Food Hydrocolloids 147 (2024) 109300

Contents lists available at ScienceDirect

Food Hydrocolloids

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

Advancing dysphagia-oriented multi-ingredient meal development: Optimising hydrocolloid incorporation in 3D printed nutritious meals

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ARTICLE INFO

Keywords:
Dysphagia
IDDSI
Pea protein
Thickeners
Rheology
3D printing

ABSTRACT

Dysphagia (DP) is a growing health concern in today's ageing population, leading to high demand for DP-oriented food. 3D printing is a promising novel technology for developing new attractive and appetising products. Therefore, we aimed to develop a 3D-printed shaped meal, to serve as a nutritious DP-oriented food. The texture was modified with the addition of different thickeners: 2.0% (w/w) k-carrageenan gum (KC) and 1.0 or 1.5% (w/w) guar gum (GG), xanthan gum (XG), locust bean gum (LBG), and gum arabic (GA). Upon characterising and mapping the rheological behaviour involved in extrusion-based 3D printing, the higher concentrations of GG, XG, LBG and GA were found to significantly increase the yield stress and apparent viscosities of the ink formulations. In addition, the colour attributes were examined, while a low population of total viable bacteria (TVC) was observed. The DP-oriented formulations had high fibre content, regulating bowel function and glucose metabolism in the elderly. According to the International dysphagia diet standardisation initiative (IDDSI), KC/XG1 and KC/LBG1 were classified as level 5 indicative of minced and moist dysphagia diet, while KC/GA1, KC/GA1.5, KC/XG1.5, and KC/GG1.5 were classified as level 4, that can be bitten or chewed if the tongue control is reduced. All ink formulations demonstrated high printing precision with excellent self-supporting capability and smooth surface texture that were easy to extrude and print complex samples. This study provides valuable insights into addressing dysphagia by developing a nutritious meal using 3D printing.

1. Introduction

Dysphagia (DP), the medical term for swallowing impairment, can have various causes. Ageing itself is one of the many causes of DP that leads to an abnormal delay in the transit of a liquid or solid bolus (Cho et al., 2015) and is associated with the weakening of the muscles involved in swallowing (Sura, Madhavan, Carnaby, & Crary, 2012). Population-based surveys estimate that DP prevalence reaches about 20% of the population at the age of 50 or older (Cichero et al., 2017; National Health Service, 2018) and exceeds 60% of people living in aged care facilities (Engh & Speyer, 2022). Disease-related factors have also been associated with DP development. More specifically, oropharyngeal damage (attributed to nervous system dysfunction such as stroke, brain tumour, and Parkinson's disease), oesophageal injury (e.g., mouth or throat cancer, gastro-oesophageal reflux disease, scleroderma, and achalasia), and structural abnormalities (e.g., webs, diverticula, strictures, masses) have been reported to cause DP (Makowska, Kloszewska, Grabowska, Szatkowska, & Rymarczyk, 2011; Mann, Hankey, & Cameron, 2000; Schache & O'Rourke, 2021). People with DP may avoid eating and drinking due to a fear of choking, which can lead to severe malnutrition and dehydration (Altman, Yu, & Schaefer, 2010). Additionally, individuals with DP avoid enjoying meals and social interactions with others, key elements of healthy ageing (Balandin, Hemsley, Hanley, & Sheppard, 2009; Smith, Bryant, & Hemsley, 2022).

Successful DP management interventions can significantly improve the nutritional status of individuals through the increased oral intake of food or liquids (Wright, Cotter, & Hickson, 2008). It has been documented that increasing bolus viscosity from liquid to pudding significantly reduces the prevalence of laryngeal penetration and aspiration. Similarly, alteration of solid foods (by dicing, chopping, mincing, or

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https://doi.org/10.1016/j.foodhyd.2023.109300
Received 8 June 2023; Received in revised form 6 September 2023; Accepted 15 September 2023

pureeing) is a common approach to making these materials easier for oral processing and swallowing (Gallegos, Brito-de la Fuente, Clavé, Costa, & Assegehegn, 2017). To this point, the International Dysphagia Diet Standardisation Initiative (IDDSI) has developed testing methods intended to confirm the flow or textural characteristics of modified foods and thickened liquids used for individuals with DP (IDDSI, 2019). The white paper published by the European Society of Swallowing Disorders (ESSD), suggests that clinical effectiveness of texture-modified food relies on both rheological properties and practical measurements. Also, the paper identified a lack of standardised definitions for viscosity levels, with multiple subjective terms being used to describe the same range of viscosity levels (Newman, Vilardell, Clavé, & Speyer, 2016).

However, the visual presentation of texture-modified diet, designed for individuals with DP, significantly affects their level of enjoyment and can lead to feelings of self-consciousness and exclusion from social gatherings (Shune & Linville, 2019). Therefore, novel approaches to prevent DP-related malnutrition is more urgent than ever. To this end, 3D food printing technology allows visual customisation that may improve the appearance of texture-modified food providing nutrition support to DP individuals. 3D printing is an additive manufacturing (AM) technique for fabricating a wide range of structures and complex shapes (Ekonomou, Soe, & Stratakos, 2023). During the past few years, there have been some efforts to develop appealing 3D printed, DP-oriented food products with the incorporation of food thickeners aiming to modify food texture and visco-elastic properties that make food easy to swallow and process (Dick, Bhandari, Dong, & Prakash, 2020, 2021a; Liu, Xing, et al., 2023; Mirazimi, Saldo, Sepulcre, Gràcia, & Pujola, 2022; Pant et al., 2021). Some of the most widely used thickeners that are also "Generally Recognized as Safe" (GRAS) food additives by the U.S. Food and Drug Administration (FDA) are the KC, XG, GG, GA, and LBG (Liu, Zhang, & Bhandari, 2018; US Food and Drug Administration, 2017). Adding thickeners alone or in combination into food can lead to forming strong gel structures to increase the viscosity of food and liquids. Therefore, adding thickeners is an effective way to create mixtures with improved rheological properties, printing performance and texture of DP-oriented food due to their well-defined properties (Chen, Zhang, Sun, & Phuhongsung, 2022; Tan, Toh, Wong, & Li, 2018) that correlates to the textural attributes of the product (O`Sullivan, 2017).

Moreover, all texture-modified DP foods for extrusion-based printing reported so far in the literature are developed using a single ingredient or dehydrated, freeze-dried powders. This is due to the complexity of the interactions that may occur between the thickeners and the food nutrients such as protein, lipids, carbohydrates, vitamins, and minerals. In the survey of Smith et al. (Smith, Bryant, & Hemsley, 2023), participants with DP characteristically mentioned that 'all the food is like wet dog food' highlighting the high importance of providing these people with meticulously designed, safe, tasteful, nutritious, and appealing texture modified food.

Therefore, the present study aimed to investigate the appropriate combination of thickeners to develop multi-ingredient, nutritious, rich in calories and safe to swallow food formulations that can be easily 3D printed to create personalised shapes providing nutritional support to DP individuals. Initially, the rheological and textural properties of the ink formulations were investigated. The colour attributes and microbiological quality of the ink formulations were also determined. Subsequently, the food formulations were evaluated as potentially safe DP foods according to the IDDSI framework. Finally, their ability to be printed in complex 3D shapes was also explored to ensure that can be used to improve the appetite of DP patients.

2. Materials and methods

2.1. Raw materials

Commercially available, fresh garden peas, Greek strained yoghurt with 5% fat, extra virgin Greek olive oil, and vegetable stocks were purchased from a local retailer. Herbal's Magic, 100% natural organic mint leaves powder, was purchased from Amazon, UK. KC (sulfated plant polysaccharide, code: 22,048), XG from *Xanthomonas campestris* (code: G1253), GG (code: G4129), LBG from *Ceratonia siliqua* seeds (code: G0753), and GA from acacia tree (code: G9752) have been purchased from Sigma Aldrich (UK). All the nutritional facts for the ingredients used are shown in Table S1.

2.2. Preparation of food ink formulations

A total of 230 g of fresh garden peas were weighed, added to a glass beaker, and microwaved for 5 min until overcooked. Then two vegetable stocks were added to 180 mL of warm distilled water and mixed with the overcooked garden peas, 110 g of Greek yoghurt (5% fat), 60 mL of Greek extra virgin olive oil, and 0.5 g of peppermint powder in a cup and blended for 2 min to make a fine puree with no lumps using a Ninja Blender (Ninja Blender with Auto-iQ, 1000-Watt, Amazon, UK).

Following, the mixture was separated into portions of 100 mL prior to the addition of the gums. Consistently the same concentration of 2.0% (w/w) KC was used for all ink formulations in combination with 1.0 or 1.5% (w/w) of GG, GA, XG, and LBG. The gums were then added separately and mixed uniformly for 1 min with the garden peas' puree to make the ink formulations. Therefore, from now on the final ink formulations will be referred as KC/GG1, KC/GA1, KC/XG1, and KC/LBG1 for them with KC 2.0% and 1.0% (w/w) of gums and KC/GG1.5, KC/GA1.5, KC/XG1.5, and KC/LBG1.5, respectively for the samples containing KC 2.0% and 1.5% (w/w) of the gums. Then, all food formulations were wrapped tightly to avoid any moisture evaporation and were left for 30 min at 90 °C in an oven (Fisherbrand Oven 65 L, Thermoscientific, UK) for the denaturation of the proteins. Subsequently, all food formulations were left in an incubator to cool down at 25 °C for 1 h and 30 min. Finally, all formulations were sieved using a food-grade stainless steel fine mesh to avoid the presence of lumps.

2.3. 3D printing process and parameters

A 3D food printer (Foodini, Natural Machines, Spain) with control-heated (0–90 °C), stainless steel capsules was used. The 3D printer consists of a full closed print chamber and a maximum printing volume of 110 mm height and 257 *x* mm in diameter. The samples were kept and printed at 25 °C directly on a food-grade silicone mat on a rotating base with a diameter of 278 mm. The food inks were fed into the capsule and pushed automatically through a nozzle with a diameter of 1.5 mm, at a scanning speed of 2200 mm/s, extrusion speed of 1.8. A hollow cylinder with a 20 mm outer diameter, 4.5 mm wall thickness and 20 mm height was fabricated to evaluate the printability of each ink formulation. A cuboid shape with a 15 mm edge length was 3D-printed to evaluate for the fork pressure test.

2.4. Rheological properties of food ink formulations

Rheological properties were determined using a Haake MARS rheometer (Thermo Scientific, Karlsruhe, Germany), which was equipped with cylinder sensor system Z20 DIN (bob diameter = 20 mm and inner cup diameter = 21.7 mm, 4.2 mm gap) for the steady-state flow measurements, while for the rest of the measurements serrated parallel-plate (35 mm diameter, 1 mm gap) probe was employed. Prior the measurement, samples were left to rest for 300 s to release residual stresses induced by sample loading. Moreover, in order to prevent drying of the samples during the measurements, solvent trap was used. Steady-state flow measurements were performed by increasing linearly shear rate from 0 to 100 1/s during 180 s and the recorded data were shear stress (Pa) and viscosity (Pas). Frequency sweep tests were carried out in the frequency range of 0.1–10 Hz, at constant stress of 1 Pa, which was within the linear viscoelastic region that was previously determined in stress sweep measurement by increasing shear stress values from 0.01

to 2000 Pa. The obtained data in these measurements were storage (elastic) (G′) and loss (viscous) modulus (G″). Additionally, creep and recovery tests as a small deformation tests in which sample structure was not destroyed during the measurements were performed. Creep phase was measured at applied stress of 10 Pa during 180s, which was followed by recovery phase carried out at stress of 0 Pa during 420 s. Finally, yield stress value was determined by shear stress ramp method in which shear stress increased from 1 to 2000 Pa during 120 s and resulting deformation was recorded. The obtained data was plotted as a deformation – stress curve in a double logarithmic scale and yield stress value was determined by HAAKE RheoWin Data Manager software (version 4.80.001). All rheological tests were conducted in triplicates at 25 °C.

2.5. Colour attributes and microbiological analysis of food ink formulations

2.5.1. Colour measurement

The colour was measured directly on the sample's surface using a portable colourimeter (Chroma Meter CR–400, Konica Minolta, Japan). The determination of the colour for all samples, including control, was performed at room temperature (25 °C). CIELAB parameters L* (brightness), a* (+a, redness; −a, greenness), and b* (+b, yellowness; −b, blueness) were obtained. For each sample three measurements were made from different spots on the surface of each sample.

2.5.2. Microbiological analysis

All microbiological media were supplied by Oxoid (Lancashire, UK). Ten (10) grams from each sample were transferred aseptically into a stomacher bag with 90 mL of Maximum Recovery Diluent (0.1% w/v peptone, 0.85% w/v NaCl; MRD) and homogenized for 2 min at 250 rpm using a Stomacher. Then, a volume of 0.1 mL from the appropriate 10-fold serial dilutions, using the spread plate technique, was used to enumerate: a) the total viable counts (TVC) on plate count agar (PCA) incubated for 48–72 h, b) the counts (*Pseudomonas* spp.) on cetrimide–fucidin–cephaloridine agar (CFC), incubated for 48 h, and c) the yeasts and moulds on potato dextrose agar (PDA) for 5–7 days at 25 °C. Additionally, a volume of 1 mL of serial dilutions in MRD was used to enumerate: a) counts on VRBGA (Violet-Red Bile-Glucose Agar) by counting only the red/purple colonies with a diameter highest than 0.5 mm surrounded by a halo for 24 h at 37 °C and b) the lactic acid bacteria (LAB) on De Man, Rogosa, Sharpe agar (MRS), incubated for 72 h at 25 °C. All results were expressed as Log CFU/g.

2.6. Assessment of nutritional facts of food ink formulations

The nutritional facts used for the ink formulations' labelling were calculated using an online nutrition calculation software (NutriCalc, UK). The final nutritional information was subtracted from the software after adding each ingredient and the quantities used for the preparation of the ink formulations. The nutrition back of the pack labels designed by the authors shows the legal requirements per serving and per 100 g of the ink formulations.

2.7. Textural analysis of food ink formulations

Texture profile analysis (TPA) of 3D-printed ink formulations was performed at 25 °C using a texture analyser (TA.XT Plus, Stable Micro Systems, UK) equipped with a 10 Kg load-cell, and attached with a compression platen (P/50). The samples were fed into the stainless-steel container and printed in a cuboid shape with a 15 mm edge length directly on a surface that was removed from the printer and added under the texture analyser to avoid the disruption of the samples prior to the analysis. Before the test, height and weight calibration were carried out. The sample was then placed at the centre of the platform under the compression platen (P/50) during the test. The double-cycle compression test was performed at pre-test speed of 5 mm/s, test speed of 1 mm/s, post-test speed of 2 mm/s, holding time of 2 s, trigger force of 10 g, and compression strain at 45%. All measurements were performed in triplicate at room temperature (25 °C).

2.8. IDDSI testing for the level definition of the food ink formulations

2.8.1. IDDSI testing

The most recent IDDSI Framework Testing Methods 2019 were used to identify and describe the properties of the food formulations with various concentrations of thickeners (IDDSI, 2019). The IDDSI Framework provides a commonly accepted terminology to describe texture-modified foods in parallel with their flow or textural properties. It can then be classified into 8 levels (0–7) feasible for people with various levels of swallowing disorders according to their characteristics, where drinks and liquids can be classified from Level 0 (thin) to Level 4 (extremely thick) and foods from Level 4 (pureed) up to Level 7 (regular, easy to chew). The final texture of our food samples before the addition of the thickeners was puree-like. For this reason, following the IIDSI Framework's guidelines, the spoon tilt and fork tests were used. The spoon tilt test was used to identify the stickiness and cohesiveness of the formulations by getting a spoonful of each sample that was allowed to slip off the spoon. To increase the comparability and repeatability of our results, the fork test was performed using a 3D-printed cuboid shape with a 15 mm edge length. A stainless-steel fork with 4 mm gaps between the prongs was used to assess the softness/hardness, firmness, and particle size of the inks by pressing them with the fork to observe the applied pressure up to the level that the thumbnail blanches.

2.8.2. Image acquisition and processing

All pictures were captured with a digital single-lens autofocus Camera HD 2.7 K 48 MP (STUOGYUM, Amazon, UK). Consistent lighting was ensured using a white mini studio light box (DUCLUS, Amazon, UK) equipped with 40 LED aerial lights positioned overtop of the samples.

2.9. Statistical analysis

All experiments were performed in triplicate. All data acquired were expressed as mean ± standard deviation (SD), and the Excel Microsoft® Office 365 (ver. 16.48) was used to plot graphs. All data were subjected to a one-way analysis of variance by ANOVA test using the IBM® SPSS® statistics 26 software for macOS (SPSS Inc.). The student's t-test was used to determine significant differences between two groups at a 5% level of significance.

3. Results and discussion

3.1. Rheological properties of ink formulations

3.1.1. Yield stress

Hydrocolloids are a heterogeneous group of long-chain polymers used as functional ingredients in food formulation as thickening and gelling agents for increasing food consistency, controlling the microstructure, some sensory properties (texture and flavour), and shelf life (Gawai, Mudgal, & Prajapati, 2017). Considering these properties after the addition of hydrocolloids either individually or in combination into a food, the rheological properties are changing significantly, and their role in the adjustment of yield stress, viscoelastic properties etc., must be evaluated. In our study, it was crucial to examine the rheological behaviour of the formulations. This examination helped understand how these formulations perform in 3D printing and how they affect the swallowing characteristics for DP patients.

The yield stress for the food ink formulations was investigated as one of the most essential parameters for DP-oriented food. According to Liu, Bhandari, Prakash, Mantihal, and Zhang (2019), the performance of ink extrusion in 3D printing is significantly influenced by yield stress, which indicates the minimum force needed to start fluid flow. Initially, there was a plateau of the elastic modulus (G') and viscous modulus (G'') values for all the formulations, where G' was the dominant modulus over G'' (Fig. S1), similar to the results observed by Xing et al. (2022) that developed 3D printed black fungus-based DP oriented food. Yield stress values were obtained by the shear stress ramp method and presented in Table 1. The highest yield stress of 785.05 ± 7.45 Pa observed for the KC/GG1.5 formulation means it will need more force to start the extrusion through the nozzle during 3D printing. This can be easily controlled by changing the scanning speed, extrusion speed, and increasing the nozzle's diameter, to improve the food ink's flowability. In all cases, the yield stress was significantly increased by increasing the gum concentration in the inks (Table 1). The KC/GG1 and KC/GG1.5 formulations revealed significantly higher yield stress among the tested formulations due to the higher molecular weight of GG generating internal microstructure that was more resistant to deformation in the shear stress region (Casas, Mohedano, & García-Ochoa, 2000). The higher the molecular weight of a polymer, the greater the intrinsic viscosity it produces in an aqueous medium (Saha & Bhattacharya, 2010). For patients with DP, the speed at which the bolus is squeezed back and propelled into the pharynx depends on the stress/force that is exerted by the tongue on the bolus and on the viscosity of the bolus resisting the deformation that is inevitable during the propulsion step (Burbidge, Cichero, Engmann, & Steele, 2016). Similar to our results, Liu et al. (2021) observed that the yield stress of Shiitake mushroom ink formulations was improved when the amount of XG and KG addition increased from 0.3 to 0.9%. This effect was attributed to forming of an ordered structure of intermolecular associations from the higher addition of XG and the cross-linking of the KG chains to create a three-dimensional network that traps the water to form a resistant structure to flow. Putting this into a clinical context, it can be stated that elevating the viscosity of fluid would result in a decelerated bolus movement in the mouth, thereby facilitating its handling and diminishing involuntary, untimely spillage of bolus into the pharynx (Saha & Bhattacharya, 2010). The reduction in speed would indicate a smaller dependency on patients for bolus control.

3.1.2. *Flow behaviour – viscosity*

The 3D printing performance can be further explained by the flow behaviour of the food ink formulations versus shear rate (Fig. 1). Viscosity is an important factor that can affect the flow rate of the material through a nozzle during 3D printing. For example, if the material is too thin, it may flow quickly, resulting in a messy and inaccurate print, whereas a more viscous material can be used to print well-adhered deposited layers to create complex structures. Therefore, from a fluid mechanics perspective, it had to be considered how the motion of the bolus in the mouth of a patient with DP is controlled.

Table 1
Yield stress of the ink formulations.

Ink formulations	Yield stress [Pa] ± SD
Control	49.05 ± 11.25a
KC/GG1	682.60 ± 0.69 A d
KC/XG1	640.65 ± 36.78 A cd
KC/GA1	625.80 ± 40.53Ac
KC/LBG1	548.85 ± 1.10 A b
KC/GG1.5	785.05 ± 7.45 B b
KC/XG1.5	763.05 ± 87.03BCE
KC/GA1.5	710.85 ± 16.80BCE
KC/LBG1.5	733.35 ± 8.03BCE

Values represent the means ± standard deviation; n = 3. Different uppercase letters indicate significant differences between the same ink formulations with varying concentrations of thickeners. Different lowercase letters indicate significant differences among ink formulations with the same concentration of thickeners.

In the current study, a wide range of hydrocolloids has been used to help us explore the shear-thinning behaviour of the developed ink formulations to improve the safety and efficacy of swallowing for individuals with DP, as shown in Fig. 1. Initially, the apparent viscosities of control, KC/GG1, KC/GA1, KC/XG1, and KC/LBG1 ink formulations at 0.57 s^{-1} were 10.83 ± 0.01, 613.15 ± 0.01, 221.85 ± 0.56, 423.50 ± 0.03, and 471.10 ± 0.24 Pa s, respectively (Fig. 1A and B). The apparent viscosities of KC/GG1.5, KC/GA1.5, KC/XG1.5, and KC/LBG1.5 ink formulations close to zero were 1271.50 ± 0.03, 283.20 ± 0.08, 357.45 ± 0.07, and 661.70 ± 0.00 Pa s, respectively (Fig. 1B). Sahin & Ozdemir (Sahin & Ozdemir, 2004) found results consistent with ours, indicating that the addition of thickeners such as XG, GG, and LBG led to an increase in the apparent viscosity of formulated kinds of ketchup. The highest increase was observed with GG and LBG, followed by XG. The apparent viscosity of all ink formulations depended on the applied shear rate and decreased while the shear rate increased, revealing shear thinning characteristics. When the shear rate increased from approximately 0.5 s^{-1} to 3.5 s^{-1}, the apparent viscosity of KC/GG1, KC/GA1, and KC/XG1 decreased almost by three times and halved for the KC/LBG1 (Fig. 1A). The lower decrease of viscosity observed for the KC/LBG1 formulation can be due to the characteristics of LBG that is galactomannan with low content of galactose swells, while it degrades and loses viscosity in higher temperatures than the tested temperature of 25 °C (Koocheki, Ghandi, Razavi, Mortazavi, & Vasiljevic, 2009; Turabi, Sumnu, & Sahin, 2008). The same trend was observed for the food ink formulations with the addition of 2.0% (w/w) KC and 1.5% (w/w) of GG, GA, XG, and LBG (Fig. 1B). Sahin & Ozdemir (Sahin & Ozdemir, 2004) found that addition of LBG, tragacanth gum, GG and XG to ketchup resulted in greater shear thinning properties. Shear thinning is a beneficial effect for DP-oriented food that allows the food bolus to be easily swallowed while constant tongue stress is applied, ejecting the bolus onto the pharynx (Nicosia, 2007). In higher shear rates and after 10 $s^{-1,}$ the ink formulations' viscosity was decreased under 100 Pa s, except for KC/LBG1.5, which was 109.15 ± 0.01 Pa s. Yu et al. (Yu, Chi, Li, Wang, & Wang, 2022), in their research for the development of a potato starch gel that can be 3D printed after the incorporation of different gums, demonstrated that with the increased concentrations of LBG, a stronger gel network structure was revealed and more energy was necessary to complete an oscillating shear because of the larger G' storage modulus that we will discuss in our results later. In combination with LBG, KC demonstrates synergistic effects and forms a strong interaction that leads to higher viscosities that are not desirable for some food products, such as beverages (Krempel, Griffin, & Khouryieh, 2019). In the study of Mirazimi et al. (Mirazimi et al., 2022), only a slight change was observed in the apparent viscosity of sieved DP-oriented puree potato formulation with 3 g soy and 0.2 g agar after 0.3 s^{-1}. The greater shear thinning of our food ink formulations compared with the results of Mirazimi et al. (Mirazimi et al., 2022) clearly states the best choice and more appropriate combinations of thickeners for developing a DP-oriented meal that can be visually customised and shaped by 3D printing technology. Even though it is a relatively new field, there is an increased interest. A few recent studies support our statement showing that thickeners like KC, XG, GG, and GA can be incorporated for the successful development of DP-oriented meat (Dick, Bhandari, & Prakash, 2021a; Dick et al., 2020) and or single ingredient (Liu, Chen, et al., 2023; Liu et al., 2021; Liu, Xing, et al., 2023; Xing et al., 2022) that can be 3D printed. Diañez et al. (Diañez et al., 2021) used Fresubin® Clear Thickener (FCT) as a commercial thickener composed of XG, modified starch, maltodextrin, modified cellulose and flavoring for 3D printing a simulated fried egg using orange juice and skimmed milk with modified rheological properties for DP management.

This study evaluated the performance of textured modified ink formulations with different thickeners that were tested at 100 s^{-1} shear rates in an attempt to further the understanding on 3D printed DP-oriented foods with appealing shapes. Although the inks were tested at 100 s^{-1} the oral and pharyngeal shear rates differ significantly (Nishinari et al., 2016; Ong, Steele, & Duizer, 2018) and in future studies

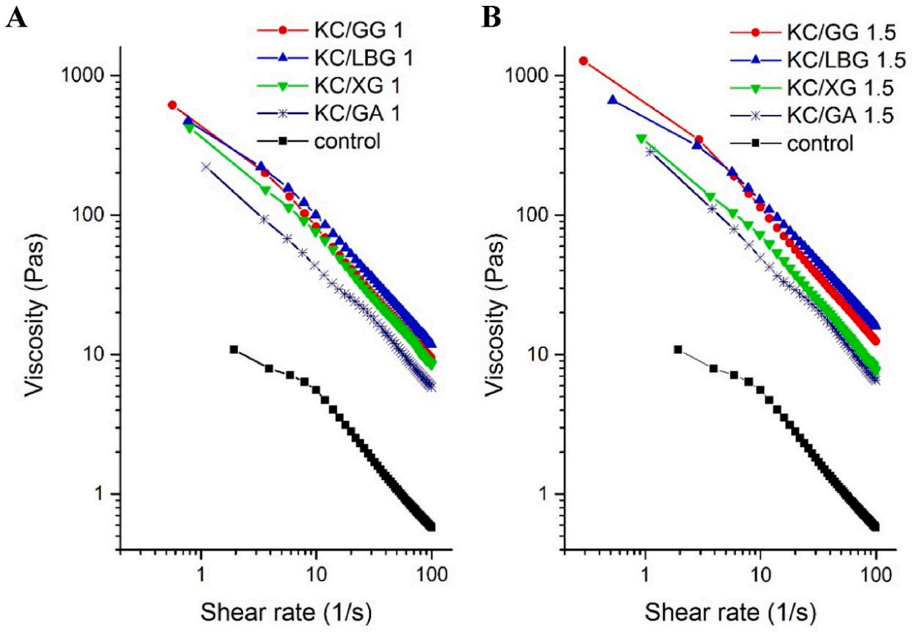

Fig. 1. Flow curves of the ink formulations (A) Control without the addition of thickeners, KC/GG1, KC/GA1, KC/XG1, and KC/LBG1, and (B) Control without the addition of thickeners, KC/GG1.5, KC/GA1.5, KC/XG1.5, and KC/LBG1.5, at 25 °C.

rheological measurements will include a wider range of shear rates (>100 s^{-1}).

3.1.3. Creep and recovery

The rheology test known as creep has been a traditional method and can be used to assess the ability of 3D-printed samples to retain themselves. This test involves applying small constant stress to the sample over an extended period while measuring the resulting small movements, providing valuable insights into the sample's behaviour. As shown in Fig. 2A, the "viscoelastic" properties of the material are resolved with time into $G_{1,}$ which is the instantaneous elastic response, G_2/η_1 the viscously retarded elastic deformation (delayed elastic response), and $\eta_{1,}$ which represents the steady state of viscous flow that is a straight line. At the final point, all the elastic structure (JE) has been stretched, and a pure viscous flow has been left in the sample. Then, the elastic recovery compliance (JR) should be the same as JE, and the space left is the irrecoverable viscous deformation of the samples. The same applies for Fig. 2B and C.

As seen in Fig. 2A, the deformation performance of the control sample was equal to 0.0081045 Pa^{-1} with a dominant elasticity (J_R/irrecoverable flow) of 1.66. A significantly smaller deformation of 0.000506167 (KC/GG1), 0.000471067 (KC/GA1), 0.000482667 (KC/XG1), and 0.0005526 Pa^{-1} (KC/LBG1) was observed for our food ink formulations after the addition of the thickeners compared to the control

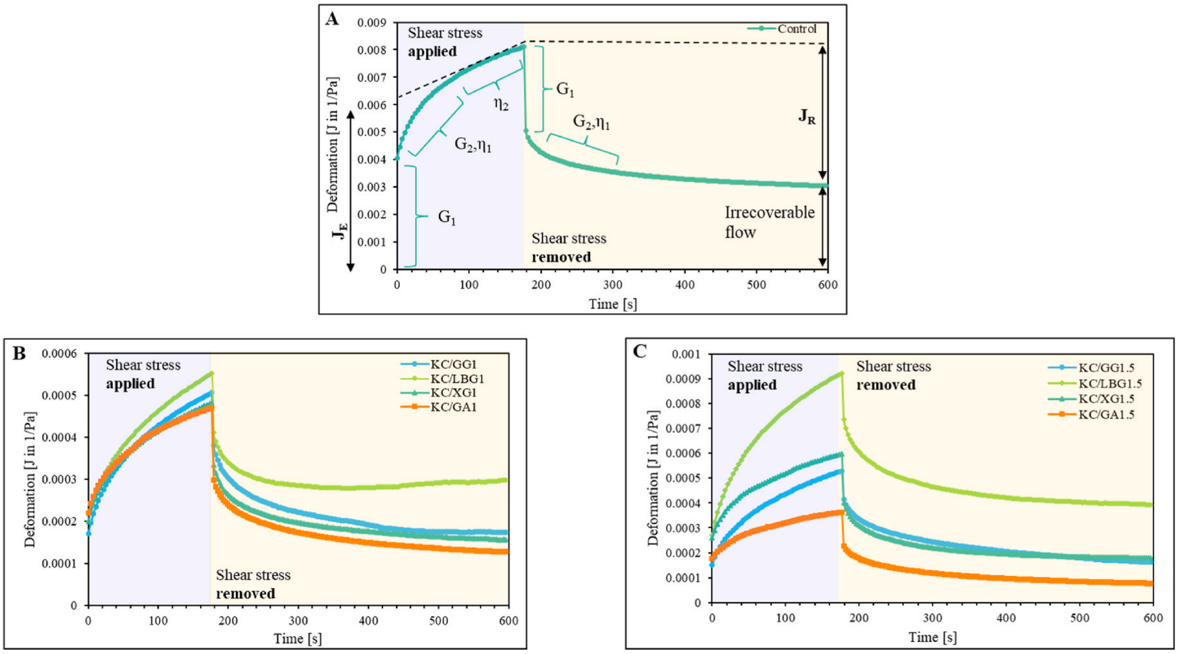

Fig. 2. Creep and recovery response for the ink formulations (A) Control without the addition of thickeners, (B) KC/GG1, KC/GA1, KC/XG1, and KC/LBG1, and (C) KC/GG1.5, KC/GA1.5, KC/XG1.5, and KC/LBG1.5.

sample (Fig. 2B). The dominant elasticity of KC/GG1, KC/GA1, KC/XG1, and KC/LBG1 was 1.91, 2.71, 2.09, and 0.85, respectively. As seen from the results, even though the deformation was smaller than control for all the food ink formulations after the addition of 1% of the thickeners, the dominant elasticity of KC/LBG1 was lower than the control. KC/LBG1 revealed a low self-supporting capability, suggesting a non-friendly DP-oriented sample, as this can lead to difficulty in swallowing and an increased risk of aspiration or inhalation of food into the lungs. Similar results were observed in Fig. 1B for the food ink formulations after the addition of 1.5% of thickeners, where although KC/LBG1.5 revealed a good resistance to compressed deformation during 3D-printing (0.0009229 Pa^{-1}) had a low self-supporting capability of 1.35. In compliance with our results, other studies suggested that the addition of XG and KC improved the deformation resistance capability of DP-oriented ink formulations (Liu et al., 2021; Xing et al., 2022). In the same studies, GA was characterised as a non-friendly thickener for food development for individuals with DP in contrast to our results. This might be due to the concentration of GA and the type of food they developed, as the thickening effect of GA depends on these factors (Saha & Bhattacharya, 2010). GA is widely used in the food industry and is widely known for its low viscosity (Williams & Phillips, 2009). In the current study, GA revealed the lowest deformation among all samples (Fig. 2B and C) and acted synergistically with KC, which is a thickener widely used in dairy products (as Greek yoghurt which was used in this study) to form a strong network structure by interacting with the denaturised proteins of k-casein (Puvanenthiran, Goddard, McKinnon, & Augustin, 2003; Shchipunov & Chesnokov, 2003). While our findings may be useful for DP patients, healthcare providers, and food manufacturers in creating suitable 3D printed foods, it is important to conduct a clinical trial with individuals with dysphagia in the future in order to validate the safety of these 3D printed foods.

3.1.4. Frequency sweep

After investigating the ink formulations' deformation performance, examining their viscoelastic behaviour is another important characteristic of thickened DP-oriented food products. As the tongue squeezes the food into the pharynx, progressively, a bolus tail is created between the tongue and the palate, and the bolus head is moved towards the pharynx (Nakagawa et al., 2014). At this point, viscosity is the most critical factor controlling the flow rate (Burbidge et al., 2016). For healthy individuals, bolus viscosity is almost insignificant during swallowing, but it is of utmost importance for individuals with DP. Higher viscosity gives them time to propel the entire bolus into and through the pharynx and avoid choking during food swallowing (Nicosia, 2007). Furthermore, frequency sweeps can be used to describe the self-supporting capability of the ink formulations after their extrusion through the nozzle of a 3D printer (Dick et al., 2021b; Liu et al., 2019).

Table 2

Frequency sweep rheological measurements. Storage modulus (G') and loss modulus (G'') are reported at 1 Hz.

Samples	G' in Pa ±SD	G'' in Pa ±SD
Control	571 ± 24.05a	108 ± 6.43a
KC/GG1	13,105 ± 275 A b	3584 ± 37 A b
KC/XG1	10,402 ± 797Ac	2421 ± 209 A b
KC/GA1	8134 ± 84 A d	1680 ± 3Ac
KC/LBG1	11,260 ± 180Ae	3428 ± 45.5 A d
KC/GG1.5	15,845 ± 605 B b	4258 ± 166 B b
KC/XG1.5	8370 ± 468.5BCE	1892 ± 66BCE
KC/GA1.5	10,685 ± 425 B d	2304 ± 59.5 B d
KC/LBG1.5	10,530 ± 410 A d	3479 ± 75Ae

Values represent the means ± standard deviation; n = 3. Different uppercase letters indicate significant differences between the same ink formulations with varying concentrations of thickeners. Different lowercase letters indicate significant differences among ink formulations with the same concentration of thickeners.

As shown in Table 2, for all the food ink formulations, G' was higher than G'' over the frequency sweep, indicating a strong internal network arrangement characteristic of a gel-like structure. With increasing frequency, G' and G'' values increased gradually (Fig. S2). KC is a gelling agent that forms a strong network structure by interacting with the positively charged region of κ-casein (in yoghurt) and its negatively charged sulphate group (de Vries, 2009; Verbeken, Thas, & Dewettinck, 2004). KC is well known for its synergistic interactions with other thickeners developed in several food formulations (Saha & Bhattacharya, 2010). In the current study, the storage modulus (G') and loss modulus (G'') at 1 Hz, of all food ink formulations significantly increased compared to the control (Table 2, $p < 0.05$). The storage modulus (G') of all formulations (except LBG) with 2% (w/w) KC and 1.5% (w/w) of thickeners was significantly increased compared to the same formulations with 2% (w/w) KC and 1.0% (w/w) of thickeners (Table 2, $p < 0.05$). Similar results were observed for the loss modulus (G''), where only KC/LBG1.5 revealed a non-significant increase compared to KC/LBG1 (Table 2, $p > 0.05$). A decrease of the storage modulus (G') after adding higher XG concentration has been previously observed by Liu, Chen et al. (Liu, Chen, et al., 2023). The authors suggested that the higher concentration of XG obstructed the successful construction of a strong gel network structure due to the increased rate of intermolecular aggregation that led to phase separation. The weaker gel observed after adding 1.5% XG might also be an effect of the sieving process, as presented in the study of Mirazimi et al. (Mirazimi et al., 2022). In other cases, the addition of 1.79% gelatin increased G' and G'', up to 104% and 64%, respectively, and this was due to the formation of a more robust internal network in chicken meat puree (Bulut & Candoğan, 2022). A higher increase of G' was observed in the study of Liu et al. (Liu et al., 2021) after adding 0.3 and 0.9% KC from 39,554 Pa to 60,890 Pa, explained by the easier formation of a network with double helices caused by the higher concentration of KC.

3.2. Colour attributes and microbiological characterization of ink formulations

The physicochemical characteristics and the microbiological quality and safety of food is important for the public health and especially for elderlies or people with other health issues. The colour attributes (L*, a*, and b*) of our food ink formulations are presented in Table 3. Colour development is an essential factor that can significantly affect the consumers' acceptance of a food product. In the current study, visual appearance is of great importance for individuals suffering from DP that may lose their appetite when the food is not visually appealing. The addition of XG 1.0 and 1.5% (w/w) and GA 1.0% (w/w) significantly decreased the L* value of the ink formulations leading to a slightly darker colour (Table 3, $p < 0.05$). Similar results with no apparent

Table 3

Colour attributes of lightness (L*), redness (a*), and yellowness (b*)on Day 0 of the ink formulations with different concentrations of thickeners ± SD.

	L*	a*	b*
Control	51.27 ± 1.40a	−7.32 ± 0.28a	21.87 ± 0.73a
KC/GG1	48.38 ± 1.28Aa	−6.74 ± 0.20 A b	18.71 ± 0.71 A b
KC/XG1	44.73 ± 0.48 A b	−6.56 ± 0.16Aa	20.06 ± 0.48Aa
KC/GA1	45.90 ± 1.92 A b	−6.75 ± 0.32Aa	21.33 ± 1.00Aa
KC/LBG1	52.77 ± 0.74Aa	−7.93 ± 0.09Abc	24.44 ± 0.32Ac
KC/GG1.5	54.81 ± 0.54 B b	−8.22 ± 0.08 B b	25.71 ± 0.38 B b
KC/XG1.5	47.51 ± 0.44 B b	−7.35 ± 0.11BCE	22.93 ± 0.42Ba
KC/GA1.5	54.06 ± 1.57Ba	−7.69 ± 0.22Ba	24.27 ± 0.78 B b
KC/LBG1.5	50.43 ± 1.48Ba	−7.65 ± 0.22Ba	23.43 ± 0.65Aab

Values represent the means ± standard deviation; n = 6. Different uppercase letters indicate significant differences between the same ink formulations with varying concentrations of thickeners. Different lowercase letters indicate significant differences among ink formulations with the same concentration of thickeners.

pattern were observed for the food ink formulations' a × and b × values. Only KC/GG 1.5% (w/w) ink formulation revealed higher lightness (L*), redness (a*), and yellowness (b*) compared to the control (Table 3, $p < 0.05$). However, even though some statistically significant differences were observed in the food ink formulations' colour attributes of the ink formulations, no noticeable colour change was observed by the naked eye. In the study of Bulut & Gökçen (Bulut & Candoğan, 2022), 1.79% gelatin incorporation did not significantly affect the L* value of pureed chicken meat. The variations in colour attributes observed in our study are believed to be caused by small vegetable particles included in the veggie stock added to the food mix of our ink formulations.

The microbiological quality of the food ink formulations after 3D printing at 25 °C was determined by means of bacterial counts and is displayed in Table 4. A low population of TVC of 2.29 ± 0.11 Log CFU/g was observed before printing (control). No significant differences in the population of TVC were observed for most food ink formulations ($p > 0.05$) except KC/GG1.5 (2.48 ± 0.00 Log CFU/g) and KC/GA1.5 (2.78 ± 0.18 Log CFU/g) as seen in Table 4. The above results suggest that 3D food printing and postprocessing (handling, sieving etc.) of the ink formulations did not contribute to the initial bacterial load of the samples. However, the sanitization of each part in contact with food before its application at home, in restaurants and at the industrial scale is necessary. *Pseudomonas* spp. And members of fungi, yeasts and moulds are the common spoilage agents of vegetables (Alegbeleye, Adedokun, Strateva, & Stratev, 2022; Barth, Hankinson, Zhuang, & Breidt, 2009). Greek yogurt is a lactic acid fermented milk product and, as a dairy product, is also susceptible to fungal spoilage (Buehler, Martin, Boor, & Wiedmann, 2018). Therefore, the growth of yeasts and moulds, LAB, and *Pseudomonas* spp. Was investigated for all the food ink formulations. An analogous pattern with TVC was observed, where the counts of yeasts and moulds for all the samples after printing ranged from 2.00 to 2.54 Log CFU/g. No growth was observed on CFC and MRS media, and all the counts of *Pseudomonas* spp. And LAB were under the detection limit of 2.00 and 1.00 Log CFU/g, respectively (Table 4). According to Regulation (EC) 853/2004 of the European Parliament, Enterobacteriaceae must be absent from dairy products as it indicates cross-contamination or poor handling. No counts on VRBGA for Enterobacteriaceae were found in our 3D-printed samples (<1.00 Log CFU/g). In our study, lower bacterial counts were observed due to the freshness of all ingredients used and further cooking process at 90 °C for 30 min.

This study provides crucial information about the safety and quality of 3D-printed DP-oriented food and can significantly impact the consumers' opinion and acceptance of 3D-printed food. In the survey of Tesikova et al. (Tesikova et al., 2022), it seems that 72.4% of the respondents don't know or believe that there is an increased risk of microbial contamination for 3D printed food, and 59.5% of the respondents are afraid that 3D printed food might be harmful to their health. However, in the survey by Manstan & McSweeney (Manstan & McSweeney, 2020), almost half of the consumers declared excited about trying 3D printed food and that 3D printing is a great novel technology for the development of personalized food, especially for individuals' needs and preferences. The results identified by these studies highlight the importance of the current research.

Table 4
Bacterial counts on Day 0 of the 3D-printed ink formulations with different concentrations of thickeners ± SD.

	Bacterial counts (Log CFU/g)				
	PCA	PDA	CFC*	MRS*	VRBGA*
Control	2.29 ± 0.11a	2.24 ± 0.24a	<2.00	<1.00	<1.00
KC/GG1	2.39 ± 0.09Aa	2.00 ± 0.00Aa	<2.00	<1.00	<1.00
KC/XG1	2.30 ± 0.30Aa	2.00 ± 0.00Aa	<2.00	<1.00	<1.00
KC/GA1	2.30 ± 0.00Aa	2.00 ± 0.00Aa	<2.00	<1.00	<1.00
KC/LBG1	2.30 ± 0.00Aa	2.24 ± 0.24Aa	<2.00	<1.00	<1.00
KC/GG1.5	2.48 ± 0.00 A b	2.00 ± 0.00Aa	<2.00	<1.00	<1.00
KC/XG1.5	2.15 ± 0.15Aa	2.54 ± 0.06 B b	<2.00	<1.00	<1.00
KC/GA1.5	2.78 ± 0.18 B b	2.00 ± 0.00Aa	<2.00	<1.00	<1.00
KC/LBG1.5	2.39 ± 0.09Aa	2.54 ± 0.06 A b	<2.00	<1.00	<1.00

Values represent the means ± standard deviation; n = 6. Different uppercase letters indicate significant differences between the same ink formulations with varying concentrations of thickeners. Different lowercase letters indicate significant differences among ink formulations with the same concentration of thickeners.

*No statistical analysis was performed for the bacterial counts on CFC, MRS and VRBA as no growth was observed and the results reported as < 2.00 for CFC and <1.00 for MRS and VRBGA; under the detection limit.

3.3. *Assessment of nutritional facts of ink formulations*

Malnutrition in older adults has been recognised as a challenging health concern associated with not only increased mortality and morbidity, but also with physical decline significantly affecting quality of life (Norman, Haß, & Pirlich, 2021, p. 2764). There is strong evidence that DP is associated with high risk of frailty and malnutrition in older adults characterized by substantial weight loss, decrease of lean body mass and muscle strength (de Sire et al., 2022, p. 982; Yang et al., 2022). One way to prevent dysphagia-related malnutrition is by consuming texture-modified foods that are easier to chew and swallow while being nutritionally beneficial and readily consumable, like conventional meals (Wu, Miles, & Braakhuis, 2020). Even though there has been an increased interest over the last few years in the production of DP-oriented food using 3D printing technology. To the best of the authors' knowledge, there is no published work on the preparation of a multi-ingredient, nutritious, rich in calories 3D printable DP-oriented food ink. In this study, we specially designed a recipe to meet the nutritional needs of DP individuals and investigated how this can be 3D printed to meet the criteria of a visually appealing dysphagic food. Fig. S4 illustrates the caloric intake, carbohydrates, fat, fibre, protein, and minerals per 100 g and per serving of the ink formulations with 2% (w/w) and 1.0 or 1.5% (w/w) of the incorporated thickeners. A combination of fresh garden peas, Greek yoghurt with 5% fat, extra virgin olive oil, vegetable stocks, and organic mint powder were selected to produce a full DP meal. Fresh garden peas have a high nutritional value of plant-based protein and low allergenicity (Roy, Boye, & Simpson, 2010). Garden peas have also been used as an alternative source of protein with a low impact on CO_2 gas emissions per kg (González, Frostell, & Carlsson-Kanyama, 2011), while the positive health effects of vegetarian diets are well known (Key, Appleby, & Rosell, 2006). Greek yoghurt with 5% fat provides sufficient calories and increases the intake of bioactive peptides, probiotics, and calcium (Theodorou & Politis, 2016), while the extra virgin olive oil is rich with health promoting monounsaturated fats and antioxidants for the elderly (Gorzynik-Debicka et al., 2018, p. 686). The mint powder is rich in nutrients and may help improve brain function or relieve indigestion (Curutchet, Dellacassa, Ringuelet, Chaves, & Viña, 2014), while the vegetable stocks are a source of fibre, contain iron, sodium and several nutrients that can improve digestion and enhance the final smell and taste of the food (Wotton, Crannitch, & Munt, 2014).

Gums used as thickeners are indigestible in the upper gastrointestinal (GI) tract due to their low susceptibility to enzymatic hydrolysis by digestive enzymes in the mouth, stomach, and small bowel (American Dietetic Association, 2002). DP-oriented food is not processed under high heat treatments that can cause nutritional loss (Dick et al., 2021a; Kouzani et al., 2017; Pant et al., 2021) but is cooked with higher amount of water that leads to the unfolding and denaturation of proteins that increases their bioavailability to proteolytic enzymes in the stomach and the GI tract (Lorenz, Iskandar, Baeghbali, Ngadi, & Kubow, 2022). Gums have a high-water binding capability and tend to be indigestible but would thicken the stomach contents under acidic conditions (Turgeon & Rioux, 2011). Therefore, during consumption, the gums will thicken in the stomach under acidic conditions and prolong digestion. In this way, they can improve nutrient absorption and provide a good bulk for the colon (Lorenz et al., 2022; Turgeon & Rioux, 2011). As shown in Figs. S4A and B, the incorporation of thickeners did not contribute to the nutritional value of the food ink formulations. On the other hand, the addition of 2% (w/w) KC and 1.0 or 1.5% (w/w) of GA, GG, XG, and LBG increased the fibre content of the formulations at 4.4 g and 4.6 g per 100 g and 98 kcal, respectively (Figs. S4A and B). According to the Regulation (EC) No 1924/2006 regarding the list of nutrition claims of the European Union (Commission Regulation, 2012), we are claiming that our food ink formulations are high in fibre content as they contain more than 3 g of fibre per 100 kcal (Figs. S4A and B). Gums as dietary fibres can offer a protective effect against numerous diseases such as cardiovascular, inflammatory bowel, and Crohn's disease and may help to normalize blood sugar and cholesterol levels (Barak & Mudgil, 2014; Mortensen et al., 2017; Mudgil, Barak, & Khatkar, 2014; Prasad, Thombare, Sharma, & Kumar, 2022; Sworn, 2021). Additionally, fibres regulate bowel function and glucose metabolism in the elderly (Volkert et al., 2019). Due to the lack of functional, nutritious, and appealing food options specifically developed for DP patients, the food ink formulations developed in this study have the potential to improve a person's quality of life during mealtime.

3.4. Textural analysis of ink formulations

Any food can be defined by its textural characteristics. Hardness, adhesiveness, resilience, and cohesiveness, presented in Fig. 3, are considered as the most important parameters for DP-oriented food (National DP Diet Task Force, 2002).

The TPA test (two-bite compression mode) was conducted to simulate the mastication process that starts with the first bite when taking the food in the mouth (Laguna, Sarkar, & Chen, 2017). Hardness is related to the force needed to cause permanent deformation to the food during mastication. All ink formulations were significantly harder than the control (Fig. 3A, $p < 0.05$), except the KC/GA1 (37.34%) and KC/GA1.5 (47.06%) (Fig. 3A, $p > 0.05$). This was consistent with the results shown in section 3.1.3, where KC/GA1 and KC/GA1.5 had the lowest deformation resistance. This was due to the nature of GA to form low viscous gels as it prevents hydrogen bond formation (Xing et al., 2022; Zhao et al., 2021). On the other hand, GA formulations were found with the lowest adhesiveness indicating that less force will be required for this sample to be removed from the teeth and tongue during eating. The same result was observed by Xing et al. (Xing et al., 2022) with the addition of GA in concentrations of 0.3, 0.6, and 0.9% in the black fungus to develop a DP-oriented mix. KC/GG1, KC/GG1.5, KC/LBG1, and KC/LBG1.5 demonstrated higher adhesiveness than the control and among the same formulations with increased concentration of thickeners (1.0 or 1.5%). The higher adhesiveness of food can increase the risk of pharyngeal residue due to its sticky nature during swallowing. Avoiding foods with sticky or adhesive textures in a dysphagic diet is recommended. This is because the residue can accumulate in the oropharynx, which may increase the risk of aspiration after swallowing (Park, Kim, Lee, & Park, 2017). Adding a higher concentration of XG significantly decreased the adhesiveness from -104.48 g s for KC/XG1 to -31.05 g s for KC/XG1.5 (Fig. 3B, $p < 0.05$). When the concentration of XG increased, a significantly higher resilience of 2.44% (KC/XG1) compared to 2.96% (KC/XG1.5) was observed (Fig. 3C, $p < 0.05$). The cohesiveness of these samples was significantly higher than control but was not affected by the XG's concentration (Fig. 3D). These results indicate the ability of XG with an elevated concentration to create a more resilient, cohesive, and non-adhesive sample that can withstand compression during swallowing in a food bolus shape to be safer for people with DP. Except for XG, all formulations presented significantly higher resilience than the control and their counterparts when adding a higher concentration of GA, GG, and LBG (Fig. 3C, $p < 0.05$). KC/GA1.5 exhibited a significantly higher cohesiveness of 21.21 than KC/GA1 with 18.45 (Fig. 3D, $p < 0.05$).

When considering a DP-oriented food, hardness is a crucial point during the first bite, as cohesiveness and resilience during mastication and adhesiveness ensure that no food residues will remain in the mouth of the individual. Furthermore, as the point of view of the current research was on the 3D printing of these ink formulations to offer a unique mealtime experience with visually appealing food, a correlation between TPA analyses and rheological properties must be considered (Fig. S1). A good correlation between viscosity and hardness has been revealed in the current (Fig. S3) and other studies for various food ingredients and thickeners (Liu, Xing, et al., 2023; Qiu, Zhang, Bhandari, Chitrakar, & Chang, 2023; Zhu et al., 2023). Qiu et al. (Qiu et al., 2023) pointed out that thickeners such as XG and basil seed gum (BSG) or their combination could be used to develop DP-oriented food with desired printing performance. To develop dysphagia-oriented products, a comprehensive analysis of their texture, flow, viscoelasticity, and sensory properties during oral processing is necessary. This research should encompass all phenotypes of patients with dysphagia, as their behaviour

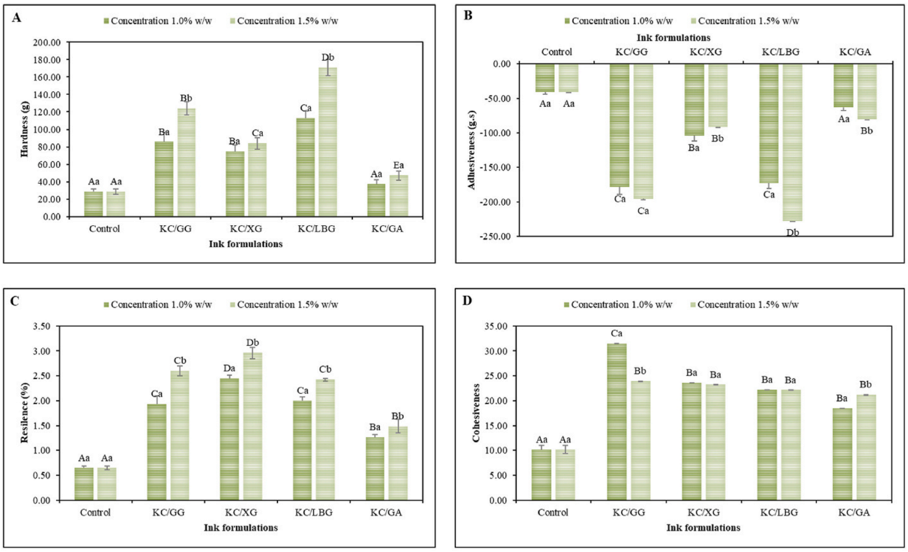

Fig. 3. Texture profiles of A) hardness, B) adhesiveness, C) resilience, and D) cohesiveness of all the ink formulations and control. All values are presented as the means ± standard deviation; $n = 6$. Different uppercase letters indicate significant differences between the same ink formulations with varying concentrations of thickeners. Different lowercase letters indicate significant differences among ink formulations with the same concentration of thickeners.

cannot be fully explained by a single metric (Newman et al., 2016; Ribes, Grau, & Talens, 2022).

3.5. IDDSI testing

The IDDSI Testing Methods are a precise way to evaluate the consistency and texture of texture-modified products for individuals with

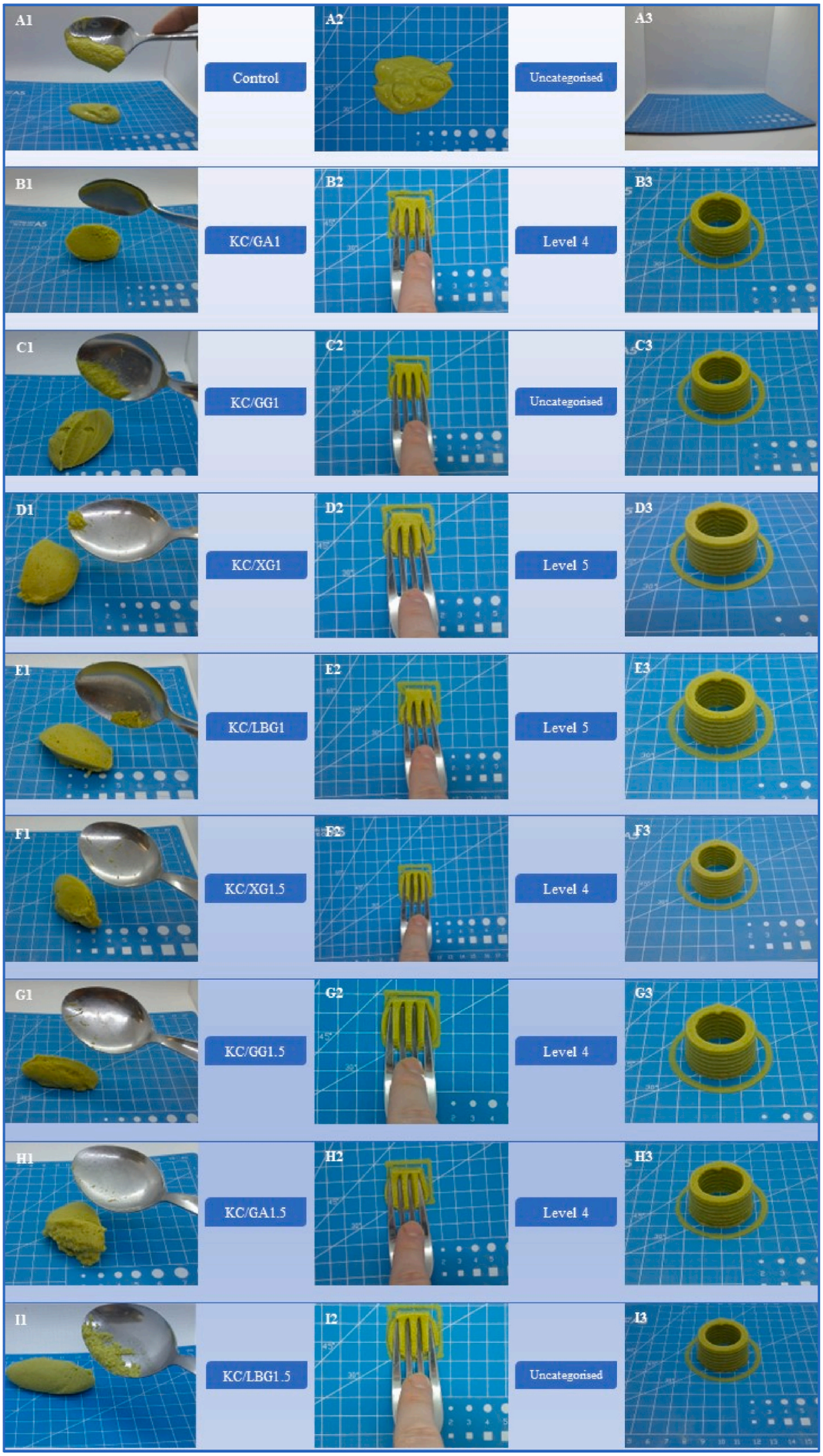

Fig. 4. Classification of all the ink formulations and control, according to the IDDSI protocol investigated by A-I (1) the spoon tilt test and (2) the fork pressure test, and (3) the hollow cylinder test evaluating the self-support capability of the ink formulations after 3D printing.

DP (IDDSI, 2019). The spoon tilt, fork pressure tests, and the 3D printing of the hollow cylinder presented in Fig. 4 were performed at 25 °C (room temperature) as the intended serving condition.

During the spoon tilt test control sample had a liquid form and could not entirely fall off the spoon or be 3D-printed. KC/GA1 and KC/GA1.5 formulations slide off the spoon completely and effortlessly without any flicks (Fig. 4B1 & H1). Initially, KC/XG1, KC/GG1, and KC/LBG1 were characterised as Level 5 “Minced and Moist” samples according to the IDDSI protocol, as some residue and a thin film left on the spoon (Fig. 4B-D1). During the fork pressure test, the same samples need a slight pressure from the fork (4 mm gap between the progs) without making the thumbnail blanching, as seen in Fig. 4B-D2. Our food ink formulations underwent a sieving process. All samples were easily moulded with minimal pressure during the fork pressure test. This pressure was insufficient to cause the thumbnail to turn white, and there were no lumps or excessive granulation. In addition, a clear pattern was formed on the surface of the material. KC/GA1 was the only formulation with KC 2% (w/w) and 1.0% of thickener that was characterised as Level 4 “Pureed, Extremely Thick”. The renewable nature of GA and the fact that is not only biocompatible but also biodegradable (Prasad et al., 2022), make it a sustainable option of gum for DP-oriented food without the need to add synthetic additives. GA has been widely used in traditional medicine to alleviate a variety of ailments, including sore throats, painful joints, common colds, and intestinal and stomach disorders (Prasad et al., 2022). Due to the higher adhesiveness observed in section 3.4, the KC/LBG1.5 was considered uncategorised to avoid the risk of pharyngeal residue due to its sticky nature during swallowing. LBG, in combination with other gums such as KC, forms a gel with more elasticity and strength and provides a creamy mouthfeel in food applications (Barak & Mudgil, 2014; Goycoolea, Morris, & Gidley, 1995). LBG has a great ability to bind water (Barak & Mudgil, 2014). This was obvious as the KC/LBG1.5 formulation with higher concentration revealed a drier surface and feeling than any other formulation in agreement with the rheological properties in section 3.1.2, where KC/LBG formulations revealed the lowest decrease in apparent viscosity during the applied shear rates. On the other hand, KC/XG1.5 slid off the spoon easily without shaking, it was moist, soft, and not sticky, and retained its shape on the spoon and when printed on a hollow cylinder shape as shown in Fig. 4F3. KC/GG1.5, was also moist with a soft texture, and completely fell off the spoon with some shaking (Fig. 4G1). Initially, the KC/GG1 was uncategorised, and KC/XG1 formulation was categorised as Level 5. After adding a higher concentration (1.5%) of the same thickeners, both samples were categorised as Level 4, in agreement with the higher yield stress results observed in section 3.1.1. KC/XG1.5 and KC/GG1.5 formulations passed the fork pressure test (Fig. 4F-G2) and were characterised as Level 4 according to the IDDSI’s terminology and definitions. In a study by Liu, Xing, et al. (2023), it was observed that an increase in XG addition during the spoon tilt test resulted in a reduction of food residue on the spoon. XG has a smooth texture (Bhat, Wani, Mir, & Masoodi, 2022) and can potentially enhance the texture of modified foods for individuals who suffer from DP.

Therefore, based on our food ink formulations’ suitable texture qualities, rheological properties, and ability to retain their shape, as a proof-of-concept, Fig. 5 demonstrates their ability to be printed in complex geometries of 3D objects (honeycomb and waves). The KC/XG1.5 ink was used as a representative DP-oriented, Level 4 formulation (Fig. 4). The 3D-printed samples presented an appealing appearance, with a smooth, moist surface seen in the close-up view with excellent layer adhesion and support without losing shape. This offers new opportunities for individuals suffering from DP to have the chance to enjoy visually appealing food. Furthermore, Farrer et al. (Farrer, Olsen, Mousley, & Teo, 2016) highlighted that the lack of appetite that can lead to malnutrition in DP patients could be improved by enhancing the appearance of the food compared with their current diet, that primarily consists of mashed and puree-like food. It is important to emphasise the necessity of a shared approach in a diverse landscape of dysphagia research. Towards this direction, combining data from different protocols, guidelines, and associations in the future could provide a comprehensive understanding of how IDDSI levels relate to various rheological parameters outlined by other organisations, like ESSD, to create professional standards of practice and guidelines.

4. Conclusion

To the best of our knowledge, this is the first study that developed multi-ingredient meal oriented for older adults with DP using 3D printing technology. For this purpose, we used food materials rich in macro and micronutrients, as well as different combinations of GRAS thickeners with well-established gastro-intestinal benefits. After incorporating thickeners, two Level 5 and four Level 4 food ink formulations (based on IDDSI framework) were successfully designed. Combining KC with 1.0 or 1.5% (w/w) of GG, XG, and GA, excellent rheological results with increased viscosity and good self-supporting capability of the ink formulations for shaping 3D designs were identified. In fact, results indicated that adding LBG 1.0% (w/w) in combination with KC had low self-supporting capacity, while KC/LBG1.5 had the highest adhesiveness according to the TPA analysis suggesting a non-friendly DP-oriented sample. A correlation between TPA analyses and rheological properties

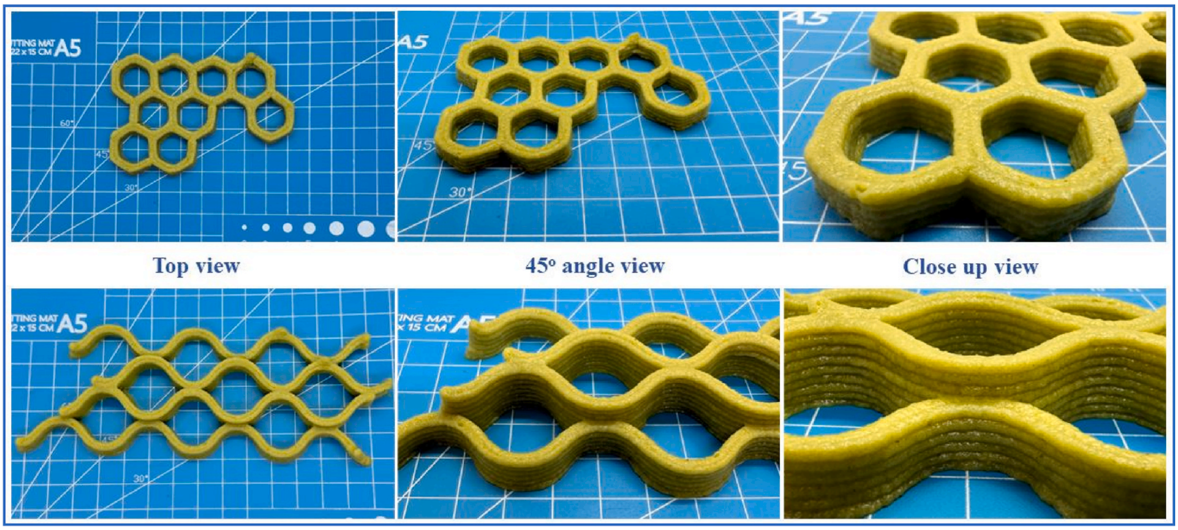
Top view
45° angle view
Close up view

Fig. 5. Representative pictures of complex 3D-printed structures using KC/XG1.5 ink formulations in different angle views.

must be considered for the development of DP-oriented food with desired printing performances. 3D printing and postprocessing (handling, sieving etc.) of the ink formulations did not affect the microbiological quality of the samples on Day 0. So far, all studies have solely relied on single ingredients and dehydrated, freeze-dried food powders for extrusion-based printing. This study offers significant novel insights into the development of nutritious, visually appealing, DP-oriented multi-ingredient food using 3D printing technology.

Funding

This research was funded by an internal competitive grant awarded to Alexandros Ch. Stratakos, Shwe Soe and Aristea Gioxari from the University of the West of England, Bristol.

CRediT authorship contribution statement

S. I. Ekonomou: Writing – original draft, Software, Methodology, Validation, Investigation, Data curation, Formal analysis. M. Hadnađev: Review & editing, Validation, Investigation, Data curation, Formal analysis A. Gioxari: Review & editing, Validation, Investigation, Data curation, Formal analysis, Funding acquisition. O. R. Abosede: Data curation, Formal analysis S. Soe: Review & editing, Resources, Funding acquisition. A. Ch. Stratakos: Formal analysis, Writing – review & editing, Supervision, Resources, Conceptualization, Funding acquisition.

Declaration of competing interest

All authors declare no conflict of interest.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to thank Anastasia Sidiropoulou for her valuable assistance in developing the graphical abstract.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodhyd.2023.109300.

References

Alegbeleye, O., Adedokun, O., Strateva, M., & Stratev, D. (2022). Microbial spoilage of vegetables , fruits and cereals. *Appl. Food Res., 2*(1), Article 100122. https://doi.org/10.1016/j.afres.2022.100122

Altman, K. W., Yu, G. P., & Schaefer, S. D. (2010). Consequence of dysphagia in the hospitalized patient: Impact on prognosis and hospital resources. *Archives of Otolaryngology - Head and Neck Surgery, 136*(8), 784–789. https://doi.org/10.1001/archoto.2010.129

American Dietetic Association. (2002). *National dysphagia diet: Standardization for optimal care*. https://books.google.co.uk/books?hl=en&lr=&id=MZ5mSbGPOE4C&oi=fnd&pg=PP13&dq=National+Dysphagia+Diet+Task+Force.+(2002).+Introduction:+Textural+property+considerations+of+foods+for+dysphagia.In+National+dysphagia+diet:+Standardization+for+optimal+care+&ot.

Balandin, S., Hemsley, B., Hanley, L., & Sheppard, J. J. (2009). Understanding mealtime changes for adults with cerebral palsy and the implications for support services. *Journal of Intellectual and Developmental Disability, 34*(3), 197–206. https://doi.org/10.1080/13668250903074489

Barak, S., & Mudgil, D. (2014). Locust bean gum: Processing, properties and food applications-A review. *International Journal of Biological Macromolecules, 66*, 74–80. https://doi.org/10.1016/j.ijbiomac.2014.02.017

Barth, M., Hankinson, T. R., Zhuang, H., & Breidt, F. (2009). Microbiological spoilage of fruits and vegetables. *Compendium of the Microbiological Spoilage of Foods and Beverages, 135–183*. https://doi.org/10.1007/978-1-4419-0826-1_6

Bhat, I. M., Wani, S. M., Mir, S. A., & Masoodi, F. A. (2022). Advances in xanthan gum production, modifications and its applications. *Biocatalysis and Agricultural Biotechnology, 42*(October 2021), Article 102328. https://doi.org/10.1016/j.bcab.2022.102328

Buehler, A. J., Martin, N. H., Boor, K. J., & Wiedmann, M. (2018). Evaluation of biopreservatives in Greek yogurt to inhibit yeast and mold spoilage and development of a yogurt spoilage predictive model. *Journal of Dairy Science, 101*(12), 10759–10774. https://doi.org/10.3168/JDS.2018-15082

Bulut, E. G., & Candoğan, K. (2022). Development and characterization of a 3D printed functional chicken meat based snack: Optimization of process parameters and gelatin level. *Lwt, 154*(November 2021). https://doi.org/10.1016/j.lwt.2021.112768

Burbidge, A. S., Cichero, J. A. Y., Engmann, J., & Steele, C. M. (2016). 'A day in the life of the fluid bolus': An introduction to fluid mechanics of the oropharyngeal phase of swallowing with particular focus on dysphagia. *Applied Rheology, 26*(6), 8–17. https://doi.org/10.3933/APPLRHEOL-26-64525

Casas, J. A., Mohedano, A. F., & García-Ochoa, F. (2000). Viscosity of guar gum and xanthan/guar gum mixture solutions. *Journal of the Science of Food and Agriculture, 80*(12), 1722–1727. https://doi.org/10.1002/1097-0010(20000915)80:12<1722::AID-JSFA708>3.0.CO;2-X

Chen, Y., Zhang, M., Sun, Y., & Phuhongsung, P. (2022). Improving 3D/4D printing characteristics of natural food gels by novel additives: A review. *Food Hydrocolloids, 123*, Article 107160. https://doi.org/10.1016/j.foodhyd.2021.107160. Elsevier.

Cho, S. Y., Choung, R. S., Saito, Y. A., Schleck, C. D., Zinsmeister, A. R., Locke, G. R., et al. (2015). Prevalence and risk factors for dysphagia: A USA community study. *Neuro-Gastroenterology and Motility, 27*(2), 212–219. https://doi.org/10.1111/nmo.12467

Cichero, J. A. Y., 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 Regulation (EU). (2012). Amending Regulation (EC) No 1924/2006 with regard to the list of nutrition claims. *Official Journal of the European Union L, 310* (1047), 36–37.

Curutchet, A., Dellacassa, E., Ringuelet, J. A., Chaves, A. R., & Viña, S. Z. (2014). Nutritional and sensory quality during refrigerated storage of fresh-cut mints (Mentha×piperita and M. spicata). *Food Chemistry, 143*, 231–238. https://doi.org/10.1016/j.foodchem.2013.07.117

Diañez, I., Gallegos, C., Brito-de la Fuente, E., Martínez, I., Valencia, C., Sánchez, M. C., et al. (2021). Implementation of a novel continuous solid/liquid mixing accessory for 3D printing of dysphagia-oriented thickened fluids. *Food Hydrocolloids, 120*, Article 106900. https://doi.org/10.1016/j.foodhyd.2021.106900

Dick, A., Bhandari, B., Dong, X., & Prakash, S. (2020). Feasibility study of hydrocolloid incorporated 3D printed pork as dysphagia food. *Food Hydrocolloids, 107*, Article 105940. https://doi.org/10.1016/J.FOODHYD.2020.105940

Dick, A., Bhandari, B., & Prakash, S. (2021a). Printability and textural assessment of modified-texture cooked beef pastes for dysphagia patients. *Future Foods, 3*(June 2020), Article 100006. https://doi.org/10.1016/j.fufo.2020.100006

Dick, A., Bhandari, B., & Prakash, S. (2021b). Effect of reheating method on the post-processing characterisation of 3D printed meat products for dysphagia patients. *Lebensmittel-Wissenschaft & Technologie, 150*, Article 111915. https://doi.org/10.1016/j.lwt.2021.111915

Engh, M. C. N., & Speyer, R. (2022). Management of dysphagia in nursing homes: A national survey. *Dysphagia, 37*(2), 266–276. https://doi.org/10.1007/s00455-021-10275-7

Farrer, O., Olsen, C., Mousley, K., & Teo, E. (2016). Does presentation of smooth pureed meals improve patients consumption in an acute care setting: A pilot study. *Nutrition and Dietetics, 73*(5), 405–409. https://doi.org/10.1111/1747-0080.12198

Gallegos, C., Brito-de la Fuente, E., Clavé, P., Costa, A., & Assegehegn, G. (2017). Nutritional aspects of dysphagia management. *Advances in Food & Nutrition Research, 81*, 271–318. https://doi.org/10.1016/BS.AFNR.2016.11.008

Gawai, K. M., Mudgal, S. P., & Prajapati, J. B. (2017). Stabilizers, colorants, and exopolysaccharides in yogurt. In *Yogurt in health and disease prevention* (pp. 49–68). Academic Press. https://doi.org/10.1016/B978-0-12-805134-4.00003-1.

González, A. D., Frostell, B., & Carlsson-Kanyama, A. (2011). Protein efficiency per unit energy and per unit greenhouse gas emissions: Potential contribution of diet choices to climate change mitigation. *Food Policy, 36*(5), 562–570. https://doi.org/10.1016/j.foodpol.2011.07.003

Gorzynik-Debicka, M., Przychodzen, P., Cappello, F., Kuban-Jankowska, A., Gammazza, A. M., Knap, N., et al. (2018). Potential health benefits of olive oil and plant polyphenols. *International Journal of Molecular Sciences, 19*(3), 686. https://doi.org/10.3390/IJMS19030686, 2018, Vol. 19, *Page 686*.

Goycoolea, F. M., Morris, E. R., & Gidley, M. J. (1995). Viscosity of galactomannans at alkaline and neutral pH: Evidence of 'hyperentanglement' in solution. *Carbohydrate Polymers, 27*(1), 69–71. https://doi.org/10.1016/0144-8617(95)00030-B

IDDSI. (2019). IDDSI framework - testing methods. *Dysphagia, 32*(July), 293–314. www.iddsi.org.

Key, T. J., Appleby, P. N., & Rosell, M. S. (2006). Health effects of vegetarian and vegan diets. *Proceedings of the Nutrition Society, 65*(1), 35–41. https://doi.org/10.1079/pns2005481

Koocheki, A., Ghandi, A., Razavi, S. M. A., Mortazavi, S. A., & Vasiljevic, T. (2009). The rheological properties of ketchup as a function of different hydrocolloids and temperature. *International Journal of Food Science and Technology, 44*(3), 596–602. https://doi.org/10.1111/j.1365-2621.2008.01868.x

Kouzani, A. Z., Adams, S., Whyte, J., D, Oliver, R., Hemsley, B., et al. (2017). 3D printing of food for people with swallowing difficulties. *KnE Engineering, 2*(2), 23. https://doi.org/10.18502/keg.v2i2.591

Krempel, M., Griffin, K., & Khouryieh, H. (2019). Hydrocolloids as emulsifiers and stabilizers in beverage preservation. In *Preservatives and preservation approaches in* *beverages: Volume 15: The science of beverages* (pp. 427–465). Academic Press. https://doi.org/10.1016/B978-0-12-816685-7.00013-6.

Laguna, L., Sarkar, A., & Chen, J. (2017). Eating capability assessments in elderly populations. *Nutrition and Functional Foods for Healthy Aging*, 83–98. https://doi.org/10.1016/B978-0-12-805376-8.00010-1

Liu, Z., Bhandari, B., Guo, C., Zheng, W., Cao, S., Lu, H., et al. (2021). 3D printing of Shiitake mushroom incorporated with gums as dysphagia diet. *Foods, 10*(9), 1–20. https://doi.org/10.3390/foods10092189

Liu, Z., Bhandari, B., Prakash, S., Mantihal, S., & Zhang, M. (2019). Linking rheology and printability of a multicomponent gel system of carrageenan-xanthan-starch in extrusion based additive manufacturing. *Food Hydrocolloids, 87*, 413–424. https://doi.org/10.1016/j.foodhyd.2018.08.026

Liu, Z., Chen, X., Dai, Q., Xu, D., Hu, L., Li, H., et al. (2023). Pea protein-xanthan gum interaction driving the development of 3D printed dysphagia diet. *Food Hydrocolloids, 139*(January), Article 108497. https://doi.org/10.1016/j.foodhyd.2023.108497

Liu, Z., Xing, X., Mo, H., Xu, D., Hu, L., Li, H., et al. (2023). 3D printed dysphagia diet designed from Hypsizygus marmoreus by-products with various polysaccharides. *Journal of Food Engineering, 343*(November 2022), Article 111395. https://doi.org/10.1016/j.jfoodeng.2022.111395

Liu, Z., Zhang, M., & Bhandari, B. (2018). Effect of gums on the rheological, microstructural and extrusion printing characteristics of mashed potatoes. *International Journal of Biological Macromolecules, 117*, 1179–1187. https://doi.org/10.1016/j.ijbiomac.2018.06.048

Lorenz, T., Iskandar, M. M., Baeghbali, V., Ngadi, M. O., & Kubow, S. (2022). 3D food printing applications related to dysphagia: A narrative review. *Foods, 11*(12). https://doi.org/10.3390/foods11121789

Makowska, I., Kloszewska, I., Grabowska, A., Szatkowska, I., & Rymarczyk, K. (2011). Olfactory deficits in normal aging and Alzheimer's disease in the polish elderly population. *Archives of Clinical Neuropsychology, 26*(3), 270–279. https://doi.org/10.1093/arclin/acr011

Mann, G., Hankey, G. J., & Cameron, D. (2000). Swallowing disorders following acute stroke: Prevalence and diagnostic accuracy. *Cerebrovascular Diseases, 10*(5), 380–386. https://doi.org/10.1159/000016094

Manstan, T., & McSweeney, M. B. (2020). Consumers' attitudes towards and acceptance of 3D printed foods in comparison with conventional food products. *International Journal of Food Science and Technology, 55*(1), 323–331. https://doi.org/10.1111/ijfs.14292

Mirazimi, F., Saldo, J., Sepulcre, F., Gràcia, A., & Pujola, M. (2022). Enriched puree potato with soy protein for dysphagia patients by using 3D printing. *Food Frontiers*, 1–10. https://doi.org/10.1002/fft2.149. February.

Mortensen, A., Aguilar, F., Crebelli, R., Di Domenico, A., Frutos, M. J., Galtier, P., et al. (2017). Re-evaluation of guar gum (E 412) as a food additive. *EFSA Journal, 15*(2). https://doi.org/10.2903/J.EFSA.2017.4669

Mudgil, D., Barak, S., & Khatkar, B. S. (2014). Guar gum: Processing, properties and food applications - a Review. *Journal of Food Science and Technology, 51*(3), 409–418. https://doi.org/10.1007/S13197-011-0522-X/TABLES/3

Nakagawa, K., Matsuo, K., Shibata, S., Inamoto, Y., Ito, Y., Abe, K., et al. (2014). Efficacy of a novel training food based on the process model of feeding for mastication and swallowing – A preliminary study in elderly individuals living at a residential facility. *Japanese Journal of Comprehensive Rehabilitation Science, 5*, 72–78. https://doi.org/10.11336/jjcrs.5.72, 0.

National Dysphagia Diet Task Force. (2002). Introduction: Textural property considerations of foods for dysphagia. In *National dysphagia diet: Standardization for optimal care* (pp. 1–4). Chicago, IL: American Dietetic Association.

National Health Service. (2018). *Dysphagia (swallowing problems) - causes - NHS*. https://www.nhs.uk/conditions/swallowing-problems-dysphagia/causes/.

Newman, R., Vilardell, N., Clavé, P., & Speyer, R. (2016). Effect of bolus viscosity on the safety and efficacy of swallowing and the kinematics of the swallow response in patients with oropharyngeal dysphagia: White paper by the European society for swallowing disorders (ESSD). *Dysphagia, 31*(2), 232–249. https://doi.org/10.1007/s00455-016-9696-8

Nicosia, M. A. (2007). A planar finite element model of bolus containment in the oral cavity. *Computers in Biology and Medicine, 37*(10), 1472–1478. https://doi.org/10.1016/j.compbiomed.2007.01.007

Nishinari, K., Takemasa, M., Brenner, T., Su, L., Fang, Y., Hirashima, M., et al. (2016). The food colloid principle in the design of elderly food. *Journal of Texture Studies, 47*(4), 284–312. https://doi.org/10.1111/jtxs.12201

Norman, K., Haß, U., & Pirlich, M. (2021). Malnutrition in older adults—recent advances and remaining challenges. *Nutrients, 13*(8), 2764. https://doi.org/10.3390/NU13082764, 2021, Vol. 13, *Page 2764*.

Ong, J. J.-X., Steele, C. M., & Duizer, L. M. (2018). Challenges to assumptions regarding oral shear rate during oral processing and swallowing based on sensory testing with thickened liquids. *Food Hydrocolloids, 84*, 173–180. https://doi.org/10.1016/j.foodhyd.2018.05.043

O'Sullivan, M. G. (2017). Instrumental assessment of the sensory quality of food and beverage products. In *A handbook for sensory and consumer-driven new product development* (pp. 151–175). Elsevier. https://doi.org/10.1016/B978-0-08-100352-7.00008-7.

Pant, A., Lee, A. Y., Karyappa, R., Lee, C. P., An, J., Hashimoto, M., et al. (2021). 3D food printing of fresh vegetables using food hydrocolloids for dysphagic patients. *Food Hydrocolloids, 114*, Article 106546. https://doi.org/10.1016/J.FOODHYD.2020.106546

Park, H. S., Kim, D. K., Lee, S. Y., & Park, K. H. (2017). The effect of aging on mastication and swallowing parameters according to the hardness change of solid food. *Journal of Texture Studies, 48*(5), 362–369. https://doi.org/10.1111/JTXS.12249

Prasad, N., Thombare, N., Sharma, S. C., & Kumar, S. (2022). Gum Arabic – a versatile natural gum: A review on production, processing, properties and applications. *Industrial Crops and Products, 187*(PA), Article 115304. https://doi.org/10.1016/j.indcrop.2022.115304

Puvanenthiran, A., Goddard, S. J., McKinnon, I. R., & Augustin, M. A. (2003). Milk-based gels made with κ-carrageenan. *Journal of Food Science, 68*(1), 137–141. https://doi.org/10.1111/j.1365-2621.2003.tb14129.x

Qiu, L., Zhang, M., Bhandari, B., Chitrakar, B., & Chang, L. (2023). Investigation of 3D printing of apple and edible rose blends as a dysphagia food. *Food Hydrocolloids, 135* (August 2022), Article 108184. https://doi.org/10.1016/j.foodhyd.2022.108184

Ribes, S., Grau, R., & Talens, P. (2022). Use of chia seed mucilage as a texturing agent: Effect on instrumental and sensory properties of texture-modified soups. *Food Hydrocolloids, 123*, Article 107171. https://doi.org/10.1016/j.foodhyd.2021.107171

Roy, F., Boye, J. I., & Simpson, B. K. (2010). Bioactive proteins and peptides in pulse crops: Pea, chickpea and lentil. *Food Research International, 43*(2), 432–442. https://doi.org/10.1016/J.FOODRES.2009.09.002

Saha, D., & Bhattacharya, S. (2010). Hydrocolloids as thickening and gelling agents in food: A critical review. *Journal of Food Science and Technology, 47*(6), 587–597. https://doi.org/10.1007/s13197-010-0162-6. Springer.

Sahin, H., & Ozdemir, F. (2004). Effect of some hydrocolloids on the rheological properties of different formulated ketchups. *Food Hydrocolloids, 18*(6), 1015–1022. https://doi.org/10.1016/j.foodhyd.2004.04.006

Schache, A., & O'Rourke, A. (2021). Dysphagia. In *Evidence-based laryngology* (pp. 175–195). StatPearls Publishing. https://doi.org/10.1007/978-3-030-58494-8_9.

Shchipunov, Y. A., & Chesnokov, A. V. (2003). Carrageenan gels in skim milk: Formation and rheological properties. *Colloid Journal of the Russian Academy of Sciences: Kolloidnyi Zhurnal, 65*(1), 105–113. https://doi.org/10.1023/A:1022335428512

Shune, S. E., & Linville, D. (2019). Understanding the dining experience of individuals with dysphagia living in care facilities: A grounded theory analysis. *International Journal of Nursing Studies, 92*, 144–153. https://doi.org/10.1016/J.IJNURSTU.2019.01.017

de Sire, A., Ferrillo, M., Lippi, L., Agostini, F., de Sire, R., Ferrara, P. E., et al. (2022). Sarcopenic dysphagia, malnutrition, and oral frailty in elderly: A comprehensive review. *Nutrients, 14*(5), 982. https://doi.org/10.3390/NU14050982, 2022, Vol. 14, *Page 982*.

Smith, R., Bryant, L., & Hemsley, B. (2022). Dysphagia and quality of life, participation, and inclusion experiences and outcomes for adults and children with dysphagia: A scoping review. *Perspectives of the ASHA Special Interest Groups, 7*(1), 181–196. https://doi.org/10.1044/2021_PERSP-21-00162

Smith, R., Bryant, L., & Hemsley, B. (2023). The true cost of dysphagia on quality of life: The views of adults with swallowing disability. *International Journal of Language & Communication Disorders, 58*(2), 451–466. https://doi.org/10.1111/1460-6984.12804

Sura, L., Madhavan, A., Carnaby, G., & Crary, M. A. (2012). Dysphagia in the elderly: Management and nutritional considerations. *Clinical Interventions in Aging, 7*, 287–298. https://doi.org/10.2147/CIA.S23404

Sworn, G. (2021). Xanthan gum. *Handbook of Hydrocolloids*, 833–853. https://doi.org/10.1016/B978-0-12-820104-6.00004-8

Tan, C., Toh, W. Y., Wong, G., & Li, L. (2018). Extrusion-based 3D food printing - materials and machines. *International Journal of Bioprinting, 4*(2). https://doi.org/10.18063/IJB.v4i2.143. Whioce Publishing Pte. Ltd.

Tesikova, K., Jurkova, L., Dordevic, S., Buchtova, H., Tremlova, B., & Dordevic, D. (2022). Acceptability analysis of 3D-printed food in the area of the Czech republic based on survey. *Foods, 11*(20). https://doi.org/10.3390/foods11203154

Theodorou, G., & Politis, I. (2016), 10.1080/09540105.2015.1129598. *Effects of peptides derived from traditional Greek yoghurt on expression of pro- and anti-inflammatory genes by ovine monocytes and neutrophils* (Vol. 27, pp. 484–495). https://doi.org/10.1080/09540105.2015.1129598, 4.

Turabi, E., Sumnu, G., & Sahin, S. (2008). Rheological properties and quality of rice cakes formulated with different gums and an emulsifier blend. *Food Hydrocolloids, 22*(2), 305–312. https://doi.org/10.1016/j.foodhyd.2006.11.016

Turgeon, S. L., & Rioux, L. E. (2011). Food matrix impact on macronutrients nutritional properties. *Food Hydrocolloids, 25*(8), 1915–1924. https://doi.org/10.1016/J.FOODHYD.2011.02.026

US Food and Drug Administration. (2017). *Code of federal regulations, 21 CFR 172.620. Title 21 – food and drugs, volume 3, chapter I – food and Drug administration, department of health and human services. Part 172 – food additives permitted for direct addition to food for human consumption. Subpart G – gums*. Chewing Gum Bases and Related Substances.

Verbeken, D., Thas, O., & Dewettinck, K. (2004). Textural properties of gelled dairy desserts containing κ-carrageenan and starch. *Food Hydrocolloids, 18*(5), 817–823. https://doi.org/10.1016/j.foodhyd.2003.12.007

Volkert, D., Beck, A. M., Cederholm, T., Cruz-Jentoft, A., Goisser, S., Hooper, L., et al. (2019). ESPEN guideline on clinical nutrition and hydration in geriatrics. *Clinical Nutrition, 38*(1), 10–47. https://doi.org/10.1016/J.CLNU.2018.05.024

de Vries, J. (2009). Hydrocolloid gelling agents and their applications. In *Gums and stabilisers for the food industry* (Vol. 12, pp. 23–31). The Royal Society of Chemistry. https://doi.org/10.1039/9781847551214-00023.

Williams, P. A., & Phillips, G. O. (2009). Gum Arabic. In G. O. Phillips, & P. A. Williams (Eds.), *Handbook of hydrocolloids* (pp. 627–652). Woodhead Publishing.

Wotton, K., Crannitch, K., & Munt, R. (2014), 10.5172/Conu.673.31.1.44. *Prevalence, risk factors and strategies to prevent dehydration in older adults* (Vol. 31, pp. 44–56). https://doi.org/10.5172/CONU.673.31.1.44, 1.

Wright, L., Cotter, D., & Hickson, M. (2008). The effectiveness of targeted feeding assistance to improve the nutritional intake of elderly dysphagic patients in hospital.

Journal of Human Nutrition and Dietetics, 21(6), 555–562. https://doi.org/10.1111/j.1365-277X.2008.00915.x

Wu, X. S., Miles, A., & Braakhuis, A. (2020). Nutritional intake and meal composition of patients consuming texture modified diets and thickened fluids: A systematic review and meta-analysis. *Healthcare, 8*(4), 579. https://doi.org/10.3390/HEALTHCARE8040579, 2020, Vol. 8, Page 579.

Xing, X., Chitrakar, B., Hati, S., Xie, S., Li, H., Li, C., et al. (2022). Development of black fungus-based 3D printed foods as dysphagia diet: Effect of gums incorporation. *Food Hydrocolloids, 123*, Article 107173. https://doi.org/10.1016/j.foodhyd.2021.107173

Yang, R. Y., Yang, A. Y., Chen, Y. C., Lee, S. D., Lee, S. H., & Chen, J. W. (2022). Association between dysphagia and frailty in older adults: A systematic review and meta-analysis. *Nutrients, 14*(9), 1812. https://doi.org/10.3390/nu14091812

Yu, H. ze, Chi, S. yi, Li, D., Wang, L. jun, & Wang, Y. (2022). Effect of gums on the multi-scale characteristics and 3D printing performance of potato starch gel. *Innovative Food Science and Emerging Technologies, 80*(February), Article 103102. https://doi.org/10.1016/j.ifset.2022.103102

Zhao, H., Kang, X., Zhou, X., Tong, L., Yu, W., Zhang, J., et al. (2021). Glycosylation fish gelatin with gum Arabic: Functional and structural properties. *Lebensmittel-Wissenschaft & Technologie, 139*, Article 110634. https://doi.org/10.1016/J.LWT.2020.110634

Zhu, J., Cheng, Y., Ouyang, Z., Yang, Y., Ma, L., Wang, H., et al. (2023). 3D printing surimi enhanced by surface crosslinking based on dry-spraying transglutaminase, and its application in dysphagia diets. *Food Hydrocolloids, 140*(2), Article 108600. https://doi.org/10.1016/j.foodhyd.2023.108600

Ekonomou, S.I., Soe, S., & Stratakos, A. C. (2023). An explorative study on the antimicrobial effects and mechanical properties of 3D printed PLA and TPU surfaces loaded with Ag and Cu against nosocomial and foodborne pathogens. *Journal of the Mechanical Behavior of Biomedical Materials, 137*, Article 105536. https://doi.org/10.1016/j.jmbbm.2022.105536