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Three-dimensional food printing: Emerging technology, materials, applications, challenges and future perspectives

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Abstract

Three-dimensional (3D) food printing is an emerging additive manufacturing technology that enables the fabrication of edible products through the computer-controlled, layer-by-layer deposition of food materials. Unlike conventional food processing, 3D printing provides an opportunity to simultaneously control the geometry, texture, composition and nutritional characteristics of food products. The technology has attracted increasing attention because of its potential for personalized nutrition, functional food development, alternative protein utilization, food waste valorization and sustainable food manufacturing. Extrusion-based printing remains the most widely investigated approach because of its compatibility with a broad range of food materials, relatively simple equipment requirements and ability to process viscous food formulations. Other approaches include inkjet printing, binder jetting and selective laser sintering. Successful printing depends strongly on the rheological and physicochemical characteristics of the food ink, including viscosity, yield stress, shear-thinning behaviour, cohesiveness and structural recovery. Applications have expanded from confectionery and bakery products to meet analogues, plant-based foods, dairy products, functional foods, nutritionally fortified foods and foods designed for elderly and dysphagic populations. Recent developments have also explored 4D printing, artificial intelligence-assisted process optimization and the use of food-processing by-products as printing materials. Despite these opportunities, challenges related to printability, printing speed, food safety, nutritional stability, consumer acceptance, standardization and industrial scalability remain. This review summarizes the principles, printing technologies, food materials, applications, advantages, limitations and future prospects of 3D food printing, with particular emphasis on personalized nutrition and sustainable food production.

Keywords: 3D food printing, additive manufacturing, food ink, extrusion printing, personalized nutrition, functional food, food waste valorization, sustainability

Introduction

The food industry is increasingly moving toward technologies capable of producing foods that are nutritionally customized, convenient, sustainable and attractive to consumers. Conventional food-processing systems are generally designed for large-scale production of standardized products. Although these systems provide high productivity and consistency, they offer limited flexibility for producing foods according to individual nutritional requirements, sensory preferences or specific geometric designs. Three-dimensional food printing (3DFP), an application of additive manufacturing, has emerged as a potential technology to address some of these limitations.

3D food printing involves the creation of an edible three-dimensional structure through the controlled deposition of food material according to a digitally designed model. The process generally involves formulation of a printable food material, digital modelling, slicing of the model into layers, deposition of the material and, where required, post-processing such as baking, drying, steaming or frying. Recent reviews describe 3DFP as a technology capable of connecting digital food design with physical food production while enabling control over food shape, texture and composition.

The technology is particularly attractive because food products can theoretically be designed according to individual requirements. For example, the quantity of protein, carbohydrates, dietary fibre or selected micronutrients can be adjusted during formulation. This has generated interest in applications involving elderly consumers, individuals with dysphagia, athletes, children, patients requiring specialized diets and consumers seeking personalized nutrition. Recent literature further emphasizes the potential of 3D printing to combine nutrition, digital design and consumer-specific food experiences.

In addition to personalization, 3D printing may contribute to sustainable food production by utilizing underused raw materials and food-processing by-products. Cereal fractions, fruit and vegetable residues, plant proteins, alternative proteins and other unconventional ingredients have been investigated as printing materials. Consequently, 3DFP is increasingly being considered not simply as a novel food-shaping technique but as a potential platform for future food manufacturing.

Principle and Processing Workflow of 3D Food Printing

The basic principle of 3D food printing is similar to additive manufacturing used in engineering, except that the deposited material must be edible and possess appropriate food-processing characteristics.

A typical workflow consists of the following stages:

Digital design → Model slicing → Food-ink preparation → Loading → Controlled extrusion/deposition → Layer-by-layer construction → Post-processing → Quality evaluation

Initially, a three-dimensional digital model is generated using computer-aided design software or obtained from a digital food library. The model is then divided into thin

horizontal layers using slicing software. Printing parameters such as nozzle diameter, printing speed, extrusion rate, layer height and infill pattern are defined. The food material is subsequently deposited according to the programmed path.
The success of the process depends on the ability of the material to flow through the nozzle while maintaining sufficient structural integrity after deposition. Therefore, the rheological properties of food inks are among the most important determinants of printability. Materials commonly require shear-thinning behaviour: viscosity decreases during extrusion under shear and subsequently increases after deposition, allowing the printed layer to retain its shape. Research has demonstrated that material properties, nozzle dimensions and extrusion conditions strongly influence printing accuracy and structural stability.

Major 3D Food Printing Technologies
Several additive manufacturing approaches have been investigated for food applications.

1. Extrusion-Based Printing
Extrusion is currently the most widely used 3D food-printing technology. In this method, food ink is forced through a nozzle using pneumatic pressure, a syringe mechanism or a mechanical screw. The material is deposited continuously along a predetermined path to create successive layers.
Materials such as dough, chocolate, fruit and vegetable purees, mashed potatoes, cheese, meat and meat analogues, gels and protein-based formulations have been investigated using extrusion printing. Its popularity is associated with comparatively simple equipment, relatively low cost and compatibility with viscous food materials.
However, extrusion printing is strongly dependent on rheology. Excessively viscous materials may require high extrusion pressure, whereas materials with very low viscosity may spread after deposition and fail to maintain the intended shape.

2. Inkjet Printing
Inkjet printing deposits very small droplets of food material onto a surface. It is particularly suitable for low-viscosity formulations and precise deposition of colours, flavours, nutrients and bioactive compounds.
The major advantage is high deposition precision. However, the requirement for suitable droplet formation limits the range of food materials that can be processed using conventional inkjet systems.

3. Binder Jetting
In binder jetting, a liquid binder is selectively deposited onto layers of powdered food material. The binder joins the powder particles to create the desired structure.
This technique is potentially useful for powdered ingredients, confectionery and nutritionally formulated products. Nevertheless, post-processing and structural strength remain important considerations.

4. Selective Laser Sintering
Selective laser sintering uses a laser to selectively fuse powdered materials. Although extensively developed in non-food additive manufacturing, its application to foods remains comparatively limited because of concerns regarding thermal effects, ingredient stability and processing conditions.
Current literature identifies extrusion, inkjet, binder jetting and selective laser sintering as the principal approaches investigated for food printing, with extrusion remaining the dominant technology.

Food Materials Used in 3D Printing
The development of suitable food inks is one of the most important aspects of 3DFP. A food ink must possess adequate flowability during extrusion and sufficient stability after deposition.

1. Carbohydrate-Based Materials
Starch, wheat flour, rice flour, maize flour, oats and other cereal ingredients are widely investigated. Starch gelatinization and retrogradation significantly influence the structural characteristics of printed products.
Cereal-based printing also provides opportunities to incorporate millets, pulses, dietary fibre and other nutritionally valuable ingredients. This is particularly relevant for developing products with enhanced protein and fibre content.

2. Protein-Based Materials
Proteins from dairy, meat, legumes and alternative sources have attracted considerable interest. Plant proteins such as soy, pea and other legume proteins can be incorporated into printable formulations for developing protein-rich foods and meat analogues.
Unconventional protein sources are another emerging research area. Their incorporation into 3D and 4D printing could support the development of sustainable protein products, although further work is needed to understand their rheological, functional and sensory behaviour.

3. Fruits and Vegetables
Fruit and vegetable purees can be converted into printable formulations. Their use provides opportunities for developing snacks, desserts, fortified foods and products with high levels of bioactive compounds.
However, their high moisture content and variable rheological properties can make shape retention difficult. Hydrocolloids and other structuring agents may therefore be used to improve printability.

4. Hydrogels
Hydrocolloids such as alginate, carrageenan, pectin, gelatin and other gelling systems can provide structural support to printed foods. Hydrogels are particularly relevant for soft foods and specialized diets.

5. Functional Ingredients and Nutraceuticals
3D printing provides an opportunity to incorporate functional ingredients such as dietary fibre, antioxidants, vitamins, minerals, probiotics and plant bioactives into customized food structures. A 2024 systematic review highlighted the influence of additives on printability, nutritional characteristics, techno-functional properties and antioxidant properties of 3D-printed foods.

Factors Affecting Printability
Printability refers to the ability of a food formulation to be successfully deposited and retain its intended three-dimensional structure.

1. Rheological Properties
Viscosity, yield stress, viscoelasticity, shear-thinning behaviour and structural recovery are critical parameters. An ideal food ink should flow readily through the nozzle under applied pressure but recover sufficient viscosity after deposition to maintain its shape.

2. Nozzle Diameter
Nozzle diameter affects extrusion pressure, printing resolution and processing time. Smaller nozzles can produce finer structures but may increase extrusion resistance and clogging.

3. Printing Speed
Increasing printing speed can improve productivity but may reduce deposition accuracy if the extrusion rate is not synchronized with printer movement.

4. Layer Height
Layer height influences the interaction between successive layers and consequently affects structural integrity and surface quality.

5. Infill Density and Pattern
Infill percentage determines the internal structure, weight, texture and mechanical properties of the printed food. Different infill patterns can also be used to create specific textures and geometries.

6. Temperature
Temperature influences viscosity, phase transitions and structural properties. Chocolate, for example, requires controlled temperature conditions for successful printing. Some hydrocolloid and starch-based formulations also exhibit strong temperature-dependent behaviour.
Recent reviews emphasize that the simultaneous optimization of material characteristics and printer parameters is essential for improving printing accuracy and efficiency.

Applications of 3D Food Printing
1. Personalized Nutrition
Personalized nutrition represents one of the most important potential applications. Food composition can theoretically be adjusted according to age, lifestyle, dietary preference and nutritional requirements. The digital nature of 3DFP also provides an opportunity to create databases containing formulations and nutritional profiles.
Recent research considers personalized and digitally designed foods as one of the major pathways through which 3DFP could transform food manufacturing and consumption.

2. Foods for Elderly and Dysphagic Consumers
Elderly consumers may require foods with modified texture, increased protein density and improved ease of swallowing. 3D printing can produce soft, visually attractive foods with controlled texture and nutrient composition.
This application is particularly significant because conventional texture-modified foods can sometimes have poor visual appeal. 3D printing can reconstruct nutritionally appropriate foods into recognizable or attractive shapes.

3. Functional and Fortified Foods
The technology can be used to incorporate vitamins, minerals, proteins, fibre and bioactive compounds into customized products. Such approaches could be particularly valuable where nutritional deficiencies need to be addressed while maintaining consumer appeal. Recent reviews identify personalized functional foods as a rapidly developing area of 3DFP research.

4. Plant-Based and Alternative Protein Foods
3D printing can facilitate the controlled deposition of plant proteins to create complex structures. It may therefore contribute to the development of customized meat analogues and alternative protein foods.
The ability to manipulate internal architecture could eventually allow manufacturers to reproduce desirable characteristics such as fibre orientation, firmness and bite.

5. Food Waste Valorization
Food-processing by-products represent a promising source of ingredients for 3D printing. Fruit peels, vegetable residues, cereal by-products, spent grains and other nutrient-rich materials may be incorporated into printable formulations.
This approach aligns 3DFP with circular-economy principles by converting low-value materials into higher-value food products. Recent research specifically identifies food-waste valorization as an expanding application of 3D printing, although material variability and regulatory requirements remain important challenges.

6. Space and Remote Food Production
3D printing has potential applications in environments where food variety and storage are challenging, including space missions. Digital recipes combined with shelf-stable ingredients could theoretically allow food structures to be fabricated according to individual requirements.

7. Gastronomy and Customized Food Design
Restaurants and food designers can use 3D printing to create complex shapes and textures that are difficult to achieve through conventional processing. The technology therefore provides opportunities for culinary creativity and novel gastronomic experiences.

Advantages of 3D Food Printing
The major advantages include:
1. Personalization of food composition and shape
2. Precise control over portion size
3. Potential for personalized nutrition
4. Production of complex geometric structures
5. Integration of multiple ingredients
6. Potential utilization of food-processing by-products
7. Digital storage and reproduction of food designs
8. Possibility of controlled texture modification
9. Potential reduction in material waste
10. Development of novel functional and fortified foods

The technology may also shorten certain supply-chain steps because food products can potentially be produced close to the point of consumption. However, claims regarding sustainability must be evaluated using complete life-cycle assessments because printer energy consumption, ingredient preparation and post-processing also contribute to environmental impact.

Challenges and Limitations

Despite substantial research progress, 3D food printing has not yet achieved widespread industrial adoption.

1. Limited Printing Speed

Conventional extrusion printers are generally slower than established industrial food-processing systems. Printing complex structures layer-by-layer can therefore limit productivity.

2. Food Ink Standardization

There is no universally accepted standard defining the ideal rheological or physicochemical properties of a printable food ink. Ingredient variability further complicates process optimization. Recent literature continues to identify food-ink standardization as a major research gap.

3. Food Safety

Food printers contain multiple surfaces, nozzles and channels where food residues may accumulate. Poor cleaning and sanitation can increase microbial risks. Printer design, hygienic construction, cleaning procedures and control of the time-temperature history of food materials are therefore essential.

4. Nutrient Stability

Heat-sensitive nutrients and bioactive compounds may degrade during printing or subsequent post-processing. Optimization of processing conditions is therefore necessary to preserve nutritional quality.

5. Consumer Acceptance

Consumer acceptance depends not only on nutritional value but also on appearance, familiarity, texture, flavour, perceived naturalness and willingness to consume technologically produced food. Consumer studies indicate that food neophobia and perceptions of novelty can influence acceptance.

6. Economic Feasibility

The cost of specialized food printers, formulation development, maintenance and quality control may limit adoption, particularly for small food-processing enterprises.

7. Regulatory and Standardization Issues

Regulatory frameworks specifically addressing 3D-printed foods, printable formulations, processing conditions and printer hygiene are still developing. Harmonized standards for printing parameters, safety assessment and product characterization are needed before large-scale commercialization. Recent reviews specifically identify the absence of harmonized standards as a bottleneck for mass production.

Emerging Trends and Future Perspectives

The next phase of 3D food printing is likely to involve integration with artificial intelligence, advanced materials and digital nutrition.

1. Artificial Intelligence-Assisted Printing

Machine-learning algorithms can potentially predict printability from rheological and formulation data and optimize printing speed, pressure, temperature and nozzle characteristics. AI could reduce experimental trial-and-error and facilitate automated process control.

2. 4D Food Printing

Four-dimensional food printing extends 3D printing by introducing controlled changes in food structure or properties over time in response to environmental stimuli such as temperature, moisture or pH. This could create foods that change colour, shape, texture or sensory characteristics during cooking or consumption.

3. Personalized Digital Nutrition

Future food printers may integrate nutritional databases, individual dietary information and digital recipes to produce meals with precisely controlled nutrient compositions.

4. Sustainable Food Manufacturing

Combining 3D printing with alternative proteins, millets, pulses, algae and food-processing by-products could support more resource-efficient food systems. However, sustainability should be established through quantitative life-cycle and techno-economic assessments rather than assumed solely from the ability to use food residues.

5. Smart and Automated Food Printing

Integration of sensors, machine vision, artificial intelligence and real-time quality monitoring could enable automated adjustment of printing parameters. Such systems could detect defects in printed structures and modify extrusion conditions during production.

Conclusion

Three-dimensional food printing represents an important emerging technology at the intersection of food science, engineering, nutrition and digital manufacturing. Its greatest potential lies not simply in producing attractive food shapes but in enabling the digital design and controlled manufacture of personalized foods. Extrusion-based printing currently dominates because of its flexibility and compatibility with diverse food materials, while inkjet, binder jetting and laser-based approaches offer specialized possibilities.

The technology has promising applications in personalized nutrition, functional foods, texture-modified foods, alternative proteins, space food, gastronomy and food-waste valorization. Recent developments in AI-assisted printing, 4D food printing and sustainable ingredient utilization are further expanding its potential.

Nevertheless, major barriers remain, particularly regarding printability, processing speed, food safety, nutritional stability, sensory quality, consumer acceptance, economic feasibility and regulatory standardization. Future research should therefore move beyond laboratory-scale demonstration toward systematic evaluation of food safety, nutritional bioavailability, life-cycle sustainability, techno-economic feasibility and consumer behaviour.

Overall, 3D food printing should be regarded as a platform technology rather than a single food-processing operation. Its integration with artificial intelligence, personalized nutrition, alternative proteins, functional ingredients and circular-economy approaches could contribute to a more flexible and consumer-oriented food manufacturing system. The transition from experimental prototypes to commercially viable products will depend on multidisciplinary research, standardized methodologies and appropriate regulatory frameworks.

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