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RESEARCH ARTICLE

Enriched puree potato with soy protein for dysphagia patients by using 3D printing

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Abstract

Dysphagia affects a person's ability to swallow, and it causes health problems by directly limiting nutritional intake, being the elderly the most at-risk group and also likely to be deficient in nutrition. Diets for patients with dysphagia require textural modifications to offer soft and safe food to swallow. Puree is easily consumed by the elderly, being an alternative food preparation providing essential nutrition for people with dysphagia. In this study, we aimed to create different formulations with soy protein and agar added to potato puree to add nutritional value and end up with printable material by designing food for the elderly and people with dysphagia. Some enriched potato puree formulations were obtained by adding soy protein (3%, 5%, and 7%) and up to 0.2% agar. The use of three-dimensional food printing allows visual customization with appeal benefits of nutritional food formulations for specific consumers. The rheology and texture profile analysis of the different formulations has been performed. According to International Dysphagia Diet Standardisation Initiative (IDDSI) scales, the texture of all modified samples was suitable for people with swallowing difficulties. The samples with agar presented a better-printed shape and a more viscous-like behavior than the samples with soy protein. These findings highlight that soy protein could modify the texture and, from the nutritional point of view, add value to the formulations. The addition of 0.2% agar can establish good material for designing three-dimensional (3D)-printed food that allows the creation of textures in accordance with the needs of the elderly and people with dysphagia.

KEYWORDS
IDDSI, texture modified, thixotropy, TPA, viscosity, yield stress

1 | INTRODUCTION

Dysphagia is an age-related disease and one of the dominant problems for the elderly. Dysphagia is directly linked to nutritional deficiency and expansion risk of pneumonia for its impairment on the swallow function (Sura et al., 2012). The topic of dysphagia in the elderly has become an increasingly important concern (Aslam & Vaezi, 2013). Approximately one quarter of elderly patients in care centers had dysphagia, whereas almost half were malnourished (Bomze et al., 2021). Untreated dysphagia may affect protein-energy malnutrition, leading to life-threatening conditions, a result of increased risk of accompanying infections related to the immune system due to the nutritional deficit (Hudson et al., 2000). Dysphagia can be managed by prescribing texture-controlled diets that seek to modify the consistency of foods and/or drinks by changing the rate at which food is transported through the pharynx and thus decreasing the risk of aspiration (Quinchia et al., 2011). For solid kinds of food, the texture is an important factor to be considered because textural changes occur more drastically during oral processing in solid foods than in liquid foods. Rheological properties have a key role to understand swallowing process, being of paramount importance to be aware of dysphagia (Gallegos et al., 2012). Recently, the practical method for testing food texture and thickened fluids developed by International Dysphagia Diet Standardization Initiative (IDDSI) have been widely welcomed by evaluating diets for patients with dysphagia due to its simplicity and reliability (Cichero et al., 2017). Hadde & Chen, 2021, identified several points regarding the relevant parameters of swallowing for dysphagia management. One of the important parameters of texture-modified foods is the degree of structure, which is a combination of textural properties and particulate properties of the bolus, such as hardness, cohesiveness, adhesiveness, and particle size. It is possible to have indirect information about particle size by measuring the IDDSI fork test and information related to food cohesiveness, adhesiveness, and hardness by measuring the IDDSI spoon tilt test.

Since recently, three-dimensional (3D) printing has gotten high consideration for customized food and personalized meals, and the use of this technology has become very important for people with specific nutritional requirements such as the elderly and people with swallow difficulties (Pant et al., 2021; Pérez et al., 2019). Adapting 3D printing in the food sector induced a new challenge because most of the food materials often consist of different ingredients with distinct physicochemical properties (Godoi et al., 2016).

For elderly adults, nutrition plays an essential role in health and function (Baum & Wolfe, 2015). A dietary protein intake of at least 1.2 g/kg·day is required for older people (Nowson & O'Connell, 2015). Soy protein has multiple health benefits, because its high nutritional value and desirable functionality have been included in a wide variety of formulated foods (Kinsella & Whitehead, 1989). Many studies show that consuming soy protein might be the reason for lower incidences of certain diseases (Hagen et al., 2009), and it is recognized that soy protein at the same time as a low-fat diet can decrease the risk of certain cancer (Lille et al., 2018; Nestel, 2002). Agar is obtained from seaweed, and due to its characteristic physicochemical, mechanical, and rheological properties, it can modify food texture and is useful to control the rheological properties in the design of foods for the elderly. The most important function of agar at low concentration is as a thickening agent (Nishinari et al., 2016).

Protein and starch are used in the formulation of many foods because of their textural characteristics and structural gelation behavior. The texture and stability of protein–polysaccharides interactions depend on the properties of protein and polysaccharides but in addition, their interaction will show the strength (Hemar et al., 2002). In recent years, we can find an increasing number of studies on the interaction between starch and polysaccharides in academic and industrial sectors (Quan et al., 2020). Adding soy protein to potatoes is not just to create a formulation with high nutritional value and have a healthy product, but to enrich a better physiochemical, functional, and sensory characteristic potato product for the elderly and people with dysphagia (Alvarez et al., 2012).

The overall objective of this study was to determine the effect of soy protein and agar on the physicochemical properties of a formulation based on puree potato for patients with dysphagia. The specific objectives of this study were to study the rheological and textural measurements to characterize the suitable range of formulation ingredients for people with dysphagia, and to create printable nutritional formulations to investigate possible opportunities to personalize food for the elderly with 3D food printing (3DFP) and to understand the effect of sieving on the characteristic of the puree products. Our hypothesis was to identify the suitable range of formulation ingredients that can be printable formulate products for people with dysphagia.

2 | MATERIALS AND METHODS

2.1 | Sample preparation

Dehydrated potato puree (Maggi, purchased from a local supermarket) has the following nutritional values: energy 348 kcal, fat 0.8 g, carbohydrates 75 g, fiber 6.8 g, proteins 7.4 g, and salt 0.06 g. Soy protein acid hydrolysate (SPAH) food-grade was procured from Sigma–Aldrich (nitrogen analysis ≥12% total = 75% protein, calculated applying a factor of 6.25 g prot/g N). Powdered Agar (food grade) was purchased from Panreac AppliChem.

For all the food formulations, the same base (100 ml distilled water plus 17 g potato powder) was used and differed in soy (SPAH) and agar amounts were added regarding the following codes: S3 (3 g soy), S6 (6 g soy), S9 (9 g soy), S3A (3 g soy and 0.2 g agar), S6A (6 g soy and 0.2 g agar), and S9A (9 g soy and 0.2 g agar).

Samples were prepared by boiling 50 ml distilled water to dissolve agar and added with 50 ml distilled water (25°C) where the corresponding SPAH was incorporated. Subsequently, all samples were placed in an oven at 90°C and kept for 30 min to denature the protein and, as the last step, the dehydrated potato powder (17 g) was added.

The samples were kept overnight (22–24 h) in a fridge set at 2°C, and all samples were placed in an incubator at 20°C for 2 h before starting the rheological measurements.

The whole experiment was repeated three times.

2.2 | Rheological measurements

The rheological measurements were carried out in a rheometer (Rheostress RS1, version 127, Barcelona, Spain) controlled with commercial computer software (HAAKE RheoWin 3 Job and Data Manager Software). Samples were analyzed for their viscoelastic properties using 35-mm plate–plate geometry with a 1 mm gap. After placing the sample and trimming off the excess, the sample was let to rest for 2 min before starting the assay. The temperature was kept at 20.0 ± 0.1°C during all the assays. A preliminary test was conducted to identify the deformation limits for the linear viscoelastic region.

2.2.1 | Frequency sweep test

Oscillatory tests were performed to explain the behavior of material from 0.1 to 10 Hz to understand viscous or elastic dominating properties. Each sample from each of the 16 different formulations and three repetitions were measured independently three times.

Rheological properties can be evaluated by the storage modulus (G') and loss modulus (G'').

2.2.2 | Rotational rheological measurements, thixotropy, and yield stress

The shear rate raised logarithmically from 0.1 to 10 s^{-1} during the first 30 s, kept constant at 10 s^{-1} for 30 s, and finally was cut down logarithmically again to 0.1 s^{-1} over 30 s. For each sample, we recorded the viscosity (η) and the shear stress (τ), along with the yield stress (Tabilo-Munizaga & Barbosa-Cánovas, 2005).

2.3 | 3D food printing conditions

All formulations were 3D printed using a commercial extrusion-based 3D food printer (Foodini, Natural Machines Iberia S.L., Barcelona, Spain). Samples were printed using a nozzle with a diameter of 1.5 mm, the print speed was set at 3500 mm/min, the first ingredient holds at 4.2 mm, the first layer nozzle height was 1.4 mm and at the moment it is not possible to control the temperature with Foodini machine, so all the samples were printed at room temperature at 20°C. Before printing, all the samples were sieved to avoid the presence of lumps that may affect the printing process. A spoon was used to press the samples through the 250 μm mesh sieve. Then, the stainless-steel printing capsules (100 ml) of Foodini were manually filled with the sieved samples. Food samples must be well pressed down inside printing capsules to avoid the presence of air bubbles.

Each formulation was printed three times, either in the form of a pentagon prism for TPA assay or as some complex shapes such as snowflake, mountain, and honeycomb.

2.4 | International Dysphagia Diet Standardization Initiative tests

IDDSI divides modified food into eight levels (0–7) and presents a combination of tests to confirm which level texture is modified food for people with swallow difficulties (Cichero et al., 2017). Fork pressure test and spoon tilt test were performed on the sieved samples. Fork test was done by pressing the fork by thumb until it blanched (pressure of ~17 kPa), resembling the tongue pressure while swallowing. The spoon tilt test was completed for all formulations for experimenting with adhesiveness and cohesiveness (Cichero et al., 2017; Steele et al., 2014).

2.5 | Texture properties characterization: TPA

3D-printed pentagon shape was analyzed by textural profile analysis (TPA) test to determine its textural properties. TPA of printed samples was performed at 20°C using a texture analyzer (TA.XTPlus, Stable Micro Systems, UK) with a compression plate (P/100). Double-cycle compression tests were performed at a pretest speed, test, and posttest speed of 2 mm/s, and a compression strain of 35%. Hardness, gumminess, cohesiveness, adhesiveness, and resilience were obtained from the recorded results, and duplicate values were averaged for each replicate.

The compression analysis was set at a distance of 30 mm and a speed of 2 mm/s. The method adjusted the value of the speed to the printing conditions of the Foodini.

2.6 | Statistical analysis

Statistical analyses of the data were conducted on Minitab 18 (Minitab link. Coventry, UK). Data concerning rheology and textural characteristics were tested for significant differences ($p < .05$) using analysis of variance, general linear model, and Tukey's comparison test.

3 | RESULTS

3.1 | Rheological properties of the formulation

3.1.1 | Viscosity

All soy-enriched potato puree samples exhibited a non-Newtonian behavior as can be seen by the exponential decay of the viscosity with the increase of shear strain in Figure 1.

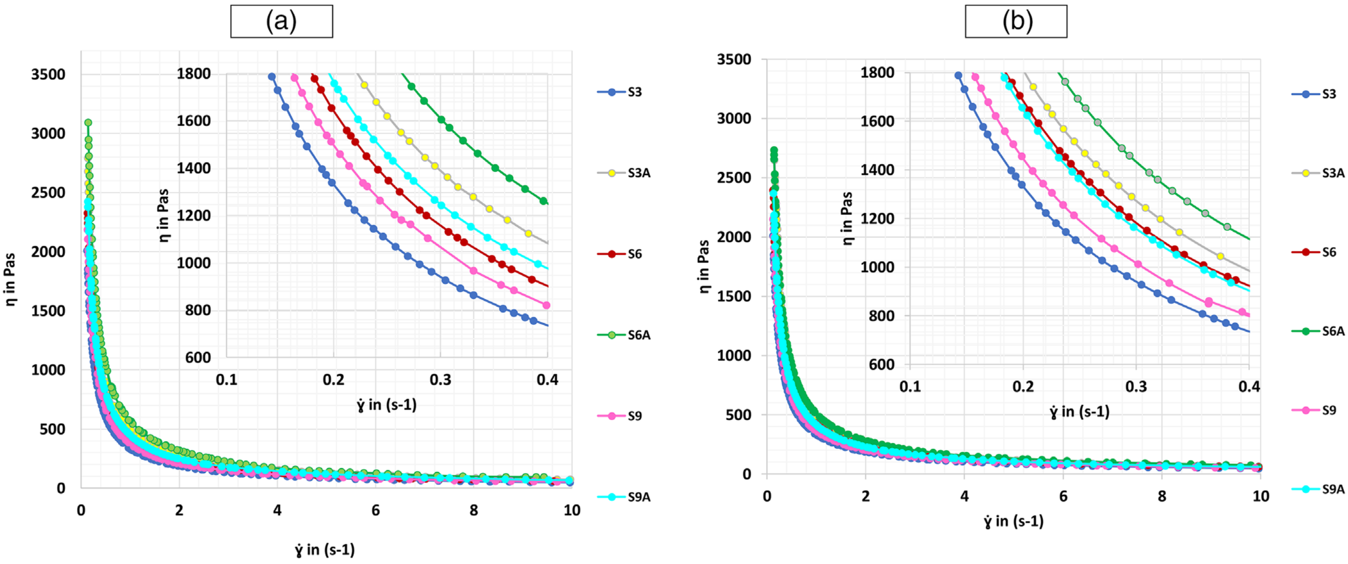

FIGURE 1 Rheological characterization of food formulations, viscosity versus shear rate. Each curve represents the average of three replicates per sample. (a) Viscosity before sieving and (b) viscosity after sieving. *Note*: S3 (3 g soy), S6 (6 g soy), S9 (9 g soy), S3A (3 g soy and 0.2 g agar), S6A (6 g soy and 0.2 g agar) and S9A (9 g soy and 0.2 g agar)

Figure 1 shows that SPAH and agar had a significant ($p < .05$) effect on increasing the viscosity. The samples with different concentrations of SPAH had increased the viscosity at 0.3 s^{-1} shear rate from 3% (S3, 925 Pa·s) to 5% (S6, 1205 Pa·s), but from 5% (S6) to 7% (S9) 1104 Pa·s rate decreased.

To evaluate the effect of sieving the formulation, a step necessary to 3D print, the rheological properties were evaluated before and after sieving. Sieving slightly decreased the viscosity for samples with agar (Figure 1). For instance, the formulation S3A changed its apparent viscosity at 0.3 s^{-1} from 1409 to 1289 Pa·s after sieving and it also occurs with S6A (from 1606 to 1458 Pa·s) and S9A (from 1244 to 1164 Pa·s). Conversely, the sieving process did not change the viscosity of the formulations without agar, irrespective of their protein content.

3.1.2 | Thixotropy

All formulations were studied varying the shear rate to characterize the effects including SPAH and agar, and to depict the effect of sieving. The results showed hysteresis loops, indicating that all formulations exhibited thixotropic behaviors.

Flow curves obtained with controlled shear stress for all formulations, before and after sieving, are presented in Figure 2. The samples showed a behavior that differs by the effect of sieving, with a reduction in the shear stress, but more noticeably in the hysteresis area for formulations with agar with a decrease that means less energy is needed to destroy the internal structure of the material responsible for the flow time dependence (Tárrega et al., 2004) in the samples that have been previously sieved.

Formulation with 6 g SPAH and 0.2 g agar (S6A) exhibited the highest degree of thixotropy, with the largest hysteresis area indicating having the strongest thixotropic properties which means requiring the highest energy to break down the internal structure, with high resistance to time-dependent flow and high levels of internal viscosity and stability. However, upon decreasing the shear rate in the last part of the test, all formulations showed the capacity to reform the damaged internal network and to recover their viscosities.

3.1.3 | Yield stress

Many methods have been applied for characterizing the yield stress of food systems (Sun & Gunasekaran, 2009). To choose the model that best fits our data, different mathematical equations or models (Power Law, Herschel–Bulkley, Casson, and Bingham models) were tested to select the best performer. Bingham was determined to be the best model to fit the flow characteristics of the samples, with a high coefficient of determination ($R > 0.98$). The Bingham model is described by the equation $\tau = \tau_0 + \eta_p \dot{\gamma}$, where τ (Pa) is the shear stress, τ_0 (Pa) is the yield stress, η_p (Pa·s) is the viscosity, and $\dot{\gamma}$ (s^{-1}) is the shear rate.

S6A presented the highest yield stress among the tested formulations (Table 1). This high yield can be explained by the effect of both agar and SPAH in the starch internal microstructure, contributing to the elasticity of the network of the potato starch puree and consequently generating a starch internal microstructure that was more resistant to deformation in the shear stress region where the sample is fully elastic.

The yield stress decreased for all sieved samples, showing the increase in the easy-flowing of the materials after passing through a sieve and breaking the bonds and strengths of the structure, especially for the formulations with agar.

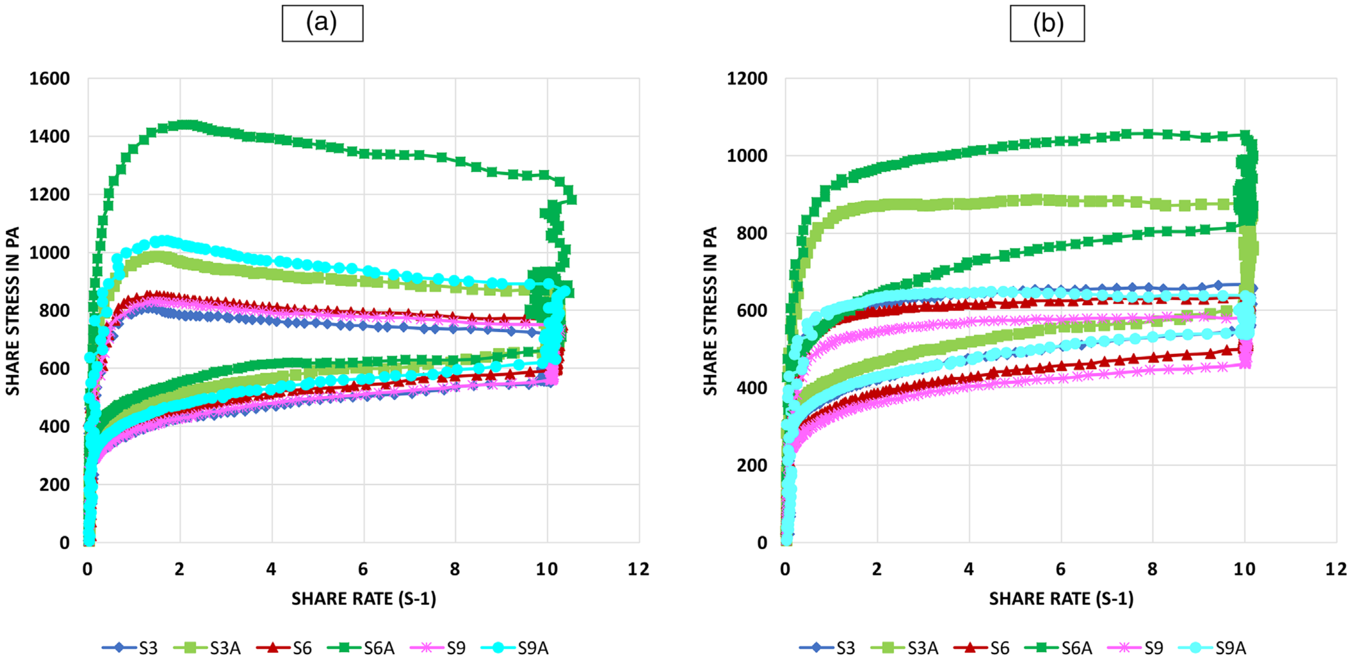

FIGURE 2 Rheological characterization of food formulations. Shear stress versus shear rate, each curve represents the average of three replicates per sample. (a) Thixotropy before sieving and (b) thixotropy after sieving. *Note*: S3 (3 g soy), S6 (6 g soy), S9 (9 g soy), S3A (3 g soy and 0.2 g agar), S6A (6 g soy and 0.2 g agar), and S9A (9 g soy and 0.2 g agar)

TABLE 1 Rotational rheological measurements, thixotropy, and yield stress, before and after sieving. The yield stress was obtained according to Bingham model $\eta = \eta_p + \tau_0/\dot{\gamma}$. The numbers represent the average of three replicates per sample

Samples	Yield stress (Pa)	Thixotropy (Pa·s)	η_p (Pa·s)	τ_0 (Pa)	R^2
Before sieving					
S3	638^{d}	4246^{c}	155^{c}	405^{b}	0.99
S6	757^{cd}	5756^{bc}	262^{bc}	453^{ab}	0.99
S9	841^{cd}	5482^{bc}	164^{c}	461^{ab}	0.99
S3A	1084^{b}	7971^{b}	386^{ab}	488^{ab}	0.98
S6A	1489^{a}	15345^{a}	549^{a}	602^{a}	0.98
S9A	950^{bc}	6854^{bc}	211^{bc}	537^{ab}	0.99
After sieving					
S3	623^{c}	3648^{bc}	76^{b}	405^{b}	0.99
S6	743^{bc}	3880^{bc}	128^{b}	406^{ab}	0.98
S9	639^{c}	2537^{c}	85^{b}	409^{ab}	0.99
S3A	881^{b}	6414^{ab}	234^{a}	456^{a}	0.98
S6A	1081^{a}	7360^{a}	315^{a}	475^{a}	0.98
S9A	707^{c}	4888^{abc}	123^{b}	422^{ab}	0.99

Note: S3 (3 g soy), S6 (6 g soy), S9 (9 g soy), S3A (3 g soy and 0.2 g agar), S6A (6 g soy and 0.2 g agar), and S9A (9 g soy and 0.2 g agar). The results with different letters in the same column are different with a significance level of $p < .05$.

3.1.4 | Viscoelastic behavior

The shallowing process is determined by the interactions between the major molecules in thickened fluids and their effects on their extensional properties. These interactions can be elucidated by studying the viscoelastic properties of the food products (Hadde & Chen, 2018; Nishinari, Fang, et al., 2019; Nishinari, Turcanu, et al., 2019). As one of the requirements for dysphagia patients is safe swallowing, the characteristic and gel properties of starch have an important role in the final product quality (Sungsinchai et al., 2019).

TABLE 2 Frequency sweep rheological measurements. Storage modulus and loss modulus are reported at 10 Hz. The numbers represent the average of three replicates per sample

Samples	G' (Pa)	G" (Pa)
Before sieving		
S3	602[e]	107[c]
S6	850 [cd]	137[c]
S9	719[de]	122 [cd]
S3A	1089[b]	185[b]
S6A	1352[a]	226[a]
S9A	974[bc]	168[b]
After sieving		
S3	599[c]	105[c]
S6	714[bc]	123[bc]
S9	613[c]	117[c]
S3A	977[ab]	165[ab]
S6A	1090[a]	184[a]
S9A	529[c]	93[c]

Note: S3 (3 g soy), S6 (6 g soy), S9 (9 g soy), S3A (3 g soy and 0.2 g agar), S6A (6 g soy and 0.2 g agar), and S9A (9 g soy and 0.2 g agar). The results with different letters in the same column are different with a significance level of $p < .05$.

Viscoelastic behavior is explained by the level and nature of the leached material and the molecular interactions upon starch granule disintegration in a 3D network structure (Alcázar-Alay & Meireles, 2015). The storage or elastic modulus G' measures the recovered or accumulated energy in each deformation cycle and determines the elastic behavior of the samples. The loss or viscous modulus G'' describes the loss of energy or dissipated energy in each deformation cycle, which describes the viscosity behavior of the material. Table 2 shows that all formulations exhibit larger G' than G'', indicating the presence of an internal network arrangement and a gel-like structure, as happens in starch-rich preparations.

The storage modulus measured at 10 Hz significantly changed with the amount of SPAH included in the formulation. It increased from 602 Pa in S3 to 850 Pa in S6 but significantly decreased to 719 Pa in S9. A similar process occurred with G'', with an increase from 107 Pa in S3 to 137 Pa in S6 and a significant decrease to 122 Pa in S9.

The effects of agar on increasing the elastic and viscous moduli of potato puree can be seen on formulation S6A, with a G' higher than that corresponding to the other samples over all the range of frequencies studied.

After sieving, all formulations show weaker structures especially samples with agar. Among all the formulations, S6A has the highest elastic modulus before (1352 Pa at 10 Hz) and after (1090 Pa) sieving and also viscous modulus before (226 Pa at 10 Hz) and after sieving (184 Pa at 10 Hz).

3.2 | 3DFP test and structure and correlation with rheology

Some requirements are necessary to find out the best formulation for any food product for 3DFP such as food type, hydrocolloids, type of printer, and so forth. Each type of food has different physical and chemical interactions with the hydrocolloids (Pant et al., 2021).

Different shapes were applied to see the printability of the formulations simply with SPAH and SPAH with agar and to test the visual performance when attempting complex structures as presented in Figure 3. All formulations were able to form stable self-supporting structures for simple shapes. The pentagon prism shape for all food formulations was able to keep the structure for more than 15 min. Honeycomb shapes were able to form a stable self-supporting. All the printing materials could build the geometry of the design of a pentagon and honeycomb while displaying abilities to print snowflakes as well.

The complicated mountain shape collapsed during printing in the formulations fortified simply with SPAH as the material was not able to tolerate the load of many layers. The formulations with agar, however, had the strength to tolerate the weight of many layers, a fact that can be explained by the addition of agar which could restrain the mobility of starch chains (Wu et al., 2009).

Some researchers (Lewis et al., 2006; Liu et al., 2018; Zhang et al., 2015) found that printed shape retention was closely related to the G' and τ_0 of materials and to develop periodic structures through 3D printing, and also found that materials with higher G' and τ_0 showed better shape retention; the τ_0 shows the minimum force necessary for material extrusion and G' reflect the mechanical strength of mixtures, which is critical for supporting subsequently deposited layers and maintaining printed shape. The samples with only SPAH had low τ_0 (Table 1) and G′ (Table 2), but the addition of agar led to an increase both in τ_0 and G'. The formulations with only SPAH did not possess enough mechanical strength for complex shapes with many layers; thus, the deformation and poor resolution supporting structure were observed in formulations without agar for complex printed objects (Figure 3). The mixture with agar and SPAH had higher τ_0 and G' and was strong enough to support the deposited layers and hold the printed structures.

3.3 | Texture properties: TPA

Formulations only with SPAH had lower hardness values than those that also contain agar and were not significantly different according to the amount of SPAH (Table 3). The formulation S6A showed significantly the highest hardness values. This was the formulation that had the best 3D shape.

High adhesiveness is a very important property of semi-solid food that needs more effort in pharyngeal swallowing in older adults (Park et al., 2020). The formulations S6A and S9A had the highest values for adhesiveness pointing to a good performance on the design of formulations for people with dysphagia.

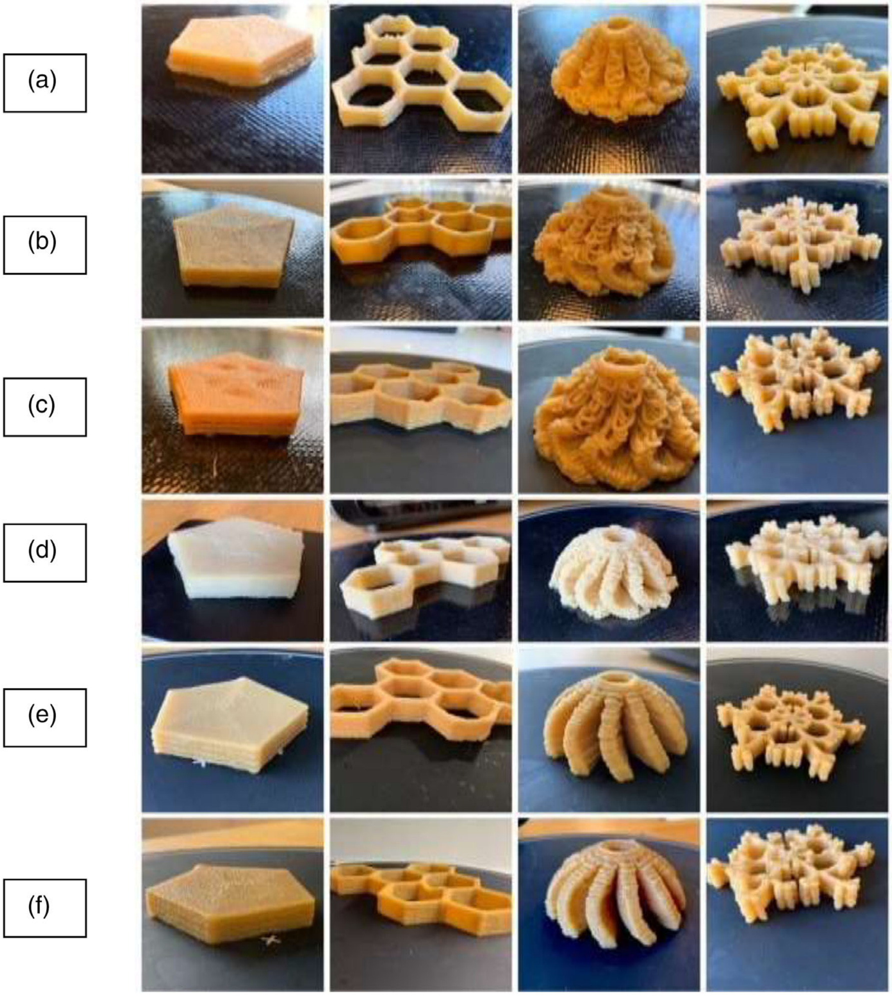

FIGURE 3 3D prints. Representative image of 3D printed shape with six formulations. *Note*: (a) S3 (3 g soy), (b) S6 (6 g soy), (c) S9 (9 g soy), (d) S3A (3 g soy and 0.2 g agar), (e) S6A (6 g soy and 0.2 g agar), and (f) S9A (9 g soy and 0.2 g agar)

TABLE 3 The average values of Textural Profile Analysis (TPA) for six formulations from three replicates

Samples	Hardness (N)	Adhesiveness (N·sec)	Resilience (–)	Cohesiveness (–)	Gumminess (N)
S3	1.01^{b}	-34.3^{a}	0.005^{bc}	0.007^{ab}	0.80^{ab}
S6	1.31^{b}	-46.9^{b}	0.006^{bc}	0.009^{a}	1.17^{ab}
S9	1.20^{b}	-28.8^{a}	0.004^{c}	0.003^{c}	0.43^{b}
S3A	2.02^{ab}	-29.8^{a}	0.014^{a}	0.005^{bc}	1.01^{ab}
S6A	5.49^{a}	-71.2^{c}	0.013^{ab}	0.006^{abc}	3.54^{a}
S9A	3.31^{ab}	-64.4^{c}	0.011^{abc}	0.006^{abc}	2.11^{ab}

Note: S3 (3 g soy), S6 (6 g soy), S9 (9 g soy), S3A (3 g soy and 0.2 g agar), S6A (6 g soy and 0.2 g agar), and S9A (9 g soy and 0.2 g agar). The results with different letters in the same column are different with a significance level of $p < .05$.

Resilience is another attribute that indicates a food's ability to resist deformation, and the samples with just SPAH had lower resilience values in coincidence with the worse performance on 3D printing tests and its difficulty to keep the designed shape.

The structural strength of internal bonds is measured as cohesiveness, which holds the food matrix together in a bolus and prevents it from disintegrating into fragments during swallowing (Sharma et al., 2017). Formulations S6 and S9 presented the highest and lowest cohesiveness, respectively, among all the tested samples.

Gumminess is the amount of work needed to make a food sample ready to swallow. Sample S6A had significantly higher values for gumminess compared to the rest.

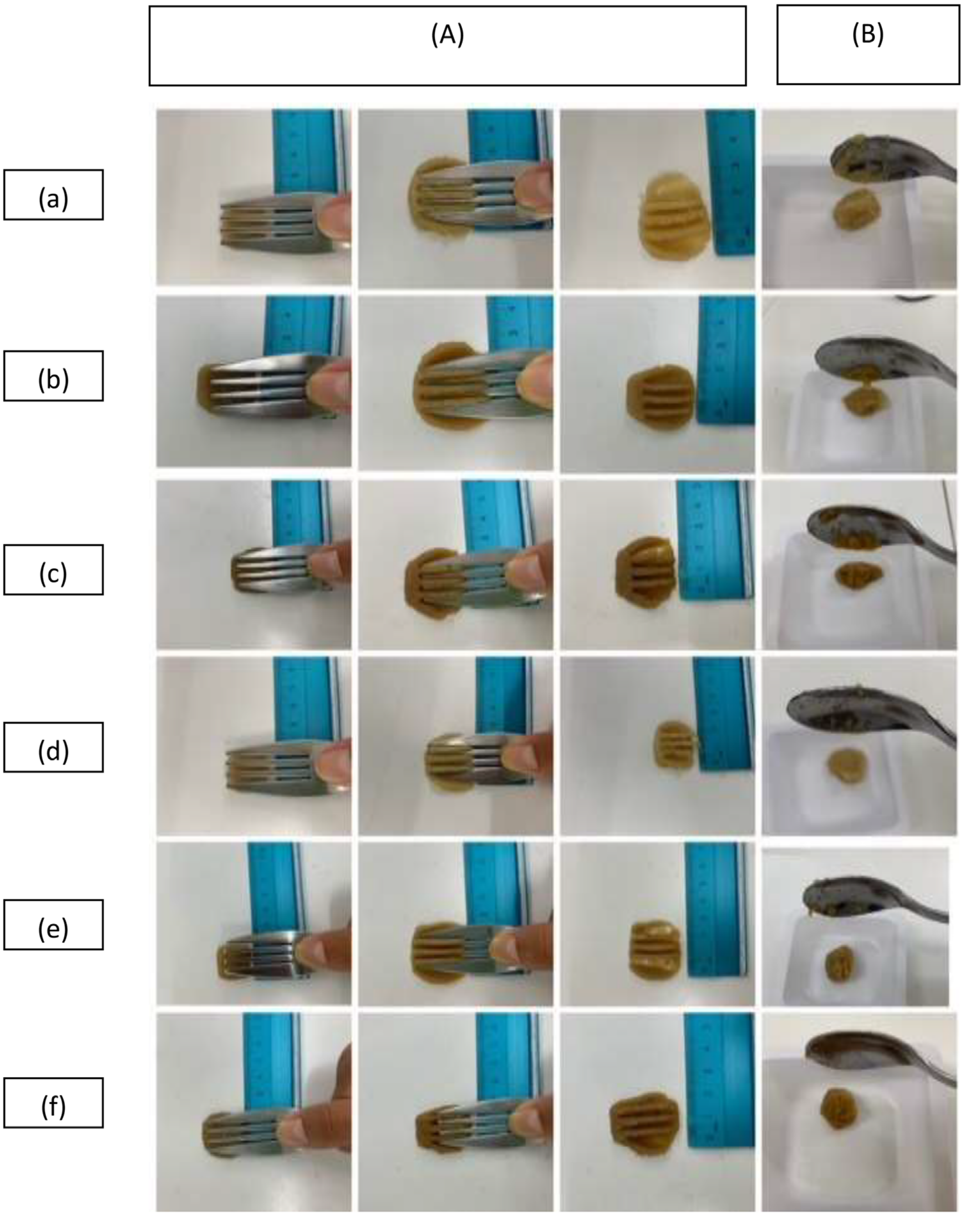

FIGURE 4 International Dysphagia Diet Standardisation Initiative (2019). Testing Methods 2.0 2019: (1) Fork pressure test on soft and bite-sized 3D printed samples and (2) spoon tilt test. *Note*: (a) S3 (3 g soy), (b) S6 (6 g soy), (C) S9 (9 g soy), (d) S3A (3 g soy and 0.2 g agar), (E) S6A (6 g soy and 0.2 g agar), and (f) S9A (9 g soy and 0.2 g agar)

Hardness, resilience, and chewiness were increased with the addition of agar, which could support the designed structure during the 3D printing process.

3.4 | Fork pressure and spoon tilt test

All the formulations could slide off the spoon on tilting and showed that they would not stick to the oral cavity. Fork pressure tests were done with all formulations and showed the indent pattern (Figure 4).

According to these tests, all formulations terminated to be transitional foods. However, all printed structures may change meantime with water/saliva in the mouth, and the time for slide off from spoon test is required further study to accept the food as a dysphagic diet food.

4 | DISCUSSION

The number of elderly and people with swallow difficulties is increasing all over the world, so personalization diet and understanding about the correct range of texture and rheological properties are necessary. Several studies show 3D printing is capable of converting mashed and not attractive dysphagia diets into appetizing foods with appealing appearance (Diañez et al., 2021; Xing et al., 2022).

The addition of SPAH and agar in the given range used in this study had a significant effect on the rheological and textural properties.

All the measured rheological parameters (viscosity, thixotropy, yield stress, and viscoelastic behavior) on the formulations without agar significantly increased with rising the soy concentration from 3% to 5%, but from 5% to 7% they had no significant differences, which can be explained by insufficient water in the formulation caused by the high concentration of solids. This phenomenon has been previously reported, with a decrease in thickening for the highest concentrations of added soy protein (Alvarez et al., 2012).

The formulations with agar showed higher values on the rheological measurements compared to the ones without agar. Agar can improve mechanical strength due to the strong interaction of hydrogen bonding and the formation of hydrophobic aggregates (Wongphan & Harnkarnsujarit, 2020). Starchy food's texture and appearance can be improved by mixing starch with hydrocolloids as both share some key behavior as being polysaccharide molecules (Bemiller, 2011).

The formulation with the highest values for all measured parameters has been S6A. This can be explained by the formation of a strongly interconnected network due to the effect of having both interactions, where a major part of the granules is strongly connected by the high molecular weight and length of the agar molecule (agar–starch), (agar–SPAH), and (SPAH–starch) interactions and the formation of (agar–agar) gel-like interactions. These interactions would result in a more elastic, structured, and gel-like microstructure than in the case of the samples with SPAH alone. Our finding highlights that the physiochemical properties for the samples with agar changed by the effect of sieving as agar could build different bonds with starch and proteins. The addition of agar improved the mechanical properties, but after passing through the sieve, physiochemical properties decreased by breaking hydrogen bonds that give strength to the 3D gel network. Passing the samples through the sieve before printing is a common practice in 3D printing, recommended for avoiding blocking the nozzles of the printer (Huang et al., 2020; Kim et al., 2018; Pant et al., 2021). Our results showed that sieving process has a significant effect on the rheological properties of samples containing hydrocolloids, and it is important to consider this effect for the food products addressed to an aging population and people with dysphagia.

SPAH addition increased the viscosity and mechanical strength of all food formulations. The resultant self-supporting capacity of 3D-printed samples was very good for simple shapes, and after adding agar, self-supporting capacity of 3D-printed samples increased and was suitable for printing complex shapes because of increasing viscosity and viscoelastic properties. Formulation S6A was available to perfectly support the extruded materials for a complex shape, and the layers remain strong during the printing process.

All samples were classified as level 4 puree dysphagia diet within the IDDSI framework.

Generally, formulation S6A (soy 6 g and agar 0.2 g) showed fine 3D printability with an appealing appearance and were acceptable for dysphagia diets. This study provides the development of dysphagia diets by emerging 3D printing technology, which would offer a more appealing appearance of the food for elderly people and people with mastication and shallowing problems.

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CONFLICT OF INTEREST

The authors confirm that they have no conflict of interest to declare for this publication.

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