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Plant-based food inks and extrusion 3D printing for personalized nutrition

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Abstract

Plant-based food inks are formulations of edible biomaterials derived from plants for printing customized three-dimensional (3D) foods or meals. Extrusion-based 3D food printing has emerged as a promising technique for producing digitally designed meals with tailored geometry, texture, and nutritional composition. These printed structures hold significant potential for personalized nutrition by enabling the development of foods aligned with individual dietary needs, metabolic responses, and sensory preferences. Successful printing and downstream dietary applications depend critically on the functional properties of food inks, including rheological behavior, printability, mechanical stability, and compatibility with nutrient or bioactive incorporation, as well as the selection of printing parameters. This review synthesizes the latest developments in plant-based ingredients and food-grade materials suitable for 3D printing, with emphasis on protein isolates, hydrocolloids, fibers, lipids, and fruit- and vegetable-derived matrices. It further examines advances in 3D food printing technologies and their capacity for customization across shape, texture, and spatial nutrient distribution. The integration of artificial intelligence (AI)-based health monitoring is discussed as an emerging framework for real-time dietary adjustment, leveraging biosensors and predictive algorithms to support precision nutrition. Key consumer, safety, cybersecurity, and regulatory considerations are evaluated to contextualize the broader adoption of AI-guided, 3D-printed personalized meals. Finally, major challenges and future research directions are identified, including the development of next-generation printable materials, the creation of closed-loop AI–printer–sensor platforms, clinical validation for chronic disease management, and strategies to improve sustainability and scalability.

Keywords: 3D printing; Personalized nutrition; Plant-based food; Artificial intelligence monitoring

1. Introduction

Precision nutrition refers to tailoring dietary intake to an individual's unique biological and lifestyle characteristics, including genetics, sex, race, health history, environmental exposures, and daily behaviors, to optimize health outcomes. This approach is supported by evidence demonstrating substantial inter-individual variability in physiological responses to the same foods, indicating that the optimal diet for one person may differ markedly from that for another. Advances in data science, multi-omics profiling, wearable sensors, and digital health technologies have accelerated the evolution of personalized nutrition from a conceptual framework to a practical, evidence-based discipline. Large-scale initiatives, such as the Nutrition for Precision Health program of the United States National Institutes of Health, aim to develop predictive algorithms that forecast individual responses to foods and dietary patterns, possibly addressing limitations of traditional "one-size-fits-all" dietary guidelines.[1-3] Collectively, these initiatives position diet as a dynamic, adaptive intervention shaped by biology, behavior, environment, and the microbiome.

In parallel, advances in food manufacturing have established three-dimensional (3D) food printing as a transformative technology capable of producing customized, digitally designed edible structures through layer-by-layer deposition. Compared with conventional food processing, extrusion-based 3D food printing offers fine control over geometry, texture, and spatial nutrient distribution.[4-6] Successful fabrication requires food inks that exhibit favorable rheological properties, such as shear-thinning behavior during extrusion and rapid structural recovery after deposition, as well as sufficient crosslinking capacity and mechanical stability to maintain the intended 3D structure.[7,8] Research has shown that the addition of cane sugar (sucrose) can significantly influence the printability of milk-solids-based food inks designed for snack production,[9] and that bioactive compounds such as micro- and nano-encapsulated omega-3 fatty acids can be potentially incorporated into food formulations to enhance encapsulation stability and enable targeted delivery within structured food systems.[10] Additionally, integrating regionally sourced plant-based ingredients enhances sustainability and supply resilience by leveraging local pulses, grains, and oilseeds; for example, Canadian Prairie crops such as lentils, chickpeas, canola, oats, and flaxseed offer abundant raw materials for nutrient-dense formulations.[11-17]

A promising next step in advancing personalized nutrition is the integration of 3D food printing with artificial intelligence (AI)-driven, closed-loop health monitoring systems. Although 3D printing enables fabrication of customized meals using food-grade ingredients, including milk powders, wheat bran, plant proteins, and composite blends, progress is constrained by the need for edible inks that are both nutritionally meaningful and mechanically suitable for extrusion. Precision nutrition provides a conceptual framework for matching printed formulations to the needs of specific populations, including children, older adults, military personnel, clinical patients, and Indigenous communities. When combined with bioinformatic sensors that continuously track physiological metrics, 3D-printed meals can be dynamically adjusted in real time. For example, continuous glucose monitoring (CGM) integrated with AI algorithms enhances glycemic control in hybrid closed-loop systems, illustrating the potential of data-driven dietary adjustments for individuals at risk of dysglycemia.[18-20] This closed-loop paradigm enables optimization of nutritional content, personalization of texture or functional ingredients, and incorporation of therapeutic compounds to support metabolic stability, recovery, and long-term health.

Together, these developments create an opportunity to rethink future food systems through the integration of plant-based ingredient science, 3D food printing technologies, and AI-enabled health monitoring, as illustrated in Figure 1. This review examines recent advances across the key components of emerging food systems, focusing on plant-based ingredients and food-grade materials for 3D printing, progress in 3D food printing technologies, and AI-based health monitoring for real-time dietary personalization. Consumer perception, food safety, cybersecurity, and regulatory considerations are discussed, and major challenges and knowledge gaps are identified, alongside recommendations for future research.

2. Potential of plant-based ingredients for the development of food inks for 3D printing

Plant-based ingredients form the foundation of many 3D-printable food inks because they provide nutritional density, sustainability advantages, and functional

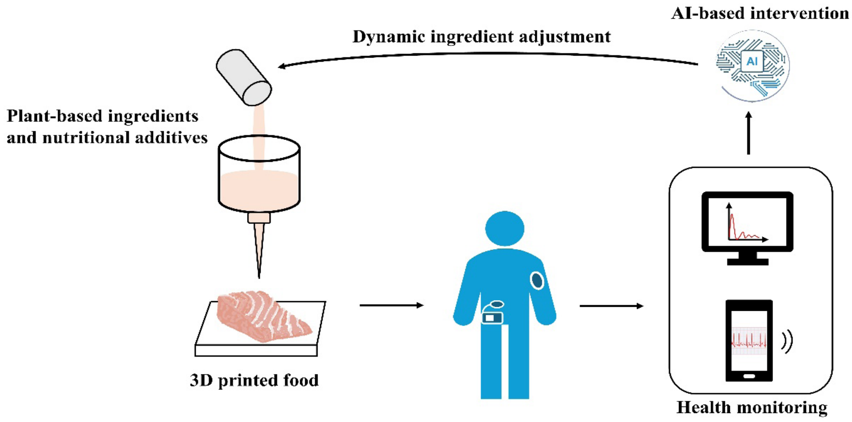

Figure 1. Schematic of future food systems to deliver meals that are personalized and adaptive to individuals' evolving needs
Abbreviation: AI: Artificial intelligence.

versatility essential for extrusion-based fabrication. Legumes, cereals, and other botanical materials provide high-quality proteins, fibers, vitamins, minerals, and phytochemicals while generating lower environmental impacts compared with animal-derived ingredients. Their wide compositional diversity enables precise tuning of rheology and texture, allowing food systems to be customized to the needs of children, older adults, patients with dysphagia, and other specialized populations. Prior studies have demonstrated that plant proteins, including soy, pea, chickpea, and faba bean, and cereal flours such as wheat and rye, can be engineered into inks that combine good printability, structural stability, and sensory acceptability.[21,22] Furthermore, plant-based matrices serve as effective carriers for probiotics, antioxidants, phenolics, and other bioactives, creating opportunities for personalized nutrition and targeted health benefits within digitally fabricated foods.

2.1. Plant-based protein

Plant proteins are among the most important building blocks for 3D food printing because they contribute directly to structural formation, rheological behavior, and nutritional value. Chickpea protein and chickpea–oat blends have been identified as promising materials for dysphagia-appropriate 3D-printed meat analogs,[14] demonstrating that these protein systems exhibit shear-thinning viscosity and dominant elastic behavior, both of which are critical for extrusion and layer stacking. Beetroot powder enhanced color, texture, and network strength, and formulations containing 1.5–3.0% beetroot successfully achieved a Level 5 (minced & moist) classification based on the International Dysphagia Diet Standardization Initiative (IDDSI) framework while retaining structural integrity after cooking.[14] These findings confirm that chickpea-based protein systems are viable for soft, cohesive meals required in clinical dietary contexts, although comprehensive sensory analyses remain essential to improve palatability and consumer acceptance.

Cereal-based proteins also show strong potential for 3D-printed foods due to their diverse functional behaviors. A recent investigation of wheat-, rye-, and soy-based doughs found that each flour type imparts distinct rheological and sensory properties; soy produced firmer, grainier structures, whereas wheat and rye yielded softer, moister textures.[22] Apple purée softened the dough slightly but did not compromise print fidelity. Consumer preference favored wheat-based products, followed by rye and soy, affirming the sensory advantages of cereal–protein combinations. Importantly, principal component analysis revealed predictable relationships between instrumental dough texture and sensory attributes, suggesting opportunities to design plant-protein formulations informed by quantitative rheological data. These insights are highly relevant for developing printable foods that meet both functional and sensory expectations.

Beyond their contribution to mechanical strength and printability, plant-based protein networks also play an important role in regulating nutrient and bioactive release in printed foods. Protein gel density, crosslinking extent, and interaction with polysaccharides influence water mobility and diffusion pathways within printed structures. When coupled with controlled printing parameters, such as filament diameter and infill spacing, these protein-rich matrices can function as semi-permeable diffusion barriers, enabling the gradual release of encapsulated nutrients, antioxidants, or probiotics during digestion. This multifunctionality positions plant proteins not only as structural building blocks but also as active carriers for targeted nutritional delivery in extrusion-based 3D printing.

2.2. Flaxseed gum and protein

Flaxseed-derived hydrocolloids and proteins are valuable for 3D printing because they provide viscosity modification, gel formation, and nutrient retention while remaining compatible with plant-based nutritional goals. It has been demonstrated that adding flaxseed gum (0.3–1.2%) to mung-bean-protein–rose-powder systems produced inks with stable, self-supporting structures that maintained shape after deposition.[15] The most effective formulation (0.9% flaxseed gum) met IDDSI Level 4 (pureed/extremely thick) requirements and enhanced phenolic retention during *in vitro* digestion. Higher levels of flaxseed gum (1.5%) caused microphase separation, indicating that hydrocolloid–protein interactions must be carefully balanced to avoid structural defects.

The role of flaxseed protein extends beyond thickening and stabilization, as it can also improve swallowability and nutritional density in pediatric applications. It was reported that incorporating 5% flaxseed protein into corn-based inks reduced stickiness and extrusion force while maintaining precise structural resolution, making the resulting foods suitable for toddlers who require safe, soft textures with appealing shapes.[16] However, increasing flaxseed protein above this level compromised structure, illustrating the importance of optimizing protein concentration for 3D-printed foods designed for specific age groups.

Further work expanded the functional capabilities of flaxseed-based gels by integrating lycopene and demonstrating controlled nutrient release during digestion.[17] The flaxseed-gum–myofibrillar-protein system strengthened protein secondary structures, improved elasticity, and provided rapid recovery after deformation. These properties allowed the printed structures to maintain form under physiological conditions, support lycopene delivery in gastrointestinal simulations, and satisfy IDDSI Level 5 requirements. Collectively, these findings indicate that flaxseed-derived materials can facilitate both structural and nutritional objectives within personalized printed diets.

2.3. Pea protein

Pea protein is widely used in 3D food printing because it reinforces gel networks, improves textural stability, and enhances protein content in plant-based formulations. When added to potato-starch matrices, pea protein increased cohesiveness, adhesiveness, and thermal stability, enabling printed structures with good resolution and minimal deformation during cooking.[23] These benefits arise from the protein's ability to participate in gelation and network formation under mild processing conditions.

More recent work highlights the importance of hydrocolloid interactions in pea-protein printing systems. It was observed that low concentrations of xanthan gum (0.05–0.3%) enhanced microstructural uniformity and mechanical strength, while higher concentrations promoted phase separation.[24] Formulations containing 0.3% xanthan gum met IDDSI Level 4 criteria and offered improved swallowing comfort, supporting their suitability for dysphagia-focused applications. Complementary results demonstrated that xanthan gum reduced viscosity and hardness in pea-protein gels, whereas locust bean gum and konjac gum increased both properties, leading to varied printability outcomes.[25] The formulation with 0.5% xanthan gum showed the best overall performance in print fidelity and sensory properties.

Alginate–pea protein systems further illustrate the structural versatility of pea protein. It has been demonstrated that increasing pea protein concentration increases enthalpy, storage modulus, and hardness, improving structural strength but also increasing the risk of residual stress accumulation during printing.[26] Layer-by-layer simulations confirmed that thicker constructs are more prone to deformation, highlighting the importance of process optimization for complex geometries.

2.4. Chickpea protein

Chickpea-based ingredients support the development of nutritionally enhanced, texturally cohesive, and print-stable food structures. A recent study demonstrated that adding 30–40% chickpea protein isolate (CPI) to corn-based gels improved adhesiveness, shape retention, and dimensional accuracy, enabling structures compliant with IDDSI Level 5 standards.[27] Gels containing 10–20% CPI remained too weak for stable printing, whereas those with 50% CPI were overly firm, reinforcing the need for balanced protein incorporation to achieve desirable textures for dysphagia-friendly applications.

Aquafaba, an increasingly popular chickpea-derived foaming agent, offers additional structural benefits. Aquafaba–water formulations (ratios of 1:2 and 1:2.5) have demonstrated foaming capacity, moisture retention, and shape stability comparable to egg whites after printing and baking.[28] These findings underscore aquafaba's relevance for vegan or allergen-free 3D-printed foods requiring aerated or soft textures without the use of animal products.

2.5. Faba bean protein

Faba bean protein has strong potential for 3D-printed seafood analogs and other structured foods due to its gelation properties and light color. It was demonstrated that faba bean protein crosslinked with transglutaminase yielded printed prawn analogs with cutting strengths comparable to real prawn tissue.[29] Curdlan-based gels offered better storage stability but weaker texturization. Increasing xanthan gum concentration impaired extrusion and reduced digestibility, indicating that hydrocolloid–protein ratios must be carefully managed.

Another recent study evaluated protein-, starch-, and fiber-rich fractions derived from faba beans, showing that low loss tangent values improved shape stability, while microstructural heterogeneity influenced the internal softness of freeze-dried printed structures.[30] These findings emphasize the importance of ingredient fractionation and structural characterization for designing faba-bean-based inks with predictable printability and texture.

Across pulse- and flaxseed-based protein systems, the capacity to simultaneously tailor texture and nutrient delivery emerges as a shared functional advantage. Moderate protein and hydrocolloid concentrations generate cohesive viscoelastic networks that stabilize printed geometries while maintaining sufficient porosity for controlled diffusion during digestion. Excessively dense or over-crosslinked systems, however, may impede release kinetics or cause incomplete gastrointestinal breakdown. These findings highlight the need to co-optimize material formulation and internal geometry when designing printed foods intended for controlled nutrient or bioactive release, particularly in clinical or personalized nutrition applications.

2.6. Canola oil

Canola-derived components contribute to 3D printing through their effects on both edible gel systems and biodegradable packaging materials. It has been demonstrated that epoxidized canola oil is an effective compatibilizer for polylactic acid/Poly(butylene adipate-co-terephthalate) blends, reducing brittleness, enhancing impact resistance, and improving inter-strand fusion during material extrusion.[31] These findings illustrate how plant-derived oils can support sustainable manufacturing of printed components that accompany food, such as edible carriers or packaging.

In edible systems, canola oil influences the flow and gelation behavior of starch-based inks. It has been shown that adding canola oil reduces viscosity and hardness in wheat-starch gels, facilitating smoother extrusion and better shape retention.[32] The 4% oil formulation displayed particularly favorable storage modulus and printing stability. However, excessive canola oil disrupted amylose–amylopectin interactions and generated lamellar microstructures prone to collapse. These observations highlight that lipid-starch ratios must be carefully controlled to achieve both desirable textures and robust printability in oil-containing food inks.

2.7. Fruit- and vegetable-based ingredients

Fruit- and vegetable-derived matrices provide natural pigments, flavors, and antioxidants that enhance the nutritional and sensory appeal of 3D-printed foods, but their low structural strength often requires modification. It was demonstrated that fruit–vegetable smoothie blends could be printed with good fidelity and retain stable antioxidant properties during refrigerated storage, although microbial contamination must be carefully managed due to their high-water activity.[33]

Arbutus unedo (strawberry tree fruit) has been shown to offer high levels of polyphenols that are retained during 3D printing, though printing parameters strongly influence antioxidant preservation.[34] Similar work has reported that black goji berries contain abundant anthocyanins, polysaccharides, and carotenoids, producing intensely colored, nutrient-dense printed desserts.[35] Despite their promise, additional studies are needed to confirm their safety and suitability for widespread clinical or commercial applications.

2.8. Comparative nutritional functionality of plant-based ingredients in 3D printing

Plant-derived ingredients contribute significantly to the nutritional functionality of 3D-printed foods. Extrusion 3D food printing provides a platform for jointly leveraging plant-based protein formulations and digitally controlled structures to tailor nutritional functionality. When the plant-based proteins discussed above are examined under comparable extrusion printing conditions, such as similar solids content, needle diameters, and printing parameters, distinct differences emerge in network formation, digestion behavior, and the ability to protect encapsulated nutrients. These differences demonstrate that protein source selection is a critical design variable for functional food printing, extending beyond considerations of printability alone.

Legume-derived proteins, particularly those from pea, chickpea, and faba bean, consistently form elastic and shear-recoverable networks under extrusion-printing conditions, enabling stable deposition and multilayer stacking. Among these systems, chickpea protein matrices typically exhibit the greatest resistance to enzymatic breakdown due to their dense and cohesive gel structures, resulting in delayed nutrient release during simulated gastrointestinal digestion.[14,27,28] Such characteristics are advantageous for applications requiring sustained protein availability or controlled nutrient absorption, including dysphagia diets and geriatric nutrition. Pea protein systems, by comparison, display moderate elasticity and greater sensitivity to formulation tuning, allowing nutrient release profiles to be modulated through adjustments in hydrocolloid content or printed architecture.[23,26] This tunability makes pea protein particularly suitable for personalized nutrition applications involving micronutrients, antioxidants, or probiotics. Faba bean protein systems occupy an intermediate position in terms of digestion resistance and network strength, especially when enzymatic crosslinking strategies are employed to reinforce gel integrity without inducing excessive rigidity.[29,30] Soy protein systems share some functional similarities with chickpea protein in forming dense, digestion-resistant matrices, though their strong thermal responsiveness necessitates careful control of processing conditions.[24] In contrast, cereal protein systems generally exhibit lower intrinsic resistance to digestion and rely heavily on starch gelatinization or blending with legume proteins to achieve comparable functional performance.[27]

Beyond formulation chemistry, extrusion-based 3D food printing enables deliberate control of nutrient release through digital design of internal structures. Infill density directly affects porosity and enzyme penetration, with high infill densities producing compact matrices that slow hydration and digestion, while low infill densities promote faster disintegration and nutrient availability.[29,30] Internal architecture further modulates nutrient bioaccessibility by altering surface-area-to-volume ratios and mechanical breakdown behavior during oral and gastric processing.[32,36-38] In addition, multilayer and compartmentalized designs enable spatial separation of ingredients, allowing sequential or delayed nutrient release that cannot be achieved through conventional mixing approaches.[4,33,34,38]

A representative example of this structure-mediated nutritional functionality is probiotic delivery using plant-protein-based 3D-printed matrices. Studies have shown that probiotics embedded within extrusion-printed protein–polysaccharide networks exhibit improved survival during simulated gastrointestinal digestion compared with non-structured systems.[36-38] In chickpea-protein-based constructs, dense outer layers act as protective barriers against gastric acidity, delaying probiotic release until intestinal conditions are reached. Similarly, pea protein-based matrices with controlled infill density allow gradual hydration and enzymatic exposure, reducing abrupt pH shock and preserving probiotic viability. These findings illustrate that protein chemistry governs microscale protection mechanisms, while printed geometry dictates macroscale release behavior, emphasizing the need to integrate material selection with digital structural design.

Collectively, the comparative evidence across plant-based protein systems indicates that no single protein is universally optimal for nutritionally functional 3D food printing. Instead, material selection must be aligned with the intended nutritional outcome, digestion profile, and architectural strategy, highlighting extrusion-based 3D printing as a shift from formulation-centric fortification toward digitally enabled nutritional engineering.

2.9. Challenges in developing plant-based food inks

Despite significant progress, formulating plant-based food inks remains challenging because sensory quality, rheological consistency, allergenicity, and regulatory requirements must be simultaneously addressed. Many legume-based formulations naturally produce beany, bitter, or grainy flavors and gritty or overly firm textures that reduce consumer acceptance. However, advances in deflavouring strategies during ingredient development are leading to more palatable ingredients. Achieving the rheological conditions needed for printing, such as high yield stress, shear-thinning behavior, and rapid post-shear recovery, may require hydrocolloids or proteins that inadvertently worsen mouthfeel. Allergenicity associated with soy, gluten, or nut-based ingredients complicates labeling and limits consumer reach. Microbial stability, retention of bioactive compounds, and regulatory approval for novel ingredients or structures require rigorous validation. As highlighted in the literature,[21,36,38] addressing these challenges requires integrated formulation strategies that reconcile printability with sensory, nutritional, and regulatory goals.

3. 3D printing foods and post-processing

3.1. Overview of 3D food printing technologies

Three-dimensional food printing is an additive manufacturing process in which edible materials are deposited layer by layer to form customized food structures with controlled geometry, texture, composition, and nutritional properties. The overall workflow is inherently iterative and described as a three-stage cycle comprising food design, printing, and evaluation, with continuous feedback among these stages enabling refinement of material formulations for ink development and printing parameters (Figure 2). This closed-loop progression distinguishes 3D food printing from conventional food processing, as each stage directly informs the next to achieve targeted sensory, structural, and nutritional outcomes.

The design stage is critical because it establishes the functional, sensory, and nutritional objectives that guide material selection and printing strategy. Unlike traditional food manufacturing, where product geometry is constrained by molds, extrusion dies, or thermal processing, 3D printing enables intentional and precise design of external appearance, internal structure, porosity, and spatial nutrient distribution. Food design is highly population-specific, reflecting differing nutritional and textural needs. For example, children may require visually appealing shapes with balanced nutrients; older adults and individuals with dysphagia may require IDDSI-compliant textures; military personnel may require shelf-stable, energy-dense foods; clinical patients may require controlled nutrient delivery or drug incorporation, such as glucagon-like peptide-1 (GLP-1) agonists for diabetes management; and indigenous communities may require formulations adapted from culturally preferred ingredients. These designs are typically created in computer-aided design software, which defines geometry, infill patterns, layer spacing, and material placement, serving as detailed blueprints for downstream fabrication.

Following the design, foods are fabricated using one of the additive manufacturing approaches capable of depositing edible materials with precision. Current methods include extrusion-based printing, selective laser sintering, binder jetting, and inkjet or material jetting. Among these, extrusion-based printing remains the predominant technique in food and other applications[7,39,40] due to its compatibility with a wide range of viscoelastic materials, including doughs, purées, gels, emulsions, and hydrocolloid-based systems, and its relatively low cost and operational simplicity. In extrusion printing systems, material is deposited through a needle or nozzle using one of three mechanisms: pneumatic-driven, piston-driven, or screw-driven extrusion (Figure 2). Pneumatic-driven systems use compressed air to dispense material and are widely adopted in printing research because they are simple to operate and easy to maintain.[39,40] In contrast, piston- and screw-driven systems deliver more consistent mechanical forces and permit finer control over flow rate, pressure, and deposition speed, making them well suited for high-precision, large-scale, or high-throughput production.[41-43] The quality of the printed structure depends heavily on printing parameters, including temperature, applied pressure, nozzle diameter, printing speed, and layer height. When these parameters are properly selected or optimized, extrusion-based systems can achieve high printability, shape fidelity, and structural stability across a diverse range of food-grade materials.

The evaluation stage examines whether printed foods, whether printed directly or after cooking and/or final processing, meet their intended functional, sensory, and nutritional specifications, providing essential feedback to improve both formulation and printing conditions. Texture evaluation focuses on dimensional accuracy, layer adhesion, porosity, mechanical strength, and post-printing stability, while sensory evaluation addresses visual appeal, mouthfeel, flavor, and overall acceptability. Nutritional evaluation assesses nutrient retention, compositional accuracy, and, when applicable, the effectiveness of personalized or targeted nutrient delivery. Findings from the evaluation stage often prompt reformulation of inks, adjustment of internal structures, or recalibration of printing parameters, reinforcing the iterative and adaptive nature of the 3D food printing process.

By integrating digital food design, advanced additive manufacturing techniques, and comprehensive evaluation, 3D food printing provides a powerful platform for producing personalized meals, texture-modified foods, and nutritionally targeted interventions. These capabilities make the technology particularly valuable for specialized populations, such as children, older adults, individuals with metabolic disorders, and those requiring modified textures for safe swallowing. More broadly, 3D food printing supports the development of highly customizable, sustainable, and digitally controlled food systems aligned with emerging trends in precision nutrition.

3.2. Food-grade ink development and properties important for 3D printing

The development of food-grade inks for 3D printing involves preparing edible materials with suitable rheological, structural, and functional characteristics. This typically requires combining plant-based proteins, hydrocolloids, lipid components, and fruit- or vegetable-based substrates to create an ink system capable of transitioning from a flowable state during printing to a self-supporting semi-solid or gel network after deposition. Plant proteins such as pea, chickpea, and faba-bean proteins contribute to network formation through heat-, pH-, or ion-induced gelation. Hydrocolloids, including flaxseed gum, xanthan gum, and carrageenan, play a central role in tuning viscosity, yield stress, and water mobility, enabling the successful printing of high-moisture matrices such as fruit purées with enhanced structural stability. Emulsion-based systems containing canola oil and protein–polysaccharide complexes further expand functionality by improving

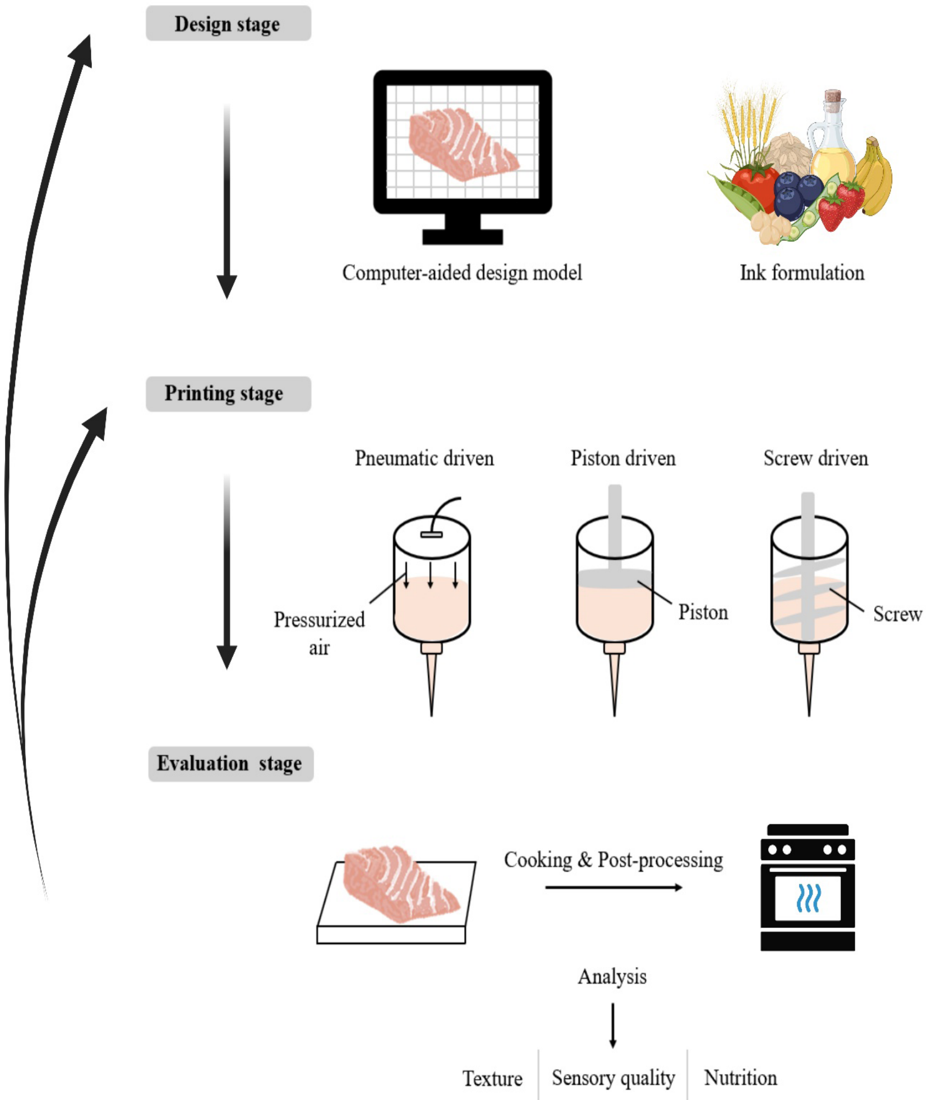

Figure 2. Schematic of the development of 3D printed foods with three key stages of food design, printing, and evaluation. Schematic created with BioRender. Chen, D. (2026) https://BioRender.com/87dv1jy

mouthfeel, modifying mechanical strength, and facilitating the creation of complex multilayered structures. Several functional requirements or properties have been identified as crucial for plant-based food inks, particularly those related to food texture, sensory quality, and nutrition.

3.2.1. Ink properties important for 3D printing

In extrusion-based 3D food printing, plant-based inks play an important role in forming food texture featured by its appearance, structural integrity, and mechanical behavior. This role is closely tied to the ink rheology, which dictates how well the ink extrudes, maintains shape fidelity, and supports multilayer deposition.[44,45] Ideal plant-based inks should exhibit shear-thinning behavior to enable smooth flow under pressure during extrusion, while rapidly recovering viscosity and elasticity after deposition to retain printed form. Microstructural interactions, such as protein–polysaccharide gelation, starch retrogradation, and lipid–protein interactions, govern firmness, elasticity, and overall textural performance of printed constructs.[7,46,47] Achieving an optimal balance of visual appearance, mechanical strength, and post-processing stability is critical for ensuring that the final product remains intact during handling, thermal treatment, storage, and consumption. Although many studies have characterized printability via rheology and observed printing performance, the term is used inconsistently; the operational consensus is that "printability" couples flow behavior, structural recovery, and dimensional fidelity validated on printed parts.[44,45]

Successful printing and subsequent consumption rely on the physical, rheological, crosslinking, and viscoelastic properties of the inks, which are important for 3D food printing, as summarized in Table 1.

Table 1. Material properties and guiding principles for 3D-printed food

Property category	Key parameters	Primary role in printing	Dominant design principle	Typical failure if not optimized
Physical properties	Surface tension; wettability (contact angle)	Filament formation and first-layer anchoring	Moderate surface tension and controlled wettability balance filament continuity and substrate adhesion[7,39,44,45]	Droplet formation, excessive spreading, poor first-layer adhesion
Rheological: Flow behavior	Apparent viscosity; shear-thinning index (n)	Extrudability and flow stability	Pronounced shear-thinning ($n < 1$) reduces extrusion force while allowing post-deposition recovery[7,44,48,49]	High extrusion force, filament breakage, nozzle clogging
Rheological: Yield stress	Yield stress (τ_0)	Resistance to gravity- and capillary-driven deformation	τ_0 must exceed gravitational stress yet remain low enough for continuous flow[7,50,51]	Filament sagging, wall collapse, spreading
Viscoelastic dominance	Storage modulus (G′); loss modulus (G″)	Shape fidelity and multilayer stability	Elastic dominance (G′ > G″ at low strain) supports dimensional accuracy[7,48,50]	Layer fusion, loss of height, poor fidelity
Viscoelastic recovery	Structural recovery rate after shear	Edge sharpness and layer definition	Rapid recovery of G′ after extrusion stabilizes geometry[7,50,52]	Rounded edges, filament merging
Crosslinking mechanisms	Ionic, thermal, enzymatic, composite	Transition from flowable ink to self-supporting structure	Gelation must occur post-extrusion and be synchronized with deposition[7,44,53]	Premature gelation (clogging) or delayed collapse
Crosslinking intensity	Network density; bond strength	Final mechanical and thermal stability	Moderate crosslink density balances stability and extrudability[14,29,53]	Brittle or overly rigid structures
Viscoelastic balance	Loss tangent (tan δ)	Stability–deformability balance	Low tan δ favors shape retention; excessively low tan δ hinders flow[7,50,51]	Collapse or poor extrusion
Printing–material coupling	Rheology–process matching (pressure, speed, nozzle diameter)	Process stability and dimensional accuracy	Printability emerges from matching ink properties to extrusion conditions[7,39,51]	Dimensional deviation, inconsistent strands
Overall printability metrics	Extrudability; filament fidelity; structural integrity	Quantitative printing performance	All three metrics must be satisfied simultaneously[50,51]	Qualitative prints with poor reproducibility

(a) Physical properties

Surface tension and wettability are important physical parameters governing the performance of food-grade inks in extrusion-based 3D printing. Surface tension, defined as the internal cohesive force acting along the ink's free surface, influences filament formation as material exits the nozzle. High surface tension may cause the ink to retract toward the nozzle tip or form droplets instead of continuous strands; however, once deposited, it can help a filament retain its profile and resist excessive spreading, thereby improving dimensional stability. Recent reviews on edible hydrogel-based inks emphasize that surface-energy-driven spreading behavior is a key determinant of first-layer fidelity and structural retention in 3D food printing systems.[7]

Wettability, as measured by the contact angle between the extruded filament and the print bed, is equally critical for establishing a stable first layer. A larger contact angle helps maintain vertical dimensional fidelity by reducing lateral spreading, whereas a smaller contact angle improves adhesion to the substrate, preventing slippage or deformation during subsequent layer-by-layer deposition. Studies on extrusion-based deposition illustrate that adhesion, spreading behavior, and surface interactions between the ink or material solution and the printing substrate are essential factors governing first-layer stability and overall geometric accuracy.[39,54-58] As illustrated in Figure 3A, strands printed at different contact angles result in distinct first-layer geometries. A larger contact angle promotes height retention, while a smaller angle enhances substrate anchoring and helps preserve structural integrity throughout the printing process.

(b) Rheological properties

The rheological or flow behavior of a food-grade ink used in extrusion-based 3D food printing is a central determinant of food texture. Flow behavior describes the resistance of the ink to deformation under shear, typically characterized through the relationship between shear stress and shear rate (Figure 3B), where their ratio defines the apparent viscosity. Viscosity governs how readily an ink flows through the nozzle during deposition and how effectively it stabilizes in place afterward. In food printing systems, rheological properties are strongly influenced by ingredient concentration (such as protein, starch, or hydrocolloid levels), particulate density, temperature, and formulation techniques, paralleling findings reported across hydrogel-based edible inks in extrusion food-printing research.[48,59,60] As illustrated in **Figure 3B**, rheological behavior in 3D-printed dysphagia formulations is highly sensitive to compositional factors.[14] Increases in biopolymer concentration or particulate loading, such as the incorporation of oat protein or beetroot powder, consistently raise viscosity, elevate yield stress, and increase the force required for extrusion, while preserving the characteristic shear-thinning, pseudoplastic flow behavior essential for printability. These formulation-dependent shifts in flow properties underscore the importance of precisely controlling protein composition and particulate density when optimizing dysphagia-appropriate, extrusion-based food inks. Such effects have practical implications for selecting extrusion parameters, including pressure, speed, nozzle diameter, and processing temperature.

To mathematically describe flow behavior, several rheological models are commonly used in printing research. These include the power-law model, generalized power-law model, Carreau model, Ellis model, and Casson model,[39] all of which capture the non-Newtonian behavior typical of printable edible materials. Among these, the generalized power-law (Herschel–Bulkley) model is one of the most widely applied for extrusion-based food inks because it effectively represents yield-stress behavior and shear-dependent viscosity in protein-based, polysaccharide-based, and composite gel systems:

$$\tau = \tau_0 + K\dot{\gamma}^n \quad (1)$$

where τ is the shear stress, τ_0 the yield stress, K the consistency index ($Pa \cdot s^n$), and n the flow index. The material behaves like a solid when $\tau < \tau_0$, while for $\tau > \tau_0$ it flows and may exhibit shear-thinning when $n < 1$ or shear-thickening when $n > 1$. For Newtonian fluids, $\tau_0 = 0$ and $n = 1$. In food printing applications, K generally increases with concentration or reduced temperature, while n quantifies the rate of change in viscosity with shear. These parameter dependencies have been widely documented in studies of edible hydrogels and food-gel systems used for 3D printing.[48,59]

Flow behavior of food inks is commonly measured using rotational rheometers (cone-and-plate, parallel-plate, or cup-and-bob geometries), capillary rheometers, or oscillatory rheometry. These techniques assess apparent viscosity, yield stress, shear-thinning characteristics, thixotropy, and viscoelastic moduli. The measured flow behavior is then fitted by using the aforementioned models for flow behavior prediction and printing process modeling.[54-58] Rheological characterization is considered a prerequisite for evaluating printability in extrusion-based food printing and is consistently emphasized across reviews in the field.[48,59]

The rheology of a food ink strongly influences

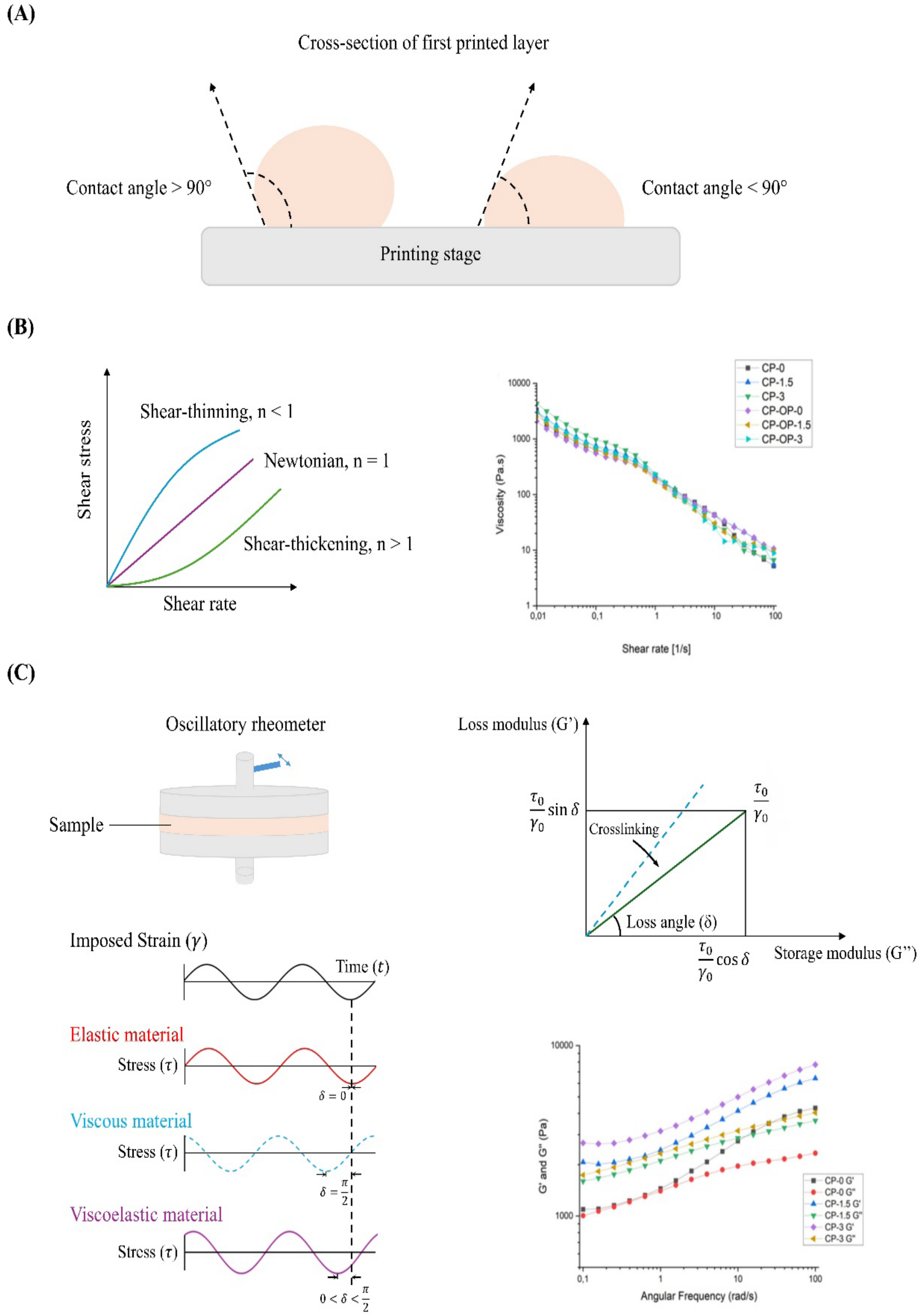

Figure 3. Important properties of food-grade inks for 3D printing. (A) Schematic of first-layer formation illustrating how surface tension and contact angle govern filament spreading and anchoring. (B) Representative flow curves depicting different flow behaviors, and example data demonstrating concentration-dependent changes in shear-rate behavior of chickpea protein (CP), oat protein (OP), and beetroot powder inks. (C) Oscillatory rheometry showing viscoelastic schematics for G', G'', tan δ, and a representative viscoelastic profile of chickpea protein (CP) and beetroot powder inks. Panels B and C reprinted with permission from Şentürk *et al.*[14] Copyright © 2025 Springer Nature.

extrudability, shape fidelity, and structural stability during the printing process. Higher viscosity generally enhances printability by reducing spreading and helping maintain filament geometry and layer stacking. High viscosity also stabilizes suspended particulates, such as plant proteins, fibers, or nutrient inclusions, preventing sedimentation during printing. However, inks with excessively high viscosity require greater extrusion pressure, which can compromise printing precision or damage heat-sensitive components such as emulsified droplets or bioactive particulates. Many reviews of 3D food printing consistently highlight this trade-off between structural fidelity and extrudability as a central challenge in ink formulations.[48,59]

Shear-thinning behavior, defined as a reduction in viscosity with increasing shear rate (Figure 3B), is widely recognized as a desirable characteristic in extrusion-based 3D food printing. Shear thinning facilitates smooth flow through the nozzle under high shear while enabling rapid viscosity recovery after deposition to preserve shape fidelity. The generalized power-law model captures this behavior via $n < 1$, with lower values indicating stronger shear thinning. Numerous studies report shear-thinning behavior as a key requirement for printable edible hydrogel and food-gel systems, as it enables stable line formation, sharp corners, and multilayer builds without slumping.[59]

(c) Crosslinking mechanisms

Crosslinking plays a critical role in enabling plant-based food inks to transition from a flowable, shear-thinning material inside the nozzle to a self-supporting structure after extrusion. The extent and mechanism of crosslinking determine key printability attributes, including yield stress, viscoelastic recovery, structural fidelity, and textural stability. Plant-derived polymers, including alginate, pectin, carrageenan, starch, cellulose derivatives, and protein–polysaccharide composites, form gel networks through physical or chemical pathways, each conferring different advantages for extrusion-based 3D food printing. Recent reviews of edible hydrogels and plant-based printing materials emphasize that understanding crosslinking principles is essential for engineering inks with robust structures and tunable nutritional profiles.[54-58] The main classes of crosslinking mechanisms relevant to food-grade inks are summarized below.

Ionic crosslinking is widely applied in 3D food printing because it enables rapid gelation under mild and food-safe conditions. Biopolymers such as alginate, pectin, gellan gum, and κ-carrageenan undergo network formation upon exposure to multivalent cations (e.g., Ca^{2+}, Mg^{2+}, K^{+}). In alginate systems, calcium ions bind to guluronic acid blocks to form the classical "egg-box" coordination structure, which quickly strengthens extruded strands after deposition. κ-carrageenan forms ion-mediated helical aggregates in the presence of potassium ions, yielding stable, thermoreversible gels with rapid setting behavior. These mechanisms are well characterized in hydrogel research and are important for foods that require immediate post-extrusion stabilization.[54]

Thermal crosslinking occurs when temperature-dependent transitions, such as gelatin helix formation, agar coil-to-helix transition, starch retrogradation, or protein denaturation, create stable network structures. Thermal gelation enables programmable solidification because materials can be extruded at temperatures where they remain flowable and then set upon cooling (or, for certain systems, heating). Gelatin-based inks extrude easily at warm temperatures but quickly form elastic gels upon cooling, while agar sets at lower temperatures yet retains structural integrity at room temperature. Reviews of food hydrogels highlight thermal gelation as a core mechanism for controlling the mechanical strength, textural properties, and sensory behavior of printed food structures.[44,45]

Enzymatic crosslinking provides a controlled, mild, and food-compatible mechanism for building covalent networks within plant-based inks. Enzymes such as transglutaminase catalyze bond formation between glutamine and lysine residues in protein matrices, increasing gel rigidity, water-holding capacity, and structural stability. This approach is particularly effective in pulse-protein, soy-protein, and cereal-protein systems used in 3D printing. Enzymatic crosslinking avoids thermal or chemical stresses that could degrade sensitive nutrients, flavors, or bioactive compounds. Reviews of hydrogel design note that enzyme-driven networks offer reproducible gelation kinetics and improve the fidelity of multilayer-printed constructs.[54-58]

Composite (multimodal) crosslinking integrates two or more gelation mechanisms, such as ionic plus hydrogen-bonding interactions, enzymatic plus thermal processes, or combinations of ionic and physical entanglement, to produce more robust and tunable food-grade gels. This strategy is particularly effective in cellulose-reinforced hydrogels, where cellulose's multi-hydroxyl structure enables hydrogen bonding and entanglement while also participating in secondary ionic or thermal interactions. Recent studies demonstrate that multimodal crosslinking enhances mechanical strength, reduces structural collapse, improves shape fidelity, and provides better control of swelling and shear-thinning behavior. These properties support the fabrication of complex, multilayer food structures and enable fine-tuning of texture, nutrient release, and post-processing behavior aligned with personalized nutrition needs.[54-58]

(d) Viscoelastic properties

Viscoelasticity is a fundamental dynamic property of food-grade inks, describing their simultaneous viscous and elastic responses to deformation. Viscous materials, such as water, resist shear flow when a stress is applied, whereas elastic materials deform under force and then return to their original state after the stress is removed. Plant-based 3D-printing inks exhibit viscoelastic properties (Table 2) as they transition from a flowable material within the nozzle to a self-supporting structure as crosslinking progresses.

Table 2. Viscoelastic properties of plant-based food inks, printability implications, and representative literature

Food ink type	Key viscoelastic characteristics	Printability implications	Representative literature
Pulse-protein inks (e.g., pea, lentil, chickpea)	Moderate to high *G*' depending on protein level/pH; strong shear-thinning driven by protein aggregation and protein–polysaccharide interactions	Good structural fidelity when elastic networks are sufficient; requires careful tuning to avoid brittleness and phase separation during multilayer builds	Overview of protein–polysaccharide systems[7]
Starch-based gels (e.g., corn, potato, wheat)	High *G*' after gelatinization; retrogradation increases *G*' over time; solid-like behavior at low frequency	High *G*' supports shape retention; shear flow tunable via amylose/amylopectin ratio or hydrocolloids; risk of premature gelation/nozzle clogging	Reviews on starch-gel printability[48,60]
Cellulose-reinforced hydrogels	High *G*' via hydrogen-bond networks and chain entanglement; pronounced shear-thinning; anisotropy with fibril alignment	Enhanced strength reduces collapse; stabilizes weaker protein/starch matrices; improved filament continuity at low solids	Composite cellulose-reinforced inks[61,62]
Emulsion-gel inks (protein–polysaccharide + oil)	Interfacial elasticity coupled with bulk gel structure; oil droplets act as active fillers to increase *G*' and alter relaxation	Tunable mouthfeel and viscoelastic damping; improved multilayer stability when droplets reinforce the matrix	Emulsion-gel reviews in food printing[59,60]

The viscoelastic behavior of plant-based food inks is most commonly characterized using oscillatory shear rheometry, a technique that probes how materials store and dissipate mechanical energy under deformation. In a typical test,[39] the sample is placed between two plates, with one plate applying a sinusoidal shear strain:

$$\gamma(t) = \gamma_0 \sin(\omega t) \tag{2}$$

while the resulting stress response is measured through the torque transmitted to the other plate. When operated within the linear viscoelastic region (LVR), the stress response is expressed as:

$$\tau(t) = \tau_0 \sin(\omega t + \delta) \tag{3}$$

where the phase angle (δ) identifies the purely elastic behavior if $\delta = 0$, purely viscous behavior if $\delta = \pi/2$, and viscoelastic behavior when $0 < \delta < \pi/2$. Decomposition of this stress signal yields the storage modulus *G*' (in-phase, elastic component) and the loss modulus *G*" (out-of-phase, viscous component), such that:

$$\tau(t) = \gamma_0 \left[G' \sin(\omega t) + G'' \cos(\omega t) \right] \tag{4}$$

Because *G*', *G*", and the loss angle depend on both frequency and strain amplitude, strain-sweep and frequency-sweep tests are routinely performed to map the LVR, assess structural resilience, and evaluate the relaxation behavior of the material. These measurements correspond to the schematics shown in Figure 3C (combined figure), illustrating the differences among viscous, elastic, and viscoelastic responses during oscillatory deformation.

In extrusion-based 3D food printing, viscoelastic properties directly affect printability and final product quality. A printable ink must exhibit low viscosity and reduced modulus under high shear to allow smooth extrusion, followed by rapid viscoelastic recovery after deposition so that the material transitions to an elastic-dominant state ($G' > G''$). This recovery preserves filament shape, prevents spreading, and supports stable multilayer assembly. The loss tangent, defined as:

$$\tan\delta = \frac{G''}{G'} \quad (5)$$

is particularly useful for assessing printing behavior: low values indicate strong structural fidelity with minimal deformation, while higher values indicate potential collapse or loss of shape during or after deposition.

Oscillatory rheometry is also essential for identifying crosslinking or gelation events, with the point at which G' surpasses G'' marking the gelation threshold. Determining this gel point is critical for materials that undergo thermal, ionic, or enzymatic gelation, including starch- and protein-based inks, because it defines the transition from fluid-like flow in the nozzle to solid-like stability after printing.

Viscoelastic behavior varies considerably across classes of plant-based food inks due to differences in polymer type, molecular interactions, and crosslinking mechanisms. Pulse-protein inks typically show moderate to high G' values and pronounced shear-thinning due to protein aggregation and protein–polysaccharide interactions, providing adequate filament stability but requiring careful tuning to prevent brittleness or phase separation during multilayer printing. Starch-based gels display strong elastic behavior after gelatinization, with G' increasing further during retrogradation, resulting in excellent shape fidelity but also potential risks of premature gelation inside the nozzle if temperature is not well controlled. Cellulose-reinforced hydrogels exhibit high mechanical strength arising from hydrogen-bond networks and chain entanglement, combined with strong shear-thinning and anisotropic viscoelasticity that help stabilize weaker protein- or starch-based matrices. Emulsion-gel inks, combining interfacial elasticity from dispersed oil droplets with bulk gel elasticity from biopolymers, offer tunable viscoelastic recovery and controlled damping during extrusion, making them suitable for personalized nutrition applications requiring precise textural and nutrient-release profiles.

Taken together, these variations indicate that printability is not governed equally by all rheological parameters, but is instead dominated by a small subset of primary variables that directly control extrusion behavior and post-deposition stability. Among these, yield stress (τ_0) and shear-thinning intensity (flow behavior index n) emerge as first-order determinants of extrudability, while elastic modulus (G') and structural recovery govern shape fidelity and multilayer stacking after deposition. The Herschel–Bulkley model provides a useful framework to link these parameters to printing outcomes, as τ_0 defines the minimum stress required to initiate flow, n quantifies the viscosity reduction under shear, and the consistency index K reflects resistance to deformation during extrusion.

Across extrusion-based food printing studies, successful printing is generally reported when yield stress exceeds the gravitational and capillary stresses acting on deposited filaments, yet remains low enough to permit continuous flow through the nozzle. Reported printable systems typically exhibit τ_0 values on the order of tens to a few hundred pascals, combined with pronounced shear-thinning behavior ($n < 1$), which reduces extrusion force without sacrificing filament stability. While shear-thinning is essential for smooth extrusion, it is insufficient on its own; printed structures with low elastic strength frequently collapse despite favorable flow behavior. Consequently, a dominant storage modulus ($G' > G''$ at low strains) is consistently associated with dimensional accuracy and the ability to sustain multilayer builds, whereas excessively high G' values impede extrusion and promote nozzle blockage.

Equally important, but often underemphasized, is viscoelastic recovery after shear cessation, which governs filament spreading, layer adhesion, and shape retention. Rapid recovery of G' following extrusion correlates with sharp filament edges and reduced dimensional deviation, whereas slow recovery results in sagging or fusion between adjacent strands. From a design perspective, extrusion-printable food inks therefore require a hierarchical balance: yield stress and shear-thinning behavior first ensure extrudability, elastic dominance subsequently ensures shape fidelity, and fast structural recovery stabilizes complex geometries. These criteria emerge consistently across rheology-focused evaluations of edible hydrogels and food gel systems and can be used as practical benchmarks for translating rheological measurements into predictive printability outcomes, rather than treating rheology as a purely descriptive property set.

In practice, systematic ink optimization is essential for successful extrusion-based 3D food printing and typically follows an iterative, design-oriented workflow. This process generally begins with compositional screening to establish printable concentration windows, ensuring that formulations are neither too dilute to maintain shape nor too concentrated to permit smooth extrusion. Subsequent rheological characterization is used to verify key properties governing printability, including shear-thinning behavior to reduce extrusion forces, adequate yield stress to limit filament collapse, and elastic dominance ($G' > G''$) to support dimensional stability after deposition. Formulations that meet these criteria are then subjected to extrusion testing, where extrudability, filament continuity, and line definition are evaluated under representative printing conditions. Finally, structural validation is performed on printed constructs before and after post-processing to assess shape fidelity, multilayer stacking, and resistance to deformation or collapse. Increasingly, printability acceptance is quantified using objective metrics rather than qualitative observation, with commonly reported criteria including dimensional deviation below 10%, consistent extrusion force profiles, and stable multilayer builds without significant spreading or sagging. Together, this workflow provides a practical bridge between rheological measurements and real printing performance, enabling more predictive and reproducible formulation development.

While empirical screening and rheology-guided tuning remain widely used, recent studies increasingly demonstrate the value of machine-learning approaches for accelerating ink-formulation optimization in extrusion-based food printing. In these frameworks, formulation variables (e.g., protein or hydrocolloid concentration, water content, particle size, crosslinker level), rheological descriptors (e.g., τ_0, n, G'/G'', viscoelastic recovery), and process parameters (e.g., pressure, nozzle diameter, speed) are treated as high-dimensional inputs to supervised learning models that predict printability outcomes such as filament continuity, dimensional deviation, extrusion force, and structural stability.[2,7,36,38] Reviews of gel-based edible inks also report that regression-based models, random forests, and neural networks can identify nonlinear interactions among formulation variables that are difficult to resolve through one-factor-at-a-time experimentation.[7,51,63]

Beyond static prediction, reinforcement learning and Bayesian optimization have been proposed to iteratively refine ink composition by minimizing print defects or extrusion energy while satisfying rheological and sensory constraints. In such systems, print quality metrics, including filament fidelity, multilayer collapse, or dimensional accuracy, serve as reward functions that guide adaptive formulation updates across successive print iterations.[2,64] These approaches are particularly relevant for plant-based inks, which exhibit batch-to-batch variability in protein functionality and hydration behavior. Machine-learning-assisted workflows, therefore, complement classical rheological screening by reducing experimental burden, expanding accessible formulation space, and enabling predictive optimization rather than empirical trial-and-error.

Importantly, machine-learning approaches for ink optimization do not replace rheology as a design foundation; rather, they leverage rheological measurements as structured features that anchor learning models in physical meaning. As such, combining rheology-based constraints with data-driven optimization represents a promising pathway toward scalable, reproducible, and application-specific food-ink design for extrusion-based 3D printing.

3.2.2. Other properties important for food-grade inks

In addition to the properties essential for 3D printing performance, food-grade inks must also satisfy other key requirements related to sensory quality and nutrition, much like traditional foods. Sensory quality, including flavor, aroma, mouthfeel, and overall palatability, is central to consumer acceptance of 3D-printed plant-based foods. The extrusion process can influence sensory attributes through shear-induced structural modification, moisture redistribution, and the thermal sensitivity of volatile flavor compounds.[52,65] Many plant proteins possess inherent off-flavors, bitterness, or beany notes; therefore, formulation strategies such as enzymatic modification, fermentation, or encapsulation are often needed to improve flavor profiles.[66] Mouthfeel is also strongly linked to rheology: smoothness, spreadability, cohesiveness, and the breakdown behavior of printed layers contribute to the eating experience, particularly for specialized applications such as dysphagia-friendly foods.[7,49] Optimizing sensory properties is therefore essential to ensure that personalized, 3D-printed nutrition solutions are not only tailored to individual dietary needs but also enjoyable and acceptable to consumers.

Nutrition is a major driver behind the development of plant-based food inks and personalized 3D food printing. The technology enables fine-tuned control over macronutrient composition, micronutrient density, and inclusion of functional bioactive compounds. Plant-based ingredients, including pea protein, soy protein, whole grains, and dietary fibers, provide a versatile foundation for nutritionally enhanced formulations designed for specific metabolic profiles, age groups, or health conditions.[67] Through layer-by-layer construction, 3D printing facilitates precise delivery of vitamins, minerals, probiotics, and phytochemicals with minimal nutrient degradation during fabrication.[65,67] This capability aligns with emerging precision-nutrition paradigms, enabling foods formulated to modulate glycemic response, support muscle maintenance, enhance gut health, or correct nutrient deficiencies. Thus, nutritional design serves as a cornerstone for advancing plant-based 3D printing toward functional, sustainable, and personalized food solutions.

3.3. Extrusion printing foods

Extrusion-based 3D food printing systems are designed to deposit continuous strands of food-grade inks to build 3D structures in a controlled, layer-by-layer manner. A typical system (Figure 4A) consists of a printing head, a three-axis positioning system, and a printing stage, all coordinated through computer-controlled motion. The positioning system moves the printing head along the X, Y, and Z axes, while the printing head extrudes the formulated food ink, loaded into a syringe or cartridge, through a nozzle onto the printing surface. Temperature control may be incorporated into the print head, cartridge, or stage to regulate the flowability and setting behavior of food materials, particularly those relying on thermal gelation or melting. Operational temperatures range from chilled conditions (≈10 °C) to highly heated environments (up to ≈200 °C), depending on formulation requirements. Nozzles may be cylindrical or tapered, typically with diameters from 0.1 mm to 2 mm; smaller nozzles generally yield higher-resolution strands. In food printing, the flow rate, ink rheology, crosslinking or setting mechanism, and the resulting structural characteristics are all central to successful printing performance.

3.3.1. Flow rate in extrusion food printing

During extrusion printing, the food ink is deposited as continuous strands whose dimensions and uniformity directly influence the accuracy and mechanical stability of the final printed structure. The flow rate (*Q*), i.e., the volumetric quantity of material extruded per unit time, is governed by process parameters (e.g., pressure, temperature), hardware characteristics (e.g., nozzle geometry and diameter), and the ink's rheological properties. Although empirical calibration is widely used, analytical models based on fluid mechanics provide systematic flow-rate predictions for non-Newtonian edible gels.

Many 3D food-printing hydrogels obey generalized power-law behavior, making models such as the Herschel–Bulkley equation particularly relevant. In pressure-driven (pneumatic) extrusion**,** applied pressure forces the ink through the nozzle. For inks following the generalized power-law model, the flow rate can be expressed as (**Equation 6**):[39]

$$Q=\frac{\pi R^3}{K^{\frac{1}{n}}\tau_w^{\,3}}\left(\tau_w-\tau_0\right)^{\frac{n+1}{n}}\left[\frac{n}{3n+1}\tau_w^{\,2}+\frac{2n^2}{(2n+1)(3n+1)}\tau_w\tau_0+\frac{2n^3}{(n+1)(2n+1)(3n+1)}\tau_0^{\,2}\right] \quad (6)$$

where τ_w is the shear stress at the nozzle wall and given by:

$$\tau_w=\frac{R\,\Delta P}{2L} \quad (7)$$

where *R* and *L* are the nozzle radius and length, and *ΔP* is the applied pressure. Since τ_w links directly to the ink's rheological parameters (yield stress τ_0, consistency index *K*, and flow index *n*), flow behavior can be modulated by adjusting pressure, nozzle geometry, or temperature. Tapered nozzles often yield higher flow rates at equivalent pressures due to reduced hydrodynamic resistance.

Mechanical extrusion systems, including screw-driven and piston-driven systems, provide greater control over flow rate than pneumatic systems. Screw systems combine drag-induced and pressure-induced flow components, whereas piston systems deliver nearly direct volumetric control (assuming incompressible inks), with flow models described in a previous study.[39] This precise control is advantageous for plant-based food inks whose rheological behavior may vary with composition or temperature. Flow-rate behavior is strongly tied to extrudability (Figure 4B), defined as the ability of an ink to form continuous, controllable filaments under specific printing conditions. Extrudability is widely acknowledged as one of the principal determinants of printability in extrusion-based food printing.[39,50]

3.3.2. Strand profile, printed structure, and printability

Once deposited onto the printing stage, the food ink is typically in a semi-liquid or gel-like state and may undergo spreading, sagging, or merging depending on its rheology and setting behavior. As illustrated in Figure 4C, the geometry of printed strands often deviates from the designed structure due to gravitational deformation, filament fusion at intersections, or insufficient mechanical strength in early layers.

The diameter (*D*) of an extruded strand can be approximated by:

$$D=\sqrt{\frac{4Q}{\pi V}} \quad (8)$$

where *Q* is the flow rate, and *V* is the nozzle movement speed. If *V* matches the "stress-free" speed, the printed filament diameter approximates the nozzle's internal diameter. Higher speeds stretch the filament, decreasing diameter and risking breakage, while lower speeds compress it, increasing diameter and risking buckling or surface irregularities.[39]

Because the printed material is initially deformable, printability is influenced not only by flow control but also by the ink's capacity to maintain shape, resist spreading, and form stable layers, as discussed previously. A widely cited framework identifies three core printability metrics:[50] (i) extrudability, the ability to extrude a continuous filament at controlled flow rates (Figure 4B), (ii) filament fidelity, agreement between printed filament geometry and nozzle geometry (Figure 4C), and (iii) structural integrity, the ability of stacked layers to maintain shape without collapse or excessive fusion (Figure 4C).

More specifically, extrudability refers to the ability of the food ink to be extruded through a nozzle to form a continuous and uniform filament under controlled printing conditions. Extrudability is typically evaluated by testing combinations of printing parameters, such as nozzle diameter, printing speed, and extrusion pressure, and analyzing the resulting strand dimensions and consistency. These tests determine whether the food ink can be reliably deposited without clogging, breaking, or spreading. Filament fidelity describes the extent to which the cross-section and shape of the extruded food filament resemble the nozzle opening. The cross-section of printed strands may vary across layers and positions due to gravitational effects, spreading, or deformation of the food material. Differences between the intended filament diameter and the printed diameter provide a quantitative measure of print fidelity. Higher filament fidelity reflects the food ink's ability to retain its shape immediately after extrusion. Structural integrity refers to the capability of the printed food structure to maintain its designed 3D shape after printing. Structural integrity is reduced when printed filaments fuse excessively at intersections, sag between layers, or collapse due to insufficient mechanical strength. This leads to deviations from the intended design, such as increased layer thickness, reduced overall height, or altered internal pore size. These metrics collectively define how well a material transitions from extrusion to structure formation during printing, providing a practical basis for evaluating the print performance of food-grade inks.

Because the printed material is initially deformable, printability depends not only on accurate flow control but also on how the ink behaves once deposited. At this stage, the influence of surface tension and wettability relates specifically to the process outcome, i.e., if first-layer adhesion is insufficient, filaments may drift or detach despite adequate ink formulation. In practice, this is managed by adjusting printing-surface energy, using edible primers, lightly roughened substrates, or supportive media to ensure consistent anchoring of the initial filament. Thus, in Section 3.3, surface tension and wettability function as process-level stability factors, rather than intrinsic material properties as discussed in Section 3.2.

Similarly, rheological properties, previously described in detail in Section 3.2, affect printing here by determining how steadily the filament flows and how precisely its dimensions can be controlled under dynamic extrusion conditions. During printing, shear-thinning behavior allows the ink to exit the nozzle smoothly, while rapid viscosity recovery prevents post-deposition spreading. Rather than redefining rheology, this section highlights its operational implications, including maintaining filament continuity, minimizing die swell or shrinkage, and ensuring synchronization between the extrusion rate and nozzle speed.

Finally, the solidification or setting mechanism influences printability here by dictating how quickly deposited strands gain mechanical strength to support subsequent layers. In contrast to Section 3.2, which explains the chemistry and physics of gelation, the focus in Section 3.3 is on timing and process integration, for example, coordinating cooling, heating, or ion-delivery conditions with deposition so that strands set neither too slowly (causing collapse or spreading) nor too rapidly (causing clogging or poor interlayer bonding). Optimal solidification, therefore, ensures stable build quality and helps achieve the intended macro-geometry of the printed structure.

3.4. Post-printing processing and structural stability

Post-printing processing constitutes a critical stage in extrusion-based 3D food printing, as subsequent thermal and physical treatments can substantially alter the structure, texture, and functional performance of printed constructs. Common post-processing operations, including steaming, baking, freezing, and refrigerated storage, interact strongly with the rheological state and crosslinking mechanisms established during printing. Consequently, printability cannot be evaluated solely at the point of deposition; instead, structural stability during post-processing must be considered an integral component of design and formulation strategies.[5,6,36,38,65]

Steaming and other thermal treatments are widely applied to set printed structures and enhance mechanical integrity, particularly in protein- and starch-based formulations. Printed inks exhibiting elastic dominance ($G' > G''$) and sufficient yield stress prior to printing generally demonstrate superior shape retention during steaming, while weakly structured systems often undergo filament fusion, layer spreading, or partial collapse.[14,24,25,53] Enzymatically crosslinked networks formed using transglutaminase, peroxidase, or related systems show

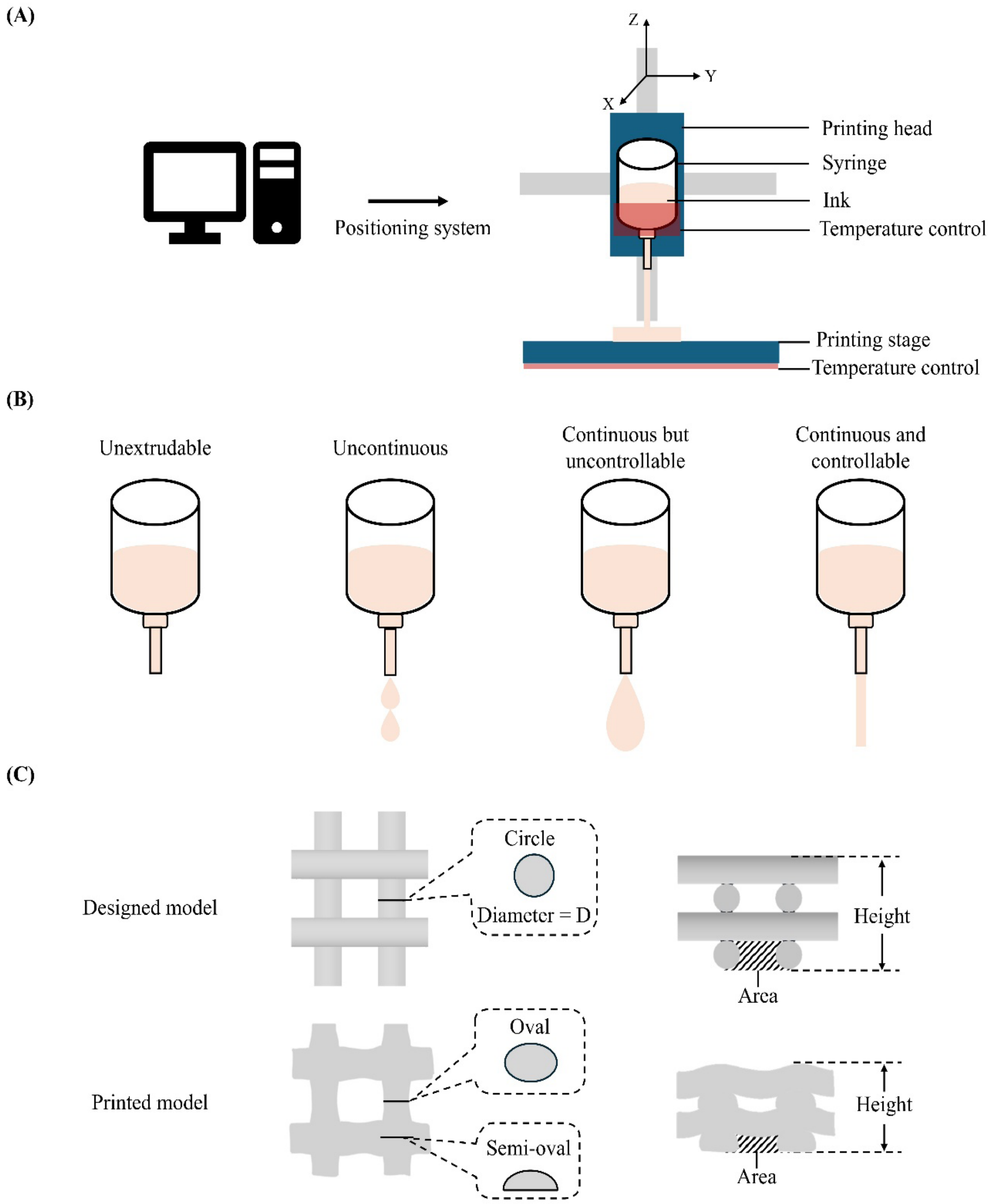

Figure 4. Extrusion food printing system and printability metrics. (A) System schematic. (B) Extrudability. (C) Difference in filament profile between designed and printed structures.

enhanced resistance to thermal deformation due to covalent network reinforcement, whereas physically crosslinked gels relying on hydrogen bonding or ionic interactions may soften or reorganize during heating, leading to dimensional shrinkage or texture loss.[29] Baking further introduces moisture gradients and surface dehydration, which can result in cracking, warping, or a heterogeneous texture when the initial water distribution and gel strength are not properly balanced.[5,32,36]

Freezing and frozen storage highlight additional stability challenges that are strongly governed by initial rheological design. Printed constructs with high free-water content and weak polymer–protein networks are particularly susceptible to ice-crystal-induced damage, resulting in syneresis, pore enlargement, and loss of cohesiveness upon thawing.[36,38] In contrast, inks with higher elastic modulus, finer microstructure, and stronger intermolecular interactions exhibit improved freeze–thaw stability. The incorporation of polysaccharides or composite gel networks can further immobilize water and restrict ice-crystal growth, although excessive addition may compromise print fidelity or sensory quality, underscoring the trade-offs between printability and storage stability.[22,36]

Moisture migration during post-printing storage plays a central role in long-term texture evolution, particularly for multilayer or infill-controlled structures. Printed foods with insufficient structural recovery or low yield stress may exhibit gradual layer sagging, compaction, or internal collapse as water redistributes under the combined effects of gravity and capillary forces. Conversely, overly rigid networks may impede moisture equilibration, leading to brittle outer layers and heterogeneous internal texture.[31,33,38] These phenomena demonstrate that both under- and over-structuring at the printing stage can negatively affect post-processing performance.

Collectively, post-printing outcomes, such as structural collapse, dimensional change, and texture evolution, are strongly governed by the initial rheological profile and crosslinking strategy of the ink. Formulations optimized for appropriate shear-thinning during extrusion, elastic dominance for shape retention, and tailored crosslinking for thermal or mechanical stabilization are more likely to maintain integrity across downstream processing steps.[7,14,36,38,53] Consequently, post-printing stability should be treated as a key design criterion in extrusion-based 3D food printing, reinforcing the need to integrate rheological characterization, printing performance, and post-processing behavior into a unified optimization and evaluation framework.

3.5. Current applications of 3D-printed foods

Three-dimensional food printing has been progressing rapidly from laboratory exploration to targeted, health-focused applications. Particularly strong advances have been achieved in dysphagia care, with growing momentum in personalized nutrition and plant-based meat analogues. Across recent clinical- and engineering-oriented studies, printable purées, gels, and restructured plant-based matrices have been tuned to reach IDDSI Levels 3–7 by controlling key extrusion parameters, such as nozzle diameter, print speed, temperature, and infill pattern, to modulate cohesiveness, adhesiveness, and shape fidelity. These findings demonstrate that clinically relevant textures can be reproducibly achieved within well-characterized process windows.[24,68-70]

Bibliometric and narrative syntheses show a sharp rise in dysphagia-oriented printable gels and a clear shift toward hydrocolloid- and plant-protein–rich formulations (e.g., xanthan, guar, pectin, alginate, carrageenan, starch; chickpea, oat, pea, soy) that deliver safe-swallowing rheology, cohesive strands, and appropriate bolus integrity.[24,69,70] In parallel, reviews emphasize nutrient-preservation strategies, minimizing thermal load and controlling pre-/post-processing, to mitigate losses of heat-sensitive vitamins and bioactives, particularly important for older adults and clinical populations requiring both texture safety and micronutrient adequacy.[65] Energy-assisted gelation (e.g., localized microwave or radio-frequency inputs during deposition) has been explored to adjust firmness on demand while maintaining post-printing stability.[71]

Mechanistic clarity is illustrated by detailed experiments on chickpea–oat matrices: chickpea and oat concentrates provide a favorable balance of water-holding capacity, digestibility, complementary amino acids, and stable extrusion behavior. For a 70:30 chickpea:oat ink with 0–3% beetroot, pseudoplastic flow ($n < 1$), elastic dominance ($G' > G''$), dimensional deviation of 6–8% (1.5 mm nozzle; 25 mm s^{-1}), and extrusion forces of 23–48 N were reported; after steaming, prints met IDDSI Level 5 by spoon-tilt, fork-drip, and fork-pressure tests.[14] These outcomes align with hydrogel science: hydrogen-bonded/ionic networks confer reversible, moist softness; enzymatic crosslinking (e.g., transglutaminase, laccase, peroxidase) yields elastic, meat-like textures under mild, food-safe conditions; and bigels/deep-eutectic–modified hydrogels enable concurrent structuring of hydrophilic and lipophilic phases to enhance cohesion, lubrication, and mouthfeel for swallow-safe bolus formation.[53] Notwithstanding this progress, reviews note barriers to high-volume clinical deployment, including slow print speeds, potential loss of nutritional quality, material instability during printing, material costs, and the need for Hazard Analysis Critical Control Point (HACCP)-aligned protocols (cleaning, traceability, allergen control) and further studies linking printed diets with nutritional status and long-term outcomes.[65,72-74]

Beyond dysphagia, a growing body of literature demonstrates that extrusion-based 3D food printing is being actively explored as a medical nutrition platform across several disease contexts. In diabetes and metabolic disorders, precision-nutrition studies increasingly recognize food structure and digestion kinetics as key determinants of postprandial glycemic response, providing a rationale for using digitally engineered food architectures alongside ingredient selection to modulate glucose release.[1,3,6] Parallel developments in geriatric nutrition highlight the promise of protein-enriched, texture-modified foods for addressing malnutrition and sarcopenia, where 3D printing enables high protein density to be delivered within soft, swallow-safe matrices without compromising acceptability.[6,14,15] In addition, functional- and encapsulation-focused studies indicate that 3D-printed protein–polysaccharide networks can act as carriers for nutraceuticals, probiotics, and therapeutic adjuncts, leveraging spatial control and matrix protection to improve stability and bioaccessibility during gastrointestinal digestion.[36-38] Emerging applications in oncology and gastrointestinal conditions further highlight the potential of 3D printing to decouple texture from nutritional composition, allowing energy-dense, immunonutrient-rich, or antioxidant-enriched foods to be formulated for patients with reduced appetite, mucosal sensitivity, or impaired digestion.[6,37,38] Collectively, these studies support the view that 3D food printing is evolving beyond dysphagia-specific texture modification toward a broader role in supporting home-based and hospital-based disease-oriented and personalized medical nutrition for different age and individual needs.

Three-dimensional printing further supports personalized nutrition by enabling per-serving control over macronutrients, micronutrients, fibers, and phytonutrients inside plant-based matrices, thus facilitating protein fortification for frailty, fiber enrichment for gut health, and mineral restriction for renal diets. Demonstrations using dual-nozzle extrusion have combined low-glycemic wheat bran and mushroom powders with milk powders to produce soft, IDDSI-characterized foods for diabetes and oral ulcer management. In streptozotocin-induced diabetic rat models, such printed foods produced lower postprandial glucose peaks than equal-mass cooked rice, indicating that engineered texture can coexist with glycemic benefits.[75] These finds align with printability-centric reviews that codify rheology-led design, shear-thinning, yield-stress windows, G'/G'' dominance and recovery, and dimensional-deviation thresholds, into quantitative criteria for reliable extrusion in clinical and consumer settings.[51]

Plant-based meat analogues represent another expanding domain in which geometric control and hydrogel-based structuring support the creation of muscle-like architectures with tailored chew and juiciness. Legume–cereal combinations such as chickpea–oat can deliver printable viscoelasticity, stable shape retention, and robust post-processing integrity, yielding analogues (e.g., "chicken thigh," "turkey breast," "sausage," "steak") that retain geometry after steaming and can be adapted for dysphagia-relevant textures when needed.[14] Recent reviews confirm that extrusion remains the predominant modality while also noting its practical limitations (throughput, cleaning, shelf life). Multi-nozzle and rapid-setting strategies are being explored to improve layering complexity and throughput.[4,44] From a formulation perspective, crosslinking and interpenetrating networks allow developers to tune water management, gel strength, elasticity, and bite, extending 3D printing from dysphagia applications into fully reconstructed plant-based meats that combine sensory appeal with nutritional intent.[53]

A consolidated overview of these applications is presented in Table 3, which summarizes the representative formulations, key ingredients, structuring agents, and characteristic printability or texture outcomes reported in the literature. Together, the entries in Table 3 provide a comprehensive snapshot of current use cases and documented 3D-printed recipes across dysphagia care, personalized nutrition, plant-based analogues, and hydrogel-based encapsulation systems.

Beyond academic studies, 3D-printed steaks, whole-cut analogues, and structured fish products have begun appearing in restaurant pilots and limited commercial rollouts. These foods exploit alternating aqueous and lipid phases to approximate marbling, layered muscle-like textures, and customized color or firmness profiles. Similar strategies have been applied to salmon-like products, enabling control over flakiness, cohesiveness, and mouthfeel. These developments echo broader assessments that identify 3D food printing as an emerging technology capable of addressing both consumer preference and food-system resilience.[74,76]

Overall, the benefits of 3D food printing extend beyond texture and flavor design. Layer-by-layer fabrication provides precise spatial control over protein, fiber, and macro- and micronutrient distribution, enabling formulations tailored to individual dietary needs. This platform also offers opportunities for oral delivery of medications and therapeutic adjuncts, supporting disease-specific diets and personalized medicine in conditions such as diabetes, gastrointestinal disorders, and neurodegenerative diseases.[73] Collectively, these applications indicate that extrusion-based 3D printing has significant potential for integrating nutritional personalization with functional structuring, supporting both consumer health and clinical practice.

Table 3. Representative applications and reported 3D-printed food formulations

Application area	Representative recipes/formulations	Key ingredients and structuring agents	Notable printability and texture outcomes	References
Dysphagia diets (IDDSI 3–7)	Restructured vegetables, fruit purées, and plant-protein–thickened soft solids tuned by extrusion parameters	Vegetable/fruit purées; pea/soy proteins (5–20%); xanthan, guar, pectin, alginate, carrageenan; modified starch	Cohesive, shape-retaining strands; controlled adhesiveness and softness; improved vitamin retention via gentle processing	24,68-70
Chickpea–oat dysphagia analogues (experimental)	"Chicken thigh," "turkey breast," "sausage," and "steak" printed from 70:30 chickpea:oat blends with 0–3% beetroot	Chickpea and oat concentrates; beetroot; xanthan; canola oil; water	Pseudoplastic flow ($n < 1$); $G' > G''$; 6–8% dimensional deviation (1.5 mm, 25 mm s^{-1}); extrusion 23–48 N; meets IDDSI Level 5 after steaming	14
Plant-based meat analogues (general)	Soy/pea/chickpea cuts printed by extrusion; colored with beetroot	Soy/pea/chickpea proteins; xanthan/carrageenan; plant oils; natural colorants	Meat-like color transitions; post-steaming shape retention; fibrous networks formed via hydrogel structuring	53,74
Personalized nutrition (elderly, clinical, wellness)	Protein-fortified purées, fiber-enriched blends, vitamin-enhanced soft foods	Legume proteins; wheat-bran, vegetable/mushroom powders; pectin/xanthan; micronutrients	Portion-precise macro/micronutrient dosing; stable soft-solid geometry for individualized dietary needs	24,47
Diabetes-friendly/oral-ulcer-compatible soft foods	Dual-nozzle low-GI meals (bran + mushroom) with milk proteins; IDDSI tested; STZ rat model	Wheat-bran and mushroom powders; milk proteins; xanthan (as needed)	Lower postprandial glucose vs. equal-mass cooked rice; soft textures tolerated during oral ulcer conditions	75
Hydrogel-based encapsulation foods	Vitamin/antioxidant/probiotic-enriched hydrogels and bigels	Alginate, pectin, gelatin; bigels; deep-eutectic hydrogels; vitamins, polyphenols, probiotics	Enhanced protection of heat-sensitive compounds; controlled release compatible with extrusion	53
Active packaging and shelf-life extension	Antimicrobial pads; oxygen/moisture-modulating films for co-use with printed foods	Chitosan–PVA hydrogels; thymol–zeolite hybrids; whey-protein hydrogels	Shelf-life extension; pH-responsive indicators suitable for clinical meal services	53
Printability and rheology model foods	Standardized gels for benchmarking extrudability, dimensional deviation, and shape retention	Xanthan/agar gels; Ca-alginate systems; protein hydrogels with defined yield-stress/viscosity ranges	Reproducible shear-thinning profiles; G'/G'' dominance; quantitative accuracy thresholds	51,74

Abbreviations: GI: Glycemic index; IDDSI: International Dysphagia Diet Standardization Initiative; PVA: Poly(vinyl alcohol); STZ: Streptozotocin.

4. Precision nutrition and artificial intelligence-enabled 3D food printing system

4.1. Precision nutrition framework

The integration of health informatics with plant-based 3D food printing enables a comprehensive precision-nutrition framework in which individualized meals can be designed based on genetics, metabolic phenotype, medical history, habitual dietary patterns, and real-time physiological feedback. Prior work has shown that digitally fabricated meals already support individualized modulation of macronutrients, micronutrients, and texture, particularly in dysphagia management, diabetes, and geriatric nutrition.[24] These capabilities provide a foundation for far more advanced personalization.

In emerging precision-nutrition systems, dietary recommendations incorporate personal genomic and transcriptomic signatures associated with nutrient metabolism, satiety response, detoxification pathways, and chronic-disease risk. AI-driven nutritional models capable of integrating multimodal biological, behavioral, and environmental data are increasingly recognized as essential for capturing the complexity of individual metabolic responses.[2] When coupled to 3D printing, such information could guide the inclusion of plant-based proteins with specific amino-acid profiles for muscle maintenance, the adjustment of prebiotic fibers to support microbiome balance, or the incorporation of bioactive phytochemicals for inflammation control. Similarly, clinical factors, such as swallowing mechanics, glycemic variability, renal function, or digestive tolerances, could be translated into structured food formats that satisfy textural-safety requirements while delivering nutrients with high bioavailability. The combination of informatics-driven diet design and plant-based 3D printing thus provides a framework for producing meals that are not only nutritionally appropriate but also structurally optimized for individual health needs.

4.2. Bioinformatic sensors

Bioinformatic sensing technologies form the data backbone of adaptive nutrition. CGM systems, wearable metabolic trackers, salivary- and breath-based diagnostic devices, ingestible sensing capsules, and microbiome sequencing platforms generate high-resolution data on physiological status, dietary responses, and metabolic patterns. When linked to a 3D food printer, these multimodal data sources could inform real-time adjustments in meal composition, texture, or nutrient density.

As biosensing platforms become increasingly sensitive, they may eventually provide indicators of dehydration, electrolyte imbalance, or early-stage inflammation. In the context of dysphagia, future systems could integrate swallowing-related sensors capable of monitoring bolus transit, tongue pressure, or pharyngeal residue. These data could guide personalized modifications to gelation kinetics, viscosity targets, and hydrocolloid ratios to match an individual's swallowing capacity, thereby enhancing both safety and nutritional adequacy.[63,77] High-frequency physiological data of this kind are also central to AI-enabled nutrition frameworks, which rely on continuous, multimodal inputs for adaptive dietary decision-making.[2]

4.3. Artificial intelligence algorithms

Artificial intelligence can function as the computational core, translating physiological data streams into adaptive printing instructions. Predictive modeling, a central component of AI, leverages historical and real-time physiological data to estimate future metabolic states, including glycemic fluctuations, micronutrient deficiencies, and signatures of emerging metabolic stress. Machine-learning methods operate on multimodal inputs, such as glucose monitoring, microbiome profiles, dietary history, and wearable-sensor data, to classify metabolic patterns or determine optimal nutrient combinations tailored to individual needs.[2]

Reinforcement learning constitutes another key AI paradigm relevant to extrusion-based food printing. In reinforcement learning, an algorithm learns optimal actions through iterative interaction with the environment, receiving reward signals when outcomes improve. In extrusion-based printing, reinforcement learning can adjust extrusion pressure, nozzle speed, hydration levels, or ingredient ratios based on feedback linked to printability, structural stability, nutrient density, or post-prandial biomarker responses. Through repeated cycles, the system converges on printing conditions that remain robust despite material variability or fluctuating environmental factors.

Such AI-enabled strategies mirror insights from extrusion-based food-printing research, which has demonstrated that nutrient delivery, shape fidelity, and textural consistency improve when algorithmic control is applied to heterogeneous, plant-based formulations.[24] In these systems, small deviations in rheology, moisture content, or thermal exposure significantly alter shape retention, sensory attributes, and nutrient preservation. Maintaining consistent print performance, therefore, requires real-time adjustments guided by computational models. Prior work highlights the sensitivity of printability and textural outcomes to rheological behavior and thermal history, underscoring the need for data-driven control strategies capable of autonomously modulating extrusion conditions.[51,64,74] Recent advances in machine-learning-based modeling of extrusion processes also reinforce the potential for predicting printability windows and flow behavior in complex materials, particularly when viscoelasticity and crosslinking kinetics interact in nonlinear ways.[64] As AI becomes more deeply embedded within precision-nutrition fabrication pipelines, ensuring transparency, interpretability, and alignment with food-safety and clinical regulations will remain essential for responsible implementation.[2]

4.4. Closed-loop systems

The long-term vision centers on a fully closed-loop nutritional ecosystem in which sensing, prediction, fabrication, and evaluation unfold as a continuous, adaptive cycle. In such a system, physiological data collected from biosensors, capturing metrics such as glycemic trajectories, microbial metabolites, inflammatory markers, hydration status, or oxidative stress, provide the informational foundation for AI-driven predictive models. These algorithms determine the nutritional adjustments required for subsequent meals, guiding the 3D printer to fabricate plant-based foods whose composition, microstructure, and functional components directly reflect the individual's real-time physiological needs.[2] Ingestion of these personalized meals generates new metabolic responses that feed back into the system, completing the loop and enabling continual refinement.

This closed-loop architecture supports finely tuned nutritional adjustments. If glycemic responses deviate from predicted curves, the system may adjust carbohydrate–fiber ratios and starch gelatinization profiles, or incorporate low-glycemic plant powders. Microbiome-derived biomarkers may prompt adjustments to prebiotic fiber concentrations or the inclusion of polyphenolic compounds known to promote beneficial taxa. Increases in inflammatory or oxidative stress markers may prompt the addition of plant-derived antioxidants, peptides, or amino acids capable of modulating immune and metabolic pathways.

Technological progress in hydrogel structuring, encapsulation, and crosslinking, combined with demonstrated printability of diverse plant-protein and polysaccharide formulations, indicates that such dynamic, feedback-driven personalization is technically attainable within modern extrusion-based printing systems.[14,53] As printing materials and sensing technologies continue to evolve, the integration of AI-guided decision-making within this loop holds significant promise for realizing an adaptive, personalized nutrition ecosystem.[2]

4.5. Data privacy and security

As precision-nutrition systems increasingly rely on sensitive data, including genomic information, real-time glucose traces, microbiome signatures, and clinical histories, robust data privacy and cybersecurity frameworks become essential. Integration with diagnostic devices and electronic health records requires secure data transmission protocols, encryption standards, user-controlled permissions, and compliance with health information regulations.

Beyond technical safeguards, ethical considerations involve ensuring equitable access, mitigating algorithmic bias, and preventing unintended inferences about medical or lifestyle conditions from dietary patterns. Clear governance mechanisms will be needed to ensure that personalized nutrition remains safe, transparent, and respectful of individual autonomy as 3D-printed food technologies move into clinical, institutional, and home environments. These ethical and governance requirements align with broader concerns raised in AI-driven nutrition and food-manufacturing systems, which highlight the need for fairness, transparency, and responsible data stewardship.[2]

5. Consumer perception, cybersecurity, safety, and regulations

5.1. Consumer acceptance

Artificial intelligence-enabled personalized 3D food printing presents major social, economic, and environmental implications; however, its successful transition from laboratory innovation to consumer adoption ultimately depends on market receptivity.[4] Although plant-based diets have gained observable momentum, public attitudes toward emerging food technologies, including 3D printing and precision nutrition, remain underexplored, with studies reporting highly variable responses.[78-80] Consumer acceptance of 3D-printed foods is heterogeneous, shaped by perceptions of trust, risk, naturalness, sensory expectations, and the perceived artificiality of digitally fabricated meals.[81-83] Cluster-based analyses identify subpopulations: some are highly receptive to technologically enhanced personalization, while others express reservations regarding unfamiliar processing methods or the authenticity of printed meals.

Trust-based constructs remain critical. Intention-to-consume studies show that perceived safety, confidence in technological systems, and beliefs about nutritional benefit strongly influence acceptance across demographic groups.[84,85] Repeated exposure to 3D-printed foods and opportunities to participate in personalizing meals have been shown to increase liking and reduce skepticism in real-world settings, including controlled military trials.[82,83] As AI-driven personalization becomes increasingly visible to consumers, perceptions of algorithmic involvement, transparency, and autonomy will require proactive attention. Studies on AI-mediated food and health decisions show that consumer engagement varies depending on AI design features and whether the technology is deployed in private or public consumption domains.[86] Additional concerns, including privacy, data security, and potential job displacement, also shape consumer hesitancy and will require systematic mitigation to ensure public trust.[85]

5.2. Food safety

Food safety remains a foundational determinant of consumer behavior and is essential for the adoption of AI-enhanced 3D-printed foods.[87,88] Plant-based printable inks typically possess high water activity, soft textures, and hydrogel-based moisture-retentive structures, creating elevated risks for microbial growth if preprocessing, printing, and postprocessing are not rigorously controlled. Case studies of 3D food printing systems emphasize the need for HACCP-aligned sanitation protocols, including validated cleaning of nozzles, tubing, reservoirs, and multi-material cartridges to prevent cross-contamination and biofilm formation.[72] Safety considerations further extend to novel plant-based composites, hydrocolloids, enzymatic crosslinkers, and functional additives, all of which must comply with food-grade material standards.

Shelf-life stability poses an additional challenge because printed foods may experience moisture migration, syneresis, or structural deterioration, with implications for microbial safety and therapeutic reliability. Recent analyses of plant-based inks highlight the need for harmonized standards, transparent labeling, and validated safety-assessment frameworks for both base materials and functional nutritional additives.[89] As printed foods move into clinical nutrition and community settings, robust traceability systems and standardized operating procedures will be essential to ensure consistent safety and quality.

5.3. Cybersecurity

The convergence of biosensing devices, AI-driven algorithms, and 3D food-printing platforms introduces significant cybersecurity considerations. Personalized nutrition systems may integrate highly sensitive biological data, including glycemic profiles, metabolic biomarkers, microbiome signatures, genetic predispositions, and detailed dietary histories, making data protection essential for both clinical and consumer trust. Reviews of AI-enabled nutrition technologies underscore the need for privacy-preserving analytic pipelines, encrypted data exchange, secure device interfaces, and strict access-control mechanisms to prevent unauthorized manipulation of printer settings, ingredient compositions, or individualized nutrient-delivery parameters.[90,91] Comprehensive cybersecurity safeguards must be integrated across software, hardware, and governance levels to ensure the safe and ethical deployment of adaptive nutrition ecosystems.

5.4. Regulatory framework

While 3D food printing holds significant promise, it also raises complex regulatory challenges. Current printed foods typically fall under existing food-safety regulations, yet the incorporation of AI-driven adaptive algorithms, plant-derived bioactive compounds, and therapeutic nutrition functions introduces overlaps with medical-device and pharmaceutical regulatory domains. Systems capable of autonomously modifying meal formulations based on physiological data blur the distinctions among conventional food, functional food, and medical nutrition therapy, highlighting the need for clear regulatory definitions, permissible claims, validation requirements, and risk classification guidelines.[90]

Additional regulatory considerations include establishing standards for food-grade printable inks, developing labeling protocols for dynamically personalized meals, ensuring allergen and additive transparency, and defining evidence thresholds for evaluating clinical claims associated with algorithm-driven nutrient personalization. Recent reviews call for multi-agency coordination to ensure safety, transparency, and accountability while enabling innovation in food-printing technologies.[89] Achieving regulatory clarity will be critical for clinical implementation and commercial scalability.

5.5. Ethical considerations

The integration of AI-enabled 3D-printed personalized nutrition introduces multifaceted ethical concerns related to data ownership, autonomy, cultural alignment, accessibility, and fairness. Systems dependent on continuous physiological monitoring may inadvertently reproduce or amplify health inequities if the underlying models are insufficiently representative of diverse populations in terms of age, cultural backgrounds, socioeconomic variation, or Indigenous community needs. Research on technology adoption emphasizes the influence of trust, perceived fairness, and algorithmic transparency on engagement with AI-mediated systems.[84]

Access and affordability represent central ethical questions. Whether personalized 3D-printed nutrition becomes widely accessible, or remains limited to high-resource settings, will determine whether the technology contributes to health equity or exacerbates disparities. Ethical frameworks must also consider the boundaries of personalization: while adaptive nutrition may enhance therapeutic outcomes, overly optimized meal design could unintentionally narrow dietary choice or reduce cultural food diversity. Ensuring that individuals retain ownership over their data, understand how algorithms influence their meals, and maintain the ability to modify or reject AI-generated recommendations remains essential for responsible implementation.[84,91]

6. Future research

Future research in 3D food printing must advance across five interconnected domains: (i) plant-based food-grade materials, (ii) integrated platforms and intelligent control systems, (iii) clinical validation, (iv) scalability and cost efficiency, and (v) environmental sustainability. Together, these areas support the emergence of data-driven, adaptive, and clinically informed nutrition systems, particularly important for chronic diseases such as diabetes, where static meal plans fail to address rapidly fluctuating metabolic needs.

6.1. Advanced plant-based food-grade materials

Future work should focus on developing plant-based printable materials defined by robust and quantifiable printability windows. Although substantial progress has been made toward characterizing rheological parameters, such as shear-thinning profiles and yield-stress thresholds, across selected plant proteins and hydrocolloids, there remains no unified framework that captures the full compositional diversity of legumes, cereals, tubers, fruits, and vegetable-derived polysaccharides used in plant-forward formulations.[51]

The protein-selection workflow provides a methodological exemplar, demonstrating how water-holding capacity, surface charge, amino-acid complementarity, digestibility, and gelation behavior directly shape extrusion stability, print fidelity, and clinically relevant textures.[14] Complementary reviews emphasize the need for open-access rheology–geometry databases linking compositional features, crosslinking mechanisms, and post-processing behavior to measurable print outcomes, thereby accelerating innovation in food-grade formulation science.[74]

6.2. Integration platforms and intelligent control systems

Another key frontier lies in the development of integrated digital ecosystems that connect 3D food printers with environmental sensors, nutrition-tracking applications, user interfaces, and electronic health record systems. At present, most 3D food printers function as isolated fabrication devices. However, several adjacent domains already demonstrate how data-driven, closed-loop architectures can be implemented in nutrition and health contexts, providing a realistic foundation for future integration with 3D food printing platforms.

Emerging technological reviews describe how machine-learning systems can be embedded into additive manufacturing workflows to monitor extrusion pressure, nozzle temperature, flow consistency, and process variability in real time, enabling adaptive parameter tuning and fault correction during printing.[2,7,36] In food engineering specifically, rheology-informed models have been proposed to link material properties to printing outcomes, allowing extrusion speed, deposition rate, and infill density to be adjusted dynamically to maintain dimensional accuracy and structural fidelity.[7,8] Reinforcement-learning frameworks have further been explored as a means to autonomously optimize printing processes through iterative feedback, reducing material waste and improving reproducibility, an approach particularly relevant for plant-based inks that exhibit batch-to-batch variability.[2,5] Advances in hydrogel science support these intelligent control strategies through the development of adaptive or "smart" plant-based inks whose viscoelastic properties can be modulated via reversible hydrogen bonding, ionic gelation, or enzyme-mediated crosslinking under mild, food-grade conditions.[53]

A particularly compelling and well-validated example of closed-loop integration is found in AI-assisted personalized nutrition for diabetes management, which provides a concrete analogue for future food-printing systems. Large-scale clinical studies have demonstrated that machine-learning models integrating CGM data, dietary intake, and physiological parameters can accurately predict individual postprandial glycemic responses and generate personalized dietary recommendations that significantly improve glycemic control compared with standardized diets.[1,3] These approaches have since evolved into AI-enabled CGM platforms that operate in real time, forecasting glucose trajectories and adapting dietary or therapeutic interventions through closed-loop feedback mechanisms, with demonstrated safety and efficacy in prediabetic and diabetic populations.[18,19]

Importantly, recent work in 3D food printing has already established the ability to fabricate soft-textured, low-glycemic foods using milk powders, wheat bran, and plant proteins, producing meals that elicit reduced postprandial glucose excursions compared with conventional carbohydrate-based foods in diabetic animal models.[75] When conceptually integrated with AI-driven CGM systems, these printable food platforms form the missing execution layer of a closed-loop nutrition system. In such a framework, real-time glycemic data would serve as input to predictive AI models, which in turn determine optimal macronutrient ratios, fiber content, hydration levels, and internal architecture; these parameters could then be directly implemented through digitally controlled extrusion and post-processing. Compared with static meal plans, this approach enables continuous personalization, rapid response to metabolic instability, and reduced cognitive burden for patients, aligning with broader visions of precision nutrition and digitally enabled healthcare.[1,6,18,36,38]

Collectively, these existing AI-assisted nutrition systems, adaptive manufacturing strategies, and clinically validated CGM-based platforms demonstrate that the proposed integration of AI, health monitoring, and 3D food printing is not purely conceptual. Rather, it represents a convergence of already-proven technologies into a unified, next-generation food-design ecosystem capable of delivering executable, personalized nutrition.

6.3. Clinical trials and evidence-based implementation

Although proof-of-concept studies demonstrate significant potential, for example, low-glycemic 3D-printed foods that reduce glucose excursions in diabetic animal models and texture-optimized meals for individuals experiencing oral discomfort,[75] rigorous human studies remain limited. Future clinical research must evaluate adaptive 3D-printed meals across prediabetes, diabetes, dysphagia, cardiovascular recovery, oncology nutrition, and geriatric care.

Key clinical endpoints include glycemic time-in-range, hemoglobin A1c (HbA1c), swallowing safety, hydration, satiety, adherence, nutrient intake, and patient-reported quality of life. Dysphagia-specific reviews report improved visual appeal and greater texture standardization; however, robust evidence concerning aspiration risk, nutrient bioavailability, and long-term outcomes remains insufficient.[68] Multicenter clinical trials will be essential to validate closed-loop personalized meals within real-world healthcare pathways.

6.4. Scalability, throughput, and cost reduction

Large-scale adoption of 3D food printing will depend on improvements in scalability, throughput, and cost efficiency. Existing printers are primarily optimized for research settings; transitioning them into hospitals, long-term care facilities, and community nutrition programs requires modular hardware design, automated sanitation systems, durable food-safe cartridge technologies, and simplified ingredient-processing pipelines.

Reviews highlight the importance of cost-effective sourcing of plant proteins, fibers, and hydrocolloids, and underscore the need for comprehensive life-cycle assessments evaluating energy consumption, labor requirements, maintenance needs, and material utilization.[74] Integration of these assessments with quantitative printability metrics, such as extrusion force, dimensional deviation, and viscoelastic recovery, will support the development of validated, high-throughput production models suitable for institutional environments.[14,51]

6.5. Sustainability and environmental performance

Finally, future research should situate 3D food printing within global sustainability goals. Plant-based 3D printing enables precision portioning, reduces food waste, and supports the upcycling of nutrient-rich side streams, especially when hydrogel systems are used to stabilize fibers, pulps, and protein fractions that would otherwise be discarded. Materials-science insights identify pathways to reduce thermal energy input, enhance moisture retention, and avoid resource-intensive processing, promoting lower-energy and higher-efficiency workflows.[53]

Comprehensive life-cycle comparisons between 3D-printed and conventionally prepared meals remain rare. Future assessments must quantify greenhouse-gas emissions, water use, nutrient yield, energy consumption, and post-consumer waste to validate the environmental advantages of plant-based printing and support its adoption within sustainable food-system strategies.[74]

7. Conclusion

Plant-based food inks and extrusion-based 3D printing together represent a rapidly evolving platform capable of transforming personalized nutrition. Advances in ingredient science, particularly the functional exploration of plant proteins, hydrocolloids, fibers, and fruit- and vegetable-derived matrices, have established the rheological and structural foundations necessary for producing stable, nutritionally meaningful 3D-printed foods. As research deepens, clearer relationships are emerging between compositional properties, shear-dependent flow behavior, crosslinking mechanisms, and viscoelastic recovery, enabling food inks that consistently meet printability, texture, and sensory requirements across a wide range of clinical and consumer applications.

In parallel, extrusion-based 3D food printing technologies have matured from proof-of-concept demonstrations to increasingly robust fabrication systems capable of controlling geometry, internal architecture, and spatial nutrient distribution with remarkable precision. Workflows that integrate computer-aided design-based design, multi-material deposition, rapid ink setting, and quantitative evaluation are allowing 3D-printed foods to meet physiologically relevant criteria, most notably in dysphagia management, diabetes-oriented soft diets, protein or fiber fortification, and plant-based meat analogues. As materials and printing strategies continue to advance, the potential for fine-tuned microstructuring, staged nutrient release, and culturally adaptive food formats is expanding rapidly.

The convergence of plant-based 3D printing with AI introduces an even greater shift toward fully adaptive, real-time nutritional personalization. Biosensors such as continuous glucose monitors, wearable metabolic trackers, and emerging digestive or microbiome sensors provide high-resolution physiological data that can drive predictive algorithms. Machine learning and reinforcement learning models are increasingly capable of translating such multimodal data into optimized printing instructions, regulating extrusion behavior, ingredient ratios, and functional properties to generate meals tailored to an individual's moment-to-moment metabolic state. Closed-loop AI-printer systems, though early in development, offer a transformative vision in which dietary interventions dynamically track health trajectories, adjust nutrient delivery, and reduce individual burden in managing chronic conditions such as diabetes.

However, realizing this future requires addressing challenges beyond formulation and engineering. Consumer acceptance remains variable, influenced by perceived naturalness, safety, transparency of AI involvement, and trust in digitally fabricated foods. Food safety, sanitation, traceability, and microbial control must be rigorously validated across both printing processes and plant-based material systems. Cybersecurity is increasingly critical as AI-driven personalized nutrition relies on sensitive health and behavioral data. Regulatory frameworks must evolve to clarify boundaries between food, functional food, and medical nutrition, and to establish validation pathways for dynamic, algorithm-controlled dietary interventions.

Looking forward, several research priorities emerge. First, standardized printability metrics and open rheology–geometry databases will be essential for accelerating formulation science and enabling reproducibility across laboratories. Second, integrated platforms linking printers with biosensors, AI engines, and clinical decision systems must be developed with clear safety, transparency, and data governance mechanisms. Third, clinical trials across diverse populations, including older adults, dysphagia patients, metabolic-disease cohorts, and culturally distinct communities, are needed to evaluate efficacy, safety, and adherence. Fourth, scalability and sustainability must be addressed by developing cost-efficient ingredients, low-energy processing strategies, and life-cycle–optimized workflows that minimize waste.

Taken together, plant-based food inks, extrusion-based 3D printing, and AI-enabled dietary monitoring form a powerful and synergistic toolkit for the next generation of personalized nutrition. By uniting advances in biomaterials, additive manufacturing, and intelligent health technologies, this field has the potential to deliver customized, nutrient-dense, culturally adaptable, and clinically responsive foods at scale. Continued interdisciplinary collaboration across food science, materials engineering, nutrition, computer science, and regulatory policy will be essential to translate these innovations into safe, equitable, and impactful solutions for global health.

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Conflict of interest

The authors declare they have no competing interests.

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