ENGINEERING Foods 2026, 1(2): 229–255
https://doi.org/10.2738/ENGF.2026.0011

Review

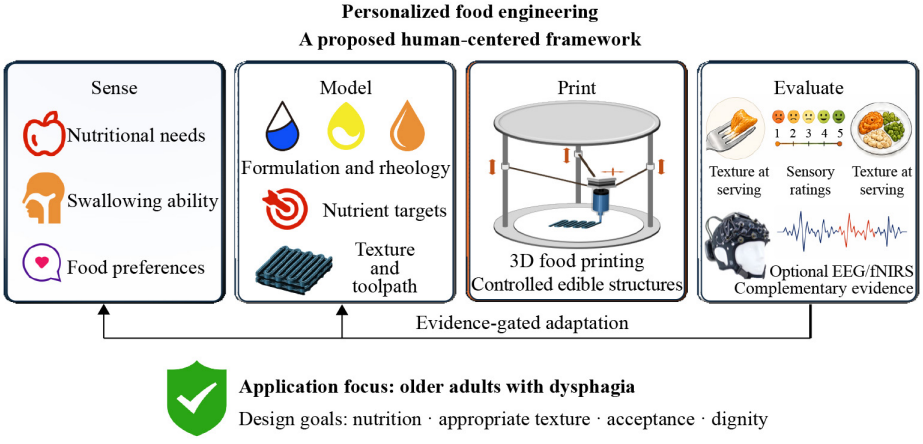
Personalized Food Engineering: 3D Printing, Precision Nutrition, Dysphagia, and EEG-Informed Sensory Evaluation

Zhou Qin, Youmin Zhang, Yuhong Xue, Fanfan Li, Xiangchun Zou, Yuqing Qi, Tianxing Wang, Yucheng Zou, Xinai Zhang, Junjun Zhang, Zhihua Li, Jiyong Shi, Xiaowei Huang(✉), Xiaobo Zou(✉)

Agricultural Product Processing and Storage Lab, School of Food and Biological Engineering, Jiangsu University, Zhenjiang 212013, China

© The Author(s) 2026. This article is published by Higher Education Press.

GRAPHICAL ABSTRACT



HIGHLIGHTS

- 3D food printing is reframed as a programmable platform for personalized food manufacturing.
- Personalized food design is interpreted as a closed-loop process linking user data, materials, printing, evaluation, and feedback.
- Dysphagia-friendly foods for older adults are identified as a realistic early application for personalized 3D printing.
- EEG-informed sensory feedback is discussed as a complementary tool rather than a standalone predictor of food preference.
- A sense-model-print-evaluate-learn framework is proposed to guide validated and human-centered personalized food systems.

ABSTRACT Personalized food is moving from a concept of dietary recommendation toward an engineering problem of designing, manufacturing, evaluating, and continuously improving edible structures for specific users. Individual differences in metabolism, swallowing ability, sensory preference, disease risk, age, culture, and eating context are now widely recognized, yet the food industry still relies largely on standardized products and broad nutritional categories. This review argues that the central challenge is not only to know what an individual needs, but to translate that knowledge into safe, acceptable, manufacturable, and verifiable foods. 3D food printing is therefore discussed not simply as a technique for shaping foods, but as a programmable manufacturing node within a broader cyber-physical food system. The review integrates printable matrix design, precision nutrition, dysphagia-friendly foods, toolpath engineering, and EEG-informed sensory feedback. This is a critical integrative review and does not report a new EEG/fNIRS dataset or classifier; instead, neurophysiological measures are evaluated as complementary inputs within a multimodal, evidence-gated design and validation workflow. Particular attention is given to older adults with dysphagia, because this group exposes the practical tension between safety, nutrition, texture, dignity, and eating pleasure. EEG-based sensory evaluation is considered as a complementary tool for understanding implicit responses, while its limits, ethical risks, and need for multimodal validation are emphasized. Finally, a sense-model-print-evaluate-learn framework is proposed to connect

Received 14 May 2026; accepted 8 Sep 2026

E-mails: huangxiaowei@ujs.edu.cn (Huang X.),
zou_xiaobo@ujs.edu.cn (Zou X.).

personal data, material design, process control, sensory assessment, and iterative learning. The future of personalized foods depends less on isolated technical novelty than on validated, evidence-gated systems that respect human needs, clinical safety, manufacturing reality, and everyday eating experience.

KEYWORDS 3D food printing; Precision nutrition; Personalized foods; Dysphagia; Elderly nutrition; EEG; Sensory feedback; Cyber-physical food engineering

1 Introduction

Food personalization is increasingly discussed across food science, precision nutrition, and intelligent manufacturing, yet the term is often used too broadly [1,2]. In many cases, it refers to dietary recommendations, nutrient adjustment, or product choice. These practices are useful, but they do not fully address the central engineering question: how can individual needs be translated into foods that can be manufactured, stored, served, eaten safely, and accepted by the intended user [3]? Conventional food manufacturing has achieved stability, affordability, and reproducibility through standardization, but this model inevitably simplifies human diversity. People differ in metabolic response, protein demand, chewing and swallowing ability, sensory sensitivity, cultural habit, appetite, emotional association, and medical risk. For healthy consumers, these differences may shape preference; for older adults, patients, and people with dysphagia, they may determine safety, nutrition, and quality of life [4,5]. Personalized food should therefore be understood not as a luxury extension of consumer choice, but as an engineering response to biological, clinical, and social variation.

Precision nutrition has made this need more visible. Wearable devices, glucose monitoring, microbiome analysis, dietary records, clinical information, and behavioral data can describe personal needs with increasing detail [6,7]. However, data collection has advanced faster than the ability to embody that data in edible products. A recommendation to increase protein, reduce sugar, control postprandial glucose, or improve fiber intake remains incomplete if the final food is still produced through a generic process (Fig. 1). Personalized food engineering must therefore convert personal information into formulation targets, texture requirements, structural designs, processing conditions, and validation criteria. This conversion is the point at which nutrition becomes manufacturable.

3D food printing is promising in this context because it offers digital control over portion size, geometry, internal structure, material distribution, and spatial composition [8]. It has been applied to chocolate, starch gels, protein gels, vegetable purees, meat analogues, cereal pastes,

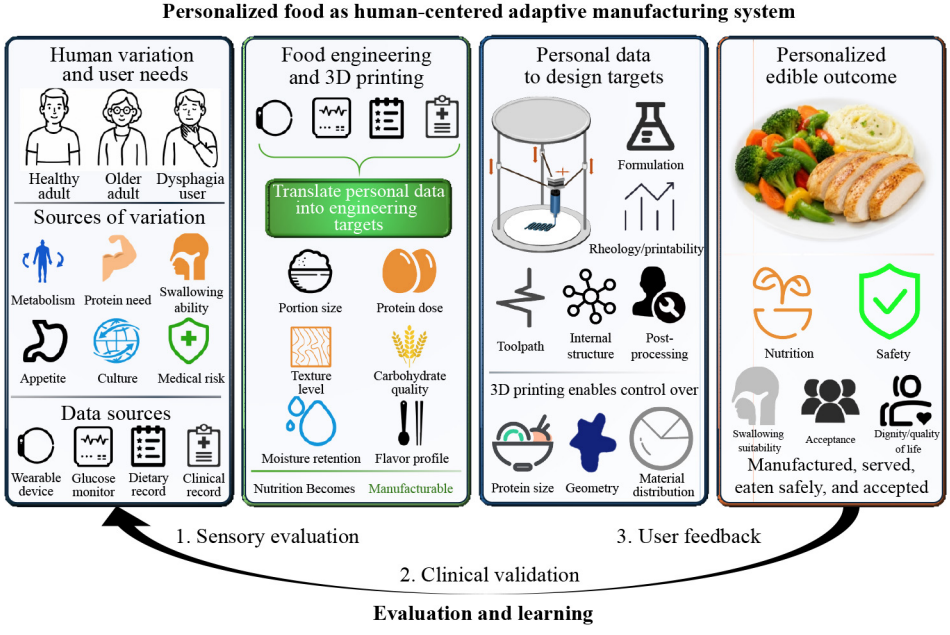


Fig. 1 Human-centered framework for personalized 3D-printed food design. Human variation is translated into engineering targets, which guide food formulation, printing control, and structure design to produce safe, acceptable, and personalized edible outcomes.

dairy systems, and hydrocolloid-based matrices. However, its value should not be reduced to visual novelty or shape fidelity. Printed food is meaningful only when its structure improves nutrition, swallowing safety, oral processing, sensory acceptance, reproducibility, or adaptation to a defined user [9]. This review therefore frames 3D food printing as one component of a larger personalized food system that links user sensing, nutritional modeling, material design, printing control, post-processing, sensory evaluation, clinical validation, and feedback learning.

These controllable degrees of freedom should be mapped to user-relevant evaluation indicators: portion size and material distribution to nutrient-dose and compositional accuracy; infill, layer orientation, geometry, and texture gradients to dimensional fidelity, instrumental texture, bolus behavior, and dysphagia-relevant classification; and visual or flavor design to sensory liking, actual intake, and repeated acceptance. Accordingly, the engineering advantage of 3D printing is not customization *per se*, but the ability to tune measurable product attributes while satisfying nutritional, swallowing-safety, oral-processing, sensory, manufacturing, and stability constraints for a defined user.

Dysphagia-friendly foods for older adults illustrate why such a system view is necessary. Dysphagia is associated with choking, aspiration, malnutrition, dehydration, reduced appetite, and loss of eating dignity [10]. Texture-modified diets can improve safety, yet they often suffer from poor appearance, monotonous texture, diluted nutrition, and low acceptance [11]. 3D printing may help rebuild recognizable food forms while maintaining controlled softness, cohesiveness, moisture, and nutrient density [12]. Sensory feedback is equally important, because a food that is nutritionally precise but unwanted will fail in practice. EEG-informed evaluation may contribute information about attention, familiarity, affective response, and cognitive load, but it should be interpreted together with behavioral and sensory evidence rather than as an independent predictor of liking [13]. The central argument of this paper is that personalized foods should be developed as validated, human-centered, adaptive manufacturing systems: responsible loops that begin with real human needs and end with foods people can safely and willingly eat.

Existing reviews have predominantly treated precision nutrition [1,2], personalized 3D food printing [3,8], dysphagia-oriented printed foods [9], and EEG-based food-choice assessment [13] as separate topics. In contrast, this critical integrative review focuses on their interfaces and organizes the evidence as an end-to-end engineering chain from user and clinical constraints to printable formulation and toolpath design, product-level performance, real eating outcomes, and iterative feedback. Adults with dysphagia are used as a demanding application case rather than the sole scope of the review, while EEG/fNIRS is evaluated as complementary evidence rather than a direct or standalone predictor of preference. The distinctive contribution is therefore a cross-domain engineering and validation framework, rather than another catalogue of printable materials, nutrition algorithms, or neural biomarkers.

2 Printable Food Matrices as the Material Basis of Personalized Food Engineering

2.1 From printability to edible performance

Printable food matrices form the material foundation of personalized food engineering, but they are still often evaluated through a narrow concept of printability. In extrusion-based 3D food printing, a matrix is usually considered printable if it can pass through a nozzle, retain its deposited shape, and support successive layers without immediate collapse [14]. These criteria are necessary, but they are not sufficient for personalized foods. A formulation may print well yet remain nutritionally inadequate, texturally unsafe, sensorially unacceptable, unstable during service, or impractical for processing and cleaning [15]. Conversely, a formulation that is safe, pleasant, and nutritionally appropriate for a target user may fail during printing because it lacks sufficient yield stress, structural recovery, or time-dependent build-up [16]. Printability should therefore be understood not as the final goal, but as an intermediate property within a broader chain that extends from ingredient preparation to eating outcomes.

This broader view is essential because printed foods must function simultaneously as materials, products, and meals. As materials, they must flow under shear, withstand extrusion, and rebuild structure after deposition [17]. As products, they must maintain composition, shape, texture, microbial safety, and physical stability during post-processing, storage, transport, reheating, and service. As meals, they must meet the sensory expectations, oral-processing capacities, health constraints, cultural habits, and emotional associations of real users. Unlike printed polymers or metals, printed foods are ultimately chewed or orally processed, formed into a bolus, swallowed, digested, and judged by the consumer [18]. Their success therefore cannot be determined only by visual stability on the printing platform. It must be assessed across the full pathway of preparation, service, oral processing, swallowing,

digestion, and user feedback.

A more rigorous understanding of printable food matrices should be based on process–structure–function relationships. The process dimension includes ingredient hydration, particle size reduction, mixing, temperature control, extrusion, deposition, post-processing, holding, and service. The structure dimension includes molecular interactions, dispersed particles, gel networks, starch granules, protein aggregates, air cells, water distribution, fat droplets, layer interfaces, porosity, and macroscopic geometry. The function dimension includes shape fidelity, texture, bolus formation, nutrient delivery, flavor release, microbial stability, service tolerance, and user acceptance. These relationships are rarely linear. Higher solids content may improve shape retention but reduce oral comfort; hydrocolloids may stabilize layers but cause gumminess or residue; protein enrichment may increase nutritional density but introduce aggregation, bitterness, or excessive firmness; and particle-size reduction may improve smoothness while changing water binding, aroma release, oxidation, and viscosity [19]. Matrix design is therefore not the search for a simply printable recipe, but a multi-objective engineering problem in which each improvement may create new constraints [20]. Table 1 summarizes representative studies that connect printability with formulation, rheology, microstructure, post-processing, texture, dysphagia suitability, and nutritional functionality.

These studies show that printable food matrices should be understood as engineered material systems rather than simple printable recipes. Formulation variables, including starch, protein, hydrocolloids, fat phase, water content, and particle size, determine the internal organization of the matrix, while printing variables such as extrusion conditions, temperature, layer height, and infill design further shape geometry, porosity, texture, and post-processing behavior [29]. These factors rarely improve performance in only one direction. Stronger gelation may enhance shape fidelity but reduce oral comfort; particle-size reduction may improve smoothness but alter hydration and viscosity; protein or emulsion enrichment may increase nutritional value while introducing firmness, phase separation, or flavor defects [30]. The evidence summarized in Table 1 therefore supports a central point of this review: personalized 3D-printed foods require multi-objective matrix engineering that connects process control, structural evolution, and final edible performance [31].

This multi-objective perspective is especially important because personalized foods are designed for specific users rather than abstract consumers. A dysphagic older adult, diabetic patient, selective-eating child, recovering athlete, or post-surgical patient may require different balances among texture, nutrient density, flavor, portion size, safety, and emotional familiarity [32]. A universal printable matrix is therefore unlikely. Instead, the field needs families of matrices with defined operating windows, known limitations, and validated adaptation rules [33]. These matrices should be characterized not only by ingredient lists, extrusion images, or single-point texture values, but by their behavior across printing, post-processing, service, and consumption [34]. Printable food matrix research should move from recipe discovery toward material system engineering. The key question is no longer whether a matrix can be printed once under ideal laboratory conditions, but whether it can reliably support a defined human need under real manufacturing and eating conditions.

Table 1 Representative experimental studies supporting process-structure-function relationships in printable food matrices.

Food matrix	Process variable	Structure-related observation	Function-related outcome	Reference
Protein-, starch-, and fiber-rich pastes	Ingredient type and mixture composition	Different protein and fiber materials showed distinct extrusion behavior and pattern stability	Demonstrated the feasibility and limits of protein- and fiber-rich printable snacks	[21]
Mashed potato with potato starch	Starch addition and rheological adjustment	Yield stress and viscoelasticity changed with starch content	Low-yield-stress samples deformed after printing, while optimized rheology improved print stability	[22]
Carrageenan-xanthan-starch gel	Hydrocolloid-starch ratio	Gel network strength and recovery behavior changed with component ratio	Printability was linked to rheological parameters and deposited structure stability	[23]
Processed cheese	Heating and extrusion during printing	Protein network and fat phase were altered by printing-related thermal and shear effects	Printed cheese showed changed texture and melting behavior	[24]
Fresh vegetable purees for dysphagia	Hydrocolloid selection and concentration	Dense microstructures and reduced water seepage were obtained with optimized hydrocolloids	Printable vegetable inks met dysphagia-oriented texture assessment and improved visual appeal	[25]
Cereal-based snack	Infill percentage and layer height	Internal geometry and relative density were modified by toolpath design	Texture could be programmed through printing parameters	[26]
Okara-based ink	Particle size and okara concentration	Smaller particles improved rheological suitability and reduced the need for rheology modifiers	Printable okara snacks with customized texture were obtained	[27]
Bean-based emulgel for dysphagia diets	High-pressure homogenization, gelatin incorporation, and oil-gel network design	Emulsion network properties controlled dimensional stability and texture	Low-oil printable emulgels were developed for dysphagia-oriented foods	[28]

2.2 Rheology as a bridge between manufacturing and eating

Rheology is central to extrusion-based 3D food printing because it determines whether a material can flow through a nozzle, recover after deposition, and maintain its printed structure. Yield stress, apparent viscosity, shear-thinning behavior, thixotropy, viscoelastic moduli, and recovery kinetics help explain extrusion stability, layer formation, collapse, and shape retention [35]. In personalized food systems, however, rheology should not be interpreted only as a machine-compatibility parameter. It is also linked to oral manipulation, perceived thickness, lubrication, swallowing comfort, bolus formation, and texture stability. The same material behavior that enables extrusion may also influence how the food spreads on the tongue, mixes with saliva, fractures during oral processing, and moves during swallowing.

This dual role creates unavoidable trade-offs. A matrix with high yield stress may retain a clean printed form but feel dense, sticky, or difficult to swallow. A strongly shear-thinning system may extrude smoothly, but insufficient recovery may cause spreading or collapse. A strong gel network may preserve geometry, yet fracture into unsafe fragments during oral processing. A weak matrix may feel soft and easy to swallow, but lose visual identity, release free water, or become unstable during holding. Rheological properties must therefore be interpreted in relation to both machine performance and human performance [36]. A food that prints well but separates, fractures unpredictably, or becomes unsafe during eating cannot be considered successful.

The field should also avoid treating specific rheological values as universal printability thresholds. A viscosity or modulus range that works for one printer, nozzle diameter, temperature, formulation, or extrusion pressure may not transfer to another system. Laboratory measurements may further fail to capture heterogeneous matrices containing fibers, particles, fat droplets, starch granules, proteins, air, and dispersed water phases. Differences in shear rate range, temperature, sample history, resting time, instrument geometry, and loading method also limit comparability across studies. Rather than searching for a single ideal viscosity, future work should develop material maps that connect rheological behavior with printer configuration, process parameters, product geometry, post-processing conditions, and eating requirements [37].

Rheology is also time-dependent. Starch pastes may retrograde, protein gels may strengthen or shrink, hydrocolloid systems may continue hydrating, emulsions may separate, and particle suspensions may sediment. A formulation that is printable immediately after mixing may become unsuitable after holding; a soft printed food may become too firm after cooling; and a dysphagia-friendly product may drift outside the safe texture range during transport or meal service [38]. The relevant question is therefore not only how the matrix behaves during extrusion, but how it changes across storage, printing, post-processing, reheating, plating, and consumption. Future studies should report recovery after extrusion, changes during holding, response to reheating, and texture at the point of consumption.

2.3 Structural nutrition and matrix design

Personalized nutrition is often discussed in terms of nutrient composition, but printed foods require a structural interpretation of nutrition. Nutritional function is not determined only by the amount of protein, carbohydrate, fat, fiber, vitamins, minerals, or bioactive compounds. It is also shaped by the matrix in which these components are embedded. Starch gelatinization, protein aggregation, fat droplet distribution, fiber hydration, porosity, particle size, water mobility, and matrix breakdown can influence digestion, nutrient release, satiety, flavor perception, and metabolic response [39]. A printed food with the same nutrient composition may therefore produce different physiological and sensory outcomes if its internal structure changes.

This structural view changes how personalized foods should be designed. If individuals differ in glycemic response, appetite regulation, swallowing ability, sensory perception, and digestive tolerance, personalization cannot rely only on adjusting nutrient amounts. It must also consider nutrient arrangement and matrix behavior. Carbohydrate structure may influence digestion rate and postprandial glucose response. Protein distribution may affect texture, satiety, flavor, and oral comfort. Fat may improve lubrication and energy density but destabilize the matrix if poorly emulsified. Fiber may support viscosity control or fermentation potential, but introduce roughness, water-binding changes, or particle-related risks. The matrix is therefore not a passive carrier of nutrients; it is the medium through which nutrients become edible, acceptable, and functional [40].

Protein enrichment illustrates this challenge clearly. Older adults often require higher protein intake, but adding protein to soft foods may create graininess, bitterness, chalkiness, excessive firmness, or poor processability. Plant proteins may have limited solubility, strong off-flavors, and unstable gelling behavior, whereas dairy and egg proteins may offer favorable gelation and familiar sensory properties but raise allergen, dietary, or cultural constraints. Protein interactions with starches, hydrocolloids, salts, lipids, and heat can alter both printability and oral texture [41]. For nutrient-dense dysphagia-friendly foods, protein must therefore be

hydrated, distributed, structured, and stabilized in ways that support texture safety, flavor acceptability, and processing stability.

Starch-based hydrocolloid systems involve similar trade-offs. Starch contributes energy, viscosity, body, and gel structure, but is highly sensitive to thermal history and water availability. Gelatinization may improve cohesiveness and printability, while retrogradation may increase firmness during storage. Hydrocolloids can control viscosity, water retention, gelation, lubrication, and shape stability, but excessive use may produce sliminess, stickiness, or unnatural mouthfeel [42]. They may also mask flavor, reduce aroma release, or interact with minerals and proteins [43]. These examples show that proteins, starches, hydrocolloids, fats, fibers, water, particles, and bioactives must be organized into structures that serve defined nutritional, mechanical, sensory, and safety goals.

2.4 Safety, flavor, and service stability

Food safety is decisive for personalized 3D-printed foods because many printable matrices are high in moisture and nutrients and are processed under mild thermal conditions. These properties can support microbial growth if time, temperature, and hygiene are not controlled. Printers also contain nozzles, tubing, cartridges, seals, and contact surfaces that may be difficult to clean, allowing residual material to accumulate, dry, or contaminate later batches [44]. In care homes, hospitals, rehabilitation centers, and personalized nutrition services, microbial risk, allergen carryover, and cross-contamination are unacceptable. Printable matrix design must therefore be considered together with hygienic equipment design. A matrix that leaves persistent residues or requires complex cleaning may be unsuitable for real deployment even if it performs well in laboratory printability tests.

Safety should be built into formulation and process design from the beginning. Personalized foods must be prepared, printed, post-processed, transported, plated, and consumed under variable institutional or home conditions. Safety design should therefore include microbial stability, allergen control, equipment sanitation, process monitoring, and service-time limits. Because many personalized foods target vulnerable users, including older adults, patients, and people with swallowing disorders, safety cannot be separated from reliability. A food that is safe immediately after printing but becomes risky after holding is not acceptable, and a matrix that prints well but increases cleaning burden or contamination risk is not translation ready.

Flavor is another critical point where matrix design and personalization intersect. Nutrient-dense ingredients often introduce sensory problems: plant proteins may create beany, bitter, or astringent notes; mineral fortification may produce metallic taste; fiber concentrates may increase roughness; lipids may oxidize; and hydrocolloids may reduce flavor intensity or alter mouthfeel [45]. These problems are especially important in dysphagia-friendly foods, where reduced appetite, altered taste, medication effects, swallowing anxiety, and negative associations with modified diets can already limit intake [9]. Printed food that is technically safe but unappetizing will fail as a nutritional intervention. Flavor should therefore be integrated into structure design, ingredient interactions, and release behavior rather than treated as a final correction.

3D printing offers opportunities for spatial flavor design, but these strategies require validation during actual consumption. Bitter or unpleasant ingredients may be embedded inside the matrix, while preferred flavors may be positioned near the surface. Aromatic compounds may be separated from reactive components until eating, and fat phases may enhance mouthfeel and flavor release. However, hidden flavors may emerge during oral breakdown, surface flavors may not sustain repeated consumption, and familiar printed forms may create expectations that the flavor or mouthfeel cannot satisfy. Flavor engineering must therefore be linked to dynamic sensory evaluation and real eating behavior.

Service stability is the final test of whether a printed matrix can function beyond the printing platform. Printed food may be held before serving, transported, reheated, cooled, combined with sauces, or assisted by caregivers. During this period, water migration, drying, syneresis, gel strengthening, aroma loss, microbial growth, and surface deformation may occur [46]. These changes can alter safety, nutrient delivery, appearance, mouthfeel, and appetite. Future studies should distinguish shelf life from service life: shelf life refers to storage stability, whereas service life refers to the period after preparation during which the product remains within its intended safety and eating-quality window. The broader principle is clear: a safe but disliked food fails, a flavorful but unstable food fails, and a printed structure that looks good but changes before eating fails. The goal is integrated performance, in which formulation, structure, process, hygiene, sensory response, and eating context are designed together.

3 Translating Precision Nutrition into Manufacturable Food Design

3.1 From personal data to design constraints

Precision nutrition begins with the recognition that

dietary response is individualized, but food engineering begins only when this recognition can be converted into manufacturable design constraints. Statements such as "this user requires better metabolic control" or "this older adult needs higher protein intake" are nutritionally meaningful, yet they cannot directly guide 3D food printing. A printer operates through material properties, extrusion behavior, toolpath parameters, portion geometry, and post-processing conditions [47]. The central translation problem is therefore how to convert individual information into food properties that can be formulated, printed, measured, served, and revised. Portion size, energy density, protein dose, carbohydrate structure, sodium level, allergen exclusion, texture category, moisture retention, flavor preference, and service stability form the intermediate engineering language through which personal nutritional needs become edible structures.

This translation is complicated because personal data differs in reliability, consequence, and actionability. A confirmed allergy is a mandatory exclusion, while a diagnosed swallowing disorder defines a safety boundary. A dietitian-prescribed protein target can guide nutrient density, but it must still be balanced with texture and palatability [48]. A glucose-monitoring pattern may suggest carbohydrate adjustment, but it does not automatically determine starch structure, fiber type, portion size, or meal timing. A microbiome profile may imply prebiotic strategies, but its interpretation remains uncertain and context-dependent [49]. A preference record may guide flavor or appearance, but it cannot override swallowing safety or clinical restrictions. These inputs cannot be treated as equivalent signals in a single optimization system. A rigorous personalized food system must grade personal data according to source, recency, certainty, and potential consequence.

Such grading is essential because personalization can become unsafe when uncertain information is given excessive authority. If swallowing status is unknown, the system should not infer a safe texture from age or preference. If metabolic data are sparse, it should not make extreme formulation changes that reduce acceptability or nutritional adequacy. The translation process should therefore distinguish mandatory constraints, adjustable nutritional targets, and preference variables. Mandatory constraints include allergy avoidance, microbial safety, texture safety, clinical restrictions, and contraindicated ingredients. Adjustable targets include energy density, protein dose, fiber level, sodium range, carbohydrate quality, portion size, and meal timing. Preference variables include flavor, color, shape, aroma intensity, cultural form, presentation style, and familiarity. Responsible personalization is controlled variation within validated boundaries, not unlimited customization.

3.2 Clinical, metabolic, and behavioral inputs

Clinical data are among the most actionable inputs for personalized printed foods because they define safety and nutritional boundaries. Age, body weight, disease status, medication use, kidney function, diabetes status, appetite, chewing ability, dental condition, swallowing diagnosis, hydration risk, and malnutrition risk can all influence food design. For older adults, these factors often interact. A single user may require high protein density, low chewing effort, controlled moisture, reduced choking risk, small portion size, familiar appearance, and mild flavor at the same time [50]. Conventional food categories rarely capture this complexity. A printed food system could adjust composition, structure, portion, and presentation simultaneously, but only if these adjustments are based on validated relationships between user constraints and food properties.

Metabolic data can refine personalization, but their practical meaning must be interpreted carefully. Continuous glucose monitoring, wearable devices, meal records, and activity data may reveal patterns in postprandial response, meal timing, sleep, and physical activity [51]. These signals could inform carbohydrate quantity, starch structure, fiber inclusion, energy distribution, or meal scheduling. However, a measured glucose response does not directly prescribe a printable formulation. The system still needs models linking ingredient composition, matrix structure, digestion kinetics, gastric emptying, and user-specific response [52]. Without such models, metabolic data may create the appearance of precision without improving food outcomes. Reducing carbohydrate content, for example, may improve one marker but reduce energy intake or acceptance in an older adult with poor appetite.

Studies in Fig. 2 clarify the pathway through which clinical and metabolic information can be incorporated into personalized food manufacturing. Personalized glycemic-response studies show that identical meals can produce highly variable metabolic responses among individuals, indicating that universal dietary recommendations may be insufficient for metabolic control. However, such data should not be converted directly into printer settings or simple carbohydrate reduction. Instead, glucose response, dietary records, activity patterns, anthropometric information, and microbiome-related data need to be interpreted through validated predictive models before they can inform carbohydrate structure, fiber inclusion, portion timing, or energy distribution [53]. In parallel, dysphagia-oriented

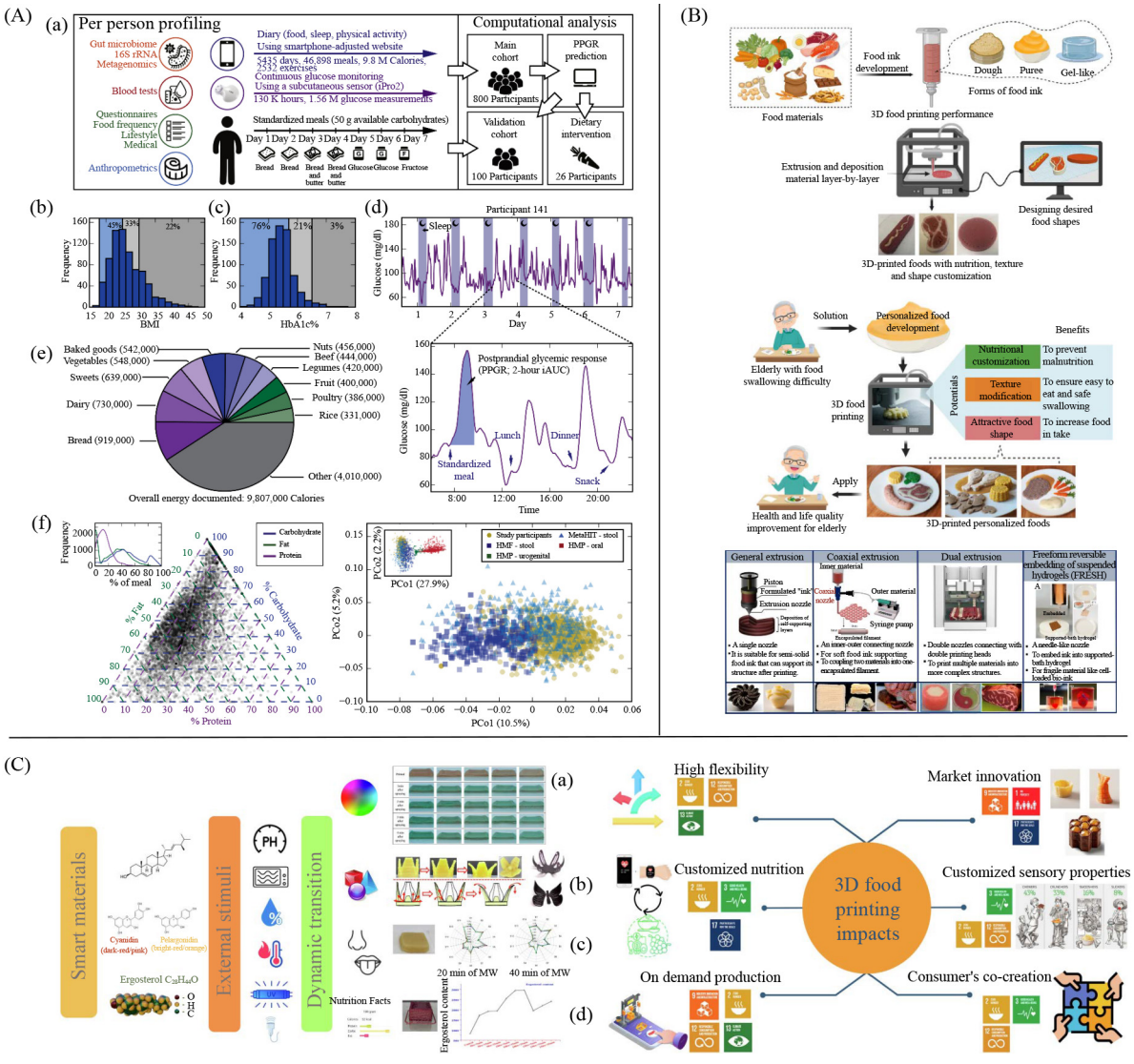


Fig. 2 Clinical and metabolic inputs for personalized 3D-printed food design. Personalized glycemic-response prediction shows that identical meals can induce different postprandial responses, supporting the need for individualized metabolic interpretation (A); Dysphagia-oriented 3D food printing translates elderly users' nutritional and swallowing constraints into nutrient-enriched, texture-modified printed foods (B); Digitally designed 3D food printing provides a manufacturing route for converting personal data into customized food structure, composition, and presentation (C).

3D food printing studies show that clinical constraints in older adults, such as swallowing safety, chewing difficulty, malnutrition risk, and reduced appetite, can be translated into food-ink formulation, hydrocolloid-assisted texture control, viscoelastic stability, nutrient enrichment, and recognizable meal structures [12]. Digitally designed 3D food printing therefore acts as a manufacturing interface between personal data and edible outcomes, but its value depends on whether the translated design targets are clinically safe, nutritionally meaningful, texturally appropriate, and acceptable during real eating [3]. This evidence suggests that the role of 3D food printing is not to mechanically execute personal data, but to manufacture food structures after those data have been translated into validated nutritional, textural, and processing targets.

Microbiome information presents an even wider gap between biological insight and manufacturable design. It may eventually guide fiber type, fermentable substrate, polyphenol delivery, or prebiotic formulation, but microbiome composition is dynamic and difficult to translate into immediate manufacturing parameters. Overstating microbiome-guided personalization could weaken credibility if the resulting food modifications are not validated at the product or user-outcome level. A cautious approach is to treat microbiome data as

exploratory or supportive unless response categories are established and design changes are safe, interpretable, and measurable [54].

Behavioral and sensory data may be more immediately useful than many advanced biological signals because they indicate whether a personalized food is likely to be eaten. Meal completion, repeated rejection, preferred flavors, eating speed, fatigue, assistance needs, cultural food identity, appetite patterns, and emotional response can all guide design [55]. If a resident consistently leaves a high-protein portion unfinished, the formulated nutrient dose is not actually delivered. If a user rejects a texture because it feels institutional, dry, or difficult to swallow, the product fails even if it meets instrumental criteria [56]. Clinical information defines non-negotiable boundaries, metabolic information refines nutritional strategy, and behavioral information tests whether that strategy survives real eating. Ignoring any layer can produce meals that are unsafe, inadequate, or simply not consumed.

3.3 Design targets as intermediate engineering language

Design targets provide the intermediate language between personal data and manufacturing. A design target is not merely a user preference or dietary recommendation; it is a food property that can be formulated, processed, measured, and adjusted. Protein per serving, energy density, viscosity range, cohesiveness, moisture retention, particle size limit, oral breakdown behavior, flavor intensity, portion size, thermal stability, and service holding time can all function as design targets. By converting personal information into these targets, the system makes personalization actionable. This step is essential because 3D printing cannot respond directly to biological or behavioral data. It can only respond to translated material, structural, and process specifications [57].

This intermediate language also prevents inappropriate direct control. A glucose profile should not directly determine nozzle pressure, a microbiome score should not directly determine layer height, and a preference survey should not directly determine protein content or texture level. Instead, personal data should influence food design through validated variables. Metabolic response may guide carbohydrate structure, fiber inclusion, or portion timing. Swallowing assessment may guide cohesiveness, hardness, particle size, lubrication, and moisture retention. Sensory history may guide flavor masking, shape selection, or aroma intensity. This mediated structure supports safety, explainability, and professional accountability, while allowing dietitians, clinicians, speech-language pathologists, food engineers, and users to communicate within a shared design space.

Design targets should be measured at the point where they matter. For dysphagia-friendly foods, texture immediately after printing is insufficient; the relevant texture is the texture at eating, after post-processing, holding, reheating, sauce addition, or transport. For nutrient delivery, a calculated formulation is insufficient; the relevant value is the retained and consumed nutrient dose. For sensory personalization, predicted liking is insufficient; the relevant outcome is repeated acceptance and intake in context. For service feasibility, a laboratory print is insufficient; the product must fit cleaning, staffing, timing, and quality-control routines. Each design target should therefore be linked to an evaluation method and use condition [58]. Otherwise, personalization remains a design intention rather than a verified outcome.

A mature personalized food system should use hierarchical targets. At the highest level, user needs are defined in terms of health, safety, acceptance, and quality of life. At the middle level, food properties such as nutrient density, texture, flavor, moisture stability, appearance, and service tolerance are specified. At the lower level, formulation and printing parameters are selected to achieve these properties. This hierarchy prevents human needs from being collapsed directly into machine instructions. Personalization is a mediated process in which user needs are interpreted, constrained, translated, manufactured, evaluated, and revised. Without this mediation, personalized food risks becoming a black-box conversion of uncertain data into unverified edible outputs.

3.4 Avoiding false precision

Precision nutrition and 3D food printing both carry the risk of false precision. A digital system may present a customized formulation with exact nutrient values, precise geometry, and algorithmic confidence, but the actual food may not deliver those values in practice. Nutrients may degrade during preparation or post-processing, portions may be left uneaten, textures may drift during service, printers may clog, and users may reject the meal. Precision in calculation is therefore not the same as precision in human outcome. This distinction is especially important for vulnerable users, because an apparently precise recommendation may create false confidence if the food is not safe, accepted, or consumed [59].

False precision can also arise from models trained on limited or overly controlled laboratory data. Food materials are inherently variable, and small changes in ingredient source, moisture content, particle size, temperature, hydration time, mixing history, or storage

conditions can alter printability and final texture. A model that predicts material behavior under ideal conditions may fail in real service environments [60]. Similarly, sensory predictions based on small, young, healthy, or homogeneous panels may not generalize to older adults, patients, or users with altered taste, smell, appetite, cognition, or swallowing ability. The system should therefore express uncertainty and update itself through feedback rather than present one optimal answer [61].

Another source of false precision is excessive personalization without evidence. It may be technically possible to vary every meal according to user data, but not every variable deserves personalization. If a design change does not improve safety, nutrition, acceptance, dignity, or feasibility, it may add complexity without value. A unique geometry is not necessarily personalized if it does not improve eating, and a formulation generated from many data inputs is not necessarily precise if it is not validated. In many settings, a controlled matrix library with options for protein level, flavor, portion size, texture, and shape may be more useful than an unlimited individualized recipe.

Precision should therefore be redefined as reliable fit rather than maximal individual variation. A personalized food is successful when it fits the user's needs within a validated operating space, not when it is uniquely different for its own sake. This concept is particularly relevant for care settings, where safety, repeatability, staff workflow, and user dignity matter as much as individual preference. Reliable fit requires evidence, monitoring, adaptation, and humility about what current data and models can support. The future of personalized food manufacturing will depend not on the appearance of precision, but on the ability to demonstrate that personalization improves real eating outcomes for defined users.

4 Personalized Formulation, Toolpath Design, and Dysphagia-Friendly Food Structures

4.1 Formulation as multi-objective negotiation

Personalized formulation should not be understood as simply adding or removing ingredients according to individual nutritional needs. In practice, it is a multi-objective negotiation among nutrition, texture, printability, flavor, safety, cost, cultural acceptability, and service feasibility [62]. Each adjustment may solve one problem while creating another. Increasing protein can improve nutritional density but may also increase firmness, bitterness, chalkiness, or heat-induced aggregation [63]. Adding fat may enhance lubrication and flavor release but destabilize emulsions. Reducing sodium may support health goals but weaken flavor acceptance, especially in older adults with reduced taste sensitivity [64]. Increasing hydrocolloids may improve shape retention and water binding, yet excessive use can produce sliminess or gumminess [65]. Reducing particle size may improve smoothness and swallowing comfort, but it can also alter hydration, aroma release, oxidation, and viscosity. Personalized formulation is therefore a systems-level design task in which every adjustment must be evaluated from material preparation to eating [66].

The formulation evidence summarized in Fig. 3 further illustrates why personalized food design should be treated as a multi-objective engineering problem. Additives such as hydrocolloids, proteins, starches, oils, flavors, probiotics, and functional compounds can improve printability, rheology, texture, nutrition, and sensory quality, but their effects are rarely independent. Soy protein-based printed foods show that protein concentration, vegetable incorporation, and infill rate can simultaneously alter shape fidelity, viscoelasticity, internal porosity, hardness, gumminess, and chewiness. Chickpea-mealworm protein systems further show that a nutritionally promising soft matrix may fail under conventional printing, while coaxial printing with alginate support can improve structural stability and produce a more cohesive bolus after oral-processing simulation [8,67,68]. These studies indicate that formulation design cannot be reduced to nutrient enrichment or additive selection alone. Each ingredient and processing choice must be evaluated across the full pathway from material preparation, extrusion, and structural formation to oral breakdown, swallowing safety, sensory acceptance, and service feasibility. Thus, personalized formulation should be understood as controlled adjustment within validated material and eating-performance boundaries, rather than unrestricted recipe customization.

This complexity explains why personalized foods require formulation logic rather than recipe substitution. Replacing sugar with a sweetener, increasing protein powder, selecting a preferred flavor, or adjusting water content may change printability, texture safety, sensory quality, and service stability. A high-protein dysphagia-friendly food is not successful simply because it reaches a target protein level. It must also remain soft, cohesive, smooth, stable during service, acceptable in flavor, and compatible with the user's oral-processing capacity. These properties require coordinated control of water distribution, protein state, starch gelatinization or

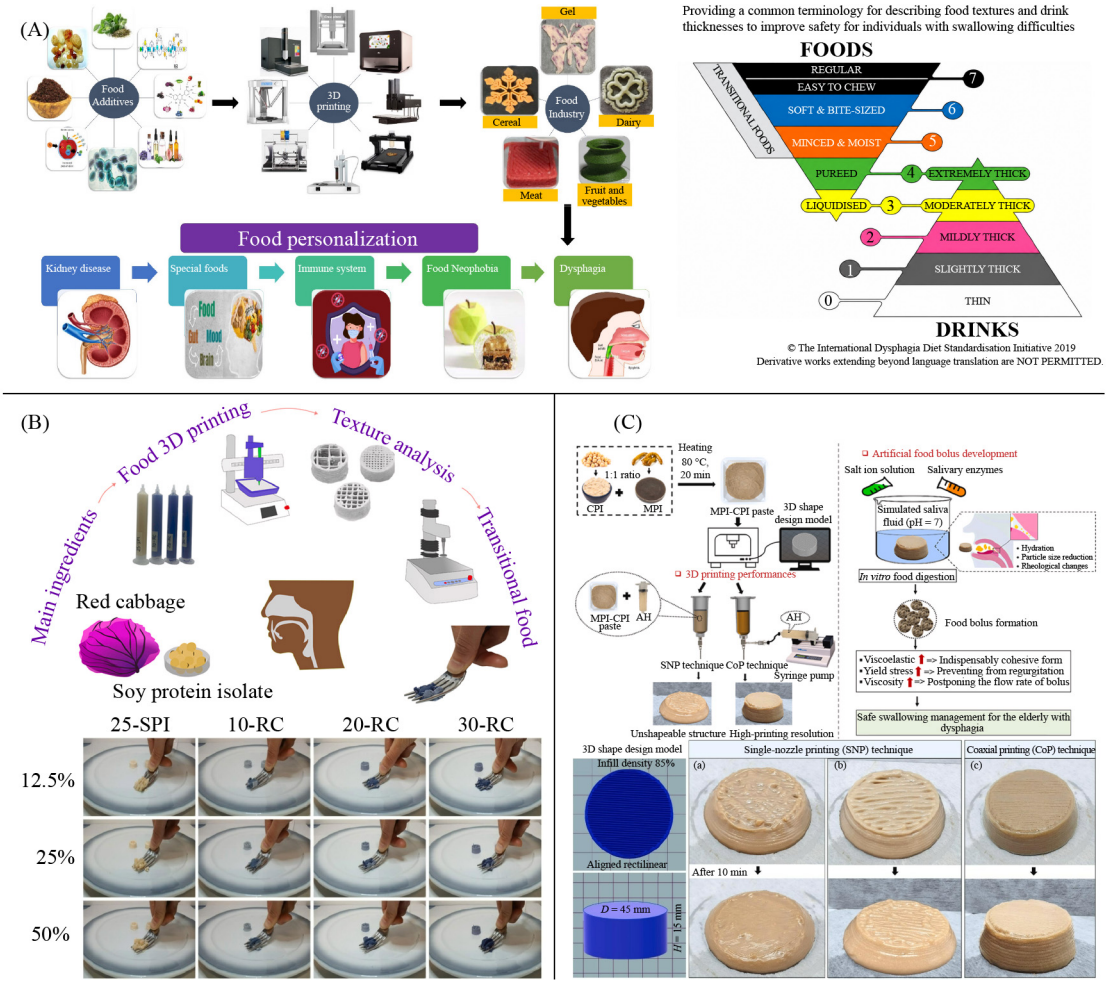


Fig. 3 Multi-objective formulation design for personalized 3D-printed foods. Additives tune printability, texture, nutrition, and sensory quality (A); Soy protein formulations link composition and infill design with dysphagia-related texture (B); Coaxial printing improves soft protein ink stability and supports cohesive bolus formation (C).

retrogradation, hydrocolloid network formation, fat droplet stability, particle size, thermal history, and post-processing conditions. Formulation therefore becomes a structured decision process in which nutritional goals are translated into material states, and material states are constrained by manufacturing and eating requirements.

Manufacturability should be built into this decision process from the beginning. A formulation that depends on rare ingredients, long hydration time, narrow temperature control, complex post-processing, or difficult cleaning may be scientifically interesting but operationally weak. In hospitals, care homes, rehabilitation centers, and home-care settings, foods must be produced reliably within limits of staff time, equipment availability, sanitation, meal scheduling, and service delay. The best formulation is not necessarily the one with the highest nutrient density or the most accurate printed shape, but the one that balances nutritional adequacy, texture safety, sensory acceptance, process robustness, and workflow compatibility. For dysphagia care, bounded flexibility may be more realistic than unlimited customization. A practical direction is to develop validated base matrices with known rheology, texture level, nutrient-loading capacity, flavor compatibility, post-processing behavior, and safety margins, then personalize them through controlled adjustments in protein density, flavor, portion size, shape, hydration, or fortification. Formulation should therefore be treated as a decision architecture: it defines what may vary, what must remain fixed, and what trade-offs are acceptable for a given user group and service scenario.

4.2 Toolpath as a functional design variable

Toolpath design is one of the most important but still underdeveloped dimensions of personalized food printing. In many studies, toolpath is selected mainly to demonstrate geometry, aesthetic quality, or shape fidelity.

For personalized food engineering, however, toolpath should be treated as a functional design variable that connects formulation with eating performance. Infill pattern, density, layer height, orientation, perimeter design, gradient structure, core-shell configuration, and multi-material deposition can influence hardness, fracture behavior, oral breakdown, sauce retention, moisture distribution, heating rate, flavor exposure, and nutrient distribution [69]. The printed structure is therefore not merely a visible shape. It is a programmed food architecture in which spatial arrangement affects deformation, nutrient release, saliva interaction, and sensory perception during eating.

This functional role is especially important for dysphagia-friendly foods. A printed food may look familiar before eating, but it must transform into a safe and cohesive bolus during oral processing. If printed layers separate into fragments, the product may become unsafe even when its initial texture appears soft. If the structure is too dense, it may require excessive tongue pressure or chewing effort; if it is too weak, it may collapse before service, lose visual identity, or release free liquid. The ideal printed structure should maintain a recognizable identity before eating while undergoing controlled disassembly in the mouth [70]. This target is more demanding than conventional shape fidelity because it requires researchers to examine how the structure deforms, hydrates, fractures, and combines with saliva under realistic oral forces.

Toolpath also creates opportunities for spatial nutrition and sensory modulation, but these strategies must be evaluated during actual consumption. Nutrients may be distributed uniformly, concentrated in a core, layered across the structure, or placed in zones with different release behavior to protect sensitive compounds, mask bitter ingredients, regulate flavor exposure, or influence digestion [71]. Preferred flavors may be positioned near the surface, while moisture-rich or fat-containing layers may improve lubrication and mouthfeel. Yet these designs can fail if the user does not consume the whole portion, if layers separate during eating, or if surface flavor improves only the first bite while repeated acceptance declines. Spatial design is meaningful only when it improves delivered dose, oral safety, sensory continuity, and intake behavior.

Toolpath design also interacts with post-processing and service conditions. A dense printed block and a porous lattice may heat, cool, dry, absorb sauce, and lose moisture differently. Layer interfaces may influence water migration, syneresis, and mechanical weakening, while surface area and porosity may affect drying, aroma loss, microbial exposure, sauce adhesion, flavor release, oral compression, and thermal response [72]. A toolpath that improves visual complexity may reduce service stability, and a structure that looks appealing immediately after printing may become unsafe or unattractive after holding. Toolpath design should therefore be integrated with formulation, thermal processing, holding time, serving method, and oral-processing evaluation. If formulation determines what the food is made of, toolpath helps determine how the food behaves.

The effect of 3D printing should therefore be interpreted through a process-structure-function chain: formulation and printing parameters modify geometry, porosity, layer architecture, material distribution, and texture; these product attributes subsequently influence oral processing, swallowing-related performance, flavor release, liking, and intake. Feedback should be collected at four levels: process signals, product tests, behavioral and sensory outcomes, and optional neurophysiological responses; printing parameters should be updated only when predefined safety and product-performance criteria remain satisfied.

4.3 Dysphagia-friendly foods as a high-value application

Dysphagia-friendly foods provide one of the strongest and most realistic application scenarios for personalized 3D food printing because the problem is urgent, measurable, and deeply human-centered. Dysphagia affects swallowing safety, nutritional intake, hydration, social participation, and quality of life. In older adults, it often overlaps with frailty, sarcopenia, cognitive impairment, dental problems, reduced appetite, medication effects, and chronic disease. Standard texture-modified diets can reduce swallowing risk, but they often produce meals that look unappealing, taste monotonous, lack recognizable identity, and provide diluted nutrition [73]. When food loses form, variety, and pleasure, users may eat less even if the diet is technically safer. In this context, dignity is not an aesthetic luxury; it is linked to appetite, intake, emotional wellbeing, and willingness to continue eating.

3D food printing may help address this problem by restoring food identity while maintaining controlled texture. A vegetable puree can be reshaped into a recognizable vegetable, a fish or meat puree can regain association with its original form, and a fortified soft matrix can be presented as a meal component rather than a medical paste. Such visual reconstruction may support appetite, familiarity, and social normality. However, shape restoration should not be equated with dignity-oriented design. A printed food may still feel artificial, sticky, dry, or culturally inappropriate. A realistic shape may raise expectations, but if flavor, aroma, temperature, or mouthfeel does not match the visual cue, acceptance

may decline. Dignity-oriented printing therefore requires alignment among appearance, flavor, texture, cultural familiarity, service presentation, and adult eating identity. It is not enough to make pureed food look like food; it must also behave like a safe and acceptable meal. Representative studies supporting this interpretation are summarized in Table 2. They show how food source, hydrocolloid addition, protein structuring, emulsion design, infill control, bioactive delivery, and multi-ingredient meal construction affect printability, texture modification, nutritional function, and dysphagia-related suitability.

Table 2 Experimental studies linking 3D food printing, texture control, visual reconstruction, and dysphagia-oriented food design.

Printed food matrix	Main design strategy	Key experimental focus	Design implications for dysphagia-friendly printed foods	Reference
Pork-based paste	Hydrocolloid incorporation	Evaluated whether modified pork paste could be 3D printed as dysphagia food	Shows that meat puree can be reconstructed into a recognizable and texture-controlled food form rather than being served as an amorphous paste	[74]
Black fungus-based paste	Addition of κ-carrageenan, xanthan gum, and arabic gum	Developed visually appealing texture-modified black fungus-based foods for dysphagia diets	Demonstrates that appearance improvement must be supported by gum-controlled rheology and texture modification	[75]
Surimi gel	Dry-spraying transglutaminase surface crosslinking	Improved printing and structural stability of surimi for dysphagia diet application	Supports the idea that fish-based dysphagia foods require controlled protein network formation, not only visual reshaping	[76]
Hypsizygus marmoreus by-product paste	Polysaccharide-assisted mushroom matrix design	Developed mushroom by-product-based 3D printed dysphagia diet with different polysaccharides	Shows that alternative ingredients can be converted into attractive dysphagia foods when polysaccharides tune viscosity, stability, and texture	[77]
Soy protein isolate and red cabbage dough	Infill-rate control	Printed samples with different internal structures and evaluated texture changes	Demonstrates that internal architecture affects hardness, gumminess, and chewiness, so toolpath design contributes to eating performance	[67]
Grape-based printed food	Bioactive-rich fruit matrix design	Evaluated anthocyanin bioaccessibility and anti-inflammatory activity in a dysphagia-oriented printed food	Supports the concept that a fortified soft matrix should deliver nutritional or functional value while remaining suitable for dysphagia use	[78]
Multi-ingredient nutritious meal	Hydrocolloid optimization in meal-level formulations	Developed 3D-printed nutritious meals and assessed International Dysphagia Diet Standardisation Initiative (IDDSI)-related texture categories	Moves the field from single puree printing toward meal-component design, which is closer to adult eating identity	[79]
Mung bean protein, rose powder, and flaxseed gum	Protein-rich texture-modified formulation	Used flaxseed gum to prepare texture-modified printed foods for older adults	Shows that protein enrichment and sensory-associated ingredients must be balanced with texture control for elderly foods	[80]
Pea protein-based gel	Different hydrocolloid systems	Studied how hydrocolloids affect pea protein-based 3D-printed dysphagia diets	Supports plant-protein dysphagia food design by showing that hydrocolloid choice controls printability and texture suitability	[81]
Pea protein-based vitamin D_3 emulsion gel	Emulsion gel stabilization and calcium alginate network formation	Achieved high printing precision, vitamin D_3 retention, and IDDSI Level 4 to 5 texture properties	Shows how functional fortification can be integrated into a swallowable printed matrix without ignoring texture safety	[82]
Faba bean protein, pea protein, mashed potato, and sunflower oil oleogel	Multi-component plant-protein meal construction	Developed multicomponent printed structures and classified them as IDDSI Level 5	Provides strong evidence that dysphagia-oriented 3D printing is moving toward complete meal structures rather than isolated gel prototypes	[58]

Current experimental evidence further supports the view that dignity-oriented 3D food printing cannot be reduced to visual reconstruction. Vegetable, meat, fish, fungal, fruit, and plant-protein systems can be shaped into more recognizable forms, but their value depends on whether these forms retain safe texture, suitable cohesiveness, controlled water behavior, nutritional density, and credible sensory cues. Hydrocolloids, protein interactions, emulsion gels, crosslinking, infill design, and multi-material assembly are therefore not only methods for improving printability; they are structural strategies for aligning appearance with oral performance and nutritional function [83]. However, most current evidence remains concentrated at the material, instrumental texture, or IDDSI-screening level. Studies on repeated intake, user satisfaction, cultural familiarity, and long-term meal acceptance are still limited. Thus, restoring food identity is meaningful only when the printed product behaves as a safe, nutritious, and acceptable meal at the point of eating.

The safety requirements for dysphagia-friendly foods are strict and cannot be relaxed in the name of personalization. Foods must be soft, cohesive, smooth, and appropriate for the individual's swallowing ability. They should avoid hard particles, dry fragments, mixed consistencies, uncontrolled liquid separation, and structures that break apart unpredictably. Safety must also be maintained during service, because a product that passes texture tests immediately after printing may change after cooling, reheating, drying, sauce addition, or delayed consumption [84]. This issue is especially relevant for printed foods because layer interfaces, exposed surfaces, and geometry-dependent moisture loss can alter texture over time. Dysphagia-oriented printing

should therefore evaluate the final served product, not only the fresh printed object.

Nutrition density and hydration add further complexity. Texture-modified diets are often diluted with water, broth, or sauce to achieve smoothness, which can reduce energy and protein density. Older adults may also consume smaller portions, making each spoonful nutritionally important. Printed matrices may incorporate proteins, fats, fibers, vitamins, and minerals in controlled structures, but fortification must not compromise texture safety or sensory acceptance. Protein may increase firmness or bitterness; fat may improve lubrication but must remain stable; fiber may support health but introduce roughness or water-binding changes [68]. Hydration should also be treated as a design target, because many older adults with dysphagia struggle with thin liquids and often dislike thickened drinks. High-moisture printed foods can support hydration only if water is retained in a cohesive, stable, and acceptable matrix [85]. Dysphagia-friendly printing is therefore not a narrow application, but a demanding test case for personalized food engineering.

4.4 Human dignity and eating identity

A major contribution of dysphagia-oriented personalized printing is that it forces food engineering to confront eating identity. Food is not only a carrier of nutrients or a material with mechanical properties; it is also connected to memory, autonomy, culture, pleasure, and social belonging [86]. For older adults, especially those living in care institutions, texture-modified diets may symbolize loss of independence and normality. Pureed foods can reduce swallowing risk, but they may also discourage eating when they no longer resemble recognizable meals. This is not a secondary concern. Food appearance, dignity, and emotional meaning can directly influence appetite, intake, meal participation, and quality of life.

Engineering dignity is difficult because it cannot be captured by a single instrumental measurement. It may depend on whether the food looks like an adult meal, resembles familiar cuisine, offers choice, fits an appropriate portion, supports shared eating, and avoids embarrassment. 3D printing offers tools for shape, portion, color arrangement, surface design, and texture control, but these tools must be guided by human understanding rather than technical capability alone. A realistic vegetable form may help one user but appear artificial to another; a culturally familiar dumpling-like form may be meaningful in one context but irrelevant in another. Personalization must therefore include sensory memory, cultural identity, and emotional meaning, not only clinical and nutritional variables.

This perspective changes how product success should be evaluated. Texture tests and nutrient analysis remain necessary, but they should be complemented by intake, repeated acceptance, meal satisfaction, fatigue, social participation, caregiver observations, and user-reported comfort where possible [87]. A product that meets mechanical criteria but is not eaten is not successful. A product that improves visual identity but increases oral-processing risk is not successful. A product accepted in a single test but rejected after repeated meals may not be practical. The relevant outcome is sustained safe eating.

Human dignity also requires user agency. Older adults should not be treated as passive recipients of algorithmically generated meals. When safety allows, they should be able to express preferences about flavor, form, portion size, meal rhythm, and familiar food identity. Caregivers and professionals should also interpret context, including mood, fatigue, illness, memory, and cultural significance. A personalized printing system should support human decision-making rather than replace it. The aim is not to choose between safety and dignity, but to engineer foods in which safety, nutrition, acceptance, and dignity reinforce one another.

5 EEG-Informed Sensory Feedback and Human-Centered Evaluation

5.1 Sensory acceptance as a limiting factor

Sensory acceptance is often where technically successful personalized foods either become meaningful or fail in practice. A food may be nutritionally optimized, structurally stable, and printable with high shape fidelity, but it cannot deliver its intended function if the user does not want to eat it. This is especially important for older adults, clinical populations, and people with dysphagia, whose appetite may already be weakened by disease, medication, fatigue, sensory decline, or negative experiences with texture-modified diets [88]. Acceptance should therefore be treated not as a final marketing test, but as a functional requirement of personalized food engineering. A meal that is rejected or only partially consumed cannot provide its designed protein dose, energy density, hydration support, or quality-of-life benefit.

Traditional sensory evaluation remains indispensable because it directly captures liking, perceived texture, flavor preference, satisfaction, and willingness to consume. Hedonic scales, descriptive analysis, ranking tests, intake observation, caregiver reports, facial expression analysis, and repeated meal studies each

provide useful evidence. However, some target users may have difficulty expressing sensory responses verbally because of cognitive impairment, communication limitations, sensory decline, fatigue, or social desirability. In dysphagia-oriented foods, rejection may arise from flavor, texture, fear of swallowing, visual unfamiliarity, or emotional resistance to modified diets. EEG-informed sensory feedback becomes relevant here as a complementary tool, not as a replacement for conventional sensory evaluation [89].

The value of EEG lies in its potential to enrich human-centered evaluation. It may help examine whether recognizable printed forms attract attention, whether certain textures or aromas increase cognitive burden, or whether familiar presentation evokes stronger engagement than amorphous purees [90]. Such information may be useful during early product development, especially when comparing shapes, surface structures, aroma strategies, or presentation modes. However, EEG should not be framed as a direct measure of liking or a tool for reading consumer preference. Neural signals are indirect, context-sensitive, and dependent on experimental design. They become meaningful only when interpreted together with explicit sensory evaluation, intake behavior, user feedback, and product-level performance.

5.2 Methodological limits of EEG in food contexts

EEG use in food evaluation requires caution because eating is a complex multisensory process involving visual expectation, aroma, taste, texture, temperature, oral manipulation, swallowing, memory, satiety, and emotion. EEG captures time-resolved brain activity, but it does not automatically identify which part of this experience produced a signal. Eating also creates artifacts from chewing, swallowing, blinking, facial muscle activity, and head movement [91]. For this reason, EEG may be more suitable for controlled stages such as visual presentation, aroma exposure, anticipatory response, or brief tasting tasks than for full meal consumption.

These limits should guide, rather than discourage, EEG use. The method should match the question. If the aim is to understand anticipatory appetite, EEG may be useful during visual exposure. If the aim is to compare cognitive burden or aversive response to textures, movement must be minimized and behavioral indicators included. If the aim is to predict long-term acceptance, EEG alone is insufficient because repeated intake depends on habit, social environment, service conditions, caregiver support, and meal fatigue. A strong signal-processing pipeline cannot compensate for a weak hypothesis or poor connection to food design decisions.

Experimental design is therefore central. Food EEG studies should consider hunger state, time of day, medication, sensory impairment, cognitive status, fatigue, food familiarity, cultural background, temperature, portion size, and presentation order. These variables are especially important for older adults and dysphagia populations. Repeated within-person designs may be more appropriate than simple between-group comparisons because personalization is concerned with individual differences. Such designs can examine whether changes in shape, aroma, texture, or familiarity produce consistent differences in neural, behavioral, and intake responses for a defined user or user group.

For future EEG/fNIRS-assisted food studies, acquisition and classification must be reported in enough detail to be reproduced. EEG reporting should include electrode layout, channel count, sampling rate, reference, impedance control, task timing, and event markers; fNIRS reporting should include optode placement, wavelengths, source-detector spacing, sampling rate, and short-separation channels where applicable. Preprocessing should specify filtering, bad-channel handling, ocular, muscle, and motion-artifact control, epoching, baseline definition, trial-rejection thresholds, and retained-trial rates. Labels should be derived from predefined product conditions, contemporaneous sensory ratings, choice, actual intake, or repeated acceptance rather than treating neural features as direct taste or preference labels. Classification should use participant-level train-test separation, leakage-resistant cross-validation, class-balance reporting, chance or permutation baselines, uncertainty estimates, and individualized calibration where justified [89,91,92].

At minimum, an EEG/fNIRS-assisted claim about food acceptance should be supported by four complementary domains: contemporaneous subjective sensory ratings, actual intake or meal completion, acceptance after repeated exposure, and stability of the intended product texture at the point of consumption. Neural measures should be considered design-relevant only when they are interpreted alongside these behavioral and product-level outcomes. Discordant results should be reported explicitly rather than collapsed into a single preference label.

Individual variability is one of the main methodological barriers to applying EEG/fNIRS in personalized food evaluation. As shown in Fig. 4, sensory responses to printed foods may differ substantially among users, and a generic model trained on limited participants may fail to capture these individual patterns. A future study should therefore use repeated within-person observations, predefined external labels such as product conditions, sensory ratings, choice, or intake, participant-level

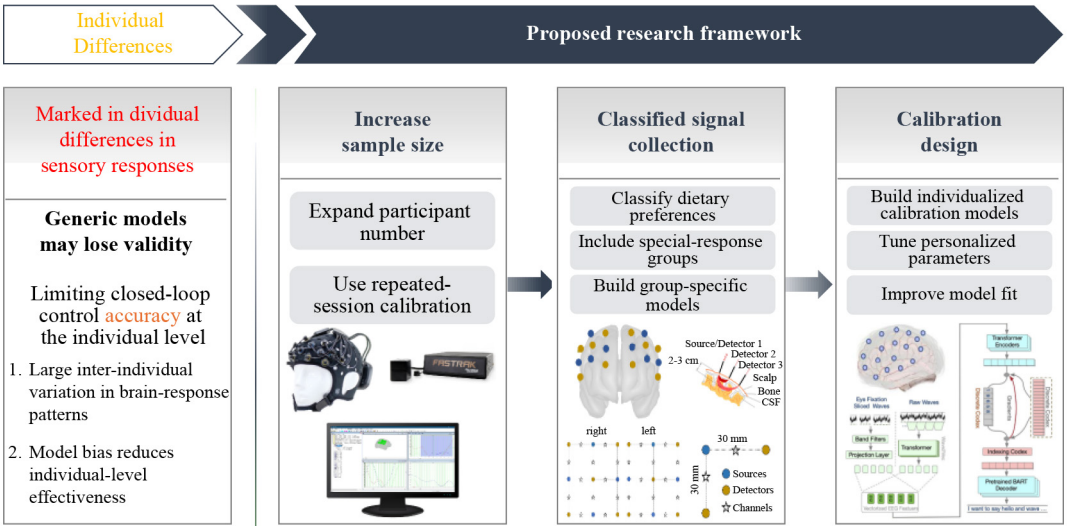


Fig. 4 Methodological strategy for addressing individual differences in EEG/fNIRS-based food evaluation. Individual variability in sensory responses may reduce the effectiveness of generic models. Increasing sample size, collecting classified neurophysiological signals, and introducing individualized calibration can improve model robustness, prediction accuracy, and suitability for personalized printed food design.

separation of training and test data, and individualized calibration. Increasing sample size alone is insufficient if trials from the same participant leak across datasets or if labels are not behaviorally validated. EEG/fNIRS signals can support personalized food design only when both population-level generalization and within-person reproducibility are demonstrated.

5.3 Responsible integration with food design

EEG-informed feedback should be integrated through a cautious evidence hierarchy [92]. It should not be placed above explicit liking, actual intake, texture safety, or user comfort [93]. A neural signal interpreted as increased attention has limited value if the food is not eaten, and a response interpreted as positive affect is insufficient if the product fails texture requirements. EEG has engineering value only when linked to modifiable design variables, such as shape, surface structure, flavor placement, aroma intensity, texture gradient, portion size, or toolpath pattern. Without this linkage, EEG remains an observational technology rather than a useful component of personalized food manufacturing [94].

Candidate design variables should be prioritized according to perceptual relevance, temporal controllability, and artifact burden. Visual attributes, including overall geometry, size, color, surface pattern, and plating, are the most suitable first-stage variables because stimulus onset can be precisely marked without eating-related movement. Aroma intensity and spatial flavor cues are second-stage candidates when delivery timing is standardized. Texture-related variables, including infill density, layer orientation, porosity, hardness, cohesiveness, and texture gradients, are relevant only in controlled single-bite designs, with neural analysis focused on pre-bite or post-swallow windows and accompanied by instrumental texture and dysphagia-relevant tests. In contrast, nutrient dose, swallowing safety, metabolic response, and long-term acceptance should never be optimized from EEG/fNIRS alone. Machine-level parameters such as nozzle temperature, extrusion rate, or printing speed should enter EEG-assisted optimization only through the perceptible product attributes that they demonstrably modify.

To make neurophysiological feedback useful for personalized 3D food printing, brain-derived signals should be connected to specific food-design questions rather than treated as direct indicators of preference. As illustrated conceptually in Fig. 5, a future EEG/fNIRS-assisted study could examine responses to controlled changes in food flavor, form, and texture. After artifact control, neural features could be interpreted alongside subjective ratings, actual intake, repeated acceptance, and product performance; any predictive model would require participant-level validation and individualized calibration. The purpose is not to replace sensory evaluation or to claim direct brain-signal control of printing, but to test whether complementary neurophysiological evidence can support an evidence-gated design loop while safety and product-performance requirements remain satisfied.

In a personalized food design pipeline, EEG may contribute at several levels. It may help compare visual formats, aroma strategies, or texture presentations during product development; provide complementary evidence

when verbal reporting is limited; or support model training when combined with sensory scores, intake behavior, and product attributes [95]. In selected clinical or elder-care contexts, it may help interpret implicit responses when users struggle to articulate preference. However, continuous EEG monitoring for everyday meal production is unlikely to be practical, necessary, or ethically appropriate. A more realistic future is targeted and periodic use in research, product optimization, and selected high-value personalization scenarios.

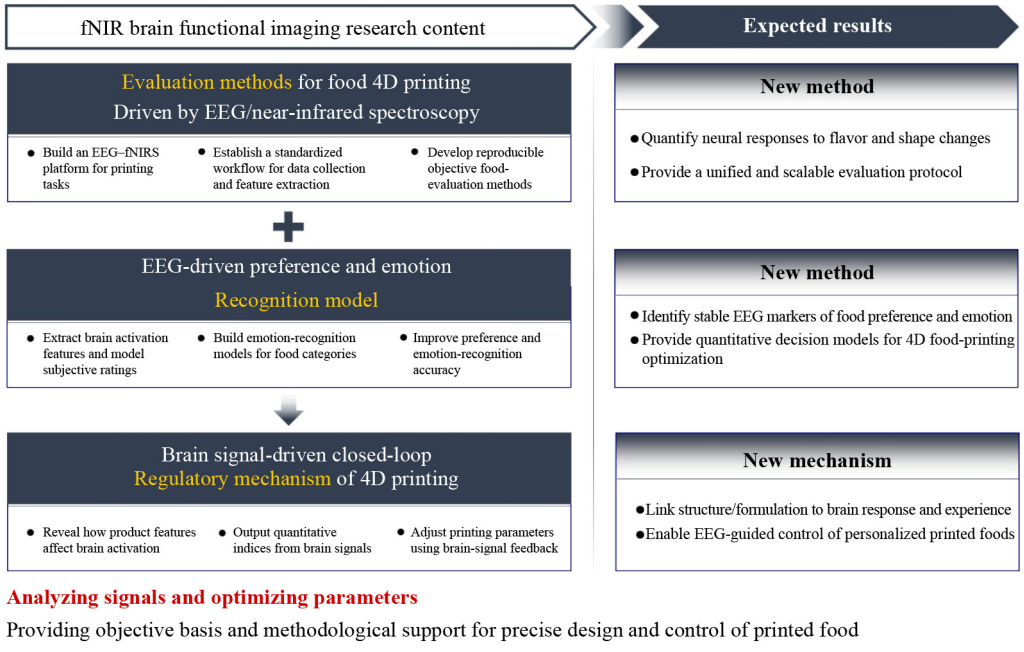


Fig. 5 Neurophysiological-feedback framework for personalized 4D/3D food printing evaluation and control. EEG/fNIRS signals can be used to quantify neural responses to printed food attributes, support preference and emotion-recognition models, and provide objective evidence for adaptive printing-parameter optimization and personalized food design.

Ethical responsibility must be considered from the beginning. Brain-related data can feel intimate even when they are not diagnostic. Users should understand what is measured, why it is collected, how it will influence food design, and who can access it. In elder-care or clinical settings, consent, decision-making capacity, caregiver involvement, and data protection require particular attention [96]. EEG should never override expressed preferences or be used as a hidden persuasion tool. Its purpose should be to support comfort, safety, nutrition, and acceptance, not to manipulate eating behavior.

5.4 Human-centered evaluation beyond the laboratory

Human-centered evaluation must extend beyond controlled sensory booths because personalized foods are consumed in real environments. A printed food designed for an older adult in a care home is shaped by serving temperature, plate presentation, staff assistance, mealtime schedule, social environment, user fatigue, oral comfort, repeated exposure, and emotional meaning. Laboratory liking scores provide useful early evidence, but they may not predict long-term acceptance or intake [97]. A product that looks attractive in a controlled test may lose appeal if it dries during service, becomes too firm after reheating, appears childish on the plate, or requires too much assistance to consume.

For dysphagia-friendly printed foods, evaluation should include texture stability at eating, intake amount, eating duration, perceived effort, signs of discomfort, caregiver observations, user satisfaction, and willingness to consume the product repeatedly. For precision nutrition, evaluation should examine whether the intended nutrient dose is actually consumed. For sensory personalization, repeated preference and qualitative feedback are essential because novelty can temporarily inflate acceptance. These outcomes are harder to collect than shape-fidelity images, but they are more relevant to real impact [98].

Negative results should be treated as valuable evidence. If a printed food is rejected, the key question is why: flavor, texture, aroma, portion size, appearance, cultural mismatch, swallowing anxiety, fatigue, or service condition. Each rejection reveals a boundary of the design space. A mature field should report not only what worked, but also what failed and under what conditions. Ultimately, sensory feedback should close the loop

between design intent and human experience. The eater is not a passive endpoint of a data-driven pipeline; eating behavior, acceptance, discomfort, memory, and dignity are part of the system itself.

6 A Sense-Model-Print-Evaluate-Learn Framework for Personalized Food Manufacturing

6.1 Rationale for a closed-loop framework

Personalized food should not be understood as a single act of customization, but as a closed-loop engineering process. Personalization is not complete when a user profile is collected, a recipe is generated, or a visually customized food is printed. A printed food becomes personalized only when its differences are linked to specific user needs, translated into measurable design targets, manufactured within validated process windows, evaluated under real eating conditions, and revised through feedback. This review therefore proposes a sense-model-print-evaluate-learn framework that connects individual data, material design, digital processing, sensory response, and outcome feedback into an adaptive system [99].

Such a framework is necessary because both food systems and human users are variable. Ingredients differ in composition, moisture, particle size, protein state, starch behavior, and functional properties. Printable matrices change through hydration, gelation, retrogradation, phase separation, or microbial risk. Printers may drift in pressure, temperature control, nozzle performance, and dimensional accuracy. Users also change: swallowing ability may decline after illness, appetite may fluctuate with medication or fatigue, and preferences may shift after repeated exposure [99]. Personalized food therefore cannot rely on static recipes or fixed parameter sets. It requires feedback logic that can detect mismatch between design intention and actual outcome.

The framework also integrates disciplines that are often treated separately. Precision nutrition defines individualized targets; food material science provides printable matrices; 3D printing enables digital fabrication; sensory science evaluates acceptance; and clinical practice defines safety requirements. The sense-model-print-evaluate-learn framework connects these domains through a shared engineering logic. Its purpose is not to remove human expertise, but to make responsibility visible by clarifying how data are collected, decisions are made, products are verified, and failures are used to improve future designs.

6.2 Sense and model

The sense stage is the entry point of personalization, but it should not become indiscriminate data collection. A personalized food system may use clinical diagnosis, swallowing assessment, nutritional prescription, allergy information, metabolic response, activity pattern, preference history, cultural habits, intake records, and selected physiological signals such as EEG. However, more data do not automatically mean better personalization. The key question is whether an input can safely and meaningfully change formulation, texture level, portion size, flavor design, toolpath structure, timing, or evaluation criteria [100]. A disciplined sensing stage should distinguish mandatory safety data, optimization data, and exploratory data.

This distinction is especially important in high-risk applications such as dysphagia-friendly foods. Confirmed allergies, swallowing status, texture requirements, and major dietary restrictions should be treated as non-negotiable. Preferences for flavor, familiar form, eating pace, or appetite pattern can support acceptance but should not override safety [101]. More complex signals, including glucose fluctuation, microbiome profile, or EEG-derived response, should influence design only through validated intermediate variables. The sensing stage must therefore include data grading, uncertainty awareness, and professional oversight.

The model stage converts sensed information into design targets and process decisions. User needs are translated into constraints such as texture level, energy density, protein dose, sodium range, allergen exclusion, moisture retention, flavor intensity, service stability, and post-processing tolerance. These targets must then be linked to formulation rules, rheological ranges, printing parameters, and evaluation methods. Models may combine rule-based logic, mechanistic understanding, empirical material maps, and data-driven prediction. However, no model should be treated as authoritative unless its predictions are bounded, interpretable, and validated.

6.3 Print and evaluate

The print stage turns modeled design into a physical food structure. It includes material preparation, cartridge loading, nozzle selection, extrusion pressure, print speed, layer height, infill pattern, temperature control, environmental conditions, and post-processing [102]. In advanced systems, sensors may monitor pressure, flow stability, temperature, dimensional accuracy, clogging, and deposition consistency [103]. These signals matter because personalized food is linked to user-specific requirements. A deviation that is acceptable in a

decorative prototype may be unacceptable when the food is intended to meet a texture level, nutrient dose, or swallowing-safety requirement. This manufacturing perspective requires documentation, traceability, and quality control. A personalized food system should record which formulation was used, which user profile or design category it served, which ingredients and cartridges were applied, which print parameters were selected, whether the process remained within limits, and whether the final product passed relevant checks. Personalization increases responsibility because the product is designed for a user whose needs may involve safety, nutrition, and dignity. Representative studies supporting this manufacturing-control perspective are summarized in Table 3, highlighting how material preparation, printing parameters, structural accuracy, post-processing, defect control, and monitoring strategies jointly determine whether a personalized printed food can meet user-specific safety and quality requirements.

The studies summarized in Table 3 show that the print stage should be treated as a quality-critical manufacturing process rather than a simple shape-generation step. Material properties, printer configuration, nozzle selection, extrusion behavior, layer design, infill structure, and post-processing conditions jointly determine whether the final food maintains its intended geometry, texture, nutrient delivery, and swallowing-related safety. Experimental studies on mashed potato, processed cheese, cereal snacks, vegetable purees, and food foams demonstrate that small changes in rheology, printing path, thermal history, or hydrocolloid stabilization can alter dimensional stability, texture, and eating suitability [109]. Reviews on defects, process control, healthcare applications, and intelligent 3D food printing further indicate that personalized printed foods require monitoring of clogging, deformation, flow instability, dimensional errors, and post-processing drift [110]. Therefore, a personalized food printer should not only execute a digital model, but also document the formulation, material batch, cartridge, nozzle, print parameters, process stability, quality checks, and final product suitability. This traceable manufacturing logic is especially important when printed foods are intended for users with dysphagia, metabolic constraints, malnutrition risk, or other safety-sensitive needs.

The evaluate stage provides a reality check. Evaluation should not stop at print fidelity. A food that holds its shape may still fail in texture safety, nutrient retention, microbial control, service stability, or acceptance. Evidence should match the claim: shape-fidelity claims require dimensional and structural data; dysphagia claims require texture, cohesiveness, particle size, moisture behavior, and oral-processing relevance; nutrition claims require retained and consumed nutrient dose; sensory personalization claims require repeated acceptance and intake in context. Evaluation should also occur at the point where performance matters, especially after holding, reheating, transport, sauce addition, or service delay [111].

6.4 Learn and adapt

The learn stage gives the framework long-term value. It closes the loop by using outcomes to improve future

Table 3 Representative studies supporting process control, monitoring, and quality assurance in personalized 3D food printing.

Main manufacturing focus	Critical parameters to record	Quality-control implication	Implications for personalized food manufacturing	Reference
Food ink materials, extrusion systems, printer configuration	Ink composition, nozzle type, extrusion mode, printer configuration	Establishes the basic link between material preparation and machine compatibility	Supports documentation of material preparation, cartridge/nozzle selection, and equipment conditions	[104]
Rheology, extrusion behavior, print stability	Apparent viscosity, yield stress, extrusion rate, nozzle diameter	Defines whether the matrix remains within a printable operating window	Shows that rheological properties directly affect extrusion and printed shape stability	[22]
Thermal/shear effects during printing, structure and texture	Printing temperature, shear exposure, extrusion condition, final texture	Treats printing as a process that can alter food structure rather than only shape it	Supports the view that print parameters are quality-critical variables	[24]
Hydrocolloid-assisted printing and dysphagia texture	Hydrocolloid type, concentration, texture category, water retention	Verifies whether printed foods meet swallowing-related texture requirements	Shows that shape fidelity alone is insufficient for dysphagia-oriented foods	[25]
Hydrocolloid-stabilized food foam for hydration and dysphagia	Foam structure, hydrocolloid system, water retention, texture stability	Expands quality control from printing success to hydration and swallowing suitability	Supports product-level validation for vulnerable users	[105]
Printing defects, failure modes, corrective strategies	Clogging, collapse, over-extrusion, under-extrusion, deformation	Identifies defect monitoring as a necessary part of process control	Supports real-time or post-print inspection of printing failures	[106]
Process control, post-processing, printed food quality	Temperature, drying/cooking conditions, storage time, post-processing method	Highlights that product quality may change after printing	Supports control of post-processing and service-related conditions	[107]
Healthcare applications, benefits, risks, safety concerns	User category, safety requirement, clinical claim, quality check	Emphasizes risk management for health-related printed foods	Supports stronger safety and quality assurance in personalized food applications	[108]
Intelligent monitoring, sensing, feedback control	Pressure, flow stability, dimensional accuracy, sensor feedback	Supports transition from open-loop printing to monitored and controlled manufacturing	Directly supports sensing, monitoring, and feedback control in personalized 3D food printing	[57]

designs. If a food is not eaten, the system should not regard it as successful simply because it printed accurately. If texture drifts during holding, the process model should be revised. If a user repeatedly accepts one flavor family but rejects another, the preference model should be updated. If a printer shows recurring pressure deviations with a matrix, formulation or parameter windows should be reconsidered. Learning transforms personalization from static customization into adaptive food engineering.

Learning should include failure. Systems that record only successful prints or positive responses generate biased knowledge. Failures reveal where formulations collapse, textures become unsafe, flavors are rejected, cleaning becomes impractical, costs become excessive, or workflows break down. These boundaries are essential for translation. However, adaptation must be governed. In high-risk applications, learning cannot mean unrestricted automatic modification [112]. A system should not autonomously change dysphagia texture levels, alter nutrient prescriptions beyond approved ranges, or infer clinical changes from limited intake data. The goal is safe adaptability, not maximum adaptability.

A mature learning system could support validated design libraries. Each entry could include formulation ranges, rheological characteristics, print parameters, post-processing conditions, final texture, service stability, nutrient capacity, sensory profile, cleaning requirements, and user suitability. Such libraries would be more useful than isolated recipes because they support controlled personalization across settings and help the field build cumulative knowledge.

6.5 Standards, governance, and digital traceability

Standards are not opposed to personalization; in high-risk food applications, they make personalization trustworthy. Texture standards provide a shared language for swallowing-related properties. Food safety systems define hygiene requirements. Nutritional guidelines establish clinical boundaries. Printer calibration supports process reliability. Data governance protects sensitive personal information. Personalized food should occur within such boundaries, not outside them.

Digital traceability is essential because personalized food links user information with manufacturing action. A system should be able to connect user needs, design constraints, formulation, print parameters, quality checks, evaluation results, and feedback. This record should answer basic questions: what was printed, for whom it was designed, which constraints were applied, which ingredients and parameters were used, whether the product passed checks, whether it was eaten, and whether any problem occurred. Without traceability, personalized printing cannot be audited or improved [113].

Data governance must also be built in from the beginning. Personalized food systems may use health records, swallowing assessments, dietary restrictions, metabolic data, preference histories, intake records, and physiological signals. Access should be role-based, collection should be minimized, and users or representatives should understand how data influence food decisions. Algorithms should be auditable when they affect safety or clinical nutrition. Interoperability will also matter. If each printer, cartridge, software system, and food-file format is incompatible, it will be difficult to compare performance, transfer validated recipes, or deploy systems across care settings. Standards, governance, and traceability are therefore part of the engineering architecture of trustworthy personalized food.

7 Translation Barriers and Future Research Agenda

7.1 Reproducibility and scale-up

Reproducibility is a fundamental barrier because food materials are intrinsically variable. Ingredients differ by cultivar, supplier, season, storage history, moisture content, particle size, protein state, starch gelatinization, and preprocessing conditions. A puree, gel, or paste that prints well in one laboratory may behave differently elsewhere, and small changes in hydration time, mixing intensity, or temperature can alter viscosity, shape fidelity, texture, and flavor [114]. This variability directly affects whether personalized foods can be produced safely and repeatedly for users with specific nutritional or swallowing needs.

Translation is therefore not achieved by printing a formulation once under controlled conditions. Real deployment in care homes, hospitals, rehabilitation centers, or home settings requires robustness under less ideal workflows. Printed foods must tolerate variation in raw materials, cartridge storage, meal scheduling, post-processing, and service delays [115]. Reproducibility should therefore be built around ingredient specifications, process monitoring, adaptive parameter control, and formulation margins wide enough for practical use.

Scale-up should also be reconsidered. Conventional scale-up aims to produce large volumes of identical products, whereas personalized 3D food printing requires reliable small-batch production with controlled variation. Throughput should be measured not only by deposition

speed, but by the number of safe, acceptable, and correctly personalized meals produced per unit of labor, equipment time, and workflow complexity. Personalization does not eliminate standardization; it increases the need to define which components can vary, which parameters must remain fixed, and how standardized modules can support individualized products.

7.2 Hygiene, regulation, and risk management

Hygiene may become a decisive barrier for clinical and elder-care applications. Many research printers were not designed as hygienic food manufacturing equipment. Open reservoirs, complex tubing, difficult-to-clean nozzles, repeated material contact, and long residence times can increase microbial risk, allergen carryover, and residue accumulation. These risks are serious because many printable matrices are high-moisture, nutrient-rich systems [116]. When target users are older adults, patients, or people with swallowing disorders, hygiene must be part of the basic design logic of both printer and formulation.

Printer design should therefore follow hygienic engineering principles. Food-contact surfaces should be minimized, accessible, cleanable, corrosion-resistant, or disposable where appropriate. Closed cartridges, validated cleaning procedures, allergen segregation, time-temperature documentation, cartridge verification, and detection of out-of-window operation should be considered essential for translation. A formulation that prints well but leaves persistent residues is not suitable for routine care use.

Regulation and risk management should also begin early. A personalized printed food may be treated as ordinary food, texture-modified diet, medical nutrition product, clinical food service, or part of a digital health system depending on its claims and use context. Claims about swallowing safety, nutritional status, disease management, or clinical outcomes require stronger evidence than claims about appearance. Personalized printing also introduces risks such as wrong user-profile selection, outdated swallowing information, wrong texture level, software errors, sensor drift, incomplete printing, and unrecorded recipe changes. Safeguards should include profile confirmation, barcode or radio frequency identification (RFID) verification, locked safety constraints, failed-print rejection, staff training, and periodic calibration.

7.3 Evidence tiers and validation pathways

Validation must move beyond shape fidelity. A printed food can look attractive and still fail in nutrition delivery, texture safety, service stability, microbial control, or user acceptance. Evidence should therefore be organized according to claim strength. At the material level, studies should evaluate rheology, extrusion behavior, shape retention, and recovery. At the food-quality level, they should examine final texture, nutrient retention, post-processing stability, microbial safety, and flavor. At the use-context level, they should assess intake, eating duration, meal satisfaction, staff workflow, cleaning burden, and service feasibility [117]. At the clinical or translational level, they should consider swallowing-related safety indicators, nutritional outcomes, quality of life, and longer-term adherence.

Not every study must address all evidence levels, but each study should state what level of claim it supports. A printable high-protein gel should not imply improved clinical nutrition without intake or outcome data. An attractive dysphagia-like shape should not imply swallowing safety without appropriate texture tests and professional oversight. An EEG study should not claim preference prediction unless neural measures are interpreted with behavioral response, explicit sensory data, and intake. Clear claim boundaries are necessary for scientific credibility.

Human-centered validation is especially important because personalized food succeeds or fails during eating. For dysphagia-friendly foods, early studies may begin with instrumental texture analysis and service-stability tests, but later studies must involve intended users under ethical and professional supervision. Evaluation should include intake, fatigue, appetite, comfort, repeated acceptance, caregiver observations, and quality of life. Repeated-use studies are particularly necessary because prototypes may perform well when novelty is high but fail over time [118].

7.4 Cost, equity, and sustainability

Cost should not be reduced to printer price. The real cost of personalized 3D food printing includes ingredients, preprocessing, cartridges, cleaning, maintenance, staff training, software, quality checks, data management, failed prints, post-processing, and service delay. A printed meal may still be justified for high-risk users if it improves intake, reduces supplement waste, lowers caregiver burden, enhances dignity, or helps prevent malnutrition-related complications. The economic question is not whether 3D-printed food is cheaper than conventional food in general, but where controlled personalization creates enough value to justify added complexity.

Equity must also be addressed early. Personalized

nutrition can become a premium service for wealthy consumers while vulnerable groups continue receiving low-quality standardized diets. Dysphagia-friendly printing offers a more meaningful ethical direction because it applies advanced food engineering to urgent nutritional and quality-of-life needs. Future studies should therefore include low-cost matrices, modular printer designs, simple quality-control methods, and workflows adaptable to different resource levels.

Sustainability should be evaluated through full workflows. 3D food printing may reduce plate waste if users eat more of meals designed for their needs, and it may support portion control or alternative ingredients. At the same time, energy use, cartridge waste, cleaning water, preprocessing, failed prints, and short service windows may offset these benefits [119]. Economic, environmental, and social value should be analyzed together and supported by evidence rather than assumed.

7.5 Research agenda for the next stage

The next stage of research should move from isolated demonstrations to validated design libraries. For dysphagia-friendly elderly foods, a useful library entry should include ingredient specifications, preparation method, rheological range, print settings, post-processing conditions, final texture, service stability, nutrient density, microbial safety, sensory profile, cleaning requirements, and user suitability. Such libraries would define safe and adaptable operating spaces rather than unlimited recipe variation.

Beyond older adults with dysphagia, the framework's workflow can be reused to translate user information into measurable design targets, link formulation and toolpath choices to product attributes, document manufacturing conditions, and guide updates through outcome-based feedback. Transferability concerns this workflow rather than unchanged formulations, thresholds, or predictive models. For metabolic personalization, evaluation should address nutrient delivery and the metabolic outcomes being claimed; for sensory or portion personalization, it should emphasize acceptance, intake, and fit to user needs. Dysphagia-specific texture classification and swallowing assessment should be required when indicated by the target population or intended claim, rather than imposed on all applications. EEG/fNIRS should remain optional; when used, its tasks, behavioral labels, calibration, and validation population should be adapted to the intended users, while artifact control and independent validation remain necessary.

Standardized reporting is also urgent. Studies should provide sufficient detail on solids content, particle size, hydration time, temperature, rheological protocol, nozzle diameter, extrusion rate, print speed, layer height, infill pattern, post-processing, storage time, service condition, texture after service, nutrient retention, and sensory methods when relevant. Standardization is not the opposite of creativity; it is what allows creative results to become interpretable knowledge.

Future research should strengthen structure–function modeling and responsible intelligent systems. Researchers need to clarify how composition, rheology, toolpath, post-processing, and service conditions determine oral breakdown, flavor release, nutrient delivery, texture safety, and user acceptance. AI, wearables, metabolic data, microbiome information, and EEG may contribute to personalization, but each signal should have a clear design purpose. The central question should not be whether more data can be collected, but whether a signal improves safety, nutrition, acceptance, or feasibility. The next generation of studies should ask whether printable materials, nutrition models, dysphagia frameworks, sensory tools, and digital manufacturing systems work together to improve eating outcomes for defined users. Recent data-driven work combining rheological characterization, controlled parameter optimization, product-quality assessment, and machine-learning classification of extrusion suitability further illustrates how measurable manufacturing feedback can reduce trial-and-error in food printing [120].

8 Conclusions

Personalized food should be understood not as simple customization, but as a rigorous food engineering system. Its value lies in connecting 3D food printing, precision nutrition, printable matrix design, dysphagia-friendly foods, and EEG-informed sensory evaluation into a shared framework for translating individual needs into manufacturable, safe, acceptable, and adaptive food structures. The proposed sense–model–print–evaluate–learn framework shifts personalized food from one-time recipe generation toward a closed-loop system in which user data, material properties, process control, sensory response, and real eating outcomes are continuously connected. In this context, 3D food printing is not merely a shaping tool, but a programmable manufacturing interface for delivering individualized nutrition, texture, and sensory experience. Dysphagia-friendly foods for older adults represent a particularly meaningful early application because they combine clear safety requirements, urgent nutritional needs, and strong human-centered value. Future progress will depend on validated matrix libraries, standardized reporting, hygienic printer design, staged evidence, cost-aware

implementation, and responsible data governance. Overall, personalized food engineering should move from technological promise toward reliable, ethical, and human-centered manufacturing. Across applications, design updates should remain within validated manufacturing and food-safety boundaries and be supported by outcomes appropriate to the intended claim. Dysphagia-specific swallowing requirements should apply where relevant, while EEG/fNIRS should remain an optional complementary input requiring validation for the intended population and task.

Data availability No datasets were generated or analyzed for this work.

Acknowledgments This work was supported by the National Key Research and Development Program of China (2022YFF1101900), the Special Funds for Jiangsu Province Science and Technology Plans (BZ2024029), the National Natural Science Foundation of China (32272407, 32372465), the Natural Science Foundation of Jiangsu Province (BK20220058, BK20220111), the Ningbo Key Research and Development Plan Project (2023Z123), the Postdoctoral Project of Institute of Modern Agriculture and Health Care Industry of Wencheng (2022NKY05), the Science and Technology research plan of Wencheng (2023GCC02), the Foundation of Jiangsu Specially-Appointed Professor (202074), the Earmarked Fund for China Agriculture Research System (CARS-27), and Natural Science Foundation of Jiangsu Province (BE2022313). The authors used GPT-5, online version as a language-editing tool to improve grammar, clarity, and readability. The AI tool was not used for data analysis, data generation, image processing, or scientific content creation. All outputs were carefully reviewed and verified by the authors, who take full responsibility for the final content.

Competing interest Xiaobo Zou serves as a member of the Editorial Board of this Journal. He was not involved in the editorial review or decision-making process for this manuscript. All editorial decisions were made independently by other members of the Editorial Board who have no conflicts of interest.

References

1. Livingstone K M, Ramos-Lopez O, Pérusse L, et al. Precision nutrition: a review of current approaches and future endeavors. Trends in Food Science & Technology, 2022, 128: 253–264
2. Qin Z, Zhai X D, Huang X W, et al. Sinusoidal voltage pulsed electrolysis induced anthocyanins discoloration: an improved method for colorful food 3D printing. Food Research International, 2026, 231: 118732
3. Derossi A, Spence C, Corradini M G, et al. Personalized, digitally designed 3D printed food towards the reshaping of food manufacturing and consumption. npj Science of Food, 2024, 8(1): 54
4. Liu Z B, Chen X, Li H B, et al. 3D printing of nutritious dysphagia diet: status and perspectives. Trends in Food Science & Technology, 2024, 147: 104478
5. Qin Z, Huang X W, Zhang X N, et al. Precision color management in 3D food printing: a dual-channel nozzle system with coaxial gradient design for minimizing waste. Innovative Food Science & Emerging Technologies, 2026, 111: 104575
6. Asnicar F, Manghi P, Fackelmann G, et al. Gut micro-organisms associated with health, nutrition and dietary interventions. Nature, 2026, 650(8101): 450–458
7. Zahedani A D, McLaughlin T, Veluvali A, et al. Digital health application integrating wearable data and behavioral patterns improves metabolic health. npj Digital Medicine, 2023, 6(1): 216
8. Abedini A, Sohrabvandi S, Sadighara P, et al. Personalized nutrition with 3D-printed foods: a systematic review on the impact of different additives. Advances in Colloid and Interface Science, 2024, 328: 103181
9. Molimi M B, Egan P, Adebo O A. Progress in three-dimensional (3D) printed foods for dysphagia patients: food sources, processing techniques, printability, nutrition, acceptability, and safety aspects. Food Research International, 2025, 202: 115629
10. Kurosu A, Osman F, Daggett S, et al. Factors associated with self-reported dysphagia in older adults receiving meal support. The Journal of Nutrition, Health and Aging, 2021, 25(10): 1145–1153
11. Wu X S, Miles A, Braakhuis A J. Texture-modified diets, nutritional status and mealtime satisfaction: a systematic review. Healthcare, 2021, 9(6): 624
12. Chao C, Nam H K, Park H J, et al. Potentials of 3D printing in nutritional and textural customization of personalized food for elderly with dysphagia. Applied Biological Chemistry, 2024, 67(1): 25
13. Inguscio B M S, Carcaterra G, Cherubino P, et al. Neuroscience meets food choice: implicit and explicit consumer responses to plant-based vs animal-based foods. Current Research in Food Science, 2026, 12: 101288
14. Dick A, Dong X P, Bhandari B, et al. The role of hydrocolloids on the 3D printability of meat products. Food Hydrocolloids, 2021, 119: 106879
15. Mudau M, Adebo O A. Three dimensional (3D)-printed foods: a review of recent advances in their ingredients, printing techniques, food printers, post-processing methods, consumer acceptance and safety. Journal of Food Process Engineering, 2024, 47(5): e14621
16. Van Der Sman R, Tian B, Ghoreishy S A, et al. Relationships between printability and rheology of inks for personalized nutrition. Current Research in Food Science, 2025, 11: 101220
17. Bugday Z Y, Venkatachalam A, Anderson P D, et al. Rheology of paste-like food inks for 3D printing: effects of nutrient and water content. Current Research in Food Science, 2024, 9: 100847
18. Wang Y M, Xin M L, Li Z Y, et al. Food-oral processing: current progress, future directions, and challenges. Journal of Agricultural and Food Chemistry, 2024, 72(19): 10725–10736
19. Ainis W N, Feng R, Van Den Berg F W J, et al. Comparing the rheological and 3D printing behavior of pea and soy protein isolate pastes. Innovative Food Science & Emerging Technologies, 2023, 84: 103307
20. Maldonado-Rosas R, Tejada-Ortigoza V, Cuan-Urquizo E, et al.

Evaluation of rheology and printability of 3D printing nutritious food with complex formulations. Additive Manufacturing, 2022, 58: 103030
21. Lille M, Nurmela A, Nordlund E, et al. Applicability of protein and fiber-rich food materials in extrusion-based 3D printing. Journal of Food Engineering, 2018, 220: 20–27
22. Liu Z B, Zhang M, Bhandari B, et al. Impact of rheological properties of mashed potatoes on 3D printing. Journal of Food Engineering, 2018, 220: 76–82
23. Liu Z B, Bhandari B, Prakash S, et al. Linking rheology and printability of a multicomponent gel system of carrageenan-xanthan-starch in extrusion based additive manufacturing. Food Hydrocolloids, 2019, 87: 413–424
24. Le Tohic C, O'Sullivan J J, Drapala K P, et al. Effect of 3D printing on the structure and textural properties of processed cheese. Journal of Food Engineering, 2018, 220: 56–64
25. Pant A, Lee A Y, Karyappa R, et al. 3D food printing of fresh vegetables using food hydrocolloids for dysphagic patients. Food Hydrocolloids, 2021, 114: 106546
26. Derossi A, Caporizzi R, Paolillo M, et al. Programmable texture properties of cereal-based snack mediated by 3D printing technology. Journal of Food Engineering, 2021, 289: 110160
27. Lee C P, Takahashi M, Arai S, et al. 3D printing of okara ink: the effect of particle size on the printability. ACS Food Science & Technology, 2021, 1(11): 2053–2061
28. Herrera-Lavados C, Tabilo-Munizaga G, Rivera-Tobar D, et al. Development of bean-based emulgels for 3D printing applications: feasibility for dysphagia diets. Journal of Food Engineering, 2023, 358: 111687
29. Addo E O, Wild S, Yousefi A, et al. Insights into the material and 3D printing behaviour of fiber-enriched protein gels. Food Research International, 2025, 203: 115873
30. Lin Q Z, Shang M S, Li X J, et al. Rheology and 3D printing characteristics of heat-inducible pea protein-carrageenan-glycyrrhizic acid emulsions as edible inks. Food Hydrocolloids, 2024, 147: 109347
31. Wang M Y, Zhang M Y, Luo X H, et al. 3D printing-driven functional food innovation: construction of personalized nutritional system and precise regulation mechanism of texture structure. Trends in Food Science & Technology, 2025, 166: 105389
32. García-Gutiérrez D, Ayala Márquez B, Gironés García X, et al. Integration of the IDDSI scale into 3D food printing: a strategy to improve food safety and quality of life for people with dysphagia. Nutrients, 2025, 17(24): 3925
33. Cui Y, Yang F, Wang C S, et al. 3D printing windows and rheological properties for normal maize starch/sodium alginate composite gels. Food Hydrocolloids, 2024, 146: 109178
34. Guo Q, Zhang M, Law C L, et al. Development of a 3D-printed food based on arrowhead (*Sagittaria sagittifolia* L.) byproducts: effects of hydrocolloids on printability and post-processing performance. Food Research International, 2025, 221(Pt 3): 117478
35. Heckl M P, Korber M, Jekle M, et al. Relation between deformation and relaxation of hydrocolloids-starch based bio-inks and 3D printing accuracy. Food Hydrocolloids, 2023, 137: 108326
36. Toniazzo T, Leverrier C, Souza N L, et al. Influence of starch-based gels on 3D food printing: linking printability, texture, rheological properties, and sensory evaluation. Future Foods, 2025, 12: 100725
37. Paolillo M, Derossi A, Van Bommel K, et al. Rheological properties, dispensing force and printing fidelity of starchy-gels modulated by concentration, temperature and resting time. Food Hydrocolloids, 2021, 117: 106703
38. Liu T, Liu C Y, Wang X. Research advances on standards and processing methods of texture-modified foods for dysphagia: a review. Discover Food, 2024, 4(1): 39
39. Kiran B S, Bashir O, Pawase P A, et al. A review of *in-vitro* digestibility models on diverse foods in various segments of human digestive tract. Discover Food, 2025, 5(1): 273
40. Prithviraj V, Díaz L P, Lemus-Mondaca R, et al. Emerging advancements in 3D food printing. Frontiers in Food Science and Technology, 2025, 5: 1607449
41. Camille H, Benjamin B, Mathieu D R, et al. Improving texture and protein content in 3D-printed plant-based foods for dysphagia: a study of pea-protein and curcumin-enriched oleogel formulations. Foods, 2026, 15(7): 1125
42. Liu W M, Chen L, McClements D J, et al. Recent trends of 3D printing based on starch-hydrocolloid in food, biomedicine and environment. Critical Reviews in Food Science and Nutrition, 2024, 64(25): 8948–8962
43. Wang D Q, Wang J, Lang Y, et al. Interactions between food matrices and odorants: a review. Food Chemistry, 2025, 466: 142086
44. Hamilton A N, Gibson K E. Efficacy of manufacturer recommendations for the control of *Salmonella Typhimurium* and *Listeria monocytogenes* in food ink capsules utilized in 3D food printing systems. Journal of Food Protection, 2023, 86(2): 100030
45. Neiers F, Alkan D, Amiri-Rigi A, et al. Food formulation: rheological and tribological determinants of oral processing and flavor perception. Food Research International, 2026, 228: 118377
46. Yang M, Chen K P, Qin Z, et al. Gel-based 3D food printing for dysphagia management: advances in personalized nutrition, texture control, and clinical translation. Gels, 2026, 12(4): 289
47. Raut S, Pawase P A, Khalid S, et al. Recent advances in 3D food printing: a critical review of emerging technologies, material innovations, and novel applications. Applied Food Research, 2026, 6(1): 101773
48. Qin Y X, Pillidge C, Harrison B, et al. Protein-rich soft foods for the elderly with swallowing difficulties: advances in formulation, characteristics, and digestibility. Annual Review of Food Science and Technology, 2026, 17: 209–232
49. Plaza-Diaz J, Herrera-Quintana L, Olivares-Arancibia J, et al. Personalized nutrition through the gut microbiome in metabolic syndrome and related comorbidities. Nutrients, 2026, 18(2): 290

50. Liu T, Zheng J H, Du J, et al. Food processing and nutrition strategies for improving the health of elderly people with dysphagia: a review of recent developments. Foods, 2024, 13(2): 215
51. Brummer J, Glasbrenner C, Hechenbichler Figueroa S, et al. Continuous glucose monitoring for automatic real-time assessment of eating events and nutrition: a scoping review. Frontiers in Nutrition, 2024, 10: 1308348
52. Wu Y, Ehlert B, Metwally A A, et al. Individual variations in glycemic responses to carbohydrates and underlying metabolic physiology. Nature Medicine, 2025, 31(7): 2232–2243
53. Zeevi D, Korem T, Zmora N, et al. Personalized nutrition by prediction of glycemic responses. Cell, 2015, 163(5): 1079–1094
54. Diacova T, Cifelli C J, Davis C D, et al. Best practices and considerations for conducting research on diet–gut microbiome interactions and their impact on health in adult populations: an umbrella review. Advances in Nutrition, 2025, 16(5): 100419
55. Giles H, Zannidi D, Clegg M E, et al. A systematic review of the factors affecting textural perception by older adults and their association with food choice and intake. Appetite, 2025, 214: 108202
56. Shimizu A, Fujishima I, Maeda K, et al. Texture-modified diets are associated with poor appetite in older adults who are admitted to a post-acute rehabilitation hospital. Journal of the American Medical Directors Association, 2021, 22(9): 1960–1965
57. Seol J, Kim J, Hong Y, et al. Toward intelligent 3D food printing: a review on the perspective of materials, fabrication, monitoring, and control. Critical Reviews in Food Science and Nutrition, 2026, 66(5): 1012–1043
58. Yellapantula S L, Dayananda B, Bhandari B, et al. Multicomponent 3D-printed dysphagia foods: integrating plant proteins, fats, and carbohydrates for nutritional and textural enhancement. Food Hydrocolloids, 2025, 168: 111525
59. Berciano S, Figueiredo J, Brisbois T D, et al. Precision nutrition: maintaining scientific integrity while realizing market potential. Frontiers in Nutrition, 2022, 9: 979665
60. Neamah H A, Tandio J. Towards the development of foods 3D printer: trends and technologies for foods printing. Heliyon, 2024, 10(13): e33882
61. Wu X Z, Oniani D, Shao Z J, et al. A scoping review of artificial intelligence for precision nutrition. Advances in Nutrition, 2025, 16(4): 100398
62. Meembidi R, Obaiah M C, Sasikala R, et al. Recent advances in 3D food printing: a review with focus on personalized nutrition and functional food applications. Food Technology and Biotechnology, 2025, 63(4): 531
63. Chow C Y, Thybo C D, Sager V F, et al. Printability, stability and sensory properties of protein-enriched 3D-printed lemon mousse for personalised in-between meals. Food Hydrocolloids, 2021, 120: 106943
64. Tomić-Obrdalj H, Keser I, Ranilović J, et al. The use of herbs and spices in sodium-reduced meals enhances saltiness and is highly accepted by the elderly. Food Quality and Preference, 2023, 105: 104789
65. Barrios-Rodríguez Y F, Molina-Montero C, Matas-Gil A, et al. From rheology to reality: a decade of protein-based 3D food printing research. Food Engineering Reviews, 2026, 18(2): 8
66. Samota M K, Kaur M, Selvan S S, et al. Shaping the future of food: 3D-printed personalized nutrition and sustainable production pathways. Food and Humanity, 2025, 4: 100625
67. Carranza T, Guerrero P, De La Caba K, et al. Texture-modified soy protein foods: 3D printing design and red cabbage effect. Food Hydrocolloids, 2023, 145: 109141
68. Chao C, Lee J H, Kim I W, et al. Investigation of 3D-printable chickpea-mealworm protein mixtures and their bolus rheology: a soft-textured and safe-swallowing food for the elderly. Food Bioscience, 2023, 54: 102924
69. Abdollahi M, Nieuwland M, Van Bommel K, et al. Texture engineering of aquatic protein-based products via 3D food printing. Future Foods, 2025, 11: 100604
70. Hassan I, Gani A, Mudabir S. Development and characterization of 3D printed fish gelatin and vegetable blends as nutritious meal for dysphagic patients. Food Hydrocolloids, 2024, 157: 110478
71. Kong D M, Zhang M, Mujumdar A S, et al. Novel coaxial 3D printing for future foods: multi-material structuring for functional and sustainable resource innovation. Innovative Food Science & Emerging Technologies, 2025, 104: 104087
72. Molina-Montero C, Matas A, Igual M, et al. Influence of internal printing pattern and infill on morphological and dimensional properties of gluten-free bread manufactured by 3D printing. Future Foods, 2025, 12: 100715
73. Wu X J, Yousif L, Miles A, et al. Exploring meal provision and mealtime challenges for aged care residents consuming texture-modified diets: a mixed methods study. Geriatrics, 2022, 7(3): 67
74. Dick A, Bhandari B, Dong X P, et al. Feasibility study of hydrocolloid incorporated 3D printed pork as dysphagia food. Food Hydrocolloids, 2020, 107: 105940
75. Xing X B, Chitrakar B, Hati S, et al. Development of black fungus-based 3D printed foods as dysphagia diet: effect of gums incorporation. Food Hydrocolloids, 2022, 123: 107173
76. Zhu J C, Cheng Y, Ouyang Z Y, et al. 3D printing surimi enhanced by surface crosslinking based on dry-spraying transglutaminase, and its application in dysphagia diets. Food Hydrocolloids, 2023, 140: 108600
77. Liu Z B, Xing X B, Mo H Z, et al. 3D printed dysphagia diet designed from *Hypsizygus marmoreus* by-products with various polysaccharides. Journal of Food Engineering, 2023, 343: 111395
78. De Oliveira Sartori A G, Saliba A S M C, Bitencourt B S, et al. Anthocyanin bioaccessibility and anti-inflammatory activity of a grape-based 3D printed food for dysphagia. Innovative Food Science & Emerging Technologies, 2023, 84: 103289
79. Ekonomou S I, Hadnađev M, Gioxari A, et al. Advancing dysphagia-oriented multi-ingredient meal development:

optimising hydrocolloid incorporation in 3D printed nutritious meals. Food Hydrocolloids, 2024, 147: 109300
80. Qiu L Q, Zhang M, Adhikari B, et al. Preparation and characterization of 3D printed texture-modified food for the elderly using mung bean protein, rose powder, and flaxseed gum. Journal of Food Engineering, 2024, 361: 111750
81. Zhu Y L, Chen L, Zhang X F, et al. 3D-printed pea protein–based dysphagia diet affected by different hydrocolloids. Food and Bioprocess Technology, 2024, 17(6): 1492–1506
82. Han Q S, Sheng G H, Bai H M, et al. Development of 3D-printed pea protein-based vitamin D3 carrier emulsion gel system with high stability and its optimization. Food Hydrocolloids, 2026, 172: 112052
83. Zhao P Y, Kou D L, Qiu R K, et al. Development of soy protein emulsion gels-based 3D printed dysphagia foods: effects of the egg white protein supplementation. Food Hydrocolloids, 2025, 160: 110737
84. Dong Y B, Dai J M, Han J J, et al. Dysphagia foods: current research, technological innovations, and future directions. Trends in Food Science & Technology, 2025, 165: 105330
85. Chu Y H, Chao J C J. Effectiveness of diet modification on dietary nutrient intake, aspiration, and fluid intake for adults with dysphagia: a meta-analysis of randomized controlled trials. The Journal of Nutrition, Health and Aging, 2025, 29(4): 100486
86. Naudé A, Kanji A. Ethical challenges and considerations in dysphagia management: a scoping review. International Journal of Language & Communication Disorders, 2026, 61(2): e70214
87. De Lichtenberg Broge E H, Wendin K, Bredie W L P. Adapting dysphagia meals for acceptance among a broader group of older adults. Journal of Sensory Studies, 2024, 39(1): e12894
88. Ascrizzi G I, Martini D, Piazza L. Nutritional quality of dysphagia-oriented products sold on the Italian market. Frontiers in Nutrition, 2024, 11: 1425878
89. Qiu F H, Shao J H, Wei Y X, et al. Decoding consumer food preferences via electroencephalography (EEG): neurophysiological mechanisms of sensory perception and therapeutic potential. Trends in Food Science & Technology, 2026, 167: 105434
90. Lim M, Park S, Lee Y, et al. Brain responses and connectivity to visual meal compositions: an EEG investigation into food liking. Food Quality and Preference, 2023, 112: 105029
91. Akshath Raj V, Nayak S G, Thalengala A. A hybrid framework for muscle artifact removal in EEG: combining variational mode decomposition, stationary wavelet transform, and canonical correlation analysis. Cogent Engineering, 2025, 12(1): 2514941
92. Torrico D D, Mehta A, Borssato A B. New methods to assess sensory responses: a brief review of innovative techniques in sensory evaluation. Current Opinion in Food Science, 2023, 49: 100978
93. Stickel L, Grunert K G, Lähteenmäki L. Implicit and explicit liking of a snack with health- versus taste-related information. Food Quality and Preference, 2025, 122: 105293
94. Kechri K, Kleisiari C, Kyrgiakos L S, et al. Emerging technologies for investigating food consumer behavior: a systematic review. Comprehensive Reviews in Food Science and Food Safety, 2025, 24(6): e70340
95. Fu Y, Wang C, He G L, et al. Neurophysiological and multimodal sensory evaluation of baijiu and food pairing liking. Food Research International, 2025, 221: 117451
96. Haag L, Starke G, Ploner M, et al. Ethical gaps in closed-loop neurotechnology: a scoping review. npj Digital Medicine, 2025, 8(1): 510
97. Low J Y Q, Antlej K, Garvey E C, et al. Recreating digital context: navigating the future of food sensory studies through recent advances and applications. Current Opinion in Food Science, 2024, 57: 101176
98. Chaffee O, Ross C F. Older adults' acceptance of ready-to-eat meals in relation to food choice and sensory ability. Journal of Food Science, 2023, 88(6): 2611–2628
99. Agrawal K, Goktas P, Kumar N, et al. Artificial intelligence in personalized nutrition and food manufacturing: a comprehensive review of methods, applications, and future directions. Frontiers in Nutrition, 2025, 12: 1636980
100. Martinho A, Ordovas J M, Daniel H, et al. Ethics and data in precision nutrition: a roadmap for responsible innovation. The Journal of Nutrition, 2026, 156(6): 101547
101. Briassoulis G, Briassouli E. AI-enabled precision nutrition in the ICU: a narrative review and implementation roadmap. Nutrients, 2025, 18(1): 110
102. Xiao S L, Yang J H, Bi Y, et al. Food 3D printing equipment and innovation: precision meets edibility. Foods, 2025, 14(12): 2066
103. Bahman M, Sandler N, Viitala T. Integration of process analytical and quality control technologies in semi-solid extrusion printing workflows. Journal of Drug Delivery Science and Technology, 2026, 122: 108401
104. Tan C, Toh W Y, Wong G, et al. Extrusion-based 3D food printing – Materials and machines. International Journal of Bioprinting, 2018, 4(2): 143
105. Lee A Y, Pant A, Pojchanun K, et al. Three-dimensional printing of food foams stabilized by hydrocolloids for hydration in dysphagia. International Journal of Bioprinting, 2021, 7(4): 393
106. Phuhongsung P, Zhang M, Devahastin S, et al. Defects in 3D/4D food printing and their possible solutions: a comprehensive review. Comprehensive Reviews in Food Science and Food Safety, 2022, 21(4): 3455–3479
107. Demei K, Zhang M, Phuhongsung P, et al. 3D food printing: controlling characteristics and improving technological effect during food processing. Food Research International, 2022, 156: 111120
108. Zhu W X, Iskandar M M, Baeghbali V, et al. Three-dimensional printing of foods: a critical review of the present state in healthcare applications, and potential risks and benefits. Foods, 2023, 12(17): 3287
109. Chirico Scheele S, Binks M, Christopher G, et al. Printability, texture, and sensory trade-offs for 3D printed potato with added

proteins and lipids. Journal of Food Engineering, 2023, 351: 111517

110. Islam M S, Shamim S U, Mazumder S, et al. Analyzing 3D food printing research trends, future directions, and feasibility in Bangladesh. Applied Food Research, 2026, 6(1): 101630
111. Nikolaou E N, Apostolidis E, Nikolidaki E K, et al. The development and optimization of extrusion-based 3D food printing inks using composite starch gels enriched with various proteins and hydrocolloids. Gels, 2025, 11(8): 574
112. Donovan S M, Abrahams M, Anthony J C, et al. Perspective: challenges for personalized nutrition in the current United States regulatory framework and future opportunities. Advances in Nutrition, 2025, 16(3): 100382
113. Zhang J, Li C F. Food safety and its digital traceability strategies: a supplier-processor profit distribution perspective. Frontiers in Sustainable Food Systems, 2025, 9: 1707114
114. Ritota M, Melloni S, Cianfrini G, et al. Recent advances in inks for 3D food printing: a review. Applied Sciences, 2025, 15(22): 11891
115. Pérez-Monterroza E J, Chaux-Gutiérrez A M, De Moura M R, et al. Fundamentals and functional applications of 3D and 4D printing in food manufacturing. Processes, 2025, 13(12): 4043
116. Abedini A, Hosseini H, Shariatifar N, et al. Studying the impact of 3D printing technology on safety indicators of plant-based burger. Food Chemistry: X, 2024, 22: 101489
117. Shao J G, Zheng Z P, Hu J M, et al. 3D-printed foods for dysphagia: a bibliometric review. Foods, 2025, 14(12): 2058
118. Cunningham N, Adeyanju A A, Adebo O A. Intention to consume 3D-printed food: perspectives across generational divides. Frontiers in Nutrition, 2026, 13: 1731967
119. Bisht A, Hussain M, Abdi G. Impact of 3D food printing techniques on waste reduction and personalized nutrition in the digital age: a review. Applied Food Research, 2026, 6(1): 101867
120. Soni R, Bhandarkar V V, K P, et al. Data-driven rheological analysis and process optimization of food inks for additive manufacturing. Rapid Prototyping Journal, 2026, 1–25