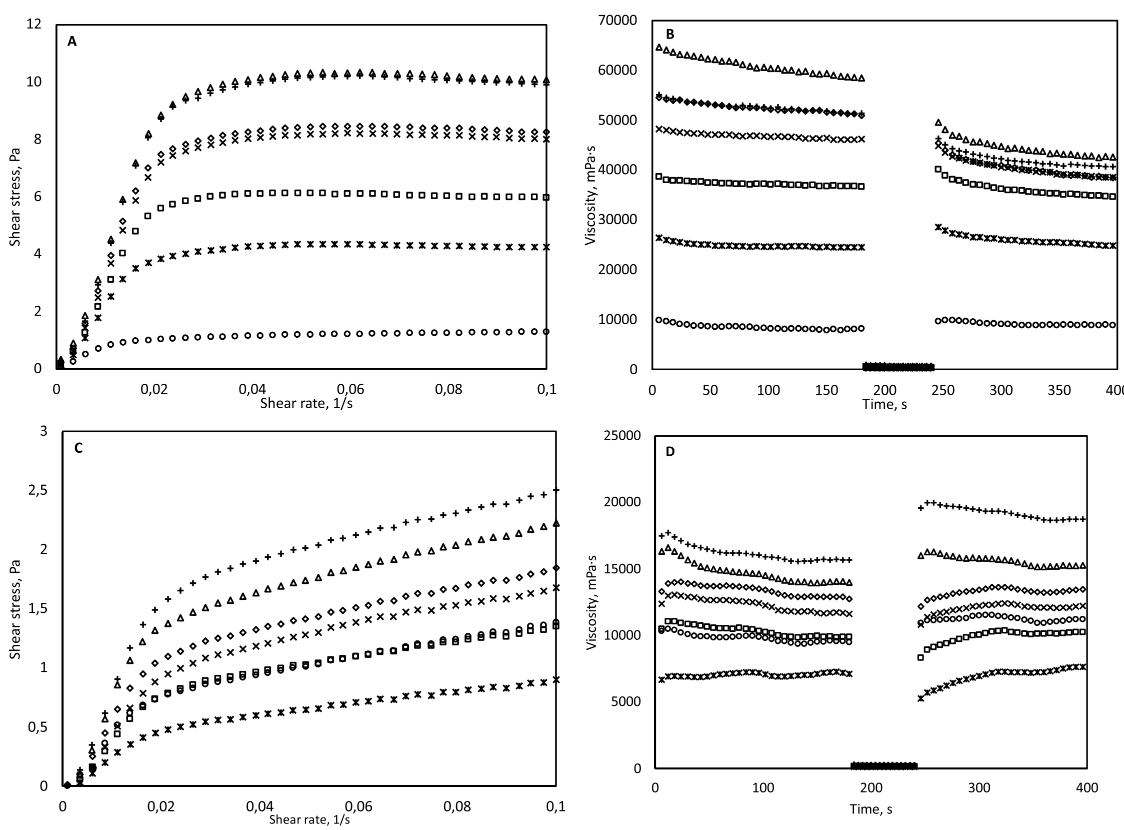


Fig. 4. Shear yield stress and recovery behavior, evaluated by the shear viscosity as a function of time in the agar (A, B) and agar-collagen (C, D) fluid gels at different pressure levels: control (○), 10 MPa (⋇), 20 MPa (□), 30 MPa (×), 40 MPa (⋄), 50 MPa (△), 60 MPa (+).

during the pharyngeal phase, which is facilitated by the formation of new domain-domain interactions between agar particles (Ghebremedhin et al., 2021). Collagen in the system protects very fine agar particles from secondary aggregation and promotes the establishment of these new interactions after deformation. In contrast, in agar fluid gels where secondary aggregation occurs, the ability to form newly rearranged structures is reduced, and a more pronounced disruption of the close-packed structure is observed.

In both cases high structural recovery was achieved, that helps to prevent bolus stagnation in the pharynx and reduces the risk of esophageal reflux. Additionally, a consistent texture and resistance to fragmentation during the esophageal phase are vital to prevent the formation of large, adhesive bolus fragments that could cause aspiration (Hadde & Chen, 2019; Marconati et al., 2019).

3.4. IDDSI tests

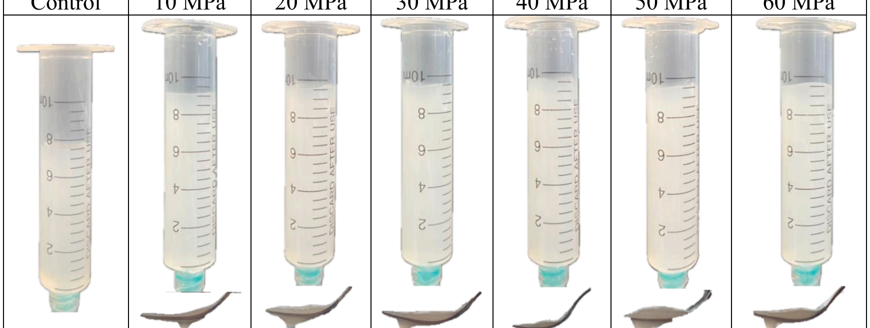
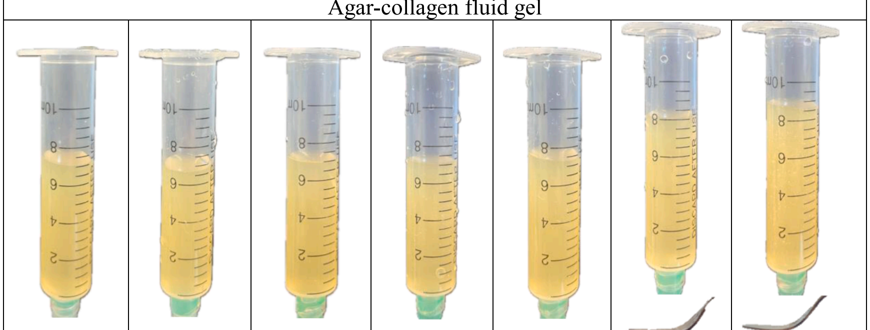
The syringe test is a straightforward method often used by hospital staff, caregivers, and patients with dysphagia to evaluate liquid consistency. Agar and agar–collagen control samples initially demonstrated an IDDSI Level 2 (mildly thick) consistency (Table 5). The transition to Level 3 was observed at a lower pressure for agar fluid gels (10 MPa) compared to agar–collagen fluid gels (50 MPa). An increase in fluid gel thickness provides individuals with dysphagia additional time to control the epiglottis, thereby promoting safer swallowing (Lin et al., 2025a,b,c). Because syringe flow test results primarily depend on fluid shear viscosity, which reflects the sample's intrinsic resistance to flow, the fork drip test outcomes are primarily influenced by fluid yield stress, which represents the properties that resist initial deformation (Cichero et al., 2017). Therefore, the fork drip test was used to evaluate the samples categorized as Level 3 in the syringe test. This test demonstrates how the fluid flows down the edge or tip due to gravity (Hadde & Chen, 2021). As shown in Table 5, agar-collagen fluid gels drip slowly through the fork prongs, leaving no traces on the fork surfaces. In contrast, agar samples drip much more slowly, leaving visible traces on the fork, indicating higher viscosity and cohesiveness (Chen et al., 2026). This behavior confirms the moderately thick (Level 3) consistency of the samples.

A strong correlation was identified between IDDSI classification and apparent viscosity for agar fluid gels. The control sample exhibited a nectar-like consistency (Level 2), whereas pressure-treated samples ranging from 10 to 60 MPa demonstrated a honey-like consistency (Level 3). In contrast, the IDDSI classification of agar–collagen fluid gels did not fully correspond with viscosity measurements. Although all samples exhibited honey-like consistency, they were classified from Level 2 to Level 3 during testing. Similar results were reported by Iman-Saliha et al., 2026, where applying pressure did not change the IDDSI level (remaining at Level 3), although viscosity at 50 s^{-1} changed from nectar-like to honey-like. Overall, the findings indicate that adjusting pressure is an effective, formulation-independent way to control the consistency of fluid gel systems.

3.5. Stability under static and dynamic conditions

The prepared fluid gels remained stable under static conditions throughout the 8-week storage period. No particle sedimentation or a layer of the transparent phase (syneresis) was visually observable. To assess the real impact of applied pressure on stability, the systems were subjected to centrifugal force, and their stability under applied

Table 5
IDDSI levels of agar and agar-collagen fluid gels under different pressures.

Agar fluid gel						
Control	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa	60 MPa
						
Level 2 **(Mildly Thick)**	Level 3 **(Moderately Thick)**					
Agar-collagen fluid gel						
						
Level 2 **(Mildly Thick)**					Level 3 **(Moderately Thick)**	

deformation (under dynamic conditions) was evaluated. All samples exhibited particle sedimentation and phase separation under centrifugal force. It was found that sedimentation degree depended on both homogenization pressure and system composition.

The Fig. 5 indicates that stability increases with increasing pressure, reaching up to 30 MPa in agar and up to 50 MPa in agar-collagen fluid gels. The most pronounced phase separation was observed in the control non-homogenized fluid gels for both agar and agar-collagen. Fluid gels, which are packed suspensions of gel particles, demonstrate this phenomenon primarily because larger particles tend to sediment and precipitate more readily (Norton et al., 1999). This observation is consistent with findings from other studies (Pissia et al., 2024; Wiking et al., 2022). Centrifugal forces disrupt the bonds between agar particles, causing them to clump and settle. It is believed that more weak interactions among the 'hairy' agar particles enhance system stability, which could explain why agar-collagen gel systems tend to be less stable (Fig. 5). In agar-collagen fluid gels, collagen molecules can penetrate between agar particles, reducing connections among them and potentially leading to excessive aggregation when centrifugal forces are applied.

In agar fluid gels, increasing the pressure above 20 MPa led to an increase in average particle size, a phenomenon typically associated with reduced stability. Nevertheless, the systems' stability improved, attributable to increased viscosity, which prevented particle aggregation and settling even under centrifugal force (Goli et al., 2025), which is closely related to the interaction between agar-agar domains discussed previously The predominance of viscosity is apparent in collagen-containing fluid gels, as their dynamic stability values remained consistently lower than those of agar fluid gels alone, even though they possess smaller particle sizes.

4. Conclusion

In summary, we applied high-pressure homogenization to modify the properties of dysphagia-friendly agar-based fluid gels during post-processing. The primary objective of reducing visible particles that could cause discomfort during consumption has been achieved. High-pressure homogenization not only reduces agar particle size but also alters the number of potential interaction sites and changes their structural re-association. These modifications improve the system's thickness and stability. It is important to highlight that these improvements occurred without altering tan δ ($p > 0.05$), confirming that the viscoelastic structure was maintained. These effects were more pronounced in systems containing only agar, because collagen molecules interfered with interactions between agar domains, thereby weakening them. This was also confirmed by the fact that achieving Level 3 consistency according to the IDDSI framework required 10 MPa for the agar fluid gel, whereas the agar-collagen systems required much higher pressures, up to 50 MPa.

This research provides valuable insights into developing foods tailored for dysphagia patients. Its novel approach to modifying food texture eliminates the need for powdered thickeners and extra preparation steps, reducing the risk of errors and inconsistent consistency. Although fluid gels are not a new concept, the application of such systems as dysphagia-oriented formulations is still in its early stages, especially regarding post-processing modification. Future studies should focus on sensory perception among dysphagia patients. At this stage, the limitation of the study is that there is no evaluation of the swallow-related rheological properties during long-term storage, which should also be addressed in further studies.

CRediT authorship contribution statement

Laura Jūrienė: Methodology. **Gintarė Dyglė:** Writing – original draft, Investigation, Formal analysis. **Daiva Leskauskaitė:** Supervision, Data curation, Conceptualization. **Viktorija Eisinaitė:** Writing – review & editing, Supervision, Data curation. **Vilma Petrikaitė:** Methodology, Formal analysis.

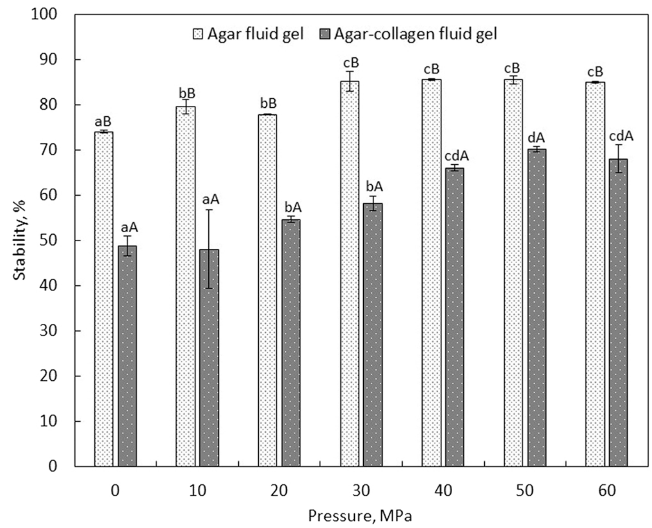


Fig. 5. Stability of agar and agar-collagen fluid gels under dynamic conditions. Values are reported as means±standard deviation; data labeled with different lowercase letters (a–d) showed statistically significant differences ($p < 0.05$) between different pressures for individual fluid gel formulation; data labeled with different uppercase letters (A–B) showed statistically significant differences ($p < 0.05$) between different fluid gel formulations.

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.

Acknowledgments

This project has received funding from the Research Council of Lithuania (LMTLT), project no. S-MIP−25–1 and agreement No S-A-UEI−23–1 (22–12–2023).

Data availability

Data will be made available on request.

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