

Design Principles of Next-Generation Texture-Modified Foods for Dysphagia Management: Integrating Rheology, Oral Processing, Nutrition, Sensory Science, and Emerging Technologies

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Abstract

Dysphagia management relies heavily on texture-modified foods (TMFs), often for individuals with difficulties chewing, controlling entrapped food in the mouth and tongue or modulating saliva during swallowing. While the main goal of conventional TMFs is to obtain such safe texture and consistency, altering the texture alone does not guarantee optimal swallowability, nutritional adequacy, sensory acceptance or long-term adherence. Thus, developing next-generation TMFs necessitates the replacement of consistency-oriented modification with an integrated food design informed by a patient-centered dual-targeting strategy.

This review synthesizes rheological concepts, oral processing biomechanical principles related to TMF structure and function as reviewed with a critical lens toward key design requirements for high-quality future TBMFs that includes citizen science approaches within the context of food innovation. Rheological parameters such as viscosity, yield stress, shear-thinning behavior, viscoelasticity and cohesiveness are ever so important in terms of bolus formation and swallowing performance. Special emphasis is placed on dynamic alterations during oral processing (mastication, saliva incorporation, lubrication and bolus transition), which cannot be sufficiently represented by static texture measurements. Nutrition design objectives are considered together with rheological requirements, in that if texture-modifying food changes do reduce total energy and/or food intake (as has been shown), there is increased demand for nutrient-dense formulations containing different forms of protein, dietary fiber, micronutrients and water. If sensory properties (but especially appearance, taste, odor, texture and visual familiarity) were major factors of food linked to acceptance or adherence to dietary plans.

Emerging technologies such as 3D printing of food, AI-assisted formulation, predictive rheological modeling and personalized nutrition open up avenues for incorporating these parameters into patient-specific TMF design. Nonetheless, barriers related to standardization, clinical validation, manufacturing scalability, and translation of instrumental measures into swallowing outcomes continue to persist. In conclusion, next-generation TMFs should not be developed in silos, but rather as an integrated food system where the swallowing safety and rheological performance are optimized with nutritional adequacy, sensory acceptability, and personalization. This approach may help bridge the gap between traditional texture modification to safer, nutritionally adequate, acceptable and patient-centred dysphagia care.

Keywords: Dysphagia; Texture-Modified Foods; Rheology; Oral Processing; Swallowing; Sensory Science; Personalized Nutrition; 3D Food Printing

1. Introduction

Dysphagia is defined as the compromised safe and efficient transport of food or liquid from the mouth to stomach, often seen in aging patients and those with

neurological disorders, head and neck disease, or other disorders that may affect swallow function. Poor management can lead to aspiration, dehydration, malnutrition and reduced food intake associated with

impaired quality of life. Because TMFs have the ability to modify the structure and consistency of food, they are used extensively in order to enhance safer oral intake according to an individual's swallowing capacity [1].

Conventional TMFs are usually specialized in the domains of texture classification and swallowing safety, which could be potentially misleading although they have a clinical impact. This description does not fully encompass the multifaceted biological transformations that occur in the oral cavity during food processing and fails to appropriately capture nutritional quality, sensory acceptability, or variability among individuals. Thus, a food meeting a prescribed texture level, may yet be nutritionally incomplete, poorly tolerated or swallowed orally in an uncontrolled manner [2].

1.1 Current Challenges in Texture-Modified Foods

TMF design is a trade-off between safety and eating quality. Foods should be soft and cohesive enough to promote bolus formation, while avoiding excessive hardness, adhesiveness, fragmentation or phase separation. Rheological properties (shear-thinning, yield stress, viscosity and viscoelasticity) are important for the deformation and flow of food, which in turn play a role in bolus control during swallowing. Nevertheless, instrumental texture or viscosity measurements do not fully capture food behavior in the oral cavity. Mastication, tongue compression, saliva incorporation, temperature, dilution, lubrication and structural breakdown gradually change the properties of food before swallowing. So the last bolus can be very much out of sync with the food that was initially offered [3].

Another big challenge is the nutritional quality. Patients in need of TMFs are often at high risk of inadequate energy and nutrient intake. Nutritive density is undeniably reduced in texture modification that involves dilution, blending, sieving or water addition [4,5]. Increased dislike due to an unattractive appearance, dull texture, change in taste and less familiar presentation contribute to even lower intake of food. As such, swallowing safety without any consideration for nutritional and sensory acceptability your TMFs may not have a wide-ranging clinical impact.

1.2 Why Next-Generation Texture-Modified Foods Are Needed

Future TMFs need to go beyond basic mechanical alteration of traditional foods towards those specially designed for dysphagia. They must be formulated with rheological properties specific to swallowing, oral processing behavior, nutritional density, sensory characteristics and/or the unique disability of each patient in their development [6].

This type of approach indicates that an integrated TMF must work well at every stage of the eating process. Before consumption, it should retain appropriate structure, have predictable textural changes during oral processing, develop a well-organised and hydrated bolus strength, provide sufficient nutrition or satiate the consumer.

New technologies open exciting new opportunities to advance them. 3D food-printing allows for control of geometries and structure, portion size, and presentation format, while numerical modeling and machine learning/computational intelligence approaches may inform potential prediction and optimization strategies. Together with personalized nutritional and swallowing requirements, these methods could lead to novel TMF that are tailored for specific patient profiles, rather than designed based on the most widely tested standard formulations [7-9].

1.3 Scope and Objectives of This Review

This review focuses on design principles needed for next-generation TMFs targeting dysphagia. Instead of concentrating on specific thickener or ingredient classes, it cuts across five interlinking dimensions: rheological performance, oral processing, nutritional adequacy, sensory acceptability and emerging technologies. This review aims to: (i) identify soft bolus rheological and structural properties relevant for safe swallowing; (ii) provide insights on how oral pre-swallow processing modifies food structure prior to use; (iii) assess nutritional factors that may influence TMF formulation; (iv) evaluate sensory factors modeling acceptability and dietary adherence; and (v) examine emerging technologies including 3D food printing, predictive models, artificial intelligence, and personalized nutrition as future tools in TMF development [10-12].

The aim of the review is to provide an integrated framework for transitioning from traditional texture modification toward clinically modified, patient-centered foods that offer a simultaneous solution to swallowing safety, nutritional adequacy, eating quality and individual needs.

2. Methodology

2.1 Review Design and Literature Search

This study used a structured narrative review to combine findings from the fields of food science, dysphagia research, nutrition, sensory science and emerging food technologies. This approach was chosen because of the multidisciplinary nature of the evidence reviewed, which included a spectrum from rheological and oral-processing experiments through to clinical, nutritional, sensory, computational and 3D food-printing studies. Method Literature search was performed on PubMed, Scopus, Web of Science and Google Scholar. When prior studies illustrated basic evidence on food rheology, oral processing and swallowing physiology, or texture modification, they were kept [13].

We systematically searched databases for all studies appearing between January 1975 and October 2023 systematically, categorizing search terms into five thematic groups: (i) dysphagia and TMFs — dysphagia, texture-modified food, texture-modified diet, thickened food; (ii) rheology and oral processing — viscosity, yield stress, shear thinning, viscoelasticity; tribology; mastication; saliva; bolus formation; (iii) nutritional design — protein enrichment, energy density dietary fiber micronutrient fortification hydration(iv) sensory design— mouthfeel palatability appearance food acceptance mealtime satisfaction(v) emerging technologies including 3D food printing artificial intelligence machine learning predictive modeling personalized nutrition. Within and between groups, terms were compiled with the use of Boolean operators AND and OR. Primary searches were supplemented with additional reference list screening of relevant studies and reviews to identify important publications not captured in our primary searches [14,15].

2.2 Study Selection and Evidence Prioritization

Studies were included if they addressed TMFs relevant to the design, characterization, performance or clinical significance specifically of TMFs for dysphagia. Eligible literature consisted of primary experimental studies, cohort studies, randomized controlled trials (RCTs), systematic reviews and high-quality narrative reviews. Food-engineering studies were only included if the findings had direct application to TMF design, e.g., oral processing, rheology or tribology of food, nutrient-fortification strategies and approaches to create personalized food. We excluded duplicate records, conference abstracts that did not provide sufficient detail of the methods used to evaluate credibility, applications outside of food and studies with no clear connection to the specific objectives of our review.

Evidence was prioritized according to relevance rather than recency. Particular emphasis was placed on approaches to establish relationships among formulation/structure/rheology, oral processing and sensory behaviour using controlled food-science studies in the case of swallowing safety and patient outcomes for clinical and dysphagia-specific studies. The latest work was put into priority for which the disciplines are moving quite quickly like 3D food printing, artificial intelligence, and personalized food design [16-18].

2.3 Data Extraction and Thematic Synthesis

Data were extracted based on the main TMF design-related variables: food composition and structure, viscosity, yield stress, shear-thinning behavior, viscoelasticity, lubrication, oral breakdown and bolus characteristics (bolus size), nutritional composition of TMFs, sensory attributes that promote patient acceptance and technological process applied. The evidence was subsequently synthesised across five interrelated design domains: Food texture Characterisation Applications in food products61. Rheology → Oral Processing and Bolus Formation → Nutrition → Sensory acceptance →Novel technologies [19].

Instead of judging these domains in isolation, focus was drawn to how they interact. Nutrient fortification, 3D printing, and AI-assisted formulation were assessed

in terms of effect on rheology and sensory quality, ability to simultaneously control texture, nutrition and appearance in addition to personalization [20].

2.4 Evaluation Framework for Next-Generation TMFs

An integrated design framework was employed to synthesize the literature wherein an efficacious next-generation TMF must meet four fundamental outcomes: safety in swallowing, nutritional adequacy, sensory acceptability and practical feasibility. Only those instrumental properties that could be associated with food behavior during consumption were taken into

consideration. Rheological and texture measurements were interpreted in conjunction with oral processing, bolus formation and swallowing obligations instead of as independent determinants of safety. Likewise, you assessed technological innovations not for their novelty of technology alone but for clinical and practical usefulness [21,22].

This framework facilitated the determination of contemporary TMF development challenges and a roadmap for research priorities from past practice reformulations toward evidence-based, patient-centered, and personalized food design.

Table 1. Literature Search Strategy and Eligibility Framework for the Review

Component	Description
Databases	PubMed, Scopus, Web of Science, and Google Scholar
Search period	Literature published with earlier landmark studies included where relevant
Core topic terms	Dysphagia; texture-modified foods; texture-modified diets; thickened foods
Rheology terms	Rheology; viscosity; yield stress; shear-thinning; viscoelasticity; tribology
Oral processing terms	Oral processing; mastication; saliva interaction; bolus formation; swallowing
Nutrition terms	Nutritional adequacy; protein enrichment; energy density; dietary fiber; micronutrients; hydration
Sensory terms	Sensory properties; texture perception; mouthfeel; flavor; appearance; food acceptance
Emerging technology terms	3D food printing; artificial intelligence; machine learning; predictive modeling; personalized nutrition
Inclusion criteria	Original research, clinical studies, relevant systematic and narrative reviews, and technological studies directly relevant to TMF design
Exclusion criteria	Duplicate publications, conference abstracts with insufficient data, non-food applications, and studies without clear relevance to TMF design
Review framework	Rheological performance; oral processing and bolus formation; nutritional adequacy; sensory quality and acceptance; emerging technologies
Main outcomes	Bolus control; swallowing safety; nutritional adequacy; food intake; sensory acceptance; patient-centered food design

3. Fundamental Design Principles of Texture-Modified Foods

Creating texture-modified foods (TMFs) is more than matching a set specification for mouthfeel. Food structure needs to be appropriate throughout preparation and service, change predictably during oral processing, and generate a bolus capable of safe and efficient transport. Hence, a better basic design of

TMFs involving rheological behavior in oral processing, bolus formation and structural stability [23-24].

3.1 Rheological Design

The rheology of food—how it deforms and flows when subjected to forces (e.g., reduced pressure) during the eating and swallowing process—is a critical piece of

information important for TMF design. Karataş, in her own words Bearing in mind that viscosity is one of the main parameters used to characterise modified foods and liquids, it should be noted that a single value for viscosity will not perfectly describe their behaviour. In addition, yield stress, shear-thinning behavior along with viscoelasticity need to be taken into account.

Viscosity influences resistance to flow. Higher viscosity may slow bolus flow velocity and make oral control easier, but too high a viscosity can cause swallowing effort to increase as well as post-swallow residue. Thus the aim is to have enough flow control without generating undue resistance [25].

Yield stress is the least amount of force to produce a flow. In semi-solid TMFs, an optimum yield stress should offer medical affordance capabilities to the food while retaining the ability to deform under tongue pressure during service. Even if some excess yield stress will contribute to oral ease of manipulation when swallowing, particularly in those where tongue force may be compromised.

Dysphagia-oriented foods benefit especially from shear-thinning behavior, where apparent viscosity decreases as shear rate increases. In this manner, a product can be relatively structured at rest but become more flowable in the presence of oral and swallowing forces. Having this balance helps with physical stability, but also ease of consumption [26].

Viscoelasticity is a type of response common to foods, where the food exhibits solid-like and liquid-type characteristics. Complete viscoelasticity is critical to the durability and deformation of bolus, while a highly elastic, brittle or adhesive element of food structure may hinder efficient oral processing.

Hence, these parameters should be studied synergistically instead of simply using viscosity as a parameter for controlling the TMF formulation.

3.2 Oral Processing and Bolus Formation

The bolus properties at the point of swallowing are not necessarily the properties of a TMF at the point of serving. In oral processing, food is compressed, deformed, fragmented, mixed with saliva and undergoes a temperature change and lubrication. Over the course of these processes, the original form of food is progressively changed into a form that will result in

a swallowable bolus. In the case of solid and semi-solid TMFs, mastication should be minimized while allowing a cohesive bolus to form. Foods that fragment into poorly controllable particles are potentially more likely to result in swallowing difficulty while, conversely, extremely adhesive foods may remain stuck on the surface of oral or pharyngeal tissues.

One fluid that has a special function is saliva, as it hydrates and lubricates food whilst changing viscosity and mechanical stability. Salivary enzymes can also manipulate specific food components during oral processing. Thus, it is preferable to determine TMFs not only before consumption but ideally also after simulated or real oral digestion. Bolus formation is the bridge between food engineering and swallowing physiology. A suitably constructed whole bolus must retain sufficient cohesion to maintain integrity, be deformable enough to traverse the swallow pathway and provide a lubrication layer that lessens friction against the oral and pharyngeal walls [27-28].

3.3 Structural Stability

TMFs shall have the desired physical attributes before use and within its period of use This structural instability can lead to the separation of water, syneresis occurring during storage and serving, phase separation, drying or uneven changes in consistency. Such changes can be detrimental to both product quality and swallowing safety.

Retention of liquids is necessary when foods are pureed and minced. Water that is not retained (also called poorly retained water) might separate from the solid phase forming combinations of consistencies that will have different swallowing properties. Thus, formulations need a structure that is homogenous but not too hard or sticky. Temperature is yet another crucial parameter because foods can be devoured hot, cold or at room-temperature. For example, temperature-driven increases in viscosity or gel strength can result in a product that behaves as expected when produced but not at the consumption temperature needed. Stability, therefore, should be reviewed under practical preparation, storage, reheating and serving conditions [29-32].

Thus, the ideal TMF would be one that is structurally stable but deforms in a controllable manner during oral processing and swallowing.

3.4 Integrating Food Structure with Swallowing Performance

The essential design challenge is not to maximize any one true rheological property, but rather, the balance of properties. High viscosity with inadequate lubrication may cause more residue; strong cohesiveness coupled with excessive adhesiveness can impair clearance; and a stable gel necessitating the use of an even greater oral force might be inappropriate for those individuals who possess quite diminished oral strength.

Thus, a better design framework takes into account the following order:

food structure — rheological response — oral transformation — bolus properties — swallowing performance

You should choose which kind of instruments to measure from this sequence. Traditional material characterization methods such as rheometry provide flow and viscoelastic behavior information, texture analysis assays the mechanical properties, while tribological scheme gives lubrication and friction details. When put into context with oral processing and swallowing behavior, such measurements become more clinically relevant [33].

Correspondingly, next-generation TMF design must target a safe processing window and not a given set of single-point viscosity or textural value. In this window, the food must be stable before it is eaten, needs to experience tolerable oral forces, create a cohesive and lubricated bolus, and flow predictably during the swallow. This integrated strategy serves as a basis for substrate mixing rheological safety with the nutritional and sensory requirements presented in depth in Dawn et al. (2023).

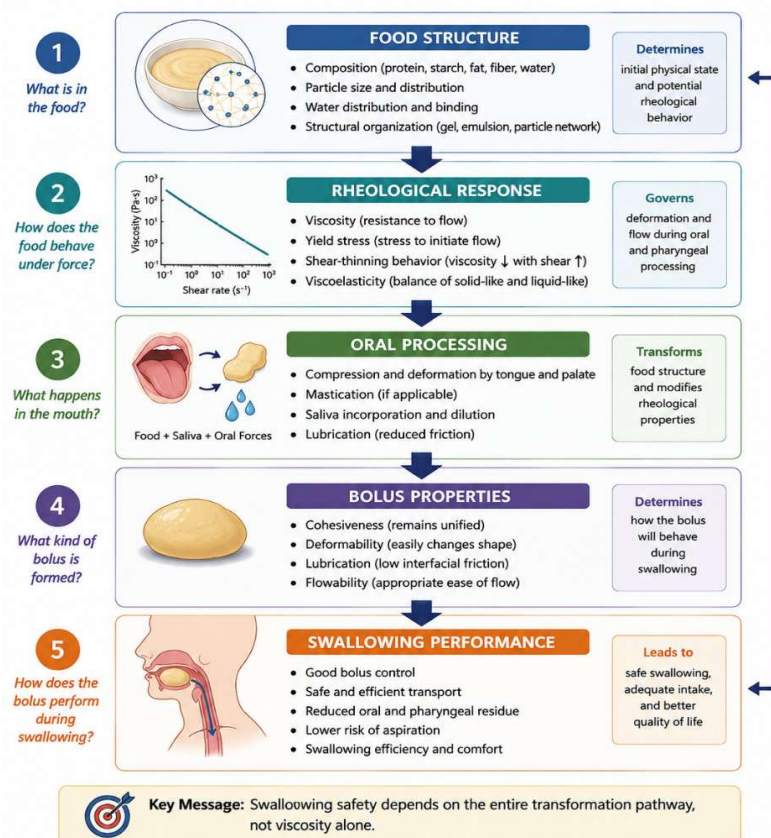


Figure 1. Integrated Relationship Between Food Structure, Rheological Behavior, Oral Processing, Bolus Properties, and Swallowing Performance in Texture-Modified Foods.

4. Nutritional Design Principles

Adequate nutrition is a core target in the development of texture-modified foods (TMFs) due to this population typically being at higher risk of insufficient dietary intake as compared with others who do not have dysphagia. Nutrient density may also be reduced with texture modification when foods are diluted by water or other liquids to achieve the desired consistency, along with potential adverse effects of poor palatability and low food variety on consumption. Therefore, next-generation TMFs need to be high in nutrients whilst doses must also remain safe and manageable to take.

4.1 Protein Enrichment

Adequate protein intake is especially critical for elderly populations and others with dysphagia who are at risk for sarcopenia and loss of functional status. Nonetheless, its presence may change the food structure (e.g., viscosity, gelation and mouthfeel). Thus, the fortification nutritional and rheological consequences have to be contemplated jointly. Protein-rich ingredients (dairy proteins, egg proteins, legume proteins and certain plant protein concentrates) used in pureed and semi-solid foods may enhance their nutritional density. They must be integrated without having excessive toughness, graininess, stickiness, or phase separation from the rubber [34].

As a result, the goal is not merely to optimize protein density but rather to obtain sufficient protein delivery while maintaining the rheologic and sensory properties for safe consumption.

4.2 Energy Density

If dietary habits limit meal size or total energy intake, increasing energy density can ensure adequate energy delivery. This can be by proper usage of fats, carbohydrate-dense ingredients or concentrated food materials instead of overstretching the solution. Fat is especially advantageous from a product development perspective because it offers high energy density and may improve lubrication and mouthfeel. But the total fat also affects a emulsion stability, viscosity and oral coating. Just like enrichment driven by carbohydrate

availability can modify water and structural properties.

Thus, energy enrichment should be formulated within the food matrix as a holistic individual nutrient adjustment.

4.3 Dietary Fiber

Dietary fiber may assist with gut health and enhance the nutritional composition of TMFs. Furthermore, sap appearances can please viscosity, absorption of marine and day stability also provide triggers for the coupling of-technique properties director nutritive helpers.

However, it is important that fiber enrichment be formulated judiciously. Higher concentrations may lead to significant increases of viscosity, strength or water demand while poorly hydrated insoluble particles can cause undesirable roughness or heterogeneity. It is therefore necessary to choose the type, particle size, properties of hydration and concentration of fiber depending on this texture and swallowing [35,36].

4.4 Micronutrient Fortification

Decreased dietary diversity and food consumption may cause micronutrient deficiency in individuals following adjusted diets. Micronutrient fortification offers a possible mechanism by which nutrient density could be increased without corresponding increases in portion size [37].

Fortification, however, should take considerations on food matrix–nutrient interactions. Some mineral salts and vitamin preparations may have an effect on flavour, color, stability or consumer convenience. Micronutrient enrichment is most beneficial when achieved in familiar foods with the expected sensory attributes preserved.

4.5 Hydration Strategies

One of the most significant nutritional aspects in dysphagia is hydration, or more specifically difficulties in consuming liquids that may lead to inadequate fluid intake. TMFs, which are foods rich in moisture like purees, gels, soups, desserts taken up to 50–60% and also considered as water-requiring structured food systems help total water intake [36].

Hydration is not all about water content. The water will have to remain correctly encapsulated inside the food matrix at the point of serving and consumption. Phase separation or release of liquid may result in an unacceptable consistency that contains chunks (in some cases surrounded by the liquid part where it has separated) while too much water binding produces a product that is too firm and not easy to swallow.

There is therefore a significant opportunity to develop food products that incorporate high levels of moisture together with appropriate structural stability to help achieve hydration from the diet [38,39].

4.6 Functional Ingredients and Nutrient-Dense Formulation

The implementation of these next-generation TMFs can contain ingredients capable of acting as both a nutritional and structural component. Proteins determine the network formation, fibres alter water retention or viscosity; lipid systems increase energy density and modify lubrication. This

multifunctionality opens doors for reduction of ingredients implemented solely for texture modification.

Nevertheless, the decision about functional ingredients needs to be made in terms of the overall food system and not a specific nutritional or rheological characteristic. Final texture and oral behaviour is obtained via interactions amongst protein, starch, lipid, fibre, water and other components.

Thus, the optimal formulation strategy is that of a nutrient-dense formulation catering to swallowing performance. Protein, energy, fiber, micronutrients and moisture are to be incorporated within a food matrix designed to hold appropriate rheological behavior, structural integrity, palatability and portion size. The nutritional optimization and texture design in this case should, therefore, happen together as one step rather than working on the nutritional content followed by the physical properties of the TMF [40].

Table 2. Nutritional Design Strategies for Next-Generation Texture-Modified Foods

Nutritional strategy	Primary purpose	Potential effect on food properties	Key design consideration
Protein enrichment	Maintain muscle mass and improve protein intake	May alter viscosity, gel strength, firmness and adhesiveness	Increase protein density without producing excessive firmness, graininess or phase separation
Energy enrichment	Increase energy intake within smaller portions	Fats may improve lubrication; carbohydrates may influence viscosity and water availability	Achieve high energy density while maintaining suitable texture and bolus properties
Dietary fiber enrichment	Support gastrointestinal health and improve nutritional quality	Can increase viscosity, water retention and structural stability	Control fiber type, concentration, particle size and hydration to prevent excessive thickness or roughness
Micronutrient fortification	Improve vitamin and mineral intake	May influence flavor, color and physicochemical stability	Select fortificants that minimize undesirable sensory and structural changes
Moisture optimization	Support fluid intake and facilitate oral processing	Influences softness, viscosity, lubrication and bolus formation	Maintain high moisture while preventing phase separation or free-liquid release

Multifunctional ingredients	Provide nutritional and technological functions simultaneously	Can modify gelation, water binding, viscosity, stability and lubrication	Consider interactions among proteins, carbohydrates, lipids, fibers and water
Nutrient-dense formulation	Deliver adequate nutrition in manageable portions	Multiple compositional changes may affect the overall food matrix	Optimize nutritional density, rheology, sensory quality and swallowing performance simultaneously

5. Sensory Design Principles

Sufficient swallowing safety and nutritional adequacy alone do not guarantee acceptance of TMFs. The foods must be acceptable (tasty, easy to make) and enjoyable enough that they are consumed regularly. Conventional TMFs can be less visually attractive, more monotonous in texture, change the perception of taste or form, and seem unappealingly presented to eat which can make it less palatable and affect appetite and eating satisfaction. It calls to recognize the sensory design side together with the rheological and nutritional optimization.

5.1 Texture and Mouthfeel

This is especially relevant for texture as TMFs are manipulated to alleviate mechanical stress during oral processing. But making food softer or smoother does not inherently mean it is going to be a good eating experience. All these are quite distinct from consistency, which must be adequate for acceptance; excess adhesiveness, gumminess, pastiness, graininess or oral coating can occur without violating the consistency performance requirement.

Interactions involving viscosity, particle size, lubrication, moisture content of food and fat content are responsible for mastication or mouthfeel. Rheological properties are important for bulk deformation and flow of the food, while lubrication becomes more relevant as food is processed between oral surfaces. As a result, foods with comparable apparent viscosity may lead to vastly different sensory experiences [41].

So the optimal design target is one that feels safe to touch and eats smoothly, whereby it has enough appropriate adhesiveness and slipperiness but not sticky or slimy.

5.2 Flavor and Aroma

Modification of texture impact flavor perception by changing the release and transport of aroma and taste compounds. The action itself of pureeing food as well as increasing viscosity or changing the food matrix may attenuate flavor delivery making preparation techniques an important consideration in functional ingredients, together with dilution during puree preparation further reducing the characteristic taste of original food.

Flavor enhancers should, therefore, make food more flavorful without adding too much extra sweetness, saltiness or artificial flavor. At clinically relevant doses, this can lead to improved palatability and herbs, spices and natural flavor components in combination with an appropriate fat system may have utility for achieving optimal palatability.

Aroma is also important for identification and normal food preconsumption. Continuous improvement of texture properties combined with preservation of well-known flavor/aroma profiles could also be effective in maintaining the sensory identity of familiar and palatable foods [42].

5.3 Appearance and Visual Familiarity

Visual perception impacts tastes, texture and general meal perceptions. We know conventional purees tend to lose their shape, color separation and visual identity if you mix certain foods in a blender so what looks the same as other food post pureeing.

Better presentation promotes recognition and might even enhance willingness to eat them. Visual Familiarity of Simulated Foods Natural colors, separated presentation of food components in individual spaces, portion shape control and recreating familiar home cooked meals or recognizable shapes can enhance visual familiarity.

This principle is particularly relevant to emerging manufacturing technologies such as 3D food printing, which can reconstitute visually identifiable structures while preserving a texture suitable for dysphagia [43].

5.4 Sensory Consistency and Food Variety

Being repeatedly exposed four to six times in a row to foods with the same smooth texture leads to sensory monotony. While some structural attributes must be restricted as it is being modified, flavour, aroma, colour, warmth or temperature of the dish, food type and recommendation does allow limited variation in texture.

Being consistent from one meal to the next is key, too. A product that is significantly different in hardness, viscosity, or appearance among batches prepared during the same preparation period may lead to reduced confidence and acceptance. Rigorous formulation and preparation protocols can also enhance safety from choking, whilst providing a reliable sensory experience.

These next-gen under Tmfs need to provide enough options within appropriate texture modulating limits instead of limiting our self with a repetitive series purees that are used over and over.

5.5 Patient Acceptance and Dietary Adherence

Patient accept is the actual byproduct of functional aesthetic design. If a food is largely rejected or eaten only in small amounts, then there is little nutritional benefit from an otherwise nutritionally optimized food. Low acceptability can lead to decreased intake of energy, protein, micronutrients and fluids, which could affect long-term adherence to texture-modified diets.

In addition to physical properties of food, factors affecting acceptance include familiarity, cultural preferences, previous eating habits, meal environment or context of consumption (e.g., social interaction), independence in eating and individual expectation. As a result, it is unlikely that one formulation will offer a suitable sensory experience to all individuals with dysphagia.

The sensory evaluation of products should not merely measure acceptance once the formulation is complete, but rather it should involve patient-centered food

design during product development. Preferential testing and consumer feedback can be used to detect undesirable characteristics of products, leading to reformulation.

5.6 Integrating Sensory Quality with Safety and Nutrition

Sensory optimisation should not occur in isolation from rheological or nutritional design. Reducing fat to enhance mouthfeel can change the structure of food; protein enrichment may influence flavor and firmness; fiber addition may result in a grainy texture; and viscosity modification may affect aroma release and oral coating.

Identifying formulations with simultaneously acceptable levels of swallowing safety, nutritional density and sensory quality is the main design challenge in this regard.

Instead, next-generation TMFs should shift away from food that is only “safe to swallow” and reorient towards food that is safe, nutritionally relevant/reasonable, recognizable as real in nature, palatable and enjoyable to actually consume. Application of sensory science early on in the formulation process is nevertheless critical to successfully translating technically superior TMFs into foods that patients are willing and able to consume consistently [44-46].

6. Emerging Technologies for Next-Generation Texture-Modified Foods

This can pave the way ahead for enabling progress of TMFs from standardized formulations to precise and individualized food systems. The principal utility is enabled through development, not merely relating to creating new foods, but developing a design for rheological performance in specific nutritional composition and sensory qualities, as well as parameters of culinary interest depending on patient-centric needs. Some of the key advancements include three-dimensional (3D) food printing, artificial intelligence (AI), predictive modeling, and personalized nutrition.

6.1 Three-Dimensional Food Printing

This method presents a degree of control in TMF formulation considering shape, portion size, internal structure and nutritional composition. This is especially important for dysphagia since traditional pureeing very often destroys the recognizable form of food.

For successful printing, a beta structuring has to be flow-able during extrusion (β state) while at the same time maintaining structural stability after deposition (α state). The formation of a printable formulation prefers to flow through the nozzle under consistent pressure and should regain enough structure to maintain deposited geometry. They establish a direct link between printability and rheological parameters – yield stress, shear-thinning behavior, viscoelasticity. However, for use in applications such as dysphagia, printability cannot be the last design criteria. While a formulation can print an excellent structure, it may still not be useful if it is too hard, sticky, low in nutrients or cannot be molded into a safe bolus. This means that printing parameters and the food properties related to swallowing need to be simultaneously optimized.

One of the main attributes of 3D printing that makes it highly applicable for next generation TMFs is its unique likelihood to merge textural design, aesthetic replication, unit dosage regulation and customized formulation into a single production platform [47].

6.2 Artificial Intelligence-Assisted Food Formulation

TMF formulations include various parameters with excellent potential for innovation, e.g., concentrations of ingredients, moisture content, processing conditions, rheological properties, nutritional targets and sensory characteristics. This is an inefficient approach because the amount of variables and experiments needed goes up exponentially (increasing cost).

Multidimensional formulation data yields different possibilities to see relationships, and artificial intelligence and machine-learning approaches create the opportunity of identifying them. Input from models that can predict viscosity, yield stress, texture, stability, printability or sensory characteristics may

include ingredient composition and processing parameters.

Thus, AI-assisted formulation research may facilitate rapid candidate screening while minimizing the experimental space needed for optimization. More complex systems could integrate multiple objectives at once, such as the identification of formulations that meet a given texture target while maximizing protein content and sensory acceptability.

Yet, predictive performance is highly dependent on the quality, volume and standardization of the data used. Thus, AI should supplement experimental rheological, sensory, nutritional, and clinical assessment rather than replace it.

6.3 Predictive Rheological and Computational Modeling

This allows us to discover a predictive model that can bridge formulation, processing, food structure and the behavior discussed in relation to swallowing. Viscosity may be predicted as shear rate function in empirical and mechanistic models, or structural recovery after deformation or modification of food properties can also be obtained as a function of the concentration and temperature of a few selected ingredients.

Computational approaches can also be valuable to probe multivalent effects on bolus deformation and flow under experimental conditions that may be difficult to reproduce. Alongside suitable physiological data, simulations may provide insights into how differences in food properties modulate transport through the oral and pharyngeal regions.

One obvious future opportunity is the coupling of experimental rheological data and computational swallowing models. These approaches may help to move formulations targets, which have often been targeted at broadly-defined consistency categories, towards food properties more closely related to swallowing performance.

However, such model outputs must be validated to an experimental and/or clinical level in order to make food design recommendations [48].

6.4 Personalized Nutrition and Patient-Specific TMF Design

Dysphagia is heterogeneous. Swallowing disability, oral strength, nutritional needs, sensory preferences, medical disease and the capacity to eat certain food structures differ across subjects. Consequently, a standardized TMF cannot help every patient.

Personalised TMF design attempts to correlate food properties with specific individual needs. The design variables can be anything ranging from texture level to portion size, energy density, protein content, moisture, flavor, appearance and many more nutritional features of the food product.

Digital formulation systems, using swallowing-related requirements and nutritional information could deliver patient-specific recipes. These formulations may then be generated either through traditional food processing or via 3D printing, depending on the desired structural resolution.

Personalization should remain clinically guided. Defining the factors under which technological systems should manipulate the food must be based on instrumental swallowing assessment, nutritional evaluation and professional judgment.

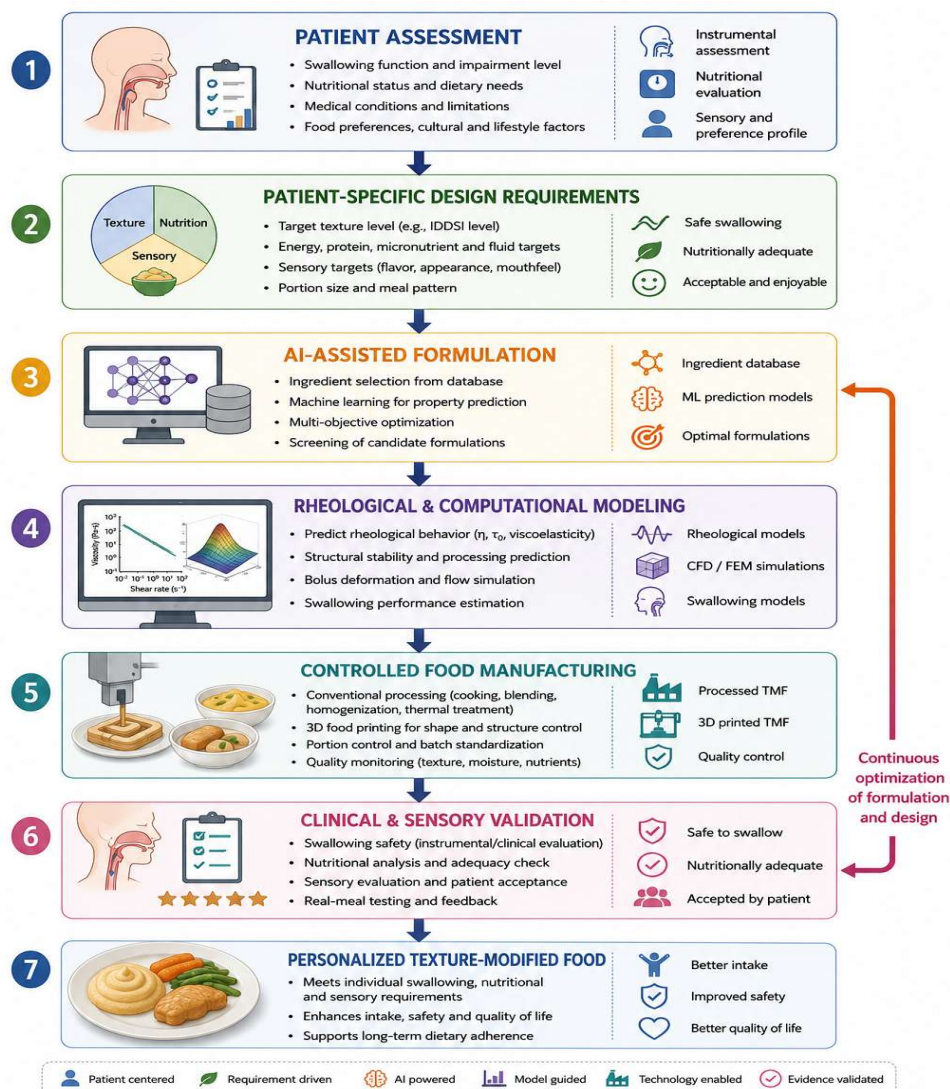


Figure 4. Integrated Digital Design Framework for Personalized Next-Generation Texture-Modified Foods.

6.5 Integrated Digital Design of Texture-Modified Foods

Indeed, the true power of emerging technology is not in its own use but in working with one another. The design of a potential TMF platform could include integration of patient limits, nutritional needs, ingredient databases (like on edible gelled structures¹⁶⁶ applications), rheological measurements¹⁵¹³², sensory preferences⁷¹, and manufacturing restrictions (e.g.⁹³).

As an example, clinical information could specify the swallowing characteristics. Nutritional assessment could set targets for energy, protein, fluid and micronutrients. Predictive algorithms could then superimpose the possible formulations, whereas rheological models might quantify their predicted flow and structural behavior. This formulation can then be produced through controlled processing or 3D printing, followed by swallowing safety and sensory acceptance testing.

This creates a closed-loop design system:

Captures the actual preclinical and clinical nutritional route of administration; basic discovery: patient assessment → design requirements → computational formulation → rheological optimization → food manufacturing (info), clinical & sensory validation; refinement of formulation

This framework also marks a shift away from tailoring foods post cooking toward designing foods upfront based on patient-specific functional requirements.

This therefore positions emerging technologies as the enablers in a TMF design approach. If technological accuracy can yield measurable gains in swallowing safety, nutritional intake, food acceptance, and quality of life then their clinical value will be unequivocal.

7. Current Challenges and Future Perspectives

Even with great strides in food rheology, nutritional formulation, sensory science and digital technologies, the translation of next-generation TMFs to standard clinical practice remains difficult. Key challenges include: standardisation, the conversion of laboratory measurements to swallow outcomes, clinical

validation, manufacturing feasibility and personalisation.

7.1 Standardization of Food Properties and Testing

Variability in the methods of characterizing TMFs is a major challenge. Various instruments and protocols are commonly employed, with different temperatures, shear conditions, and sample preparation routines may be used to assess viscosity, texture, yield stress, viscoelasticity, tribology etc. This restricts the comparison on studies and makes it hard to derive universal design criteria.

The IDDSI framework addresses a first step toward a full classification of food texture and liquid consistency; however, complementary quantitative characterization is needed for next-generation product development. To align food texture classification in practice with measurable properties of foods, there is a contemporary need for standardized rheological, mechanical and oral-processing protocols [49,50].

7.2 Linking Instrumental Measurements with Swallowing Outcomes

Another important limitation is the limited correlation between lab measurements and swallowing performance. For example, a food that has favorable instrumental viscosity or texture properties may not automatically provide effective bolus control in a person with dysphagia.

As an option for future research, consideration should be given by to find the combinations of rheological, tribological and structural parameters that are associated with clinically-relevant outcomes. There should be a stronger coupling of instrumental food characterization with swallowing measures like videofluoroscopic swallowing studies and fiberoptic endoscopic evaluation of swallowing.

Such transition is vital for establishing clinically meaningful design targets rather than exclusively empirical texture specifications.

7.3 Clinical Validation

Most of the novel TMFs are tested mainly with physicochemical, rheological, printing or sensory

experiments. Relatively fewer studies evaluate their effects directly within those suffering from dysphagia. Whether newly designed foods enhance swallowing safety, residue, efficiency, dietary intake, hydration, patient acceptance and quality of life will need to be determined in clinical studies. Additionally, studies should also examine diverse aetiologies of dysphagia as food requirements can differ between patients with neurological disease, age-related impairment, head and neck conditions and other clinical presentations. Technological advances in food formulation should not be assumed to equate with clinical benefits for patients without objective clinical validation showing an outcome change.

7.4 Manufacturing and Clinical Translation

A formulation that has been successfully formulated at a laboratory scale needs to be reproducible when produced on larger scales and stored, transported, reheated and served without degradation. Variations in processing steps may affect texture and product consistency.

Emerging technologies bring more practical challenges as well. The 3D food printing industry relies on appropriate equipment, printable formulations, controlled processing and adequate production speed. Reliable databases and standardized input data are critically important for AI-based formulation systems. Cost, staff training, hygiene preparation, integration into the clinical workflow and quality control are also parameters to be evaluated in healthcare settings.

Consequently, future development should assess technological feasibility alongside scientific performance from the earliest stages of product design.

7.5 Personalization Versus Standardization

Personalization is going to be a big part of the future but raises a massive design challenge. Standardized systems have a role in maximizing safety and consistency in clinical practice, however individuals vary greatly in their swallowing ability, nutritional requirements, sensory preferences and capacity for functional engagement.

The goal should not be freeform customization but rather personalization constrained by safe and validated limits. This allows standardized texture and testing frameworks to stipulate acceptable operating ranges, while formulation, nutrient density, flavor, appearance, and portion size is adapted according to individual need within those defined ranges.

This tactic would ideally integrate the safety benefits of standardization with the clinical and sensory advantages of customized food design.

7.6 Future Research Priorities

Future research requires integrated instead of isolated optimization of TMFs. Joint evaluation of rheological performance, oral processing, nutritional quality, sensory acceptance, and manufacturing feasibility is desired within a single design framework.

Key research priorities include identifying clinically relevant rheological and tribological thresholds for food transformation during oral processing, developing standardized protocols to evaluate the effect of these changes on swallowing, conducting mechanistically driven clinical trials of foods specifically designed to be nutrient dense but still possess optimal mouthfeel properties. More awareness should also go to culturally relevant foods and patient choices for better long-term acceptance.

The weight of the formulations can be adjusted using AI + predictive modeling for multi-objective optimization and more rapid translation into individual food structures could be facilitated with 3D food printing. These technologies nevertheless need extensive, well-defined and appropriately high-quality datasets as well as prospective clinical validation in order to be used routinely.

In the end, linking food engineering with clinical swallowing science and the patient experience destined TMF development to ultimately achieve it. Next-generation foods cannot simply be classified in terms of technological novelty, but rather ability to yield quantifiable improvements in safety, nutrient intake, acceptability and quality of life.

8. Conclusion

Next-generation texture-modified foods (TMFs) are expected to undergo a paradigm shift from

conventional consistency modification towards integrated food design. Although texture plays an important role in dysphagia management, viscosity or classification to a given texture category is not sufficient to predict swallowing safety. Based on the interactions among food structure, rheological properties, oral processing, bolus formation, nutritional composition and sensory attributes during the process of eating they should be studied as a whole.

Rheological parameters including viscosity, yield stress, shear-thinning behavior and viscoelasticity give knowledge of food deformation and flow during oral processing where the mechanical energy reshapes inherent properties by compression (bite → mastication) followed by saliva incorporation and lubrication. The formed bolus is supposed to reach an adequate degree of cohesiveness, deformability, lubrication and flowability for safe and effective swallowing. Henceforth, TMF design ought to correlate instrumental food characterization with clinically applicable swallowing performance.

Nutritional and sensory needs have to balance. While formulating nutrient-dense formulations can help resolve inadequate protein, energy, micronutrient, fiber and fluid intake; strategies to enrich foods should not alter the structure of required foods. Likewise, acceptable flavor, appearance, mouthfeel, familiarity and variety are critical in promoting food intake and long-term adherence. Overall, therefore, an ideal-technical-safe TMF is of low clinical utility if it has poor nutritional qualities or dissatisfies the patient.

Emerging technologies offer considerable tools to incorporate these requirements. Three-dimensional food printing technology has the potential to provide better structural control, portioning and visual appeal enhancement with a dynamic feature-set possibly aided through AI and predictive modeling based multi-objective formulation optimization. When integrated with swallowing, nutritional and sensory information unique to a given patient, these technologies may facilitate the construction of TMFs tailored to individual patients. Nonetheless, successful application will rely on standardized methods of characterization, databases of high-

quality information, manufacturability and clinical validation.

In summary, next-generation TMFs should be based on the individual within a given texture and not just on texture. The optimal strategy will combine rheology, oral processing, nutrition, sensory science, clinical evaluation and novel technologies in an overarching design framework. This could turn TMFs from foods that are modified to be swallowed more safely, into ones which are safe, nutritious, acceptable, individualized and palatable to eat thus improving dietary intakes and the quality of life of individuals with dysphagia.

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