Review

Received: 1 November 2025 Revised: 1 April 2026 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/jsfa.70702

Next-generation nutrition: A review of technological advances and nutritional aspects of 3D food printing

Senbakapriya Selvaraju, Nivetha Senthilkumar, Anusuya Thirumalaisamy, Megaasri Sasikumar, Mahalakshmi Balasubramaniyan, Dikshya Thiyagu and Akash Karthikeyan*

Abstract

The advent of three-dimensional (3D) food printing signifies a groundbreaking shift in the food sector, amalgamating digital technology, material science, and nutrition to produce customized, sustainable, and novel food items. This review examines technological advances and the nutritional implications of 3D food printing as a new way to make food. The technology enables the layer-by-layer construction of foods utilizing edible materials – such as purees, doughs, proteins, and hydrogels – for precise control over the shape, texture, and nutrient content. Improvements in printer design, extrusion processes, and printed biomaterials have expanded the range of compatible ingredients, including plant-based proteins, alternative flours, and nutrient-enriched formulations. Three-dimensional printing facilitates personalized nutrition by creating meals tailored to individual dietary needs, age group, or health conditions. It also supports environmental sustainability by reducing food waste and using underutilized food sources. However, challenges remain regarding printability, food safety, nutrient stability, and commercial scalability. This review emphasizes the interdisciplinary nature of 3D food printing and its potential influence on the future of nutrition, food design, and sustainable food systems.
© 2026 Society of Chemical Industry.

Keywords: 3D food printing; food technology; nutrient optimization; personalized nutrition; sustainable food systems

INTRODUCTION

Additive manufacturing (AM) is a digital technique that constructs objects using layer-by-layer material deposition. It is commonly referred to as three-dimensional (3D) printing technology. A derivative of classic AM technology, 3D food printing (3DFP) creates the required objects by depositing successive layers of edible materials using a bottom-up approach and computer-aided design (CAD) software.[1] Previously, the production of food and pharmaceutical items using printing methods was relatively rare. Given that pharmaceutical and food ingredients are absorbed directly by the body, the level of caution and innovation that characterizes the creation of 3D-printed goods offers considerable potential.

The two primary strategies for using 3D printing applications in food and nutrition will probably address specific emerging or anticipated nutritional challenges.[2] The first involves repurposing food materials to improve nutrition and reduce raw material waste. The second involves reducing the burden of diet-related diseases through strategic food design, necessitating the implementation of personalized nutrition. The goal of personalizing and customizing food materials is to meet individual nutritional requirements through the optimization of food structure and composition.[3]

The manufacturing and prototyping sectors – which formerly relied on laborious and costly processes like shaping, framing, and machining – have been transformed by additive manufacturing.[4] The technology was originally designed to create three-dimensional structures using materials such as metals, ceramics, and polymers to fabricate intricate components in a single step.

By carefully combining, depositing, and heating material layers, AM techniques have revolutionized food preparation, allowing users to experiment efficiently with various material combinations. By regulating printing material and nutritional content, this technology enables food production tailored to individual physical activity and health conditions.[5]

Charles Hull created this technology in 1983 as stereolithography (SLA). Researchers are currently using it to develop a variety of cutting-edge methods and materials for specialized applications.[6] Additive manufacturing is utilized for both prototyping and small-scale production, enabling the use of sturdy yet lightweight parts, cost-effective manufacturing, adaptable designs, and minimal material waste. Recent advances have reduced the

* *Correspondence to: A Karthikeyan, Department of Biotechnology, Vivekanandha College of Engineering for Women, Namakkal, India. E-mail: akash@vcew.ac.in*

Department of Biotechnology, Vivekanandha College of Engineering for Women, Namakkal, India

 © 2026 Society of Chemical Industry.

cost of 3D printers, making them accessible even for customized product manufacturing.[7]

Significant progress in the business and the customization of food design is possible using AM technologies. Within food engineering, AM faces several challenges, including process productivity, product innovation, and functionality. As a disruptive technology, AM is changing the food and agricultural industries. By depositing a certain material, layer by layer, in accordance with a predetermined design, this technology can produce physical components directly, allowing for flexibility in size and shape.

Additive manufacturing has expanded its applications within the food industry due to benefits such as individualized nutrition, personalized food designs, and streamlined supply chains. It is currently utilized in sectors including confectionery, military and space rations, and geriatric nutrition. Successful printing depends on precision and accuracy, which are primarily influenced by material characteristics, process variables, and post-processing procedures.[8-11]

Despite the rapid development of 3D food printing, most existing reviews have concentrated on printing methods, materials, and engineering aspects rather than nutritional functionality, digestibility, health effects, and practical implementation difficulties. Specifically, the perspectives of food science, nutrition, and biomedicine remain poorly integrated regarding the assessment of 3D-processed meals. This review seeks to address this gap by critically analyzing technology advancements, nutritional quality, individualized diet applications, and emerging obstacles to widespread acceptance.[26]

ADDITIVE MANUFACTURING TECHNOLOGY IN THE FOOD INDUSTRY

Innovations in food technology may focus on specific areas such as process engineering, product formulation, food attributes, or consumer needs yet can trigger cascading effects that alter the broader food system, eating habits, and socio-cultural domains. To create food that meets the nutritional, individual, and social requirements of every community, food industry innovation strategies must be integrated within the entire food system. Such approaches should address not only technological progress but also evolving social and environmental shifts.[12]

In a globalized world, this is essential as it offers advanced technology for producing bespoke parts in varying quantities using a variety of materials. The food and agriculture industries require significant customization in the design and development of equipment. Additive manufacturing can design and produce unique, customized food items based on the required ingredients, shapes, and colors including coffee, pizza, burgers, biscuits, cakes, chocolates, and other common foods.[8]

In addition to basic dietary preferences, personalized nutrition (PN) based on health status and body type requirements has received significant attention. When food printing is integrated with a nutrition model, users can determine nutritional distribution precisely and calculate the caloric and elemental content of manufactured products. By selecting ingredients and matching manufacturing parameters through a user interface, individuals may manage their diets more effectively. Food printing therefore offers a practical way to digitize calorie and nutrition intake, improving individual dietary control.

Online data on nutritional composition and individual and social preferences can be used to personalize nutrition in food products. Even food ingredients with well-known material qualities can be customized for each fabrication with unique compositions. The design of the recipe, printing volume, 3D model design, and flavor selection can then be used to create a fabrication plan. The recipe's design can be modified and the printing volume controlled to achieve the nutrient profile's specified levels.[13]

Personalized nutrition, which also takes into account each individual's unique body type and health situation, has received considerable attention in recent years.[14]

The COVID-19 pandemic has focused attention on public health. Creating meals with regulated gastrointestinal transit times will clearly enable improved management of nutrient kinetics and availability to meet the dietary requirements of specific groups. One of the greatest future challenges facing the food industry will be incorporating novel concepts and moving towards PN.

Although various international food research institutes and businesses are continuously implementing 3D food printing developments – incorporating diverse perspectives and beneficial food concepts – only limited research knowledge has been applied to the creation of customized foods.[3] However, several prominent nutritional strategies have attempted to develop customized food.[3]

According to the theory of PN, diets should be customized to meet each person's specific nutritional demands rather than those of general populations. A person's lifestyle, age, sex, genetics, metabolism, and microbiome all affect their nutritional requirements. For example, an older female with diabetes and a young male who is obese require different diets.[15]

It is now possible to create diet plans for particular individuals due to significant technological advances in genetics, metabolism, diagnostics, computation, and data analysis. Diets that are customized to meet each person's unique nutritional and health needs should eventually be achievable. Functional foods made with particular nutritional, nutraceutical, prebiotic, and probiotic combinations are necessary for PN.

In some situations, bioactive components can be included easily in a food matrix. In other situations, they require specific encapsulation methods to enhance their bioavailability, or to disperse or protect them. For instance, to improve water dispersibility, chemical stability, and oral bioavailability, oil-soluble vitamins (such as vitamins A, D, and E) and nonpolar nutraceuticals (such as carotenoids, curcumin, and resveratrol) can be added to delivery systems that contain tiny hydrophobic particles (such as emulsions or nanoemulsions). A single delivery system can contain one or more bioactive compounds, depending on their physicochemical and nutritional characteristics.[16]

Three-dimensional food printing techniques

Three-dimensional technology involves layer-by-layer material deposition from a pre-designed file using nozzles and software to make unique food products with intricate designs.[17] Three-dimensional printing is defined as the process of fabricating objects by depositing material through a print head, nozzle, or other printing technologies.[18] A number of food printers have been produced to create food items. These printers use cartridge tubes containing edible food solids or semi-solids (dough, puree, paste, and powder, liquids or gels created from ingredients including sugar, meat, chocolate, flour, fruits, and vegetables).[17] Three-dimensional food printing presents significant benefits in the fabrication of high-value, low-volume food products, particularly for customized applications in the food service sector. A range of printhead designs is employed to handle and dispense

© 2026 Society of Chemical Industry.

various food materials. Some systems utilize thermal energy such as lasers, hot air, or heating elements to sinter or melt powdered ingredients, whereas others use inkjet-style printheads to deposit binders or solvents precisely for shaping and assembly. Several 3D food printing techniques have been adopted in the food industry, such as binder jetting, extrusion-based printing, inkjet printing, and selective laser sintering (SLS), each characterized by a distinct mechanism.[19]

Extrusion-based 3D printing

In recent years, extrusion-based 3D printing (Fig. 1(a)) has emerged as one of the most widely adopted molding techniques in the food industry. It is easy to use and enables the production of cost-effective products. This technique was first introduced to the sector by researchers at Cornell University, marking a significant step in the integration of 3D printing technologies into food production.

Extrusion-based 3D food printing, commonly referred to as fused deposition modeling, was first utilized for printing filamentous plastics that could be melted through heating. This technique operates on a simple technical principle – utilizing pneumatic, piston-driven, or screw-driven systems – where a 3D printer continuously extrudes a molten or paste-like material through a moving nozzle. Guided by model data, the material is deposited onto the layer beneath, gradually building the structure until the final form is achieved. The major challenges in extrusion-based 3D food printing involve the properties of the printing inks, the optimization of printing parameters, and the post-processing techniques.[20] This emerging process involves filling a syringe or cylinder with malleable or slurry materials, eliminating air spaces, and extruding the material through a nozzle tip onto the printer bed.[21]

In extrusion-based food printing, the quality of the final product is determined primarily by two factors: (i) the printability of the material during extrusion, and (ii) product stability after printing. The printability of food materials is influenced by their rheological behavior, thermal properties – such as melting point and glass transition temperature – and gelation characteristics. This technique uses three additional mechanisms: screw-based extrusion, syringe-based extrusion, and air pressure-based extrusion. In screw-based extrusion, ingredients are first mixed separately and then loaded into a cartridge, then transported through a screw-driven tube and extruded through the nozzle. However, gel-like substances with high mechanical strength and viscosity

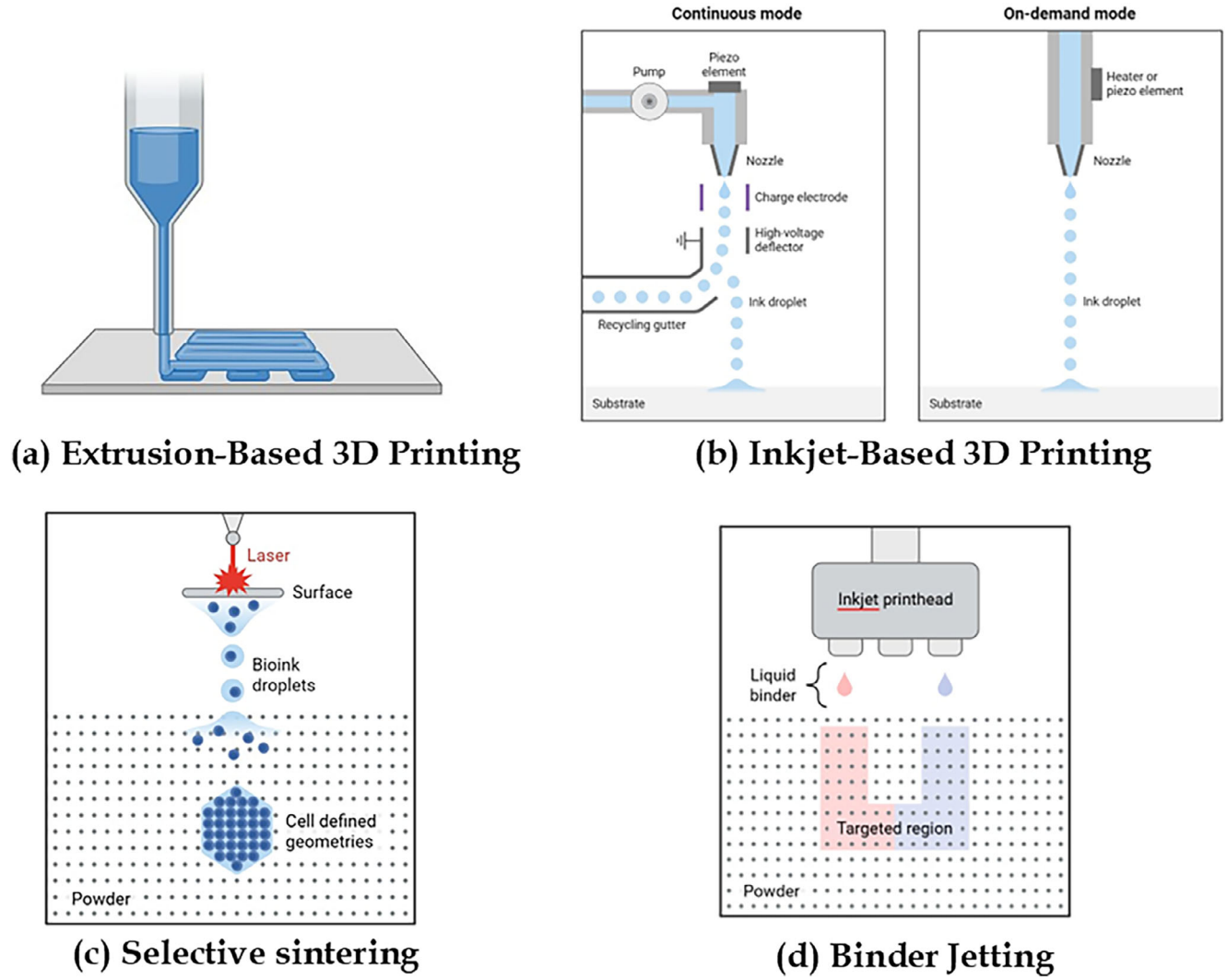


Figure 1. Different three-dimensional (3D) printing techniques: (a) extrusion-based 3D printing; (b) inkjet-based 3D printing; (c) selective sintering; (d) binder jetting.

 © 2026 Society of Chemical Industry.

are often unsuitable for 3D printing; they frequently lead to material compression, structural deformation, and reduced resolution due to weak interlayer bonding in the printed structure. In syringe-based extrusion, a stepper motor drives a plunger to push semi-solid materials – such as chocolate or dough – through the nozzle. Alternatively, air pressure-based extrusion utilizes a compressor to force material from a cartridge through the nozzle tip onto the printer bed.[22]

Inkjet-based 3D printing

Material jetting systems, especially inkjet-based 3D printers (Fig. 1(b)), have become increasingly popular in recent years due to their ability to fabricate multi-material products through the drop-on-demand (DOD) printing technique. Despite being designed for advanced manufacturing applications, inkjet-based 3D printing systems closely resemble traditional two-dimensional (2D) document printers in terms of their compact hardware design. This similarity enables them to be used in standard office environments rather than requiring strictly controlled laboratory conditions. As a result, the accessibility and convenience of inkjet-based 3D printers have contributed significantly to their increasing popularity.[23]

Inkjet 3D printing is used to create both 2D and 3D patterns based on computer-generated designs. This method requires food materials to be transformed into an 'ink' by blending them into a smooth consistency or by adding substances like hydrocolloids to help maintain the printed structure. Post-printing processes – such as cooking, baking, or chilling – are carried out separately.[24] Inkjet printing uses a thermal or piezoelectric head to release droplets onto targeted areas of food surfaces, enabling surface filling or image decoration. This technique is often applied to items like cookies, cakes, and pizzas.

Inkjet printing techniques are classified into two types: continuous jet printing and DOD printing. In continuous jet printing, ink is expelled continuously through a piezoelectric crystal vibrating at constant frequency. Conductive agents are added to the ink to achieve the required flowability. In DOD printing, ink is released from the print heads by pressure applied through a valve.

Inkjet printing typically processes low-viscosity materials that do not have sufficient mechanical strength to maintain a 3D structure, and is therefore mainly used to create two-dimensional images. To achieve high printing precision and accuracy, key factors include the compatibility between the ink and the substrate surface, the ink's viscosity and rheological properties, and the control of temperature and printing speed.[25] Three-dimensional edible food products, including cookies, cakes, and pastries, are constructed using a layered structure. This technique involves pre-patterning the food materials across multiple layers during the fabrication process.[26]

Selective sintering

Powder bed fusion is a 3D printing process that includes techniques such as SLS (Fig. 1(c)) and selective heat sintering (SHS). These methods involve using either a laser or an electron beam to melt or fuse powdered materials to build one layer at a time, resulting in a complete 3D structure. The laser scans and selectively fuses cross-sections of each layer on the powder surface. After each scan, the powder bed is lowered, and a fresh layer of powder is spread on top. This process is repeated until the final structure is complete. Finally, the unused powder is extracted and reused for subsequent printing. Selective laser sintering generally enables the fabrication of freestanding, high-resolution 3D structures with complex geometries. However, the range of usable materials is limited to powders, such as sugar, fat, or starch granules.[25] Industrial materials commonly used in this process include metals, ceramics, polymers, composites, and hybrids, but SLS, known for its high speed, precision, and range of surface finishes, can produce objects made from metal, plastic, and ceramic by using a high-powered laser to sinter polymer powders into solid structures. On the other hand, SHS employs a heated print head to melt thermoplastic powder and form 3D printed parts. Electron beam melting (EBM) uses an electron beam to provide the energy needed to heat and fuse the material.[27]

Binder jetting

Binder jetting metal additive manufacturing (BJ-MAM) (Fig. 1(d)), commonly referred to as metal 3D printing, is a powder bed-based additive manufacturing technique. In this process, liquid binder droplets are deposited selectively to bond powder particles, forming near-net-shape components. These components are then densified through a sintering process. Binder jetting metal additive manufacturing is recognized for its versatility in processing a variety of materials and its suitability for high-volume production.[28]

Binder jetting 3D printing (BJ3DP) is a 3D printing method that uses a powder bed and a liquid binding agent to build objects layer by layer. In this process, a binder solution is selectively deposited onto a bed of powder, causing the powder particles to adhere and form solid structures based on a digital model. A typical BJ3DP system includes a binder reservoir, a powder reservoir, and a build platform.[29] During printing, powder is dispensed from the powder reservoir onto the build platform. A roller then spreads the powder into a thin, even layer. Guided by the design file, the printer jets the binder solution onto specific areas of the powder bed to create the first layer of the object. This sequence of spreading powder and applying binder repeats layer by layer until the full object is formed.

Originally developed and patented at the Massachusetts Institute of Technology by Emanuel Sachs, BJ3DP was later commercialized by Z Corporation, which improved the technology by incorporating color printing and popularized the term '3D printing'. Today, BJ3DP is widely used in rapid prototyping and has found applications in fields such as electrochemistry, plastic surgery, bone scaffold fabrication, and the cosmetics industry.[30]

NUTRITIONAL IMPLICATIONS OF 3D FOOD PRINTING

Personalized nutrition

The primary goal is to facilitate diet and lifestyle changes that lead to improved health outcomes and enhanced physiological function. This integrative approach draws on expertise from a range of disciplines, including nutrition science, clinical medicine, genomics, epigenetics, systems biology, and behavioral science.[31]

Customizable nutrients for individual dietary nutrition

Personalized nutrition involves customizable nutrient composition – specifically the targeted modification of macronutrients (such as carbohydrates, proteins, and fats) and micronutrients (including vitamins, minerals, and bioactive compounds) – to align with individual metabolic needs and health objectives. Emerging tools – such as advanced nutritional assessments, digital health technologies, and omics-driven analyses – make it possible to develop highly personalized dietary strategies. These

© 2026 Society of Chemical Industry.

strategies often involve the intentional design of food structure and composition to enhance nutrient absorption, optimize metabolic responses, and cater to individual preferences. This degree of personalization enables more effective dietary interventions and promotes long-term, sustainable health benefits.[32] Advances in 'omics' fields such as microbiomics, proteomics, metabolomics, transcriptomics, and genomics research along with data technology, have progressively transformed customized dietary intake into a practical reality.

Genomics

Genomics has advanced into the post-genomic era, with genomic data now widely applied to customize nutritional supplementation giving rise to the interdisciplinary field of nutrigenetics. Three levels should be included in PN in the future, according to the International Society of Nutrigenetics/Nutrigenomics (ISNN): (i) conventional nutrition, guided by general suggestions according to socioeconomic, gender, and age characteristics; (ii) individualized nutrition that incorporates phenotypic data reflecting an individual's current nutritional status; and (iii) genotype-driven nutrition tailored to rare or common genetic variants. This framework underscores a shift from broad dietary guidelines toward more stratified and genetically informed PN strategies.[33]

Transcriptomics

Transcriptomics is used primarily to profile gene expression in living organisms under specific nutritional conditions, offering a comprehensive view of how dietary interventions influence intracellular RNA transcripts.[34]

There are two primary technologies used to measure the transcriptome: hybridization-based methods (e.g., microarrays) and sequence-based methods (e.g., RNA sequencing or RNA-seq). Transcriptomics studies reveal the expression status of specific genes or the entire set of expressed genes (the transcriptome) in an individual at a given time. The outcomes of such studies depend largely on technologies like real-time polymerase chain reaction (PCR) and high-throughput DNA microarrays.[35] RNA sequencing (RNA-seq) has also emerged as a powerful alternative, offering broader coverage of RNA types and providing more detailed functional insights. Transcriptomic analysis enables the examination of mRNA expression levels and differential variations in gene expression in reaction to dietary modifications or other influencing factors.[30] Transcriptomics offers molecular-level understanding of the biological reactions taking place at various phases of the 3D food printing process. The mechanical and osmotic stresses imposed by pre-processing steps like ingredient preparation, grinding, hydration, and formulation can change the expression of genes linked to stress response, protein modification, and carbohydrate metabolism, which in turn affect printability and flow behaviour.[36] Extrusion-based printing causes transcriptional alterations related to structural integrity, protein folding, and energy metabolism by subjecting food matrices to shear stress, pressure, and temperature changes during the processing stage. Thermal and oxidative stresses further modify genes related to lipid oxidation, starch transformation, and nutrient stability during post-processing stages like baking, frying, or drying. Transcriptomic analysis provides deeper insight into how processing conditions influence the structural and functional properties of 3D-printed foods, helping connect production methods with final quality characteristics. [37]

Proteomics

Traditional nutrition research focused primarily on providing essential nutrients for nourishment and preventing specific nutrient deficiencies or related disorders. Nutriproteomics uses proteomic tools to analyze molecular and cellular changes in protein expression and how they interact with other nutrients, recognizing that the bioavailability and function of nutrients – including bioactive peptides and proteins – can be influenced by the presence of other dietary components.[38] As a potential tool in PN, nutriproteomics can aid in the quantification and characterization of food-derived bioactive peptides and proteins, and the discovery of biomarkers to better understand their mechanisms of action and effectiveness. Nutriproteomics also holds potential for advancing medical and nutritional research by transforming biomarker and drug development, supporting nutraceutical discovery, modeling biological processes, linking diet to disease in preclinical studies, and paving the way toward PN strategies.[39]

Although transcriptomic analysis sheds light on alterations in gene expression at the mRNA level, post-transcriptional regulation means that these alterations do not always translate into functional results. Thus, by examining the proteins that carry out biological processes directly, proteomics enhances transcriptomics Proteomics focuses on large-scale protein identification and measurement, including structural alterations, interactions, and enzymatic activity.[40] Proteomic techniques are especially helpful in the context of 3D food printing for assessing how processing parameters affect protein behavior at various stages of production. Shear stress and hydration can change the solubility and conformation of proteins during pre-processing and extrusion, which can impact rheological characteristics and print stability. Subsequent post-processing procedures, such as heating or frying, further induce protein denaturation, aggregation, and cross-linking. These processing-induced protein alterations – which are directly related to the texture, digestibility, and nutritional value of 3D-printed foods – can be identified using mass spectrometry-based proteomic techniques.[41]

Metabolomics

'Metabolomics' refers to the study of metabolites – small molecules – found in biological samples. The complete set of these metabolites in a given sample is known as the 'metabolome'.[42] Metabolomics is considered the end point of human molecular analysis. Its application in dietary intervention research offers a more profound understanding of how diet influences metabolic changes, health, and related disorders, as well as the relationship between genotype and phenotype. Metabolomics can be applied in nutritional interventions to find biomarkers in food and support the evolution of customized diet plans and medicine.[43]

The microbiome

The microbiome is a primary source of human variation influencing dietary responses and it can be utilized for personalized diagnosis and the stratification of dietary responses and recommendations. Moreover, the microbiota is modifiable through interventions such as probiotics, prebiotics, antibiotics, and more recently, postbiotics – offering promising opportunities for preventive and therapeutic personalization of dietary strategies. Although the function of the commensal microbiota was largely disregarded until recently, its role in individual responses to meals and its ability to link environmental factors to host physiology are now widely acknowledged. Incorporating the microbiome as a key factor in explaining personal

 © 2026 Society of Chemical Industry.

uniqueness has led to a paradigm shift in understanding of inter-individual variability and its impact on responses to environmental influences such as diet.[44]

Nutrient retention

A systematic experimental approach was adopted to investigate the dynamics of nutrient retention. One study[45] evaluated how various preparation and treatment methods influenced the preservation of essential nutrients in diverse food ingredients. Monitoring tools were used to observe internal changes during processing, while nutritional analyses were conducted both before and after treatment to measure nutrient degradation. This approach enabled a quantitative understanding of factors affecting nutrient stability. By applying various processing techniques and ingredient types, the study aimed to reveal the intricate relationships between food treatment methods and nutritional preservation.[46]

Post-processing

After 3D printing, certain foods undergo post-processing to enhance accuracy, stability, and edibility. Techniques such as drying, freezing, boiling, baking, and steaming are applied to improve these aspects. However, not all food materials need post-processing. For example, 3D prints made from chocolate, cheese, or sugar do not require cooking, drying, or frying.[47] These materials may only need a mild cold setting to maintain their structural integrity. In contrast, wheat dough or other cereal-based doughs require additional cooking methods like baking or frying to become edible. Post-processing also helps improve the sensory qualities of food, such as reducing moisture content during baking and frying, which increases hardness and reduces stickiness.[48]

Drying

Drying encompasses methods like freeze-drying (FD), hot air drying (AD), and vacuum microwave drying (MVD). It is a common post-processing technique for preparing and storing food at ambient temperature.[49] When integrating drying with 3D printing technology, it is important to select the appropriate method carefully, as different drying techniques can yield significantly different outcomes. Vacuum microwave drying is a hybrid method that combines the advantages of low energy consumption, fast volumetric heating from microwave drying, and reduced evaporation temperature.[50]

Deep frying

Deep frying, also known as immersion frying, is a cooking technique in which food is submerged in hot oil for varying durations, typically heated to around 180 °C and exposed to air. This process induces several chemical and physical modifications to the food, such as Maillard reactions, protein denaturation, starch gelatinization, moisture reduction, and the formation of a crunchy crust. Nutrient-dense snacks were developed using barnyard millet, fried gram, and ajwain seeds, and were post-processed in 3D food printing using various methods including deep frying, hot-air drying, and microwave drying.[51]

Baking

Baking is the most widely used technique for cooking in 3D food printing, involving the use of dry heat, which transfers from the outer surface to the inner parts of the product, typically within an enclosed space such as an oven. During baking, various physicochemical changes take place, including protein denaturation, caramelization, starch gelatinization, the development of a porous structure and crust, moisture loss through evaporation, and expansion in volume. Baking also affects bioactive compounds, as the high temperature can rupture cell walls, leading to increased antioxidant capacity in baked products. Differences in the antioxidant capacity of free extracts have been observed between conventionally baked biscuits and those produced through 3D printing.[52]

Other methods

Various other post-processing methods, such as steaming, blanching, and roasting, are also used in food printing. Most of these techniques alter the shape and structure of printed products after they are printed. This highlights the ongoing need to identify and optimize the most effective post-processing methods.[53] Figure 2 shows the different stages of the 3D food-printing process.

Potential for dietary interventions

Behavioral lifestyle interventions involving dietary recommendations are commonly used to support weight loss, which can reduce the risk of chronic ailments such as type 2 diabetes, hypertension, and certain cancers in some individuals.[54] These interventions encompass various dietary strategies – such as low energy density, low carbohydrate content, and low fat or calorie content – aimed at creating the energy deficit necessary for weight loss. While many people experience at least moderate weight loss and some achieve significant results through these approaches, the specific impact of different dietary treatments on quality of life (QOL) remains poorly understood.[55] Figure 3 explains the step-by-step process of the 3D food printing technique.

Elderly care

Older adults have distinct nutritional requirements. Research indicates they exhibit a higher anabolic threshold for dietary protein or amino acids to effectively stimulate muscle protein synthesis.[56] Recent reviews suggest that individuals in the 'oldest old' category may require protein intakes exceeding 1.0 g kg^{-1} body weight, with data from smaller samples of healthy octogenarians suggesting a range of 0.8–1.5 g kg^{-1}.[57] Maintaining vitamin D levels within the range of 40–60 nmol L^{-1} has been linked to advantages for cognitive function, muscular strength, and overall musculoskeletal health. Dietary patterns rich in fruits, vegetables, nuts, dairy, fish, and whole grains are connected to a slower decline in muscle strength. Age-related changes in gut microbiota may further impact nutrient absorption and availability. Notably, much of the existing research on the nutritional needs of the oldest old has been conducted in outpatient settings.[56]

Sports

Dietary supplements can play a major part in helping athletes meet their caloric, carbohydrate, and protein requirements. Various supplement products have been shown to enhance performance. Athletes engaged in moderate-to-high-volume training often require increased intake of carbohydrates and protein to meet their macronutrient requirements.[58] Ideally, most carbohydrates should come from complex sources with a minimal to moderate glycemic index, commonly referred to as 'slow carbs'. Suitable examples include fruits, vegetables, whole grains, and legumes. Inadequate protein intake can lead to a negative nitrogen balance, leading to increased protein breakdown, delayed post-exercise recovery, and potentially contributing to muscle

 © 2026 Society of Chemical Industry.

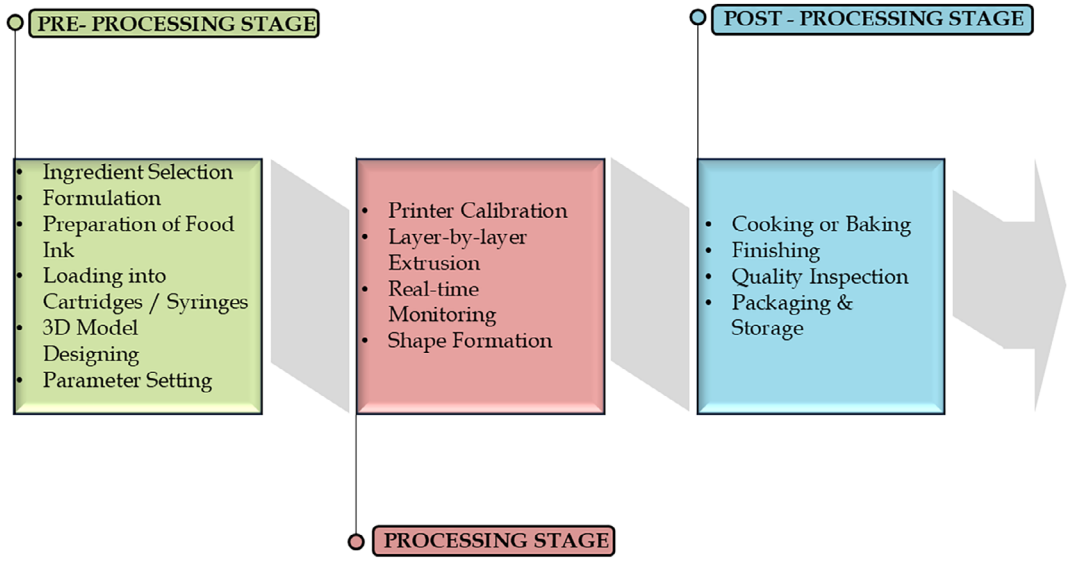


Figure 2. Stages of the three-dimensional (3D) food printing process.

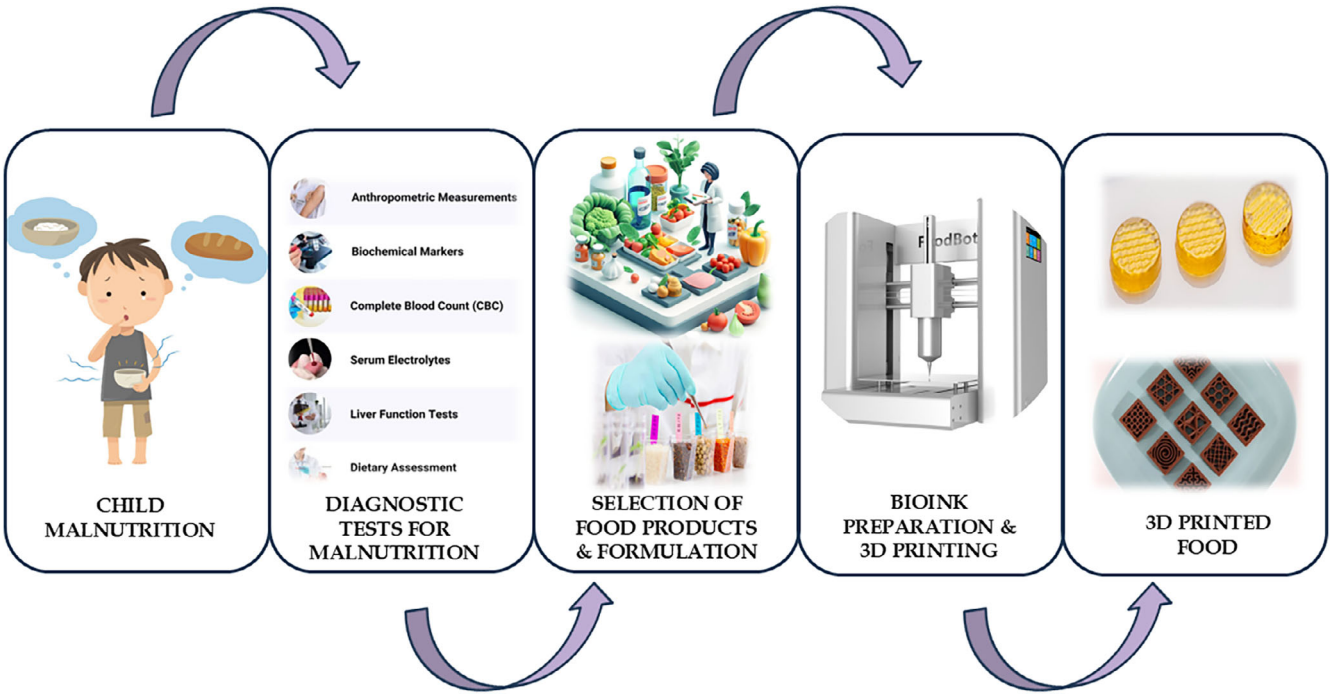


Figure 3. Three-dimensional (3D) food printing process.

wasting, training intolerance, and overtraining. To maintain a neutral or positive nitrogen balance and support recovery, it is essential to consume adequate amounts of protein.[59]

Clinical diet

The main goal of clinical nutrition in older adults is to supply sufficient energy, high-quality protein, essential micronutrients, and adequate hydration to fulfill the unique physiological demands of aging.[60] As people age, they frequently encounter changes in appetite, digestion, nutrient absorption, and metabolism, which can increase the risk of nutritional deficiencies. If left unaddressed, these deficiencies may contribute to conditions such as malnutrition, sarcopenia, frailty, and weakened immune function. Ensuring optimal nutritional status in older adults is crucial to avoid illness and to sustain physical independence, promoting activity levels, and enhancing the ability to participate in rehabilitation.[61] Adequate nutrition plays a vital role in improving overall quality of life, supporting cognitive and physical health, and reducing the likelihood of hospital readmissions, institutional care, and associated health-care costs. The general therapeutic goals of clinical nutrition such as preventing malnutrition and supporting recovery are consistent across age groups but the focus often shifts in geriatric care. For younger patients, reducing morbidity and mortality may be the primary concern, whereas in

 © 2026 Society of Chemical Industry.

elderly people, particularly those with chronic illnesses or reduced life expectancy, the emphasis is typically on preserving quality of life, functional capacity, and independence.[62]

Challenges in maintaining bioavailability and digestibility

Bioavailability and digestibility are important elements that can be affected considerably by the processing conditions and formulation strategies used in 3D food printing. In particular, high-temperature processing is known to reduce the nutritional content of foods through mechanisms such as the Maillard reaction, where proteins interact with polysaccharides, resulting in the loss of essential amino acids.[63] This presents a major challenge for 3D printed foods – especially when developing formulations for vulnerable populations, such as patients with dysphagia, where maintaining nutrient integrity is vital. The processing methods used in 3D food printing often involve lower temperatures and high moisture levels, which are better suited to preserving nutrient bioavailability.[64] Moist heat can promote protein denaturation or unfolding, making proteins more accessible to proteolytic enzymes during digestion in the stomach and small intestine. However, balancing the need for structural stability of the printed product with the requirement for enhanced digestibility remains a substantial challenge. Optimizing printing parameters, ingredient selection, and post-processing treatments is therefore essential to ensure that 3D printed foods are both nutritionally adequate and easily digestible.[64]

Advantages

Customized food and waste reduction

The food processing industry is witnessing an increase in the use of 3D printing technology, which shows promise in personalized nutrition, customized food design, and rapid testing of creative culinary concepts. This technology enables the creation of intricate food structures tailored to individual dietary needs, potentially transforming how we approach food customization and production.[65] The Food and Agriculture Organization defines food loss as the reduction in food quantity or quality brought about by the choices and actions of food suppliers in the chain – excluding consumers, food service providers, and retailers. Food waste, however, happens at the consumer and retail levels. By repurposing residues from cereals, meat, dairy, fruits, and vegetables, 3D food printing offers an innovative approach to transform these materials into value-added products. In addition to reducing food waste, this process optimizes food manufacturing. Integrating 3DFP into the supply chain can also promote a more equitable distribution of food resources, addressing disparities and bolstering food security.[66] Figure 4 shows the different applications of 3D food printing technology.

Cost-efficient and personalized nutrition

By incorporating 3D food printing into the food industry, it may be possible to reduce production costs and create foods with digitally customized nutrient compositions, customizable designs, and individualized dietary options. Recent advances in innovative ingredients, printing technologies, specialized food printers, and post-processing methods have enhanced this technology's capabilities. These developments collectively position 3D food printing as a promising solution to bolster global food security.[53]

Utilization of plant-based ingredients and on-demand production

Three-dimensional food printing, particularly using extrusion-based methods, offers considerable potential for utilizing plant-based materials to create customized, nutritious, and sustainable food products.[67] This technology enables the design of foods tailored to individual dietary needs and preferences, enhancing personalization in nutrition. Plant-derived ingredients such as chocolate (hot-melt materials), hydrogels, and soft materials like cereals, fruits, and vegetables are commonly used due to their favorable properties for printing, including appropriate viscosity and structural integrity.[68] In addition to encouraging the creation of varied food textures and flavors, using these materials simplifies the food supply chain by enabling on-demand manufacturing. Plant-based ingredient integration also satisfies customer demand for more environmentally responsible and health-conscious food options. Despite these promising applications, maintaining consistent printability remains challenging. Ongoing research is focusing on overcoming these hurdles to fully realize the potential of 3D food printing in revolutionizing food manufacturing and consumption.[69]

Dysphagia-friendly food solutions in health care

Three-dimensional food printing presents a promising solution for creating dysphagia-friendly foods by enhancing the visual and textural qualities of meals, improving patient appetite and nutritional intake. Through extrusion-based methods, a variety of foods can be printed to comply with International Dysphagia Diet Standardisation Initiative (IDDSI) texture standards, ensuring safety and consistency.[70] The technology also enables the fortification of meals with essential nutrients, addressing nutritional deficiencies among dysphagia patients. The ease of preparation and reduced need for specialized culinary skills make 3DFP a practical option for healthcare facilities, ultimately contributing to better patient outcomes and quality of life. By enabling the creation of aesthetically pleasing, safe-to-eat meals that adhere to standardized texture levels, this technology significantly benefits individuals with swallowing difficulties. It supports PN through nutrient fortification and ensures consistency in food quality while streamlining preparation procedures at medical facilities.[64]

Nutrition for the elderly and age-related health needs

According to WHO projections, neurodegenerative disorders (NDDs) will overtake cancer as the world's second biggest cause of death by 2040, mostly as a result of an ageing population. Age is the primary risk factor for non-communicable diseases (NDDs), such as Huntington's disease (HD), Parkinson's disease (PD), Alzheimer's disease (AD), and amyotrophic lateral sclerosis (ALS). The prevalence of these illnesses rises exponentially with age. For example, PD is roughly 1% more common in people over 65 and 4.3% more common in people over 85. Aging leads to various detrimental changes in the body, such as the accumulation of DNA damage, mitochondrial dysfunction, and oxidative stress, which contribute to neuronal degeneration, resulting in a progressive loss of synapses, inflammatory responses in the nervous system, and ultimately neuronal death. Although these phenomena are observed in neural tissues affected by degenerative lesions, their sequence and intensity vary among individuals. According to the latest statistics released by the Alzheimer's Association International, by 2030, it is projected that 75 million individuals worldwide will suffer from Alzheimer's disease (AD), the most common form of dementia, which manifests clinically primarily through cognitive dysfunction and memory impairment.

 © 2026 Society of Chemical Industry.



Figure 4. Applications of three-dimensional (3D) food printing.

The pathological manifestations of AD include κ-amyloid toxicity, hyperphosphorylation of τ proteins, degeneration of the cholinergic system, genetic mutations, vascular factors, oxidative stress, neuroinflammation, mitochondrial dysfunction, impairments of autophagy, abnormalities in insulin signaling, and imbalances in the gut microbiota.[71] The application of 3D printing technology to develop personalized meals for older adults with dysphagia shows significant promise. By adjusting both texture and nutritional content, this approach provides a customized solution that can enhance the quality of life for individuals with swallowing difficulties. Precise control over food texture improves safety while ensuring adequate nutrient intake, making it an important advancement in nutritional care and overall meal satisfaction for this vulnerable group. [72]

Therapeutic and allergen-free food personalization using 3D printing

Three-dimensional food printing is revolutionizing personalized diets, especially for vegan, gluten-free, and allergen-free needs. It uses plant-based ingredients like legumes, nuts, and fungi, along with natural binders such as hydrocolloids, to create meals that match specific dietary requirements. This technology makes it possible to regulate the nutritional content precisely and add necessary vitamins and minerals that are suited to each person's unique health needs. It ensures that people with dietary limitations receive appropriate nutrients without sacrificing flavour or texture, which is especially advantageous for them. It is now possible to customize food textures, forms, and nutrient content precisely due to this creative method, which makes it simpler to create meals that are suited to both particular health requirements and personal preferences. The capability to integrate fortified ingredients, such as vitamins, minerals, and functional nutrients, into the printing process also offers the potential to improve dietary intake and prevent malnutrition, a common issue among the elderly population. The technology enables the production of visually appealing food, which can stimulate appetite in individuals with reduced interest in eating, thereby promoting better overall nutrition. Efficient meal planning is made possible by 3D food printing, which also improves food accessibility and acceptability and guarantees that senior citizens eat meals that are well-balanced and full of nutrients.[73]

In one study, three-dimensional food printing was applied to develop a fruit-based snack tailored for children, emphasizing personalization in both shape and nutrition. By adjusting printing parameters like flow rate and speed, the researchers demonstrated how the snack's texture and structure could be optimized.

 © 2026 Society of Chemical Industry.

This application highlights the potential of 3D printing to create personalized, health-oriented foods that are both visually appealing and suitable for specific dietary needs, making it particularly valuable for developing allergen-free, vegan, and child-friendly products. [74]

Three-dimensional food printing enables efficient meal planning while improving food accessibility and acceptability, increasing the likelihood that senior citizens consume well-balanced, nutritious meals. The technology allows precise incorporation of nutrients, active compounds, and textures to enhance therapeutic outcomes and support medical nutrition therapy. It also contributes to sustainability by utilizing unconventional ingredients and reducing waste, while opening creative avenues in gastronomy through the production of intricate food structures and novel culinary experiences.[75]

Future trends and challenges

The intersection of artificial intelligence (AI), machine learning (ML), and 3D food printing represents a transformative frontier in modern technology.[76] As the global population is projected to reach nearly 10 billion by 2050, the demand for sustainable, high-quality food products continues to escalate.[77] However, the efficient deployment of this technology depends on overcoming inherent challenges such as production inconsistencies, material limitations, and scalability issues.[76]

Artificial intelligence and ML provide powerful tools to address these challenges using advanced computational methods. Real-time visual evaluation of printed layers using convolutional neural networks (CNNs) can detect structural and surface faults. Recurrent neural networks (RNNs) and long short-term memory (LSTM) models enable time-series forecasts of extrusion stability and rheological behavior during continuous printing. Random forest and support vector machine (SVM) algorithms are used to classify material printability according to compositional and flow properties.[73] Adaptive process control is further facilitated by reinforcement learning (RL) approaches, which dynamically modify printing parameters – such as temperature, printing speed, and nozzle width – in response to sensor feedback. Food structures can be realistically optimized prior to manufacturing using digital twin technologies and AI-driven simulation frameworks, increasing output and decreasing material waste. Despite this potential, several barriers remain, including unstructured and incomplete datasets, regulatory constraints, and a lack of standardized methodologies. Moreover, the diverse range of 3D food printing technologies and materials further complicates the development of universally applicable AI solutions.[76]

The evolution of AI-powered 3D food printing is poised to revolutionize not only the production of food but also related sectors such as agriculture, health care, and commercial food services. Models based on AI can optimize ingredient utilization, monitor crop quality, and detect food adulteration, enabling a comprehensive approach to food safety and sustainability.[77] However, interdisciplinary cooperation between scholars, industry stakeholders, and regulatory agencies will be necessary to realize these advantages. The present status of artificial intelligence and ML in 3D food printing was examined in a review by Rojek *et al*.,[76] which identified key trends, challenges, and future opportunities for growth.[76]

Personalized nutrition is a growing field that customizes dietary recommendations based on an individual's unique traits such as genetics, lifestyle, environment, and health condition to enhance health, prevent disease, and support long-term well-being.[78] Unlike traditional, one-size-fits-all dietary guidelines, PN integrates a comprehensive array of scientific disciplines, including nutrition science, genomics, epigenetics, systems biology, medicine, and behavioral science, to design individualized nutrition plans.[79] By considering biological and environmental elements that affect how food reacts, PN offers a more precise and adaptive approach to diet and lifestyle modification. Key components of PN include genetic testing, microbiome analysis, and the incorporation of lifestyle components like exercise, rest, stress reduction, and eating patterns. Real-time data collection and adaptive nutritional recommendations are also made possible by developments in wearable biosensors, AI-powered dietary assessment systems, and machine learning-based microbiome analytics. Precision-based nutritional therapies can be produced by integrating genomic, metabolomic, and lifestyle data using deep learning models like artificial neural networks and gradient boosting algorithms.[1] Although evidence suggests that PN can enhance motivation, support behavior change, and lead to improved health outcomes, further research is necessary to determine its relative effectiveness compared to generalized public health recommendations.[79]

Food 3D printing offers the ability to control texture, nutritional content, and integrate nutraceuticals, going beyond aesthetic design. This technology also supports sustainability efforts, including waste valorization and the development of eco-friendly packaging solutions. Extrusion-based printing is especially notable for its capacity to manage the flow and rheological properties of food materials, with important factors like nozzle height, diameter, and printing speed influencing the final product's quality. However, challenges persist in determining the printability of materials and ensuring post-printing stability and mechanical integrity. Finite element modeling (FEM) combined with AI-assisted parameter optimization is one example of an advanced computational modeling technique that makes it possible to simulate extrusion flow behavior, structural deformation, and post-printing stability. By fusing machine learning algorithms with physics-based simulations, hybrid models increase prediction accuracy and lessen the need for empirical investigation.[80]

Food printing, also known as food-layered manufacturing, has emerged as a transformative technology in the food industry, offering unprecedented possibilities for customization, efficiency, and sustainability.[81] While technical advancements in 3DFP have enabled the creation of intricate and innovative food products, consumer acceptance remains a critical challenge.[82]

Factors such as sensory expectations, food safety, and nutritional value significantly influence public perceptions and adoption rates. Addressing these concerns is essential for the integration of 3DFP into mainstream applications, particularly in domestic and culturally specific markets. Social media data and structured surveys can be used to assess customer opinions using machine learning-based sentiment analysis and natural language processing (NLP) techniques, allowing for the prediction of acceptance drivers such as perceived sustainability, naturalness, and safety.[78]

Three-dimensional food printing synthesizes advances in material science, post-processing methods, and technology adoption, highlighting the interplay between product novelty, consumer knowledge, and behavioral intentions. By examining these dynamics, the discussion provides insights for designing consumer-centric 3DFP solutions that strike a balance between creativity, practicality, and sensory appeal.[81,82]

© 2026 Society of Chemical Industry.

AUTHOR CONTRIBUTIONS

Senbakapriya Selvaraju: formal analysis, writing – original draft. Nivetha Senthilkumar: formal analysis, writing – original draft. Anusuya Thirumalaisamy: formal analysis, writing – original draft. Megaasri Sasikumar: writing – original draft. Mahalakshmi Balasubramaniyan: writing – original draft. Dikshya Thiyagu: writing – original draft. Akash Karthikeyan: conceptualization, formal analysis, project administration, supervision, writing – original draft, writing – review and editing.

FUNDING INFORMATION

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1 Godoi FC, Prakash S and Bhandari BR, 3D printing technologies applied for food design: status and prospects. *J Food Eng* **179**:44–54 (2016).
2 Sun J, Zhou W, Yan L, Huang D and Lin L-y, Extrusion-based food printing for digitalized food design and nutrition control. *J Food Eng* **220**: 1–11 (2018).
3 Eswaran H, Ponnuswamy RD and Kannapan RP, Perspective approaches of 3D printed stuffs for personalized nutrition: a comprehensive review. *Ann 3D Printed Med* **12**:100125 (2023).
4 Siacor FDC, Chen Q, Zhao JY, Han L, Valino AD, Taboada EB *et al*., On the additive manufacturing (3D printing) of viscoelastic materials and flow behavior: from composites to food manufacturing. *Addit Manuf* **45**:102043 (2021).
5 Bravi L and Murmura F, Additive manufacturing in the food sector: a literature review, in *Macromolecular Symposia*. Wiley Online Library, (2021).
6 Ngo TD, Kashani A, Imbalzano G, Nguyen KT and Hui D, Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. *Compos Part B Eng* **143**:172–196 (2018).
7 Bhatia A and Sehgal AK, Additive manufacturing materials, methods and applications: a review. *Mater Today Proc* **81**:1060–1067 (2023).
8 Javaid M and Haleem A, Using additive manufacturing applications for design and development of food and agricultural equipments. *Int J Mater Prod Technol* **58**:225–238 (2019).
9 Jadhav A and Jadhav VS, A review on 3D printing: an additive manufacturing technology. *Mater Today Proc* **62**:2094–2099 (2022).
10 Matias E and Rao B, 3D printing: on its historical evolution and the implications for business, in *2015 Portland International Conference on Management of Engineering and Technology (PICMET)*. IEEE, Portland (2015).
11 Jiménez M, Romero L, Domínguez IA, Espinosa MM and Domínguez M, Additive manufacturing technologies: an overview about 3D printing methods and future prospects. *Complexity* **2019**:9656938 (2019).
12 Earle MD, Innovation in the food industry. *Trends Food Sci Technol* **8**: 166–175 (1997).
13 Sun J, Peng Z, Yan L, Fuh JY and Hong GS, 3D food printing—an innovative way of mass customization in food fabrication. *Int J Bioprint* **1**: 27–38 (2015).
14 Rodgers S, Minimally processed functional foods: technological and operational pathways. *J Food Sci* **81**:R2309–R2319 (2016).
15 Eetemadi A, Rai N, Pereira BMP, Kim M, Schmitz H and Tagkopoulos I, The computational diet: a review of computational methods across diet, microbiome, and health. *Front Microbiol* **11**:393 (2020).
16 McClements DJ, Barrangou R, Hill C, Kokini JL, Lila MA, Meyer AS *et al*., Building a resilient, sustainable, and healthier food supply through innovation and technology. *Annu Rev Food Sci Technol* **12**:1–28 (2021).
17 Agunbiade AO, Song L, Agunbiade OJ, Ofoedu CE, Chacha JS, Duguma HT *et al*., Potentials of 3D extrusion-based printing in resolving food processing challenges: a perspective review. *J Food Process Eng* **45**:e13996 (2022).
18 Lille M, Nurmela A, Nordlund E, Metsä-Kortelainen S and Sozer N, Applicability of protein and fiber-rich food materials in extrusion-based 3D printing. *J Food Eng* **220**:20–27 (2018).
19 Kewuyemi YO, Kesa H and Adebo OA, Trends in functional food development with three-dimensional (3D) food printing technology: prospects for value-added traditionally processed food products. *Crit Rev Food Sci Nutr* **62**:7866–7904 (2022).
20 Guo Z, Arslan M, Li Z, Cen S, Shi J, Huang X *et al*., Application of protein in extrusion-based 3D food printing: current status and prospectus. *Foods* **11**:1902 (2022).
21 Hussain S, Malakar S and Arora VK, Extrusion-based 3D food printing: technological approaches, material characteristics, printing stability, and post-processing. *Food Eng Rev* **14**:100–119 (2022).
22 Liu Q, Zhang N, Wei W, Hu X, Tan Y, Yu Y *et al*., Assessing the dynamic extrusion-based 3D printing process for power-law fluid using numerical simulation. *J Food Eng* **275**:109861 (2020).
23 Yang H, Lim JC, Liu Y, Qi X, Yap YL, Dikshit V *et al*., Performance evaluation of ProJet multi-material jetting 3D printer. *Virtual Phys Prototyp* **12**:95–103 (2017).
24 Burke-Shyne S, Gallegos D and Williams T, 3D food printing: nutrition opportunities and challenges. *Br Food J* **123**:649–663 (2021).
25 Liu Z and Zhang M, 3D food printing technologies and factors affecting printing precision, in *Fundamentals of 3D food printing and applications*. Elsevier, pp. 19–40 (2019).
26 Sun J, Peng Z, Zhou W, Fuh JY, Hong GS and Chiu A, A review on 3D printing for customized food fabrication. *Procedia Manuf* **1**:308–319 (2015).
27 Shahrubudin N, Lee TC and Ramlan R, An overview on 3D printing technology: technological, materials, and applications. *Procedia Manuf* **35**:1286–1296 (2019).
28 Lores A, Azurmendi N, Agote I and Zuza E, A review on recent developments in binder jetting metal additive manufacturing: materials and process characteristics. *Powder Metall* **62**:267–296 (2019).
29 Dini F, Ghaffari SA, Jafar J, Hamidreza R and Marjan S, A review of binder jet process parameters; powder, binder, printing and sintering condition. *Metal Powder Report* **75**:95–100 (2020).
30 Sen K, Mehta T, Sansare S, Sharifi L, Ma AW and Chaudhuri B, Pharmaceutical applications of powder-based binder jet 3D printing process–a review. *Adv Drug Deliv Rev* **177**:113943 (2021).
31 Wang F, Zheng J, Cheng J, Zou H, Li M, Deng B *et al*., Personalized nutrition: a review of genotype-based nutritional supplementation. *Front Nutr* **9**:992986 (2022).
32 Singar S, Nagpal R, Arjmandi BH and Akhavan NS, Personalized nutrition: tailoring dietary recommendations through genetic insights. *Nutrients* **16**:2673 (2024).
33 Ferguson LR, De Caterina R, Görman U, Allayee H, Kohlmeier M, Prasad C *et al*., Guide and position of the international society of nutrigenetics/nutrigenomics on personalised nutrition: part 1-fields of precision nutrition. *Lifestyle Genomics* **9**:12–27 (2016).
34 Elliott RM, Transcriptomics and micronutrient research. *Br J Nutr* **99**: S59–S65 (2008).
35 Perkel J, *Transcriptome Analysis: Microarrays, Qpcr and Rna-Seq*. Biocompare: The Buyer's Guide for Life Scientists, (2013).
36 Dong Z and Chen Y, Transcriptomics: advances and approaches. *Sci China Life Sci* **56**:960–967 (2013).
37 Stark C, Jenison SE and Ngo MT, Omics approaches to study and model cell-cell interactions in engineered tissues. *Frontiers in Chemical Engineering* **7**:1629455 (2025).
38 Pandita D and Pandita A, Omics technology for the promotion of nutraceuticals and functional foods. *Front Physiol* **13**:817247 (2022).
39 Abril AG, Pazos M, Villa TG, Calo-Mata P, Barros-Velázquez J and Carrera M, Proteomics characterization of food-derived bioactive peptides with anti-allergic and anti-inflammatory properties. *Nutrients* **14**:4400 (2022).
40 Aebersold R and Mann M, Mass spectrometry-based proteomics. *Nature* **422**:198–207 (2003).
41 Cravatt BF, Simon GM and Yates Iii JR, The biological impact of mass-spectrometry-based proteomics. *Nature* **450**:991–1000 (2007).

 © 2026 Society of Chemical Industry.

42 Mussap M, Zaffanello M and Fanos V, Metabolomics: a challenge for detecting and monitoring inborn errors of metabolism. *Ann Transl Med* **6**:338 (2018).
43 Tebani A and Bekri S, Paving the way to precision nutrition through metabolomics. *Front Nutr* **6**:41 (2019).
44 Bashiardes S, Godneva A, Elinav E and Segal E, Towards utilization of the human genome and microbiome for personalized nutrition. *Curr Opin Biotechnol* **51**:57–63 (2018).
45 Wieringa FT, Laillou A, Guyondet C, Jallier V, Moench-Pfanner R and Berger J, Stability and retention of micronutrients in fortified rice prepared using different cooking methods. *Ann N Y Acad Sci* **1324**: 40–47 (2014).
46 Moyo HN, The impact of food processing techniques on nutrient retention and bioavailability. *Int Res J Eng Technol* **8**:435–460 (2024).
47 Zhong L, Lewis JR, Sim M, Bondonno CP, Wahlqvist ML, Mugera A *et al.*, Three-dimensional food printing: its readiness for a food and nutrition insecure world. *Proc Nutr Soc* **82**:468–477 (2023).
48 Yatmaz HA, 3D-printed meat paste using minimal additive: assessment of rheological and printing behavior with post-processing stability. *Food Biophysics* **19**:503–516 (2024).
49 Nwankwo CS, Okpomor EO, Dibagar N, Wodecki M, Zwierz W and Figiel A, Recent developments in the hybridization of the freeze-drying technique in food dehydration: a review on chemical and sensory qualities. *Foods* **12**:3437 (2023).
50 Calín-Sánchez Á, Lipan L, Cano-Lamadrid M, Kharaghani A, Masztalerz K, Carbonell-Barrachina ÁA *et al.*, Comparison of traditional and novel drying techniques and its effect on quality of fruits, vegetables and aromatic herbs. *Foods* **9**:1261 (2020).
51 Dangal A, Tahergorabi R, Acharya DR, Timsina P, Rai K, Dahal S *et al.*, Review on deep-fat fried foods: physical and chemical attributes, and consequences of high consumption. *Eur Food Res Technol* **250**: 1537–1550 (2024).
52 Waseem M, Tahir AU and Majeed Y, Printing the future of food: the physics perspective on 3D food printing. *Food Physics* **1**:100003 (2024).
53 Mudau M and Adebo OA, Three dimensional (3D)-printed foods: a review of recent advances in their ingredients, printing techniques, food printers, post-processing methods, consumer acceptance and safety. *J Food Process Eng* **47**:e14621 (2024).
54 Gostoli S, Raimondi G, Popa AP, Giovannini M, Benasi G and Rafanelli C, Behavioral lifestyle interventions for weight loss in overweight or obese patients with type 2 diabetes: a systematic review of the literature. *Curr Obes Rep* **13**:224–241 (2024).
55 Godos J, Guglielmetti M, Ferraris C, Frias-Toral E, Domínguez Azpíroz I, Lipari V *et al.*, Mediterranean diet and quality of life in adults: a systematic review. *Nutrients* **17**:577 (2025).
56 Dowling L, Lynch DH, Batchek D, Sun C, Mark-Wagstaff C, Jones E *et al.*, Nutrition interventions for body composition, physical function, cognition in hospitalized older adults: a systematic review of individuals 75 years and older. *J Am Geriatr Soc* **72**:2206–2218 (2024).
57 Tucker E, Luscombe-Marsh N, Ambrosi C and Lushington K, Nutritional status and quality-of-life of older adults in aged care: a systematic review and meta-analysis. *Exp Gerontol* **162**:111764 (2022).
58 Kerksick CM, Arent S, Schoenfeld BJ, Stout JR, Campbell B, Wilborn CD *et al.*, International society of sports nutrition position stand: nutrient timing. *J Int Soc Sports Nutr* **14**:33 (2017).
59 Pramuková B, Szabadosová V and Šoltésová A, Current knowledge about sports nutrition. *Australas Med J* **4**:107 (2011).
60 Cederholm T, Standard operating procedures for ESPEN guidelines and consensus papers. *Clin Nutr* (2015).
61 Liu S, Zhang L and Li S, Advances in nutritional supplementation for sarcopenia management. *Front Nutr* **10**:1189522 (2023).
62 Volkert D, Beck AM, Cederholm T, Cruz-Jentoft A, Goisser S, Hooper L *et al.*, ESPEN guideline on clinical nutrition and hydration in geriatrics. *Clin Nutr* **38**:10–47 (2019).
63 Zhu W, Iskandar MM, Baeghbali V and Kubow S, Three-dimensional printing of foods: a critical review of the present state in healthcare applications, and potential risks and benefits. *Foods* **12**:3287 (2023).
64 Lorenz T, Iskandar MM, Baeghbali V, Ngadi MO and Kubow S, 3D food printing applications related to dysphagia: a narrative review. *Foods* **11**:1789 (2022).
65 Escalante-Aburto A, Trujillo-de Santiago G, Álvarez MM and Chuck-Hernández C, Advances and prospective applications of 3D food printing for health improvement and personalized nutrition. *Compr Rev Food Sci Food Saf* **20**:5722–5741 (2021).
66 Taneja A, Sharma R, Ayush K, Sharma A, Mousavi Khaneghah A, Regenstein JM *et al.*, Innovations and applications of 3-D printing in food sector. *Int J Food Sci Technol* **57**:3326–3332 (2022).
67 Wen Y, Chao C, Che QT, Kim HW and Park HJ, Development of plant-based meat analogs using 3D printing: status and opportunities. *Trends Food Sci Technol* **132**:76–92 (2023).
68 Waghmare R, Suryawanshi D and Karadbhajne S, Designing 3D printable food based on fruit and vegetable products—opportunities and challenges. *J Food Sci Technol* **60**:1447–1460 (2023).
69 Wang M, Li D, Zang Z, Sun X, Tan H, Si X *et al.*, 3D food printing: applications of plant-based materials in extrusion-based food printing. *Crit Rev Food Sci Nutr* **62**:7184–7198 (2022).
70 Padhiary M, Barbhuiya JA, Roy D and Roy P, 3D printing applications in smart farming and food processing. *Smart Agric Technol* **9**:100553 (2024).
71 Ma M, Gu J, Wang D-A, Bi S, Liu R, Zhang X *et al.*, Applications of 3D printing in aging. *Int J Bioprint* **9**:732 (2023).
72 Chao C, Nam HK, Park HJ and Kim HW, Potentials of 3D printing in nutritional and textural customization of personalized food for elderly with dysphagia. *Appl Biol Chem* **67**:25 (2024).
73 Xie Y, Liu Q, Zhang W, Yang F, Zhao K, Dong X *et al.*, Advances in the potential application of 3D food printing to enhance elderly nutritional dietary intake. *Foods* **12**:1842 (2023).
74 Derossi A, Caporizzi R, Azzollini D and Severini C, Application of 3D printing for customized food. A case on the development of a fruit-based snack for children. *J Food Eng* **220**:65–75 (2018).
75 Arshad R, Saqib A, Sharif HR, Liaqat A and Xu B, Recent advances in 3D food printing: therapeutic implications, opportunities, potential applications, and challenges in the food industry. *Food Res Int* **203**: 115791 (2025).
76 Rojek I, Mikołajewski D, Kempiński M, Galas K and Piszcz A, Emerging applications of machine learning in 3D printing. *Appl Sci* **15**:1781 (2025).
77 Natarajan S and Vijayakumar P, Food quality optimization using artificial intelligence and machine learning, in *Food in the Metaverse and Web 30 Era: Intersecting Food, Technology, and Culture*. IGI Global Scientific Publishing, pp. 57–70 (2025).
78 Prasad G, Padhiary M, Hoque A and Kumar K, Ai-driven personalized nutrition apps and platforms for enhanced diet and wellness, in *Food in the Metaverse and Web 30 Era: Intersecting Food, Technology, and Culture*. IGI Global Scientific Publishing, pp. 125–158 (2025).
79 Donovan SM, Abrahams M, Anthony JC, Bao Y, Barragan M, Bermingham KM *et al.*, Personalized nutrition: perspectives on challenges, opportunities, and guiding principles for data use and fusion. *Crit Rev Food Sci Nutr* **65**(30):7151–7169 (2025).
80 Liu Z, Zhang M, Bhandari B and Wang Y, 3D printing: printing precision and application in food sector. *Trends Food Sci Technol* **69**:83–94 (2017).
81 Raja V, Nimbkar S, Moses JA, Ramachandran Nair SV and Anandharamakrishnan C, Modeling and simulation of 3D food printing systems—scope, advances, and challenges. *Foods* **12**:3412 (2023).
82 Bareen MA, Prakash S, Sahu JK, Bhandari B and Naik S, Understanding the intention of consumers towards 3D food printing: exploratory study of psychological factors and sensory analysis. J Food *Sci Technol* **18**:1–12 (2025).

 © 2026 Society of Chemical Industry.