

Optimizing texture-modified broccoli purées for dysphagia diets in collective catering

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ABSTRACT

Texture-modified foods (TMFs) are essential to ensure safe swallowing in individuals with dysphagia, particularly in collective catering systems where meals are prepared in advance and regenerated before service. However, limited evidence exists on how culinary processing, storage, and regeneration conditions affect the structural stability and sensory suitability of vegetable purées compliant with the IDDSI framework. This study aimed to optimise broccoli purées for collective catering by evaluating the effects of cooking, processing, thickening, storage, and regeneration on texture, colour, stability, and sensory properties, while ensuring compliance with IDDSI Level 4.

The experimental work was conducted in two phases. In Phase 1, the effects of cooking method (boiling vs. steaming), mechanical grinding, and freezing on purée structure were assessed. Steaming cooking and subsequent freezing produced smoother and more cohesive textures, aligning with sensory preferences and indicating improved swallowability. However, these treatments also increased syneresis and led to colour loss, revealing the need to balance structural softening with matrix stability and visual quality. In Phase 2, the impact of hydrocolloids (xanthan gum, xanthan–guar blend, and modified starch) on stability and texture was evaluated after refrigerated storage and regeneration. Gum-based thickeners improved uniformity, reduced adhesiveness, and prevented syneresis, whereas starch-based purées remained firmer and darker. Steam regeneration preserved texture, colour, and sensory quality more effectively than dry heat, which promoted firming and surface dehydration.

Overall, the results demonstrate that combining culinary techniques with tailored thickening strategies can produce stable, palatable broccoli purées suitable for dysphagia diets in professional kitchens. Integrating instrumental and sensory evaluations proved essential for identifying formulations that simultaneously meet safety, sensory, and operational requirements.

1. Introduction

Dysphagia is defined as difficulty or inability to perform normal swallowing, that is, the safe transport of food and liquids from the mouth to the stomach. It is commonly observed worldwide, and its prevalence has increased in recent years (Rajati et al., 2022). The reported prevalence varies considerably depending on the population: from 36.5 % in hospitals (Rivelsrud et al., 2023) to 56.1 % in residential aged-care facilities (Roberts et al., 2024). Dysphagia is associated with severe complications, including malnutrition, dehydration, and aspiration pneumonia, along with psychological and social consequences that

significantly affect quality of life (McGinnis et al., 2019; Coelho-Júnior et al., 2025). Proper management requires early detection, active treatment, and compensatory strategies such as adapting food texture and drink viscosity and controlling posture during swallowing (Yang et al., 2023).

Texture modification is essential for meeting the nutritional needs of individuals with dysphagia (Cichero et al., 2017), who require foods that are not only safe and easy to swallow but also nutritious and sensorially acceptable. This is particularly important in institutional and collective catering settings, where consistency, safety, and sensory quality must be maintained across large-scale production (Miles et al., 2020; Kuo et al.,

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2025). Texture-modified foods (TMFs) are therefore a cornerstone of dysphagia management (Raheem et al., 2021; Liu et al., 2024, 2025). These foods must exhibit specific structural properties—adequate softness, moisture, cohesiveness, and ease of bolus formation—while avoiding sticky, brittle, or runny consistencies that may increase aspiration risk (Tokifuji et al., 2013; Park et al., 2017). Bolus rheology studies further highlight the importance of balanced viscoelasticity in facilitating swallowing (Ishihara et al., 2011; Gallegos et al., 2023).

Despite their importance, global standardization of TMF swallowing related parameters remains limited (Raheem et al., 2021), partly due to insufficient communication between food-service professionals and clinical practitioners. To address this, the International Dysphagia Diet Standardisation Initiative (IDDSI) was established in 2012, providing a universally applicable framework for defining TMFs and liquids across ages, cultures, and care settings (Cichero et al., 2017). Nevertheless, standardized culinary protocols for producing TMFs are still lacking, resulting in inconsistencies in nutritional value, texture, appearance, and sensory quality (Keller et al., 2012; Wu et al., 2022). Moreover, the shelf life and stability of TMFs under cold-chain conditions—critical for collective catering systems—remain scarcely studied. In cold-line workflows, meals are prepared in advance, refrigerated, and regenerated before service (Marcotrigiano et al., 2023), introducing challenges in maintaining quality, safety, and textural integrity. Merino et al. (2020) demonstrated the feasibility of developing stable and sensory-acceptable TMFs for adults with cerebral palsy and dysphagia, representing an important step forward, although available studies still focus largely on ready-to-eat or long-shelf-life products (Abu Zarim et al., 2021; Akçay & Alkan, 2023).

Vegetable consumption is a central recommendation of national and international dietary guidelines (USDA and HHS, 2025; EFSA, 2025; WHO, 2025). However, individuals with dysphagia often struggle to safely consume vegetables in their natural form. Vegetable purées—particularly those derived from fibrous matrices such as broccoli—present specific technological challenges in achieving IDDSI-compliant textures that remain appealing in terms of flavour, colour, and mouth-feel. Processing steps including cooking, freezing, and grinding strongly influence particle size, homogeneity, and colour, with implications for

texture, nutrient retention, and visual quality (Sharma et al., 2017; Giura et al., 2022). Broccoli was selected as the model matrix due to its fibrous structure and intense green pigmentation, which make it particularly sensitive to culinary processing and therefore suitable for evaluating the impact of cooking, processing, storage, and regeneration on texture and visual stability in dysphagia-oriented purées. The adaptation of broccoli purées to central kitchen and collective catering systems requires not only standardisation but also optimisation of culinary processes to ensure safety, stability, and operational feasibility. Complex or time-consuming protocols may hinder implementation, compromising access to inclusive diets for individuals with dysphagia.

Therefore, this study addresses the optimisation of broccoli texture modification from a culinary and gastronomic perspective by evaluating the effects of cooking, mechanical processing, hydrocolloid addition, cold storage and regeneration conditions. The objective was to develop a broccoli-based purée suitable for dysphagia diets, compliant with IDDSI Level 4, and optimised for application in collective catering systems operating under cold-line conditions

2. Materials and methods

2.1. Experimental design

The study was conducted in two sequential experimental phases (Fig. 1), designed to optimize the preparation of broccoli purées suitable for dysphagia diets and to evaluate their technological and sensory stability under realistic storage and regeneration conditions.

2.1.1. Phase 1 – Effect of cooking and processing conditions

The first phase aimed to determine the optimal technological conditions for producing a smooth, homogeneous, and level 4 IDDSI-compliant broccoli purée. Two cooking methods—reflux boiling (BO) and steam oven (ST)—were combined with two mechanical grinding techniques, immersion blender (I) vs. food processor (P) and the application or omission of a freezing step prior to analysis (F). The resulting samples (BO_I, BO_P, ST_I, ST_P, ST_F) were evaluated to identify the combination that provided the most favorable texture and overall

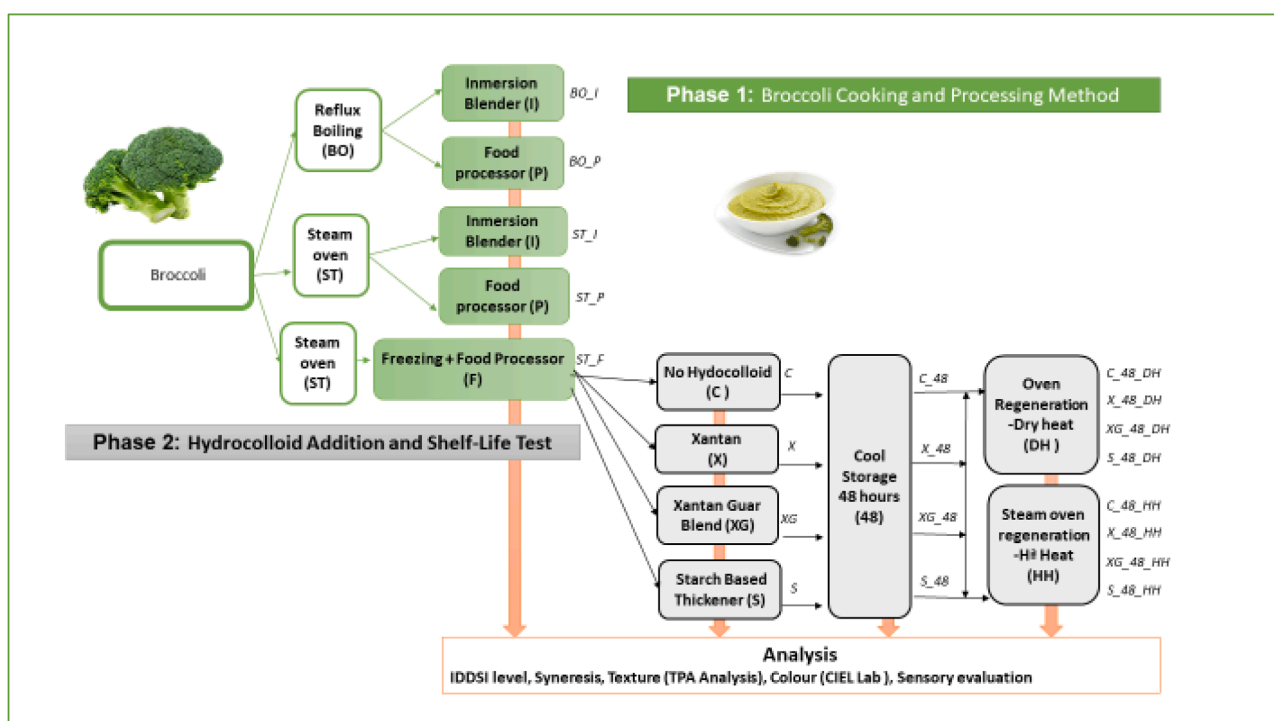


Fig. 1. Experimental design.

suitability for subsequent formulation. Evaluations included IDDSI Level 4 standard testing, syneresis quantification, instrumental texture, colorimetry, and sensory assessment to characterize the physicochemical and organoleptic properties of the purée.

2.1.2. Phase 2 – Effect of hydrocolloids and storage stability

The second phase examined the influence of different hydrocolloids on the technological and sensory stability of broccoli purées vs. control (C). Three thickening agents were tested: xanthan gum (X), a xanthan–guar commercial blend (XG), and a modified starch-based thickener (S) in freshly prepared samples. The samples were subjected to a 48-hour refrigerated storage period (C_48, X_48, XG_48, S_48), followed by regeneration in a combi oven under two programs: dry heat (C_48_DH, X_48_DH, XG_48_DH, S_48_DH) and steam oven cooking (C_48_HH, X_48_HH, XG_48_HH, S_48_HH). This phase aimed to assess the effects of hydrocolloid type and regeneration method on the stability of the textural parameters, syneresis, color, and sensory profile.

2.2. Materials

Broccoli florets (*Brassica oleracea* var. *italica*) were purchased as a frozen product from a local supermarket (Carrefour, Madrid, Spain). Three thickening agents were used: xanthan gum (Tradíssimo S.A., Barcelona, Spain), a commercial thickener based on maltodextrin, xanthan gum and guar gum (Nutilus Clear, Nutricia S.R.L., Spain) and a modified corn starch based thickener (Nutavant, Persan Farma S.L. Spain).

2.3. Sample preparation

2.3.1. Phase 1 – Broccoli cooking and processing method

The procedure for reflux boiling was adapted from (Guillén et al., 2017) consisting in boiling broccoli in water (1:3 ratio) for 8 min. Steam cooking was carried out in a professional combi oven (Rational SCC 61, Italy) at 100 % humidity and 100 °C for 18 min, following the manufacturer's guidelines. Freezing was performed in a conventional freezer at –18 °C (Bosch KE KGNN36A, Spain)

Grinding was carried out either with an industrial immersion blender (Taurus BAPI 1000 Rocket, Spain) for 35 s at maximum power or with a food processor (Blixer 6 v.v, Robot Coupe, Vincennes, France) for 60 s at speed 9 (1000 rpm). For samples cooked in the steam oven and subsequently frozen, grinding was extended to 300 s at speed 9. In all cases, grinding times were chosen based on preliminary studies to achieve an IDDSI level 4.

The freezing step was selectively applied to the steam-cooked sample processed with a food processor (ST_F) as an exploratory condition. This combination was chosen due to its relevance for collective catering workflows, where steam cooking, food processors, and intermediate freezing are commonly used to facilitate stepwise production and storage.

2.3.2. Experiment 2 – Hydrocolloid addition and shelf-life study

Broccoli was steam-cooked (100 % humidity, 100 °C, 18 min), frozen at –18 °C, and ground using the Blixer 6 v.v food processor at speed 9 for about 5 min until an IDDSI Level 4 texture was achieved. Hydrocolloids were incorporated during grinding to ensure uniform distribution at the following concentrations: xanthan gum, 1.6 %; xanthan-guar gum, 1.6 %; starch-based thickener, 2.0 %. Concentrations were determined based on manufacturer recommendations and corroborated with values reported in previous literature on dysphagia-oriented food formulations.

Prepared samples were stored under refrigeration (7 °C) for 48 h. After storage, they were regenerated in a professional combi oven (Rational SCC 61, Italy) for 5 min under two different conditions: dry-heat program (100 °C without humidity) or steam program (100 °C + 100 % humidity), and subsequently analyzed.

2.4. IDDSI assessment

Samples were evaluated at 55 ± 5 °C using IDDSI methods (Cichero et al., 2017), including the Spoon Tilt and Fork Drip tests, to verify compliance with IDDSI Level 4 (puréed foods). These assessments were performed by a single trained researcher with expertise in IDDSI methodology to ensure high reliability and consistency in categorization. These empirical visual methods allowed confirmation of flow behavior, cohesiveness, and particle size.

2.5. Syneresis

Syneresis was determined in duplicate by centrifuging 40 g of sample in 50 mL Falcon tubes at 3140 g for 45 min at 20 °C (Muadklay & Charoenrein, 2008). The amount of separated water was weighed and expressed as percentage of syneresis per 100 g of sample:

$$\% \text{Syneresis} = (\text{g of released water} / \text{g of sample}) \times 100$$

The objective of this determination was to evaluate the structural stability of the purées under accelerated conditions and to detect potential phase separation. Rather than establishing an absolute requirement of 0 % syneresis, this test was used as a practical indicator of water retention capacity and matrix integrity. Low syneresis values were considered desirable to minimize the risk of liquid separation during handling, serving, or oral processing. It should be noted that centrifugation-induced syneresis represents a stress test and does not necessarily reflect visible phase separation under normal consumption conditions.

2.6. Texture profile analysis (TPA)

Texture Profile Analysis (TPA) was performed using a TA-XT2i texture analyzer (Stable Micro Systems, Vienna, Austria). TPA was selected due to its widespread application in the characterization of texture-modified foods for dysphagia and its suitability for formulation screening and process optimization in foodservice contexts (Ibañez et al., 2022). Test conditions were adapted from Sharma et al. (2017) for the characterization of semi-solid, dysphagia-oriented foods.

Samples were placed in cylindrical aluminium molds (10 cm internal diameter, 4.5 cm height), which were completely filled to ensure a consistent and reproducible sample geometry and full confinement during testing. This approach allowed uniform deformation conditions and minimized variability related to sample shape. A cylindrical aluminium probe (P/20R, 20 mm diameter) was used. Measurements were conducted at a test speed of 3 mm/s with a compression level of 33 %, selected to simulate oral deformation conditions relevant to individuals with dysphagia. Two consecutive compression cycles were applied at the centre of the sample. Maximum force (g) was obtained from the peak force of the first compression cycle, adhesiveness (g-s) was calculated as the negative area between the first and second compressions, and cohesiveness was defined as the ratio between the area under the second compression curve and that of the first. Three independent replicates were prepared and analysed for each sample.

2.7. Color evaluation

Color was measured by triplicate using a colorimeter (Konika Minolta CR-400, Osaka, Japan) based on the CIELAB system (L^* , a^* , b^*). Measurements were taken in triplicate. Color differences (ΔE^*ab) were calculated following CIELAB formula (CIE15, 2004):

$$\Delta E^*ab = \sqrt{(L^*m - L^*ref)^2 + (a^*m - a^*ref)^2 + (b^*m - b^*ref)^2}$$

Differences were classified as: $\Delta E^*ab < 3$ (not perceptible to the human eye), or $\Delta E^*ab > 3$ (perceptible to the human eye).

2.8. Sensory evaluation

Sensory analysis was conducted by a technical expert panel consisting of five Food Technologists with extensive experience in descriptive sensory analysis. This panel size is consistent with established methodologies for texture-modified foods where technical precision is prioritized (Ibañez et al., 2022; Merino et al., 2021). Although the assessors were already highly trained in sensory evaluation, two 30-minute calibration sessions were held prior to the study. These sessions were dedicated to reaching a consensus on the definitions of the attributes and standardizing the 10-point intensity scale for this specific broccoli matrix. Broccoli purée samples (10 ± 2 g) were served at 55 ± 5 °C in white dishes with plastic spoons. Attributes assessed included green color, broccoli flavor, homogeneity, consistency, adhesiveness, smoothness, and graininess. Responses were converted into scores from 0 to 10. Evaluation parameters were adapted from Sharma et al. (2017) and Merino et al. (2021).

2.9. Statistical analysis

Results are shown as mean values \pm standard deviation. The number of independent replicates (n) for each analysis is specified in the corresponding methodology section and figure/table descriptions. Data were analyzed by one-way analysis of variance (ANOVA). Significant differences between mean values were assessed using Tukey's *post hoc* test. For all statistical analyses, a 95 % confidence level ($p < 0.05$) was used as the threshold for significance. A multivariate analysis was performed using Principal Component Analysis (PCA) to characterize broccoli purées at the end of the shelf-life study. The analysis included sensory attributes related to texture and swallowing safety (firmness, adhesiveness, smoothness, homogeneity, and graininess), instrumental texture parameters obtained by Texture Profile Analysis (hardness, adhesiveness, and cohesiveness), and syneresis as an additional safety-related indicator. Data were analyzed using Jamovi version 2.6.45 for Mac (Jamovi, 2024). Radar charts for sensory evaluation were plotted on Microsoft Excel®

3. Results

3.1. Phase 1 – Broccoli cooking and processing method

Results of the IDDSI assessment and syneresis evaluation are shown

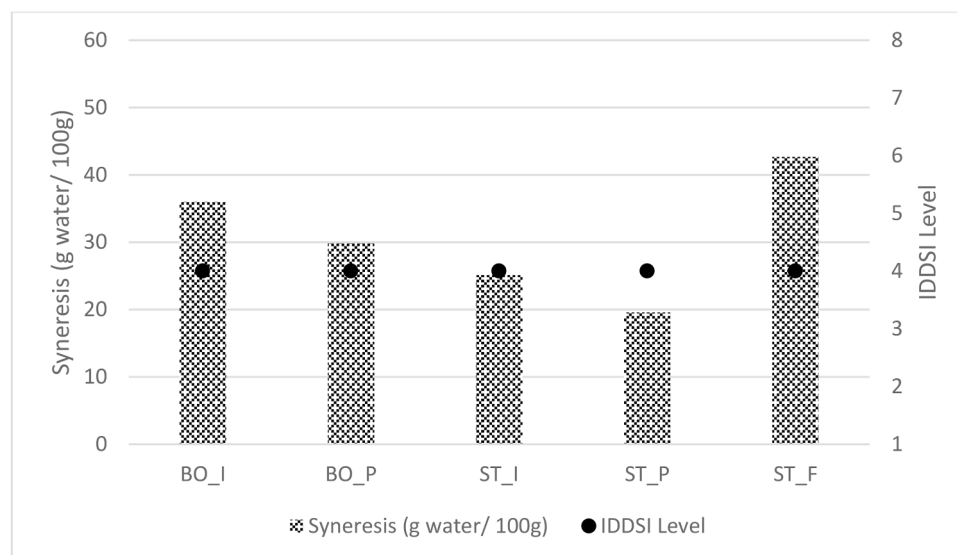


Fig. 2. IDDSI assessment and syneresis of broccoli purées prepared with different cooking and processing methods (Phase1). **Note:** BO: reflux boiling, ST: Steam oven, _I: immersion blender, _P: food processor, _F: freezing and food processor. Bars represent the mean of 2 independent replicates.

in Fig. 2. All broccoli purées met the IDDSI Level 4 requirements in both fork and spoon tests, indicating compliance with the safety criteria established for this study. Regarding syneresis, the undesired leakage of water from foods (Mizrahi, 2010), all preparations showed some degree of water separation. Steam-cooked purées (ST_I and ST_P) exhibited lower syneresis than boiled samples (BO_I and BO_P), while freezing had the greatest impact, markedly increasing water release due to ice-crystal damage to plant tissues (ST_F).

Texture parameters are summarized in Table 1. Steam oven-cooked samples without freezing (ST_I and ST_P) exhibited higher values of maximum force than reflux-boiled samples (BO_I and BO_P). Within each cooking method, purées processed with the food processor (ST_P, BO_P) showed lower values of maximum force than those processed with the immersion blender (ST_I, BO_I), indicating a finer and more homogeneous texture. Sample ST_F (steam cooking + freezing + food processor) presented the lowest values of maximum force ($p < 0.001$).

Adhesiveness was generally higher in immersion blender-processed samples (ST_I, BO_I), regardless of cooking method, while the lowest value was observed in reflux-boiled/food-processor purée (BO_P) ($p < 0.001$). Cohesiveness peaked in sample ST_F, suggesting finer particle size and better bolus formation. Since excessive firmness hinders swallowing, and cohesiveness contributes to bolus uniformity (Giura et al., 2021; Matsuyama et al., 2021), Sample ST_F represents the most favorable texture profile as it presents low firmness and adhesiveness values, along with moderate values of cohesiveness which have been reported as adequate to oral dysphagia feeding (Ismael-Mohammed, 2023)

Color coordinates varied mainly by cooking method (Table 2). Boiled samples (BO_I and BO_P) showed higher L^* (lightness) and more intense green/yellow tones (a^* and b^*), while steam-cooked samples (ST_I and ST_P) were darker and less vivid ($p < 0.001$). Sample ST_F, which included freezing, had intermediate L^* , a^* , and b^* values ($p < 0.001$). Colour differences (ΔE) confirmed that the cooking method was the dominant factor. Changing the processing device (immersion blender vs. food processor) did not significantly affect colour perception ($\Delta E < 1$ for BO_I vs. BO_P and ST_I vs. ST_P comparisons). However, all steam-cooked samples (ST_I, ST_P and ST_F) differed markedly from boiled ones (BO_I and BO_P) ($\Delta E^*ab > 3$) ($p < 0.001$). Freezing (ST_F) further accentuated colour shifts, particularly the loss of green intensity ($p < 0.001$). Thus, reflux boiling better preserved broccoli's bright green–yellow tones, while steam cooking—although texturally advantageous—resulted in duller colors. This highlights a trade-off

Table 1

TPA Analysis of broccoli purées prepared with different cooking and processing methods (Phase1).

	BO_I	BO_P	ST_I	ST_P	ST_F	<i>p</i> *
Maximum force (g)	52.62 ± 1.49a	48.54 ± 1.80b	56.89 ± 2.00c	55.84 ± 1.37ac	45.46 ± 1.26b	< 0.001
Adhesiveness (g/s)	-181.71 ± 7.24a	-118.49 ± 3.15b	-181.67 ± 6.62a	-155.14 ± 5.57c	-154.38 ± 11.96c	< 0.001
Cohesiveness	0.566 ± 0.015ab	0.528 ± 0.028ab	0.612 ± 0.030a	0.498 ± 0.020b	0.698 ± 0.034c	< 0.001

Note: BO: reflux boiling, ST: Steam oven, _I: immersion blender, _P: food processor, _F: freezing and food processor. Values represent the mean of 3 independent replicates ± standard deviation. *One-way ANOVA. Means followed by different letters are significantly different according to Tukey's HSD test ($p < 0.05$).

Table 2

CIELAB parameters and colour differences of broccoli purées prepared with different cooking and processing methods (Phase1).

	BO_I	BO_P	ST_I	ST_P	ST_F	<i>p</i> *
L* (Lightness)	51.97 ± 0.07a	51.67 ± 0.09a	48.63 ± 0.13b	48.67 ± 0.11b	49.54 ± 0.09c	< 0.001
a* (Green tone)	-14.87 ± 0.08a	-14.49 ± 0.07b	-8.13 ± 0.07c	-8.14 ± 0.10c	-8.24 ± 0.15c	< 0.001
b* (Yellow tone)	32.97 ± 0.08a	33.33 ± 0.08b	27.40 ± 0.08c	27.21 ± 0.10c	30.05 ± 0.07d	< 0.001
ΔE*ab vs A1	-	0.61 ± 0.04a	9.36 ± 0.15b	9.45 ± 0.14b	7.65 ± 0.11c	< 0.001
ΔE*ab vs B1	9.36 ± 0.11a	9.21 ± 0.13a	-	0.22 ± 0.12b	2.81 ± 0.05c	< 0.001
ΔE*ab vs C	7.65 ± 0.11a	7.37 ± 0.12a	2.81 ± 0.12b	2.97 ± 0.11b	-	< 0.001

Note: BO: reflux boiling, ST: Steam oven, _I: immersion blender, _P: food processor, _F: freezing and food processor. Values represent the mean of 3 independent replicates ± standard deviation. *One-way ANOVA. Means followed by different letters are significantly different according to Tukey's HSD test ($p < 0.05$).

between visual appeal and functional texture.

Sensory results are presented in Fig. 3. Boiled purées (BO_I and BO_P) were perceived as more consistent and slightly firmer, likely due to higher water retention and viscosity. In contrast, steam cooking combined with freezing markedly improved sensory texture: Sample ST_F (steam cooked, frozen, and processed with a food processor) was rated lowest in consistency but highest in smoothness, cohesiveness, and overall homogeneity. The influence of the processing device was

limited. Although BO_P (boiled + food processor) showed slightly reduced smoothness, no consistent trend related to equipment was observed. Overall, cooking method and freezing were the main contributors to the observed textural differences. Regarding colour perception, boiled samples (BO_I and BO_P) were rated as greener, in agreement with instrumental colour measurements. Steam-cooked purées (ST_I and ST_P) were perceived as less green but scored higher in aroma and flavour intensity.

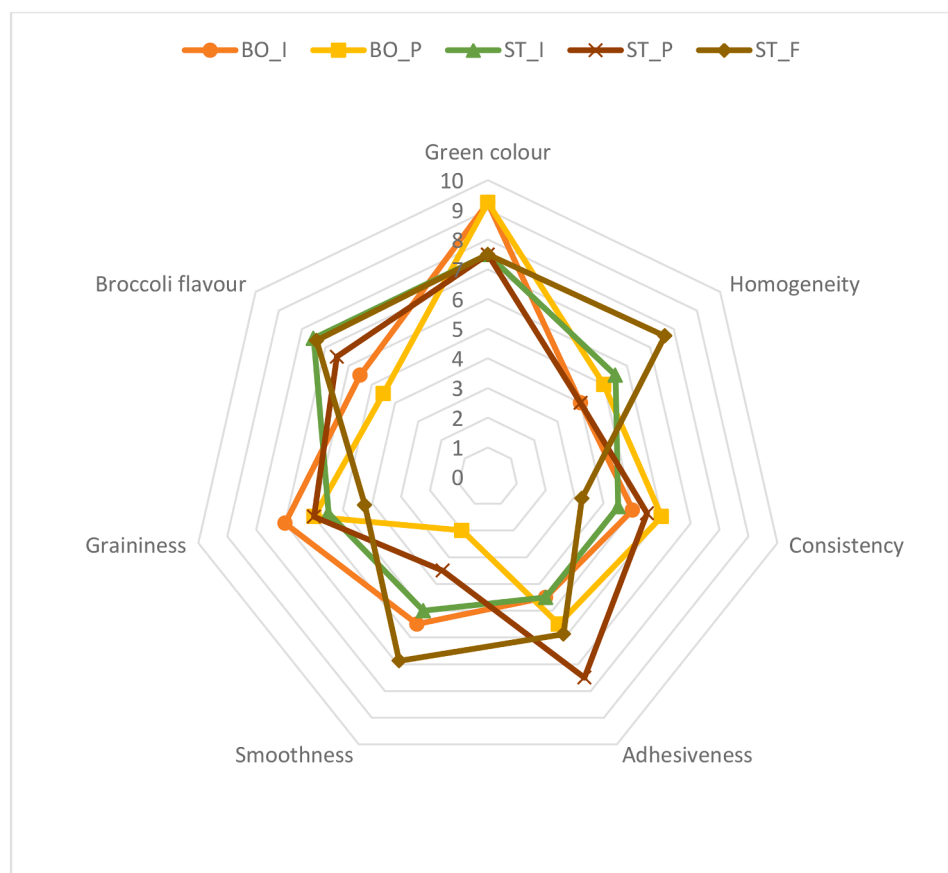


Fig. 3. Sensory analysis of broccoli purées prepared with different cooking and processing methods (Phase1). **Note:** BO: reflux boiling, ST: Steam oven, _I: immersion blender, _P: food processor, _F: freezing and food processor. Data represent the mean values of the sensory panel ($n = 5$ independent assessors).

Although the influence of cooking methods on the chemical composition and nutritional quality of broccoli has been widely studied (dos Reis et al., 2015; Soares et al., 2017; Wu et al., 2019), comparatively little attention has been paid to how cooking and mechanical processing affect texture adaptation for dysphagia-oriented foods. Most previous research has focused on nutrient retention or general sensory quality, rather than on the rheological and structural properties that directly determine swallowing safety in TMFs. In this study, the results demonstrate that the basic structure of broccoli purées is strongly influenced by the cooking method, blending technique, and freezing step, even when all samples comply with IDDSI Level 4. From a dysphagia perspective, excessive firmness may hinder bolus transport, whereas adequate cohesiveness contributes to bolus integrity and safer swallowing (Giura et al., 2021; Matsuyama et al., 2021). Under this framework, sample ST_F exhibited the most favourable textural profile, combining low perceived firmness with high smoothness, cohesiveness, and homogeneity. Steaming followed by freezing resulted in the smoothest and most cohesive purée, in agreement with previous observations in vegetable-based purées (Alvarez et al., 2009).

A direct comparison between boiling and steam cooking highlights a clear texture–colour trade-off. In line with Borowski et al. (2015), steam-based cooking methods promoted more favourable sensory texture attributes, which have been associated with greater firmness linked to protopectin content, while boiled broccoli scored lower in sensory texture quality. Conversely, regarding visual attributes, our results are consistent with Turkmen et al. (2006), who reported that boiling better preserved chlorophyll a and b and maintained a greener colour compared with steaming, despite both methods inducing pigment degradation relative to fresh broccoli.

In the present study, this trade-off was evident: steam cooking, particularly when combined with freezing (ST_F), improved textural properties relevant to swallowing safety but was associated with increased syneresis and greater colour loss. These findings confirm that, in dysphagia-oriented formulations, textural optimisation may come at the expense of visual quality, underscoring the need for subsequent stabilization strategies to balance functionality and appearance.

Establishing suitable texture characteristics is essential for developing foods adapted to dysphagic individuals. According to Ibañez et al. (2022), integrating instrumental and sensory evaluations provides a reliable approach to characterize and optimize food textures for safe swallowing. Following this rationale, in the present study the optimal

cooking and processing method for broccoli purées was selected based on both instrumental TPA and sensory evaluation results. Sample ST_F was therefore chosen as the base formulation for Experiment 2, as it provided the most balanced combination of texture, cohesion, and sensory quality—making it the most suitable starting point for further optimization with hydrocolloids and for the subsequent shelf-life study.

3.2. Experiment 2: Hydrocolloid addition and shelf-life test

3.2.1. Comparison of the effects of hydrocolloid addition in broccoli purées

The effects of adding thickeners are shown in Fig. 4 and Tables 3 and 4 (freshly prepared samples). All broccoli purée samples containing different hydrocolloids, as well as the control, were classified as IDDSI Level 4 in both the fork and spoon tests, as intended in the formulation objectives. However, syneresis analysis revealed clear differences among formulations, highlighting the advantages of gum-based thickeners. Both xanthan gum (X) and the xanthan–guar blend (XG) effectively prevented water separation, maintaining a homogeneous and stable matrix. In contrast, the purée thickened with modified starch (S) showed syneresis levels comparable to the control sample (C), indicating lower water-retention capacity. From a dysphagia safety perspective, the critical concern is visible or gravity-induced phase separation prior to or during consumption, as free liquid may alter bolus cohesiveness and flow behaviour. Although centrifugation-induced syneresis represents an accelerated stability test rather than real serving conditions, higher values suggest reduced matrix integrity and a greater likelihood of liquid separation during handling or oral processing.

TPA (Table 3) showed that hydrocolloid type had a notable influence on the structural properties of the purées, with significant differences observed for maximum force, adhesiveness and cohesiveness ($p < 0.001$). The control sample (C), without added thickener, displayed intermediate maximum force value but the highest adhesiveness. Xanthan gum (X) reduced maximum force value by $>40\%$ compared with the control and markedly decreased adhesiveness, producing a softer and less sticky matrix. The xanthan–guar mixture (XG) produced similar effects, though with slightly higher maximum force value and adhesiveness than xanthan alone. Notably, it achieved the highest cohesiveness values, which may favour bolus integrity during swallowing. These results suggest that gum-based systems provide a well-balanced texture, combining low stickiness with good cohesion. In contrast, the starch-thickened purée (S) was the firmest formulation, clearly

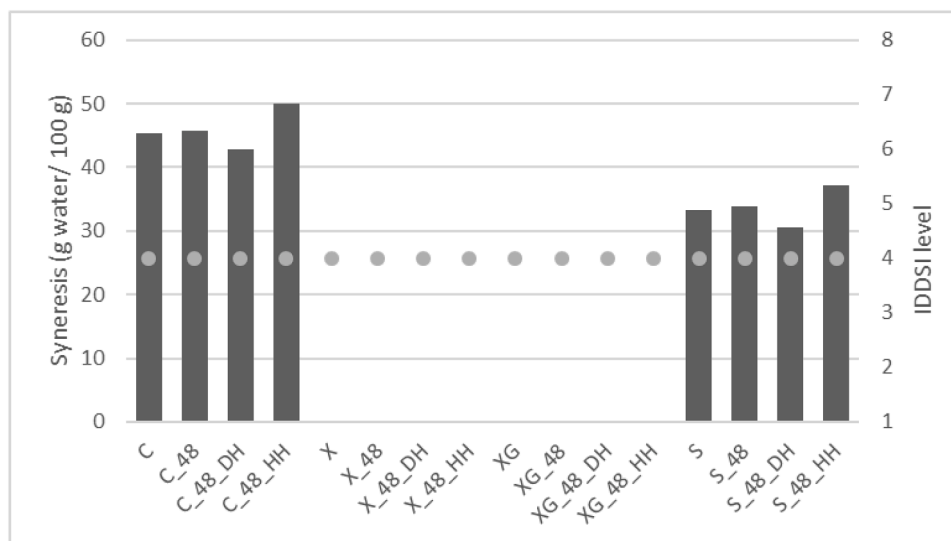


Fig. 4. IDDSI compliance and syneresis during hydrocolloid addition and shelf-life study of broccoli purées (Phase 2). **Note:** C: control, X: xanthan, XG: xanthan-guar blend, S: starch based thickener, _48: 48 hours' storage under refrigeration, _DH: dry heat regeneration, _HH: Humidity heat regeneration. Bars represent the mean of 2 independent replicates.

Table 3

TPA of experiment 2 during hydrocolloid addition and shelf-life study of broccoli purées (Phase 2).

	Control (C)	Xanthan gum (X)	Xanthan guar blend (XG)	Starch based thickener (S)	<i>p</i> *
Maximum force (g)					
Freshly prepared	53.90 ± 0.29aA	29.91 ± 1.54bA	36.77 ± 0.44cA	61.68 ± 4.06d	< 0.001
48 h refrigeration	55.73 ± 1.40aA	32.82 ± 0.65bB	38.19 ± 0.96cA	59.52 ± 2.46d	< 0.001
Refrigeration + Dry heat oven	59.22 ± 1.19aB	37.12 ± 0.98bC	43.03 ± 1.64cB	62.31 ± 1.67a	< 0.001
Refrigeration + Steam oven	54.87 ± 0.94aA	31.47 ± 1.44bAB	39.04 ± 1.20bA	57.89 ± 1.83a	< 0.001
<i>p</i> *	< 0.001	< 0.001	< 0.001	0.070	
Adhesiveness (g/s)					
Freshly prepared	-182.53 ± 18.20aAB	-79.50 ± 1.86b	-96.61 ± 2.20bA	-163.88 ± 13.93a	< 0.001
48 h refrigeration	-175.81 ± 4.90aA	-82.28 ± 0.80b	-93.29 ± 2.72cA	-160.41 ± 5.07d	< 0.001
Refrigeration + Dry heat oven	-197.87 ± 0.61aB	-91.96 ± 13.05b	-133.59 ± 11.53cB	-161.20 ± 7.33d	< 0.001
Refrigeration + Steam oven	-188.29 ± 5.96aAB	-84.42 ± 1.658b	-92.12 ± 14.59bA	-163.89 ± 4.71c	< 0.001
<i>p</i> *	0.018	0.055	< 0.001	0.881	
Cohesiveness					
Freshly prepared	0.710 ± 0.012aA	0.820 ± 0.013b	0.831 ± 0.002b	0.732 ± 0.013aAB	< 0.001
48 h refrigeration	0.740 ± 0.030aAB	0.850 ± 0.841b	0.860 ± 0.016b	0.716 ± 0.015aA	< 0.001
Refrigeration + Dry heat oven	0.790 ± 0.030aB	0.830 ± 0.028b	0.840 ± 0.022b	0.745 ± 0.014cB	< 0.001
Refrigeration + Steam oven	0.760 ± 0.030aAB	0.860 ± 0.030b	0.860 ± 0.028b	0.730 ± 0.012aAB	< 0.001
<i>p</i> *	0.002	0.175	0.068	0.027	

Note: Values represent the mean of 3 independent replicates ± standard deviation *One-way ANOVA. Means followed by different letters (rows a->d; columns A->D) are significantly different according to Tukey's HSD test ($p < 0.05$).

exceeding the hardness of the control. Adhesiveness remained comparable to the control, while cohesiveness was lower than in gum-based purées.

Colour analysis (Table 4) also showed that hydrocolloid type influenced the visual appearance of the purées, with significant differences in L^* and b^* coordinates ($p < 0.001$). Both xanthan (X) and starch (S) produced lighter samples (higher L^* values) with more yellowish tones (higher b^* values) than the control (C), whereas no significant differences were detected along the green-red axis (a^*). The ΔE^* values ($p < 0.001$) indicated perceptible colour changes relative to the control, most pronounced in the xanthan- (X) and starch-thickened purées (S), while the xanthan-guar blend (XG) produced smaller and less noticeable deviations.

Overall, the results clearly demonstrate that gum-based hydrocolloids—particularly xanthan (X) and the xanthan-guar blend (XG)—provide superior structural stability and water retention compared with modified starch (S) and the control formulation (C). The absence of syneresis in X and XG confirms their ability to maintain a stable and homogeneous matrix, a critical characteristic for dysphagia-oriented foods where water separation can compromise bolus integrity and safety (Mizrahi, 2010). These outcomes are consistent with previous studies highlighting the higher water-binding capacity of gums relative to starch-based thickeners (Pematilleke et al., 2021).

Beyond stability, textural parameters further reinforce the advantages of gum-based formulations. Xanthan substantially reduced maximum force values and adhesiveness, while the xanthan-guar blend

Table 4

CIELAB parameters during hydrocolloid addition and shelf-life study of broccoli purées (Phase 2).

	Control (C)	Xanthan gum (X)	Xanthan guar blend (XG)	Starch based thickener (S)	<i>p</i> *
<i>L</i>* value					
Freshly prepared	51.25 ± 1.71aA	57.04 ± 0.67bA	53.08 ± 0.36aA	55.91 ± 0.36bA	< 0.001
48 h refrigeration	50.35 ± 1.11aA	55.05 ± 0.87bA	53.08 ± 0.28bA	54.42 ± 0.27bB	< 0.001
Refrigeration + Dry heat oven	41.28 ± 1.44aB	45.31 ± 0.47bB	43.79 ± 0.38abB	44.96 ± 0.38bC	< 0.001
Refrigeration + Steam oven	47.99 ± 0.32aA	52.26 ± 0.62bC	50.81 ± 0.48bC	51.23 ± 0.33bD	< 0.001
<i>p</i> *	< 0.001	< 0.001	< 0.001	< 0.001	
<i>a</i>* value					
Freshly prepared	-9.62 ± 0.22A	-10.21 ± 0.63A	-9.94 ± 0.08A	-10.10 ± 0.72A	0.526
48 h refrigeration	-9.21 ± 0.39aA	-10.42 ± 0.65bA	-9.94 ± 0.34abA	-10.14 ± 0.26abA	0.046
Refrigeration + Dry heat oven	-7.32 ± 0.44aB	-8.55 ± 0.31bA	-7.92 ± 0.23abB	-8.24 ± 0.32bB	0.011
Refrigeration + Steam oven	-15.80 ± 0.29aC	-17.03 ± 0.28bB	-16.94 ± 0.33bC	-17.01 ± 0.20bC	0.001
<i>p</i> *	< 0.001	< 0.001	< 0.001	< 0.001	
<i>b</i>* value					
Freshly prepared	16.43 ± 0.94aA	21.62 ± 0.37bA	18.27 ± 0.23cA	21.01 ± 0.27bA	< 0.001
48 h refrigeration	30.56 ± 0.30aB	35.35 ± 0.53bB	31.95 ± 0.28cB	33.42 ± 0.30dB	< 0.001
Refrigeration + Dry heat oven	28.71 ± 1.00aB	32.83 ± 0.33bC	29.70 ± 0.19aC	31.88 ± 0.26bC	< 0.001
Refrigeration + Steam oven	33.40 ± 0.59aC	35.93 ± 0.27bB	33.35 ± 0.40dD	34.25 ± 0.39aB	< 0.001
<i>p</i> *	< 0.001	< 0.001	< 0.001	< 0.001	
ΔE^* vs C	-	7.80 ± 0.53a	2.63 ± 0.15b	6.57 ± 0.46a	< 0.001
ΔE^* vs C	-	7.80 ± 0.53a	2.63 ± 0.15b	6.57 ± 0.46a	< 0.001

Note: Values represent the mean of 3 independent replicates ± standard deviation *One-way ANOVA. Means followed by different letters (rows a->d; columns A->D) are significantly different according to Tukey's HSD test ($p < 0.05$).

achieved the highest cohesiveness—properties considered desirable for reducing swallowing effort and promoting bolus integrity [Matsuyama et al., 2021]. Conversely, the starch formulation produced the firmest and relatively adhesive structure, likely due to gel strengthening and retrogradation phenomena.

Regarding visual attributes, hydrocolloid addition produced moderate lightening and yellowing, particularly in samples containing xanthan or starch. This behaviour is consistent with previous reports describing colour shifts associated with hydrocolloid incorporation in vegetable matrices (Ribes et al., 2021; Abu Zarim et al., 2021; Ekonomou et al., 2024). The xanthan-guar blend induced the smallest colour deviation (lower ΔE^*), which may be advantageous when preserving the natural appearance of vegetable purées is a priority when preparing TMF.

To sum up, gum-based formulations provide a more favorable balance of stability, texture and safety characteristics than starch-thickened or non-thickened alternatives, supporting their application in dysphagia-appropriate broccoli purées.

3.2.2. Shelf-life study of broccoli purées

All formulations maintained IDDSI Level 4 consistency under all tested conditions—freshly prepared, after 48 h of refrigerated storage, and following regeneration with either dry heat or steam (Fig. 4). Syneresis behaviour mirrored that of fresh samples: xanthan and the

xanthan–guar blend effectively prevented water separation, whereas the control and the starch-thickened purée exhibited visible phase separation, particularly after steam regeneration.

Textural stability after 48 h of refrigerated storage and subsequent regeneration is presented in Table 3. Refrigerated storage induced only minor modifications across formulations. Maximum force values did not show significant changes in the control (C_48), xanthan-thickened (X_48), or xanthan–guar–thickened (XG_48) purées, indicating good short-term structural stability under refrigeration. Regeneration exerted a much greater influence on texture. Dry-heat treatment (0 % humidity) increased hardness and adhesiveness across all formulations, with the largest rise (>15 %, $p < 0.001$) observed in the control (C_48_DH) and in the xanthan–guar (XG_48_DH) blend. Steam regeneration (100 % humidity), in contrast, preserved hardness values much more effectively, resulting in textures closely resembling those of freshly prepared purées. Adhesiveness was clearly influenced by the type of thickener. No significant changes were detected in the control, xanthan-thickened, or starch-thickened samples during refrigeration or regeneration. However, the xanthan–guar formulation (XG_48_DH) exhibited a significant increase in adhesiveness after dry-heat regeneration ($p < 0.001$), indicating that the combination of gums is more sensitive to dehydration during heating. Cohesiveness remained stable across all samples, with no significant differences during storage or after either regeneration method. When comparing formulations within each phase of the study—fresh, refrigerated storage, and both regeneration conditions—all textural parameters (hardness, adhesiveness, and cohesiveness) showed significant differences between thickeners ($p < 0.001$). Overall, xanthan and the xanthan–guar blend provided the most favorable textural behaviour after storage and regeneration, maintaining soft, cohesive structures with limited increases in firmness. In contrast, starch-thickened purées remained the firmest and least deformable under both dry-heat and steam regeneration. Establishing suitable texture characteristics is essential for developing foods adapted to dysphagic individuals. In this study, TPA was selected as the primary instrumental approach because it is one of the most widely used and accepted methods for characterizing semi-solid and puréed TMFs. As highlighted in the systematic review by Ibañez et al. (2022), over 38 studies have successfully applied TPA to dysphagia-oriented products, using parameters such as firmness, adhesiveness, and cohesiveness as instrumental proxies for sensory attributes and swallowing-related performance. In the context of collective catering and foodservice applications, TPA offers several practical advantages, including standardized protocols and the ability to rapidly screen multiple formulations under realistic production conditions. However, it is important to clarify that TPA parameters serve as texture proxies rather than direct measurements of swallowing biomechanics.

Colour evolution during storage and regeneration is shown in Table 4. Significant changes in L^* occurred during shelf-life testing across all samples, particularly under dry-heat regeneration in the control and under both regeneration methods in the xanthan- and xanthan–guar–thickened samples. Starch-thickened purées also showed significant L^* differences after refrigeration and regeneration. When comparing thickeners at each stage of the study, significant differences were observed in fresh samples, after refrigerated storage, and after steam regeneration, but not after dry-heat regeneration. For the a^* coordinate, differences between thickeners were only significant under steam regeneration ($p = 0.001$). During refrigerated storage, all samples maintained their initial a^* values, but regeneration induced significant shifts across formulations. The behaviour of b^* closely resembled that of L^* , showing significant changes during shelf life in all samples and significant differences between thickeners at all stages of the study. These colour shifts translated into perceptible visual differences: dry-heat regeneration caused sample darkening (lower L^* , higher a^*), while steam regeneration enhanced green tones (more negative a^*) and increased lightness (higher L^*), resulting in a fresher appearance.

Sensory analysis corroborated several instrumental findings. Under

dry-heat regeneration (Fig. 5), xanthan-based purées (X_48_DH, XG_48_DH) were described as lighter and paler green, whereas the control (C_48_DH) and starch-thickened sample (S_48_DH) appeared darker. In terms of texture, starch-thickened purées were perceived as the firmest, adhesiveness was highest in the control and lowest in xanthan-thickened samples, and graininess was most pronounced in the control. With steam regeneration (Fig. 5), the same overall patterns were observed. The starch-thickened purée (S_48_HH) again showed the highest firmness, whereas the xanthan-thickened sample (X_48_HH) was perceived as the smoothest and least grainy. Comparing regeneration conditions, steam consistently enhanced homogeneity and reduced perceived firmness and graininess.

PCA was performed to explore the relationships between instrumental measurements, sensory attributes, thickening systems, and regeneration conditions (Fig. 6). Following the Kaiser criterion, only principal components with eigenvalues > 1 were retained. Consequently, the first two principal components were selected, explaining a substantial proportion of the total variance (77.3 % in total; PC1: 51.9 % and PC2: 25.4 %). PC1 primarily reflected variation in texture-related attributes. Positive PC1 scores were associated with higher smoothness, homogeneity, and cohesiveness, while negative PC1 scores were linked to higher maximum force, syneresis, and perceived consistency. Accordingly, xanthan- and xanthan–guar–thickened purées regenerated with steam (X_48_HH, XG_48_HH) were located on the positive side of PC1, reflecting their softer, more cohesive, and homogeneous structure. In contrast, control and starch-thickened samples, particularly after dry-heat regeneration (C_48_DH, S_48_DH), were positioned on the negative side, associated with firmer texture, higher syneresis, and lower sensory smoothness. PC2 was mainly related to adhesiveness and consistency attributes. Samples regenerated under dry-heat conditions tended to score higher along PC2, indicating increased adhesiveness and consistency perception, whereas steam-regenerated samples were positioned closer to the origin or at lower PC2 values, confirming the moderating effect of moisture during reheating. Overall, PCA revealed separation patterns according to thickener type and regeneration method, highlighting the strong alignment between instrumental texture parameters and sensory perceptions. The close proximity between sensory attributes (smoothness, homogeneity) and instrumental indicators (lower maximum force and syneresis) supports the consistency of both approaches in characterizing dysphagia-appropriate textures.

Storage and regeneration conditions influenced the structural properties of the broccoli purées, although their IDDSI Level 4 classification remained stable throughout the study. From an operational perspective, these findings are particularly relevant for cold-line catering systems, where texture-modified meals are commonly prepared in advance, refrigerated, and regenerated at the point of service. The choice of both thickening system and regeneration method therefore becomes a critical control point for ensuring consistent texture and swallowing safety. Textural behaviour was primarily affected by the regeneration method. As previously reported for TMFs, refrigerated storage caused only mild structural changes that did not compromise swallowing safety (Merino et al., 2021). In our study, hardness increased slightly during cold storage in some formulations, consistent with weak gel strengthening or incipient retrogradation phenomena. Regeneration had a more pronounced effect: dry-heat treatment promoted surface dehydration, which increased hardness and adhesiveness, whereas steam regeneration better preserved softness and cohesiveness by maintaining moisture within the matrix. These results reinforce that humidity during reheating is critical to prevent matrix collapse and maintain dysphagia-appropriate textures, in line with observations by Dick et al. (2021). Hydrocolloid type played a key role during storage and reheating. Gum-based systems (xanthan and xanthan–guar) retained more favourable textural properties than starch-thickened purées, which remained the firmest under all conditions. This behaviour aligns with previous findings reporting greater flexibility, higher water-binding capacity, and improved bolus formation in gum-based matrices

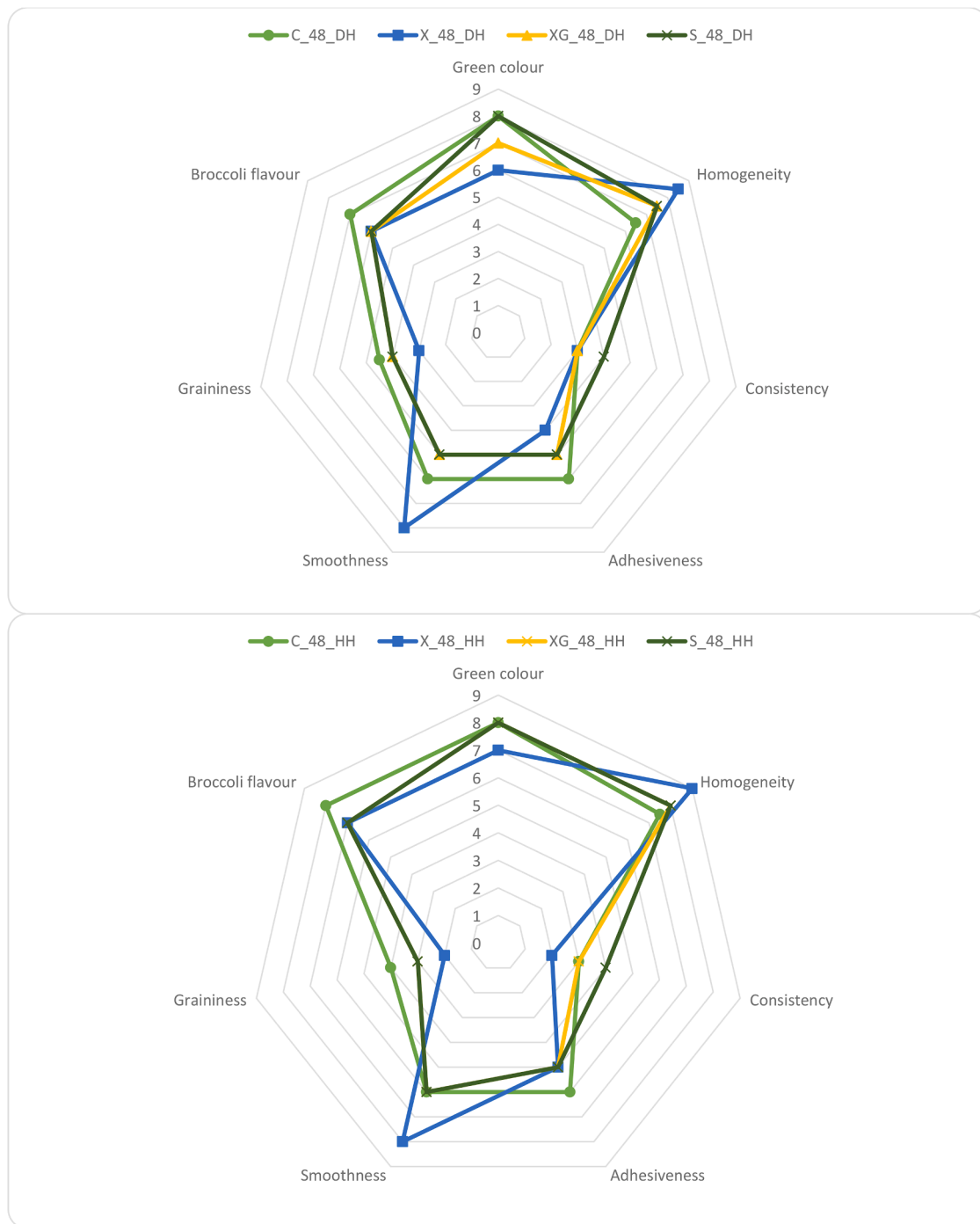


Fig. 5. Sensory profile of broccoli purées after 48 h of refrigerated storage and subsequent regeneration (Phase 2). **Note:** C: control, X: xanthan, XG: xanthan-guar blend, S: starch based thickener, _48: 48 hours' storage under refrigeration, _DH: dry heat regeneration, _HH: Humidity heat regeneration. Data represent the mean values of the sensory panel ($n = 5$ independent assessors).

compared with starch systems (Pematilleke et al., 2021). The stability of cohesiveness across conditions further supports the suitability of these gum-based formulations for dysphagia diets. Colour evolution during storage and regeneration also depended on the thickening system. Storage at 7 °C produced moderate increases in b^* values, indicating slight yellowing, consistent with colour shifts previously described in TMFs (Abu Zarim et al., 2021; Akçay & Alkan, 2023). Some hydrocolloids have been reported to provide partial colour protection by reducing pigment degradation during refrigerated storage (Ribes et al., 2021), a trend partially reflected in our xanthan-guar formulation. Regeneration effects were stronger: dry-heat treatment caused sample

darkening (lower L^* , higher a^*), while steam regeneration increased lightness and intensified green tones, generating a fresher appearance. These results highlight the importance of selecting adequate reheating conditions to maintain visual quality in texture-modified vegetable dishes. Sensory analysis corroborated many instrumental findings and emphasized the relevance of hydrocolloid type and regeneration method in determining suitability for dysphagia-oriented foods. Purées thickened with xanthan were consistently perceived as the smoothest and least grainy, while starch-based samples were rated as the firmest. Steam regeneration produced higher smoothness, greater homogeneity, and reduced graininess compared with dry-heat treatment, confirming the

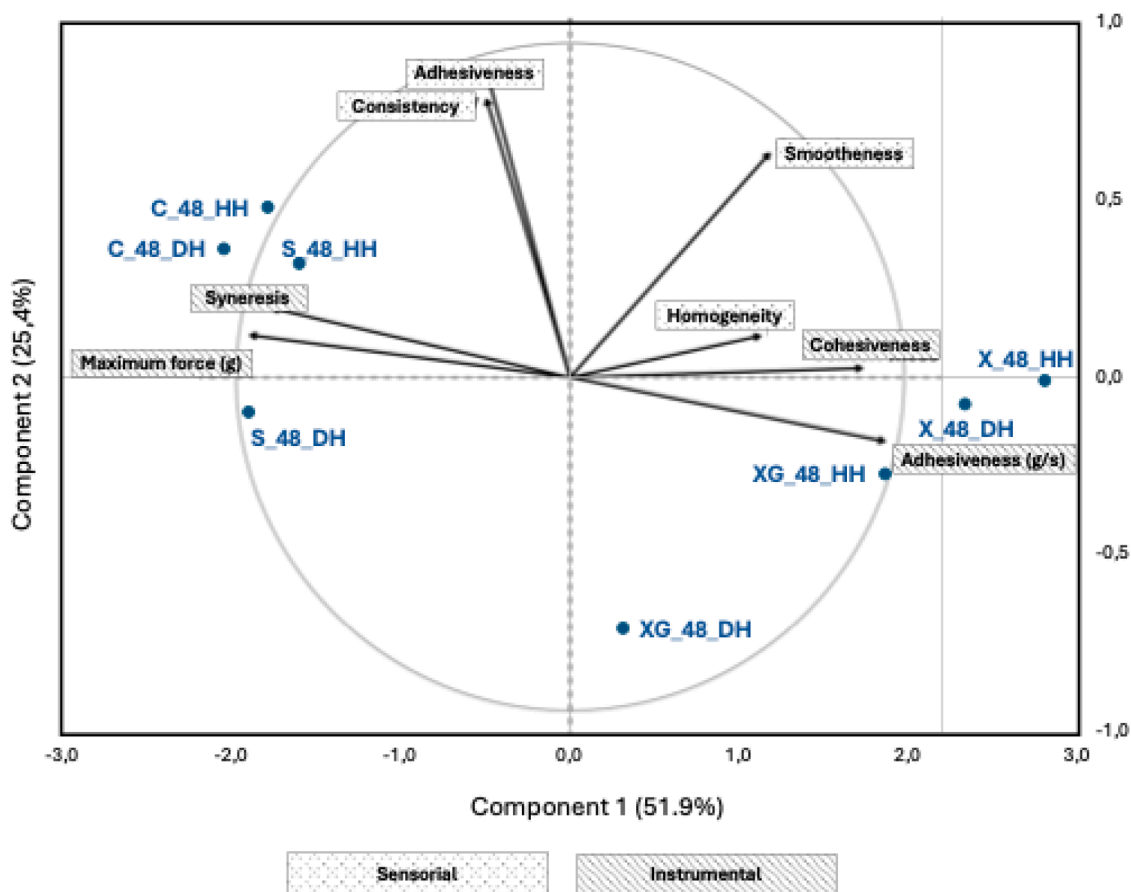


Fig. 6. Principal component analysis (PCA) plot of instrumental measurements and sensory attributes related to texture and swallowing safety of broccoli purées after 48 h of refrigerated storage and subsequent regeneration (Phase 2). **Note:** Symbols represent the mean values of instrumental ($n = 3$) and sensory ($n = 5$) parameters. C: control, X: xanthan, XG: xanthan-guar blend, S: starch based thickener, _48: 48 hours' storage under refrigeration, _DH: dry heat regeneration, _HH: Humidity heat regeneration.

critical role of moisture in preserving dysphagia-appropriate textures. These sensory findings should nevertheless be interpreted with caution, as the evaluation was conducted by a small technical panel, which, while appropriate for texture profiling, does not capture hedonic preferences or inter-individual variability in dysphagic populations.

Moreover, the integration of instrumental and sensory analyses has been proposed as a robust strategy to better understand and optimize the texture of foods designed for dysphagic individuals (Guénard-Lampron et al., 2021). In line with this approach, the selection of the most suitable thickening system in our study was guided by both instrumental and sensory performance, while incorporating an additional safety-oriented criterion, syneresis control, to ensure matrix stability and swallowing safety throughout storage and regeneration.

From a manufacturing perspective, the interaction between hydrocolloid type and regeneration method can be considered a key process control factor influencing product consistency and stability after storage. In centralized production systems, the use of gum-based stabilizers improves batch reproducibility by limiting hardness increase and syneresis during refrigeration. In addition, steam regeneration reduces textural defects associated with surface dehydration compared with dry heat, supporting more consistent quality at the point of service. These findings provide practical guidance for optimizing formulation and reheating protocols in cold-line catering and industrial foodservice settings.

4. Conclusions

The combination of gum-based thickeners—particularly xanthan

gum—and steam regeneration was found to be critical for producing broccoli purées that maintain IDDSI Level 4 compliance with optimal texture stability throughout refrigerated storage and reheating. Within the experimental conditions evaluated, both formulation strategy and regeneration method proved decisive in determining the structural integrity and technological performance of dysphagia-oriented purées.

Steam cooking combined with freezing and mechanical processing produced purées with enhanced smoothness and cohesiveness, although these treatments also increased susceptibility to syneresis. The incorporation of hydrocolloids effectively mitigated this limitation, confirming their central role in stabilizing vegetable purée matrices. Among the tested thickeners, xanthan gum showed the most balanced performance, characterized by reduced hardness and adhesiveness, adequate cohesiveness, minimal syneresis, and improved colour stability. The xanthan-guar blend also provided favorable structural properties, particularly in terms of cohesiveness, although slightly higher firmness and yellowing were observed. In contrast, modified starch formulations exhibited higher firmness and adhesiveness, indicating lower structural adaptability under the tested conditions.

Regeneration method significantly influenced final product quality. Steam regeneration (100 % humidity) better preserved softness, cohesiveness, and colour lightness, whereas dry-heat regeneration promoted surface dehydration, resulting in increased firmness and darkening. Within the experimental framework of this study, the combination of gum-based thickeners with steam regeneration provided the most consistent technological performance after storage.

From an applied manufacturing perspective, the inclusion of refrigerated storage and regeneration stages provides actionable information

for cold-line catering and centralized production systems. The identified formulation–process combinations may assist food manufacturers and institutional kitchens in optimizing production protocols, improving batch consistency, and reducing texture variability during storage and service. The stability of xanthan- and xanthan–guar–thickened purées after storage and steam reheating further supports their suitability for batch preparation, centralized production, and on-demand service in institutional foodservice settings such as hospitals and nursing homes.

Despite the robustness of the data, several limitations should be acknowledged. The sensory evaluation was conducted by a small technical expert panel, appropriate for texture profiling but not representative of hedonic preferences or the full variability of dysphagic populations. In addition, microbiological stability during storage was not assessed and remains necessary to confirm practical implementation in foodservice environments. Additionally, while TPA and IDDSI testing provided valuable structural information, future work should incorporate rheological characterization (e.g., flow curves and yield stress) to further elucidate oral processing behavior. Consequently, the findings of this study relate to instrumental texture proxies and do not describe direct swallowing biomechanics. Further studies integrating hedonic preferences, microbiological validation and rheology would strengthen the translation of these findings into operational practice.

Ethical statement

The sensory evaluation involved adult volunteer panellists and did not include vulnerable populations, clinical interventions, or the collection of sensitive personal data. The study was conducted prior to the establishment (June 2025) of the Research Ethics Committee (Comisión de Ética en la Investigación, CEIN) at the University of Zaragoza, which was created to evaluate non-biomedical research involving human participants.

At the time the study was performed, formal ethical approval was not required under the applicable institutional framework. The research was conducted in accordance with the ethical principles of the Declaration of Helsinki (as revised in 2013). All participants were informed about the study procedures, participation was voluntary, informed consent was obtained, no personal data were disclosed, and participants were free to withdraw at any time.

Declaration of generative ai and ai-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT (GPT-5, OpenAI's advanced language model) in order to assist with writing and stylistic improvement of this manuscript. After using it, the authors critically reviewed, edited, and validated all generated content. The tool was not used to generate unverified scientific content. The authors assume complete and final responsibility for the accuracy, integrity, originality, and validity of all content in the manuscript.

CRedit authorship contribution statement

Sara Remón: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Teresa Sanclemente:** Writing – review & editing, Validation, Formal analysis, Data curation, Conceptualization. **Ana Ferrer-Mairal:** Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

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Data availability

Data will be made available on request.

References

- Abu Zarim, N., Zainul Abidin, S., & Ariffin, F. (2021). Shelf life stability and quality study of texture-modified chicken rendang using xanthan gum as thickener for the consumption of the elderly with dysphagia. *Food Bioscience*, 42, Article 101054. <https://doi.org/10.1016/j.fbio.2021.101054>
- Akçay, B., & Alkan, D. (2023). Designing of texture modified fruit juices using food hydrocolloids: Storage influence on viscosity. *Heliyon*, 9(11), Article e21496. <https://doi.org/10.1016/j.heliyon.2023.e21496>
- Alvarez, M. D., Fernández, C., & Canet, W. (2009). Enhancement of freezing stability in mashed potatoes by the incorporation of kappa-carrageenan and xanthan gum blends. *Journal of the Science of Food and Agriculture*, 89, 2115–2127. <https://doi.org/10.1002/jsfa.3702>
- Borowski, J., Narwojsz, J., Borowska, E. J., & Majewska, K. (2015). The effect of thermal processing on sensory properties, texture attributes, and pectic changes in broccoli. *Czech Journal of Food Sciences*, 33(3), 254–260. <https://doi.org/10.17221/207/2014-CJFS>
- Cichero, J. A., Lam, P., Steele, C. M., Hanson, B., Chen, J., Dantas, R. O., et al. (2017). Development of international terminology and definitions for texture-modified foods and thickened fluids used in dysphagia management: The IDDSI Framework. *Dysphagia*, 32(2), 293–314. <https://doi.org/10.1007/s00455-016-9758-y>
- Commission Internationale de l'Eclairage (CIE), 2004. Colorimetry, 3rd ed. Publication CIE 15:2004. CIE Central Bureau, Vienna.
- Coelho-Júnior, H. J., Álvarez-Bustos, A., Pérez Ramírez, C., Russo, A., Rodríguez-Mañas, L., Landi, F., & Marzetti, E. (2025). Exploring the associations between dysphagia and health-related outcomes in older adults: Results from the iSirente Study. *Nutrients*, 17(13), 2149. <https://doi.org/10.3390/nu17132149>
- Dick, A., Bhandari, B., & Prakash, S. (2021). Effect of reheating method on the post-processing characterisation of 3D printed meat products for dysphagia patients. *LWT – Food Science and Technology*, 150, Article 111915. <https://doi.org/10.1016/j.lwt.2021.111915>
- dos Reis, L. C. R., de Oliveira, V. R., Hagen, M. E. K., Jablonski, A., Flores, S. H., & de Oliveira Rios, A. (2015). Carotenoids, flavonoids, chlorophylls, phenolic compounds and antioxidant activity in fresh and cooked broccoli (*Brassica oleracea* var. Avenger) and cauliflower (*Brassica oleracea* var. Alphina F1). *LWT – Food Science and Technology*, 63(1), 177–183. <https://doi.org/10.1016/j.lwt.2015.03.089>
- EFSA (European Food Safety Authority), 2025. Your nutrition needs (#Safe2Eat Campaign). Available at: <https://www.efsa.europa.eu/en/safe2eat/your-nutrition-needs> (Accessed 25 February 2026).
- Ekonomou, S. I., Hadnadev, M., Gioxari, A., Aboosed, O. R., Soe, S., & Stratakos, A. C. (2024). Advancing dysphagia-oriented multi-ingredient meal development: Optimising hydrocolloid incorporation in 3D printed nutritious meals. *Food Hydrocolloids*, 147, Article 109300. <https://doi.org/10.1016/j.foodhyd.2023.109300>
- Gallegos, C., Turcanu, M., Assegehegn, G., & Brito-de la Fuente, E. (2023). Rheological issues on oropharyngeal dysphagia. *Dysphagia*, 38(2), 558–585. <https://doi.org/10.1007/s00455-021-10337-w>
- Giura, L., Urtaasun, L., Belarra, A., Ansorena, D., & Astiasarán, I. (2021). Exploring tools for designing dysphagia-friendly foods: A review. *Foods (Basel, Switzerland)*, 10(6), 1334. <https://doi.org/10.3390/foods10061334>
- Giura, L., Urtaasun, L., Ansorena, D., & Astiasarán, I. (2022). Effect of freezing on the rheological characteristics of protein enriched vegetable puree containing different hydrocolloids for dysphagia diets. *LWT*, 169, Article 114029. <https://doi.org/10.1016/j.lwt.2022.114029>
- Guénard-Lampron, V., Masson, M., & Blumenthal, D. (2021). Critical review of sensory texture descriptors: From pureed to transitional foods for dysphagia patients. *Journal of Texture Studies*, 52(5–6), 665–678. <https://doi.org/10.1111/jtxs.12604>
- Guillén, S., Mir-Bel, J., Oria, R., & Salvador, M. L. (2017). Influence of cooking conditions on organoleptic and health-related properties of artichokes, green beans, broccoli and carrots. *Food Chemistry*, 217, 209–216. <https://doi.org/10.1016/j.foodchem.2016.08.067>
- Ibañez, F. C., Merino, G., Marín-Arroyo, M., & Beriain, M. J. (2022). Instrumental and sensory techniques to characterize the texture of foods suitable for dysphagic people: A systematic review. *Comprehensive Reviews in Food Science and Food Safety*, 21(3), 2738–2771. <https://doi.org/10.1111/1541-4337.12957>
- Ishihara, S., Nakauma, M., Funami, T., Odake, S., & Nishinari, K. (2011). Swallowing profiles of food polysaccharide gels in relation to bolus rheology. *Food Hydrocolloids*, 25(5), 1016–1024. <https://doi.org/10.1016/j.foodhyd.2010.09.022>

- Ismael-Mohammed, K., Bolivar-Prados, M., Laguna, L., & Clavé, P. (2023). Measuring the rheological and textural properties of thick purees used to manage patients with swallowing disorders. *Nutrients*, *15*, 3767. <https://doi.org/10.3390/nu15173767>
- The Jamovi project (2024). Jamovi. (Version 2.6) [Computer Software]. Available at <https://www.jamovi.org> (Accessed 25 February 2026).
- Keller, H., Chambers, L., Niezgodá, H., & Duizer, L. (2012). Issues associated with the use of modified texture foods. *Journal of Nutrition, Health & Aging*, *16*(3), 195–200. <https://doi.org/10.1007/s12603-011-0160-z>
- Kuo, Y. T., Chen, P. R., & Yang, S. C. (2025). Effects of a food-shaping agent on the texture and palatability of hospital-pureed meat: A comparison of subjective and instrumental assessments. *Foods (Basel, Switzerland)*, *14*(20), 3574. <https://doi.org/10.3390/foods14203574>
- Liu, T., Zheng, J., Du, J., & He, G. (2024). Food processing and nutrition strategies for improving the health of elderly people with dysphagia: A review of recent developments. *Foods (Basel, Switzerland)*, *13*(2), 215. <https://doi.org/10.3390/foods13020215>
- Liu, X., Feng, Y., Li, R., Zhang, H., Ren, F., Liu, J., & Wang, J. (2025). Comprehensive review of dysphagia and technological advances in dysphagia food. *Food Research International*, *199*, Article 115354. <https://doi.org/10.1016/j.foodres.2024.115354>
- Marcotrigiano, V., Stingi, G. D., Nugnes, P. T., Mancano, S., Lagreca, V. M., Tarricone, T., et al. (2023). Collective catering activities and official controls: Dietary promotion, sustainability and future perspectives. *Healthcare*, *11*(9), 1347. <https://doi.org/10.3390/healthcare11091347>
- Matsuyama, S., Nakauma, M., Funami, T., Hori, K., & Ono, T. (2021). Human physiological responses during swallowing of gel-type foods and its correlation with textural perception. *Food Hydrocolloids*, *111*, Article 106353. <https://doi.org/10.1016/j.foodhyd.2020.106353>
- McGinnis, C. M., Homan, K., Solomon, M., Taylor, J., Staebell, K., Erger, D., & Raut, N. (2019). Dysphagia: Interprofessional management, impact, and patient-centered care. *Nutrition in clinical practice : official publication of the American Society for Parenteral and Enteral Nutrition*, *34*(1), 80–95. <https://doi.org/10.1002/ncp.10239>
- Merino, G., Gómez, I., Marín-Arroyo, M. R., Beriain, M. J., & Ibañez, F. C. (2020). Methodology for design of suitable dishes for dysphagic people. *Innovative food science & emerging technologies : IFSET : the official scientific journal of the European Federation of Food Science and Technology*, *64*, Article 102383. <https://doi.org/10.1016/j.ifset.2020.102383>
- Merino, G., Marín-Arroyo, M. R., Beriain, M. J., & Ibañez, F. C. (2021). Dishes adapted to dysphagia: Sensory characteristics and their relationship to hedonic acceptance. *Foods (Basel, Switzerland)*, *10*(2), 480. <https://doi.org/10.3390/foods10020480>
- Miles, A., Liang, V., Sekula, J., Broadmore, S., Owen, P., & Braakhuis, A. J. (2020). Texture-modified diets in aged care facilities: Nutrition, swallow safety and mealtime experience. *Australasian Journal on Ageing*, *39*(1), 31–39. <https://doi.org/10.1111/ajag.12640>
- Mizrahi, S. (2010). Syneresis in food gels and its implications for food quality. In L. H. Skibsted, J. Risbo, & M. L. Andersen (Eds.), *Chemical deterioration and physical instability of food and beverages* (pp. 324–348). Cambridge: Woodhead Publishing.
- Muadklay, J., & Charoenrein, S. (2008). Effects of hydrocolloids and freezing rates on freeze-thaw stability of tapioca starch gels. *Food Hydrocolloids*, *22*(7), 1268–1272. <https://doi.org/10.1016/j.foodhyd.2007.06.008>
- Park, C. H., Lee, Y. T., Yi, Y., Lee, J. S., Park, J. H., & Yoon, K. J. (2017). Ability of high-resolution manometry to determine feeding method and to predict aspiration pneumonia in patients with dysphagia. *The American Journal of Gastroenterology*, *112*(7), 1074–1083. <https://doi.org/10.1038/ajg.2017.81>
- Pematilleke, N., Kaur, M., Rai Wai, C. T., Adhikari, B., & Torley, P. J. (2021). Effect of the addition of hydrocolloids on beef texture: Targeted to the needs of people with dysphagia. *Food Hydrocolloids*, *113*, Article 106413. <https://doi.org/10.1016/j.foodhyd.2020.106413>
- Raheem, D., Carrascosa, C., Ramos, F., Saraiva, A., & Raposo, A. (2021). Texture-modified food for dysphagic patients: A comprehensive review. *International Journal of Environmental Research and Public Health*, *18*(10), 5125. <https://doi.org/10.3390/ijerph18105125>
- Rajati, F., Ahmadi, N., Naghibzadeh, Z. A., & Kazemina, M. (2022). The global prevalence of oropharyngeal dysphagia in different populations: A systematic review and meta-analysis. *Journal of Translational Medicine*, *20*(1), 175. <https://doi.org/10.1186/s12967-022-03380-0>
- Ribes, S., Estarriaga, R., Grau, R., & Talens, P. (2021). Physical, sensory, and simulated mastication properties of texture-modified Spanish sauce using different texturing agents. *Food & Function*, *12*(17), 8181–8195. <https://doi.org/10.1039/D1FO00742D>
- Rivelsrud, M. C., Hartelius, L., Bergström, L., Løvstad, M., & Speyer, R. (2023). Prevalence of oropharyngeal dysphagia in adults in different healthcare settings: A systematic review and meta-analyses. *Dysphagia*, *38*(1), 76–121. <https://doi.org/10.1007/s00455-022-10465-x>
- Roberts, H., Lambert, K., & Walton, K. (2024). The prevalence of dysphagia in individuals living in residential aged care facilities: A systematic review and meta-analysis. *Healthcare (Basel, Switzerland)*, *13*(6), 649. <https://doi.org/10.3390/healthcare12060649>, 12.
- Sharma, M., Kristo, E., Corredig, M., & Duizer, L. (2017). Effect of hydrocolloid type on texture of pureed carrots: Rheological and sensory measures. *Food Hydrocolloids*, *63*, 478–487. <https://doi.org/10.1016/j.foodhyd.2016.09.040>
- Soares, A., Carrascosa, C., & Raposo, A. (2017). Influence of different cooking methods on the concentration of glucosinolates and vitamin C in broccoli. *Food and Bioprocess Technology*, *10*, 1387–1411. <https://doi.org/10.1007/s11947-017-1930-3>
- Tokifuji, A., Matsushima, Y., Hachisuka, K., & Yoshioka, K. (2013). Texture, sensory and swallowing characteristics of high-pressure-heat-treated pork meat gel as a dysphagia diet. *Meat Science*, *93*(4), 843–848. <https://doi.org/10.1016/j.meatsci.2012.11.050>
- Turkmen, N., Poyrazoglu, E. S., Sari, F., & Velioglu, Y. S. (2006). Effects of cooking methods on chlorophylls, pheophytins and colour of selected green vegetables. *International Journal of Food Science & Technology*, *41*(3), 281–288. <https://doi.org/10.1111/j.1365-2621.2005.01061.x>
- U.S. Department of Agriculture (USDA) and U.S. Department of Health and Human Services (HHS). (2025). *Dietary Guidelines for Americans, 2025-2030, 10th ed.* Available at: <https://www.dietaryguidelines.gov> (Accessed 25 February 2026).
- World Health Organization, 2025. Nutrition - maintaining a healthy lifestyle (Fact sheet). Available at: <https://www.who.int/europe/news-room/fact-sheets/item/nutrition-maintaining-a-healthy-lifestyle> (Accessed 25 February 2026).
- Wu, X., Zhao, Y., Haytowitz, D. B., Chen, P., & Pehrsson, P. R. (2019). Effects of domestic cooking on flavonoids in broccoli and calculation of retention factors. *Heliyon*, *5*(3), Article e01310. <https://doi.org/10.1016/j.heliyon.2019.e01310>
- Wu, X. S., Miles, A., & Braakhuis, A. (2022). An evaluation of texture-modified diets compliant with the International Dysphagia Diet Standardization Initiative in aged-care facilities using the consolidated framework for implementation research. *Dysphagia*, *37*, 1314–1325. <https://doi.org/10.1007/s00455-021-10393-2>
- Yang, S., Park, J. W., Min, K., Lee, Y. S., Song, Y. J., Choi, S. H., et al. (2023). Clinical practice guidelines for oropharyngeal dysphagia. *Annals of Rehabilitation Medicine*, *47*(Suppl1), S1–S26. <https://doi.org/10.5535/arm.23069>