

AN OVERVIEW OF NUTRITIOUS AND TEXTURE-MODIFIED FOODS USING 3D FOOD PRINTING

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Abstract

Three-dimensional (3D) food printing is an emerging technology that has transformed the food industry by enabling the creation of nutrition-enriched and texture-modified foods. This review paper provides a comprehensive overview of the current state of 3D food printing, focusing on its applications in producing foods with enhanced nutritional content and tailored textures. Various types of nutrition-enriched foods and texture-modified foods, including soft foods for individuals with swallowing issues, were discussed. The challenges associated with 3D food printing were examined, including texture consistency and consumer acceptance. Finally, this review explores the potential applications of 3D food printing in various sectors, including healthcare, space exploration, and sustainable food production. This review highlights the vast opportunities and challenges of 3D food printing, providing insights for future research and development in this exciting field.

Keywords: 3D foods; Nutrition; Texture modified foods; Nutrient-rich foods; Personalized foods

Introduction

Additive manufacturing is used to build physical parts or structures by depositing materials layer by layer. It is also known as solid freeform fabrication (SFF). This process is commonly known as '3D (three-dimensional) printing.' Various goods can be produced using this technology using a 3D scanner or a basic 3D model. A computer model is used to print food (CAD). A typical food printer consists of three components: a computer that runs software to facilitate user interaction with the printer, software that connects the computer to the motor control box, and motors for the food printer that are managed by the control box. Accurate material placement is

made possible by the controlled extrusion or other deposition operations of the printer. While printing, the printer effectively regulates the temperature of the materials. These are the major components enabling the development of various 3D foods.

A typical 3D printing procedure consists of several clearly defined steps. Initially, real-time item scanning or 3D model generation with computer-aided design (CAD) software is the first step. The form and surface properties are kept in a special stereolithography file format that comes with 3D printing. Subsequently, a slicing program that converts the 3D model into computer-

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generated codes converts the digital representation of the saved 3D item to the sliced information. It controls the motion of the 3D printers' motors and arms. As a result, there are very few human interactions throughout the entire printing process because it is entirely computer-controlled (Anukiruthika *et al.*, 2022).

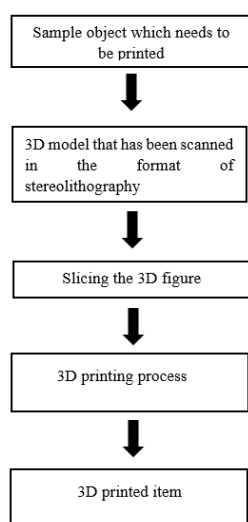


Figure 1. Shows the process involved in 3D food printing

Engineering, materials science, and culinary skills are all integrated in 3D food printing. It builds intricate food structures by layering edible ingredients. By mindfully handling the nutrient content, producing customized meals that include particular nutrients, and utilizing sustainable production practices, 3D food printing has the potential to revolutionize the food industry. Because it uses fewer resources and produces food with reduced waste, it has the potential to revolutionize the food production and consumption process from customized nutrition to ecologically conscious production (Waseem *et al.*, 2024).

The goal of using 3D printing of food is not just to improve the production process but to create innovative food designs with unique textures and possibly with improved nutritional benefits. This method is accomplished by combining the necessary components of food like carbohydrates, proteins, and fat in a way that accounts for their natural properties and how they interact when forming layers (Fernanda *et al.*, 2016).

Several industries, including the automotive, aerospace, and most recently the food industries, have used this technology to produce intricate and complex parts that are needed in their field.

Different methodologies are employed by 3D food printing technologies to develop nutritious foods. The four main methods used in 3D food printing are inkjet (liquid binding), extrusion-based printing, binder jetting, selective laser sintering, and inkjet printing (Mantihal *et al.*, 2020). Inkjet printing technology is used to create 3D designs by placing liquid droplets on a surface with the help of computer-aided design (CAD) systems. There are two ways to print inkjets: continuously and by drop-on-demand. In both cases, a fluid is forced through an opening, whereupon it fragments into a stream of droplets with the same volume but less unsteadiness on their surface.

Extrusion-based methods rely on a continuous ink flow applied layer by layer; these inks are often very concentrated colloidal inks. In this method, a moving nozzle constantly extrudes the molten material or paste-like slurry, which cools and combines the layers above. Extrusion-based printing can be divided into two categories. They were melting extrusion-based printing and soft material extrusion-based printing, depending on the temperature employed during the deposition process. In the technique of melt extrusion printing, a moving printer extrudes melted partially solid food polymer, which instantly hardens and bridges with the subsequent layers. In soft materials extrusion-based printing, the movable nozzle continuously releases paste from it, which is then adhered to previous layers (Fernanda *et al.*, 2019).

Binder jetting is the method of using a liquid binder for binding down powdered food ingredients, normally employing inkjet technology. To facilitate the binding of the particles together and create the 3D food object layer by layer, the printer applies the binder in defined places (Waseem *et al.*, 2024). With binder jetting technology, intricate and basic 3D models can be produced, and it can create colorful 3D food items using a variety of different food binders (Fernanda *et al.*, 2019).

With the use of lasers, food ingredients that are powdered can be combined in a process known as selective laser sintering. A final 3D food product is created by selectively combining the minor layers of powdered material connected layer by layer with the help of a laser (Waseem *et al.*, 2024). Highly distinctive 3D structures can be produced through selective laser sintering (Fernanda *et al.*, 2019).

By using 3D printing software that digitally extrudes material in a layered pattern, you can improve the look and add essential nutrients between layers. 3D food printing technology can control the type and quantity of ingredients, nutrients, and taste characteristics of ingredients, allowing for personalized food production. This parameter was much needed to develop a nutritious

meal for dysphagic patients who have difficulty in ingestion of foods. 3D food printing technology is capable of processing and creating a variety of designs using different ingredients such as meat, chocolate, candy, pizza dough, cotton, and sauce (Lee, 2021).

For growing children, fruits and vegetables are vital because they give them energy, vitamins, antioxidants, fiber, and other necessary nutrients. When it comes to eating fruits and vegetables, children can be picky about the food's color, flavor, texture, and form. With the help of three-dimensional printing, horticultural ingredients can be used to create unique, texturized food (Yang *et al.*, 2017). The field of digitalizing food through 3D printing holds a great place for producing individualized food with intricate geometries, precise textures, and optimal nutritional value (Dankar *et al.*, 2018a).

3D can be a better alternative to produce a nutrient-dense diet for those suffering from head and neck cancer, dysphagic individuals, elderly people, and autistic children. The common problem faced by the above patients was an issue with swallowing due to various health conditions. So, they need soft-textured foods, and at the same time, they should have healthy components. Because they require high nutrition to lead a healthy life. This parameter was greatly supported and provided by 3D food printing, as it enables the development of soft and texture-modified foods with personalized nutrition by efficiently utilizing its technology.

Nutrition Deficiency Caused by Various Disorders

Nutrition is an important parameter for health and development. The benefits of better nutrition include improved health, better immunity, and overall better functioning of the human system. There are some cases where nutrition deficiency is caused by numerous issues. Individuals with impaired masticatory function may adapt food texture to their oral condition, which can lead to decreased nutrient intake (N'gom and Woda, 2002). Similarly, dysphagia is an underlying symptom of many health problems that affect a person's ability to swallow. If you are unable to swallow properly, your food intake and therefore your micronutrient status may be limited (Rodd *et al.*, 2022). Malnutrition risk is increased by the combination of dysphagia and lack of appetite (Rothenberg and Wendin, 2015).

The majority of studies reveal those children with autism spectrum disorder (ASD) face feeding issues. These challenges frequently include:

ingesting less than the recommended amount of food and rejecting it; consuming different amounts of different food groups (e.g., eating more protein-rich foods and fewer dairy products); ignoring or favoring foods based on their texture, color, or temperature; and oral motor impairments (Shmaya *et al.*, 2015). Parents of children with ASD reported a higher prevalence of food refusal based on food texture and composition (Fisher *et al.*, 2014). Numerous case reports exist of ASD children who experienced a range of undiagnosed nutritional deficiencies to such a level that they posed a risk to health, including rickets, scurvy, and ophthalmological disorders associated with vitamin A deficiency (Shmaya *et al.*, 2015).

Malnutrition in patients with head and neck cancer is a major problem. Oral intake is directly affected by head and neck cancer, and the chance of severe malnutrition is increased by the more rigorous therapies (Dechaphunkul *et al.*, 2013). To overcome all these nutritional deficiencies, it is necessary to adapt to a new technology that provides food with the required nutrition and helps in maintaining a balanced, healthy lifestyle. 3D provides multiple ways to implement these requirements with its advanced applications.

Improved Nutrition and Texture modification by 3D food printing

3D foods are an effective approach for those with swallowing or chewing issues, including the elderly. Along with exhibiting nutritive properties and appealing sensory qualities, these foods must also be soft, safe, and easy to swallow to assist in the recovery of physiological dysfunctions and meet certain nutritional requirements (Gallego *et al.*, 2022). We can generate foods with altered textures and enhanced nutrients with the use of 3D printing technology, which can be extremely beneficial for people who struggle with swallowing or several eating disorders. 3D food printing technology has the potential to significantly enhance the nutritional value of food products. 3D printing profoundly impacts the nutritional and functional properties of food, revolutionizing its production and enhancement. By enabling customized nutrient distribution, 3D printing boosts nutrient retention and bioavailability while minimizing losses during processing. This technology also modifies textures, mouthfeel, and functionality (Varvara *et al.*, 2021).

3D Developed Food products Enriched with Various Nutritional Properties

3D food printing offers a practical means of digitizing individual calorie and nutrition intake to enhance dietary management on an individual basis. It is possible to develop a variety of nutritious foods that can be served to individuals who are malnourished or have eating problems. With its low energy consumption and ability to utilize alternative raw material sources, 3D food printing is a cost-effective, reliable food technology that can develop functional products tailored to the specific needs of each individual (Tomašević *et al.*, 2021). Numerous studies have said how 3D printing could be used to create a wide variety of food constructs, particularly cereal-based ones, from fruit and vegetables, root and tubers, milk, and milk products. Also, there is potential for producing much more value-added products (Kewuyemi *et al.*, 2022).

Fiber-Enriched Foods Developed by 3D Food Printing

Dietary fiber is a vital part of a balanced diet. Consumption of dietary fiber is linked to metabolic health. By employing 3D, numerous fiber-enriched products were developed to improve nutrition. Like cookies made with broken wheat flour and powdered grape pomace, which was rich in fiber content, they were developed using 3D printing. It helped in the development of cookies loaded with nutrients from grape pomace for increasing the nutrient level in children suffering from various food ingestion disorders (Jagadiswaran *et al.*, 2021). Using 3D food printing, fiber-enriched snacks made from mushrooms as an alternative food ingredient were developed. Mushrooms are greatly valued for their nutritional and nutraceutical features, and they can be used to make nutrient-dense meals, such as those for individualized nutrition, which will be highly beneficial in elevating the health level (Keerthana *et al.*, 2020).

Extrusion-based 3D printing was used to create dietary fiber-rich baked snack products made from whole milk powder and wholegrain rye flour. Wholegrain rye flour, an excellent source of dietary fiber, has a lot of potential when used as a component in 3D-produced healthy snack goods (Lille *et al.*, 2020). The suitability of extrusion-based 3D printing technology for food pastes composed of materials rich in protein, starch, and fiber was evaluated as a foundation for creating nutritious, personalized snack products. A promising technique for creating wholesome,

well-structured meals was extrusion-based 3D printing (Lille *et al.*, 2018). A chicken drumstick was made using 3D scanning and a timbal recipe with more fiber. The original timbale formulation was changed by adding 3 percent of citrus fiber and reducing the starch content from 8.7 percent to 3.5 percent. By balancing the reduction of starch with citrus fiber, the rheological profile was maintained (Ahlinder *et al.*, 2023).

To improve the printability of chicken meat, dietary fiber is obtained from a blend of millet-based flour. The utilization of 3D printing technology to produce meat-based materials with added dietary fiber can yield valuable insights for the creation of innovative meat products with improved nutritional value. It was discovered that the dietary fiber content of the optimized 3D-printed sample was 5.36 ± 0.19 g/100 g, which accounts for more than 10% of the RDA (Wilson *et al.*, 2023). Value-adding of orange by-products in 3D printed gels to produce a snack with added fiber. By using orange by-products, fiber-rich snacks can be produced, which may help to promote sustainable and healthful food sources (Molina *et al.*, 2023).

Spinach, a fibrous cellular material that has been freeze-dried, was evaluated for its suitability as food ink for 3D printing, and its microstructural composition was described. An investigation into the impact of particle size on printing performance revealed that adding 10% xanthan gum could potentially delay the swelling effects of spinach powder by enhancing its water-holding capacity. The larger spinach powder particle size increased the mechanical stability of the printed structures, according to the results. Additionally, this study stressed the significance of particle size as a factor to consider when evaluating the food ink's printability.

Physical characteristics like particle size, surface corrugation, and material density may be related to the printability of fibrous material due to its dense nature. Fiber-rich materials only require a certain amount of pre-processing to be suitable for 3D printing applications. To control the total solids content, which in turn affects the printing quality of the supply of fiber-rich material, this also involves size reduction and particle breakdown. The inherent potential benefits of 3D printing supplies of fiber-rich materials need to be further investigated (Anandharamakrishnan *et al.*, 2022).

These different studies show that 3D printing of various food materials, enriched with dietary fiber, offers insights for creating new, customized food products with improved nutritional content. People who struggle with swallowing difficulties and other eating disorders can easily consume 3D-

developed food products enhanced with nutritional profiles due to their altered texture, which is acceptable to those who have difficulty swallowing. Table 1 below showcases a collection of 3D-developed food products designed to incorporate various sources of fiber. These innovative products range from cookies made with broken wheat flour and grape pomace to meat-based materials using millet-based flour. Table 1 also highlights fiber-enriched snacks created from mushrooms and whole-grain rye flour. Additionally, there are food pastes composed of fiber, protein, and nutrients and snacks with added orange by-product fiber. These 3D-printed foods offer a promising approach to enhance dietary fiber intake and explore new possibilities in food production.

Table 1. Shows 3D-developed food products with fiber

Source of fiber	Product developed by 3D	Reference
Broken wheat flour and grape pomace.	Cookies	(Jagadiswaran <i>et al.</i> , 2021)
Mushrooms	Fiber enriched snacks	(Keerthana <i>et al.</i> , 2020)
Whole grain rye flour	Fiber enriched snack	(Lille <i>et al.</i> , 2020)
Food pastes composed of fiber, protein, and nutrients	Snacks	(Lille <i>et al.</i> , 2018)
Citrus fiber	Chicken drumstick	(Ahlinder, <i>et al.</i> , 2023)
Millet based flour	Meat-based material	(Wilson <i>et al.</i> , 2023)
Orange by-product	Snack with added fiber	(Molina <i>et al.</i> , 2023)

Protein Enriched Foods Developed by 3D Food Printing:

Protein provides vital nutrients for better functioning of the body. For the construction of bones and bodily tissues like muscles, protein is necessary. Peptide bonds hold the lengthy chains of linear and branched amino acids that make up proteins, a complex class of biopolymers. Proteins are essential for giving tissues their rigidity and giving cell walls the integrity of the structure. The process by which secondary and tertiary protein structures break down is known as protein denaturation, and it significantly alters the mouthfeel and texture of food items (Anandharamakrishnan *et al.*, 2022).

Edible insects have been recognized as a sustainable source of high-value animal protein, which can help meet the growing demand for meat products. Using wheat flour dough enhanced with ground yellow mealworm (*Tenebrio molitor*) larvae as a novel source of protein, 3D printing technology was utilized to create snacks with a planned cylindrical geometry. A softer dough was obtained by adding up to 20 g/100 g of ground insects. The total essential amino acid content of the printed snacks enriched with 10 and 20 percent ground insects increased significantly from 32.5 g (0 percent insects) to 38.2 g and 41.3 g/100 g, respectively (Eswaran *et al.*, 2023).

Using whey protein isolate and gelatin as ingredients, 3D printing technology was used to create protein-rich desserts. The combined effect of these two ingredients produced more stable and well-shaped 3D-printed yoghurt gels, which had a good balance of appearance, taste, flavor, and mouthfeel (Riantiningtyas *et al.*, 2021), which was highly beneficial for the elderly, autism children with abnormal eating patterns, and people with dysphagia. To create food ink for printed food products that are higher in protein, pea protein hydrolysate was added to pea protein isolate paste. A higher content of pea protein isolate resulted in improved mechanical properties for both the 3D-printed samples and food inks (Lim *et al.*, 2023).

Research indicates that 3D printing can transform bland, mashed, and unappealing dysphagia diets into visually appealing, tasty foods. Various combinations of soy protein, potato puree, and agar increase nutritional content and create printable material by creating meals for the elderly and those with dysphagia. By including soy protein and agar, some protein-enriched potato puree formulations were produced. Three-dimensional 3D food printing offers the visual customization of nutrient-dense food formulations for customers (Mirazimi *et al.*, 2022).

3D printing can be used to create steak-like meals that satisfy the dietary or energy requirements of various demographics (gender, age), as well as to customize wholesome, protein-enriched, and visually appealing foods. Using textured soybean protein and soy protein inks in place of meat, 3D printing was used to create dishes that resembled steak. For best printing results and sample integrity preservation, the ink formulation containing xanthan gum and textured soybean protein was used. It might develop into a nutritious and easily consumable product as well (Chen *et al.*, 2021). Due to the texture modification ability of 3D food printing and the development of nutrient-rich food, patients who face difficulty swallowing can be

given access to protein-enriched meals with the help of 3D printing.

Egg albumin, which comprises 54% of the protein in egg whites, is the most prevalent type of protein found in eggs. Egg white protein is a useful element in terms of both dietary needs and functionality. Due to its heat-induced edible gel properties, egg white protein has emerged as a promising 3D printing ink for the creation of innovative food varieties. The various egg white protein concentrations (0, 1.0, 3.0, 5.0, 7.0%, w/w) were incorporated to create the printing mixture for a 3D printer, which employs melt extrusion. It was discovered that the egg white protein mixture system possessed the necessary physical attributes required for 3D printing applications when combined with starch, gelatin, and sugar (Liu *et al.*, 2019). This investigation indicates that adding egg white protein, which is high in protein, to a 3D printing mixture significantly raises the protein, nutritional content, and functional properties of food. These various research findings indicate that the 3D printing of diverse food substances, enhanced with protein, provides an option for developing new, tailored food items with improved nutritional value.

Table 2. Shows 3D-developed food products with protein

Source of Protein	Product developed by 3D	Reference
Edible insects	Protein-enriched snacks	(Eswaran <i>et al.</i> , 2023)
Whey protein isolate	Protein-rich yoghurt gels	(Riantiningtyas <i>et al.</i> , 2021).
Pea protein	3D Printing ink	(Lim, 2023)
Soy protein and potato puree	Protein enriched meal	(Mirazimi <i>et al.</i> , 2022)
Food pastes composed of fiber, protein, and nutrients	Snacks	(Lille <i>et al.</i> , 2018)
Textured soybean protein and soy ink	Steak	(Chen, 2021)
Egg White protein	3D printing ink	(Liu <i>et al.</i> , 2019)

Table 2 presents a selection of 3D-printed food products designed with a focus on protein content. These innovative creations include protein-rich snacks crafted from various sources like pea protein and whey protein. Additionally, the table features 3D-printed meat analogues made from plant-based proteins, offering a sustainable and customizable alternative to traditional meat products. Furthermore, there are examples of 3D-printed pasta and noodles enriched with protein, providing

a novel way to incorporate essential nutrients into everyday meals. These 3D-printed protein-rich foods demonstrate the potential of this technology to address dietary needs and preferences in innovative ways.

Calcium-enriched Foods Developed by 3D Food Printing:

Among the minerals that are most vital to human health is calcium. It supports the growth and maintenance of strong bones and teeth. Osteoporosis can be avoided if the body has an adequate supply of calcium throughout life. It also contributes to maintaining heart health. The elderly, those with head and neck cancer, and autistic children should all get the required amount of calcium in their diets.

Milk products such as milk, cheese, and yogurt were the primary dietary sources of calcium. Protein paste prepared with milk protein concentrate and whey protein isolate at a ratio of 5/2 was able to be successfully printed and better matched the designed 3D model. 3D printing performance of a milk protein mixture was performed to utilize the quality and nutritional parameters of milk (Liu *et al.*, 2018a).

Using a 3D printer, milk-based materials were printed in 3D. The formulation of 3D printable milk inks was done without the need for extra rheological modifiers. This technique provided a simple way to create other edible inks without the need for additives and, by using milk, which is high in calcium, create a visually appealing meal without the need for temperature control (Lee *et al.*, 2020). By utilizing milk for various purposes in 3D, food rich in calcium can be produced for better health. Dairy products may be valuable for 3D food printing because milk is a complex biological fluid with several macronutrients that can form structures. Milk components are attractive for 3D printing applications because of their diverse structure-forming capabilities, which can be used as the foundation for printed dairy products or as ingredients in other printable foods (Ross *et al.*, 2019).

These are the few 3D-developed food products that contain a higher amount of calcium derived from various calcium-rich ingredients. Due to its soft texture, this allows people suffering from malnutrition and other swallowing issues to consume calcium and nutrient-dense diets. Table 3 showcases a range of 3D-printed food products designed to enhance calcium intake. These innovative creations include calcium-enriched snacks made from various ingredients like algae and

seaweed. Additionally, the table features 3D-printed dairy alternatives, such as plant-based milk and cheese, which are enriched with calcium to provide a nutritious and sustainable option for those with dietary restrictions. Furthermore, there are examples of 3D-printed pasta and noodles enriched with calcium, offering a delicious and convenient way to boost calcium consumption. These 3D-printed calcium-rich foods demonstrate the potential of this technology to address nutritional needs and preferences in innovative ways.

Table 3. Shows 3D-developed food products with calcium

Source of calcium	Product developed by 3D	Reference
Milk protein	Paste with milk protein	(Liu <i>et al.</i> , 2018)
Milk	Edible ink	(Lee <i>et al.</i> , 2020).

Various Wholesome Foods Developed by 3D food printing:

Daily intake of fruits or vegetables has a preventive impact in opposition to numerous persistent diseases, due to their bioactive compounds and strong antioxidant activity. So, it is much needed to incorporate the antioxidant and bioactive components of fruits and vegetables in the diet of people suffering from various eating and swallowing issues. 3D printing could be a promising tool to incorporate delicate and effortlessly degradable bioactive and other functional components into functional 3D food products, making a great benefit to healthy food products (Tomašević *et al.*, 2021).

Arthrospira platensis microalgae was incorporated to formulate 3D-printed cookies with new functional and antioxidant features (Vieira *et al.*, 2020). High-value proteins, long-chain polyunsaturated fatty acids, carotenoids, vitamins, minerals, phenolic compounds, and other bioactive molecules are some of the nutrients that make microalgae a novel and promising food ingredient (Gouveia *et al.*, 2010). Since cookies are popular and enjoyed by people of all ages, they are regarded as a convenient, dense snack food that provides a useful means of nutritional enhancement (Vieira *et al.*, 2020).

Polysaccharides are better suited for food printing due to their physicochemical properties and polymeric network. Supplies of printing materials based on carbohydrates have a higher capacity to

gel, which adjusts the consistency and flowability of the material. Research on the printability of brown rice and its impact on the quality of the final product was done. For the study, ready-to-cook (RTC) brown rice flour was made. Pre-gelatinization of the material supply was done to improve the molecular integrity of the starch. The flour's pasting was determined by its granule size, amylose, and amylopectin content (Anandharamakrishnan *et al.*, 2022).

Eggs are nutrient-dense and have a variety of useful qualities. While lipids, vitamins, and minerals are primarily concentrated in the egg yolk, egg proteins are similarly distributed throughout the egg white and egg yolk (Hincke *et al.*, 2019). The printability of egg yolk and egg white, when combined with rice flour, turned out to be a promising material for 3D food printing applications (Anukiruthika *et al.*, 2020).

This is how the application of 3D printing technology greatly enhances the availability of nutrient-dense foods for human consumption.

Texture Modified Foods by 3D Food Printing for Health Benefits:

The structural properties of food play an important role in the absorption of nutrients through food. Texture is a key factor in determining food preferences and can have a significant impact on consumer food choices. Changing or developing foods with the desired structure and composition allows you to get the right nutrients from food for children with autism and people suffering from swallowing issues and irregular eating disorders. Children with Autism Spectrum Disorder (ASD) were significantly more likely to reject food based on texture. Parents of children with autism spectrum disorder (ASD) reported a higher prevalence of food refusal based on food texture and composition (Fisher *et al.*, 2014).

The texture of 3D foods differs significantly from conventionally prepared foods. 3D foods can have a unique, uniform texture that is precisely controlled during the printing process, allowing for customized mouthfeel and sensory experiences. 3D printing technology has catalyzed revolutionary changes in various sectors, with a notable impact on the food industry. This technology overcomes the limitations of traditional food preparation methods (Seo and Shigi, 2024). A lot of individuals are currently involved in using 3D printing for various food applications. This can be attributed to the numerous possibilities for customization, perfection, and creativity in manufacturing foods

with unique forms and textures compared to the present conventional and expensive methods. 3D food printing is a highly precise and affordable technology that can be used to develop foods that are more accessible to people with difficulty eating and swallowing. In recent years, rice starch, cookie dough, and meat paste are some of the textures modified foods that employed the controlled deposition technique of 3D by additive manufacturing method. These studies have all delivered novel geometries with customized textures and formulas (Le Tohic *et al.*, 2018). By using 3D printing, the printability of brown rice was evaluated. In contrast to the conventional process, this technique produced brown rice with a soft texture and lower hardness. Therefore, the sample's hardness was minimized by the layer-by-layer deposition of 3D printing, making the availability of soft-textured brown rice (Huang *et al.*, 2019).

Many issues exist with the traditional food printing techniques. They are not highly customizable, which makes it difficult to make a customized texture for a person who has trouble chewing and swallowing. Additionally, it takes a lot of time and work, which inhibits innovation and originality. In contrast, traditional methods of printing food have significant maintenance costs, minimal compatibility with ingredients, and poor print quality. They are also less economical and efficient as a result of these strategies. Overall, conventional food printing techniques fail in comparison to 3D printing technology in terms of offering customized, effective, and creative food manufacturing options.

3D food printing has a unique opportunity to create geometrically complex structures. It can be used to create customized foods based on specific nutritional needs, calories, and specific shape and texture characteristics (Le-Bail *et al.*, 2020). For elderly people and people with difficulty swallowing (dysphagia), their need to eat texture-modified foods can be problematic due to their unsightly appearance and texture, which can cause food reduction and result in malnutrition. Similarly, texture can play a significant role in people with aversions to foods. Texture modifications can also be beneficial for individuals with weight problems who need to consume foods with reduced calorie content (Pereira, 2021). Textural-modified foods should also meet nutritional needs in terms of nutrient digestion and absorption and provide a pleasant sensory experience that is acceptable for the consumer (Gallego *et al.*, 2022). Patients following texture-modified diets frequently experience malnutrition because mashed and pureed foods lack appeal, this increased visual appeal of foods by 3D should help them feel

hungrier and enable the intake of soft and nutritious foods (Tim *et al.*, 2022). Providing soft, tasty, and healthy texture-modified (TM) foods to the elderly, especially those with biting or swallowing disorders or special dietary needs, is a major challenge for the food industry. To address these challenges and ensure that they receive a calorie- and nutrient-dense diet with the desired altered texture, 3D food printing can be utilized to deliver them in the desired form with essential amounts of nutrients.

When it comes to tailored meals, expert workers are needed to create designs, which usually involves a time-consuming task. Indeed, the expense of making just a few personalized items is quite significant. To achieve cost-effective mass customization, 3D can offer a creative solution. 3D-printed foods can fulfill the taste, visual appeal, consistency, chewiness, and nutritional needs of various age brackets and lifestyles through customized attributes such as taste, color, consistency, and dietary values (Nachal *et al.*, 2019).

Texture Modification of Foods by Extrusion-Based 3D Food Printing:

3D printing is a structuring tool that can change the macro- and microstructure of food products. The infill density and pattern of a 3D object can be managed with digital design software. The 3D food printing technology based on extrusion is suitable for manufacturing customized foods by altering the customized texture according to the requirements (Ma and Zhang, 2022). For extrusion-based three-dimensional (3D) printing, soy protein isolate emulsion gel inks with polysaccharides of guar gum or xanthan gum were studied. Soy protein isolate and guar gum ink 3D-printed products showed minimal dimensional printing deviation, excellent self-supporting ability, and smooth but slightly imperfect surface texture. Under certain research, this technique can be used to make soft foods (Yu *et al.*, 2022).

Also, it may be possible to create dysphagia-specific transitional food products with varying texture properties by using red cabbage with food doughs based on soy protein isolate and printing samples with varying infill rates. This will depend on the composition of the food formulation and the design of the 3D printer. An extrusion 3D printer was used in its development (Carranza, 2023). The research was conducted on the effects of four additives (agar, alginate, lecithin, and glycerol) and the applicability of extrusion-based 3D printing for creating unique shapes from potato puree. Based on the findings, it was found that optimal printability

and final product stability were obtained when using nozzle diameters of 0.5 cm and 4 mm (Dankar, 2018b). Possible uses of 3D printing technology in meat processing. An innovative internal structure combined with nutritionally balanced components can be designed to create a 3D model that addresses unique individual requirements, like difficulty swallowing and chewing. In addition, a temperature-controlled extruder-style 3D printer with a multi-head system is recommended to meet the rheological and meat safety requirements (Dick, 2019). By adjusting the infill percentage, dual extrusion 3D printing allows for the creation of visually appealing multi-material structures and offers the possibility to customize the textural characteristics of samples. Here, strawberry gels or mashed potatoes were used (Liu *et al.*, 2018b).

Using an extrusion-based food printer developed in-house, 3D-printed idli (a rice cake from South India that is steam-cooked) made from a native rice-black gram batter was strengthened with pearl millet flour. The application of food-to-food fortification and textural modification of foods through 3D printing with different infill levels opens up new printing possibilities for fermented foods. For patients experiencing nutritional loss, this will be extremely beneficial. The nutritional value of fermented foods can be obtained by consuming the millet idli with its texture altered (Raja *et al.*, 2023).

Next-generation meat substitutes, such as hybrid meat, are made by co-processing plant and animal protein components in various ratios. They are thought to be more nutritious than the plant-only meat substitutes that are currently on the market. For 3D printing, pea protein isolates and chicken mince were chosen as the primary plant protein and meat sources, respectively. 3D printing using extrusion technology was used to create the shape of a chicken nugget (Wang, 2022). Cooked beef paste formulations can be printed in three dimensions using a syringe-based extrusion 3D printer at 23°C. These formulations may be used as modified-texture foods for individuals with varying degrees of dysphagia (Dick *et al.*, 2021).

With the aid of extrusion-based 3D printing, ready-to-eat meats with a variety of textures were created through the use of finite element analysis simulation and rheological characterization. In this instance, the length, cohesiveness, void fraction, and rheological characteristics of the formulation were all greatly impacted by the elevated polyol concentration (Bareen *et al.*, 2023). This is the process of creating diversely textured and highly nutritious foods using extrusion-based 3D printing. Additionally, it develops safe and soft foods that

can be consumed by people with dysphagia, head and neck cancer, and autistic children who have trouble swallowing items.

Consumer acceptance of 3D printed food:

To learn more about and realize the views and ingestion associated with 3D foods, a survey was carried out. The findings indicated that 51.6% of people are ready to try 3D-printed foods. 3D-printed foods are also increasingly appealing to consumers who need balanced nourishment of nutrients and texture modification in foods. Of the consumers surveyed, 54.1% indicated that they would purchase 3D if it exhibited a higher nutritional content than a currently accessible product. (Silva *et al.*, 2024). For four weeks, a snack bar that was 3D printed with additional customization was used to assess consumer acceptability. Individuals assessed that the snack bar created using 3D technology was noticeably superior to what they had previously consumed after consuming it various times. Results showed that consumer's acceptability of 3D-printed food increased with repeated consumption Caulier *et al.*, 2020).

Some findings suggest that providing additional information led to a positive change in participant's perspectives, indicating that communication can impact consumers' willingness to choose printed food products (Pereira *et al.*, 2021).

Elders may be more likely to adopt 3D-printed foods if the health and commercial advantages are highlighted. According to a study, psychological factors such as environmental consciousness and knowledge of 3D printing technology, as well as the perceived usefulness of 3D printed foods such as their potential health advantages, influence senior customer's acceptance of these 3D-developed food products (Seo and Shigi, 2024).

In consideration of this, it can be suggested that there is an ample incentive to explore 3D, widening the possibility for their potential adoption into the food chain.

Future applications of 3D food printing:

Future technology involves 3D food printing, which can create innovative, special, and detailed edible creations that are visually appealing. The 3D food printer is seen as a way for future generations to enjoy food items that are both printed and edible.

A field linked to individualized nutrition involves the use of 3D food printing, powered by consumers, in senior living facilities. Through a user-friendly digital interface, elderly residents could effortlessly adjust the nutritional content and texture of their food. This approach would improve their dining experience while maintaining the balance between ease, health, and quality of life. Hospitals represent another field where advanced 3D food printers could be utilized. A 3D food printer, when combined with an intelligent digital platform, has the potential to transform the dining experience for patients staying in the hospital.

Colleges and universities represent another field where 3D food printers, powered by both prosumers and professionals, could offer significant benefits. The way people eat is evolving slowly, and there's a growing need for food that is convenient and tailored to individual needs. By merging advanced information and communication technologies with 3D food printing, it's possible to transform the dining experience on college campuses. Students could convert their 3D designs into nutritious snacks or full meals that meet their dietary needs.

3D printing technology has the potential to decrease food waste by recycling food items that are usually considered low-value, such as meat scraps, misshapen produce, and parts of fish and seafood that might otherwise be discarded. These perishables can be transformed and repurposed into forms suitable for printing at a later time. It is forecasted that going forward, 3D food printing will be capable of producing seafood and meat from cells that taste and feel as authentic as their natural counterparts, assisting in the solution of the global food scarcity issue without harming animals, using water inefficiently, or releasing greenhouse gases into the atmosphere, thus protecting the environment (Fernando *et al.*, 2018).

As 3D printing technology advances, it enables individuals to create items themselves at home by buying designs over the Internet. People can select and purchase designs from online stores via apps or websites. This will lower expenses associated with distribution, packaging, and storage; 3D printing has the potential to streamline the process of food delivery. It is anticipated that the sale of 3D food printing recipes on the Internet will be introduced soon, leading to significant competition regarding price, the variety of products offered, and the look of the manufactured items (Nachal *et al.*, 2019).

Astronaut meals are unique foods created for those in space, including astronauts and space explorers. Beyond their nutritional value and extended storage capabilities, considering the

difficulties linked to taste perception, hunger, and bodily functions, these meals demand careful consideration in their creation and composition. An exciting method being explored is 3D food printing, which has the potential to transform the production of food in space. By improving the quality of food, cutting down on storage requirements, prolonging the lifespan of food, and broadening the variety of food, the 3D food printing method could assist in long-term space missions with a smaller ecological footprint (Santhoshkumar *et al.*, 2024).

The future of 3D food printing holds immense promise, with potential applications that can transform the way we produce, consume, and experience food. Personalized nutrition will become a reality, as 3D printing enables customized meals tailored to individual nutritional needs and dietary preferences. Space exploration will also benefit, as 3D printing provides a sustainable food solution for long-duration missions. Moreover, 3D printing will play a crucial role in sustainable food production, minimizing waste, reducing energy consumption, and optimizing resource usage. The culinary world will witness a revolution, with chefs and restaurants creating intricate, complex dishes with unique textures. Additionally, 3D printing will provide nutritious food for people in need. As technology advances, we can expect automated food production, novel flavor and texture innovation, and even food preservation techniques to emerge. Overall, 3D food printing will reshape the food industry, making it more sustainable, personalized, and innovative, with far-reaching impacts on our daily lives.

Challenges associated with 3D food printing:

A significant hindrance to the application of 3D printing is the scarcity of readily printable materials. For printing, appropriate material needs to have certain qualities. Several factors can alter the printed structures, including printing and motor speed, nozzle tip diameter, nozzle height, extrusion rate, and temperature. To balance the ideal circumstances and the intended result, optimization of the material formulation and the printing process's parameters is required.

A further obstacle in the production of 3D-printed goods is the requirement for some of these items to undergo additional processing steps, like baking, frying, and steaming. Such procedures can lead to deformities in the product's form and alterations in its properties. Being subjected to heat during preparation can lead to changes in the item's texture, lead to the Maillard reaction, and cause

water to evaporate, while also affecting the appearance and nutritional value of the food. To tackle this challenge, different post-processing techniques like microwave vacuum drying and infrared heating can assist in preserving and enhancing the qualities of the printed structures in food (Pereira *et al.*, 2021). The lack of skilled labor, high production costs, intricate logistics, and varying product demand present obstacles to the adoption of digitalized technologies. The continued difficulty in obtaining 3D-printed foods is attributed to food safety laws, piracy, production costs, resource and energy consumption, large-scale commercialization, and business competition. Good manufacturing practices for 3D food printing are still being developed (Anandharamakrishnan *et al.*, 2022).

3D food printing using extrusion techniques might be able to meet the majority of the energy and customized nutrition needs of astronauts on extended missions in space by making use of various fruits, vegetables, meats, and nutrients as printing substances. Despite the potential benefits, incorporating 3D food printing technology in human-involved space missions faces considerable limitations due to technological and economic obstacles. These include sourcing suitable printing materials, overcoming the challenges of adapting food to microgravity, ensuring post-printing palatability, and addressing engineering complexities when transporting food products within existing technological capabilities (Zhang *et al.*, 2022).

Foods that are 3D printed may fall into the large category of imitation foods, which need special labelling to set them apart from other processed foods. To prevent consumers from being confused when choosing foods, the use of specific labelling must be highly encouraged. The advantages of 3D food printing are accompanied by problems with food safety and health risks associated with these foods. The result of 3D food printing is promising in terms of food delivery that is safe, through appropriate sanitation, but there are concerns about the permissibility and cross-reactivity of the food ingredients used. Furthermore, maintaining clean and sanitary conditions would be challenging without the establishment of industry standards and regulations during large-scale implementation. The labelling of foods printed using 3D technology is still controversial, aside from food safety. Microbial safety, process safety, worker safety, food poisoning, food adulteration, food fraud, copyright issues, piracy of 3D model designs, e-commerce trade, and patents are some of the concerns surrounding 3D printed foods. The regulations

currently in place for traditional food manufacturing may not apply to 3D printing, raising new issues that need to be addressed. When 3D printing technology becomes more widely used, there may be potential for adulteration, or in the event of incorrect processing, it might contain food allergies. These kinds of problems already arise in conventional food production methods. Both national and international food safety and quality control laws need to be implemented (Crevel *et al.*, 2008). Labelling is a big and frequent legal problem that arises with 3D printed foods. (Anandharamakrishnan *et al.*, 2022).

While 3D food printing shows great potential, it also confronts numerous technical hurdles. These hurdles include the necessity to enhance precision in printing, particularly in situations where the nutritional content must be perfectly uniform, and the handling of the material's flow and consistency. Modifying the viscosity and consistency of food-grade substances is crucial for effective printing and requires highly focused research. Tackling these problems through scientific methods is crucial to avoid the challenges associated with them.

The challenges associated with 3D food printing can be overcome by identifying their root causes, driving technological advancements, and exploring alternative approaches. By addressing the underlying issues, improving printing technologies, and developing innovative solutions, the hurdles of texture consistency, flavor preservation, scalability, and cost-effectiveness can be successfully navigated. This multi-faceted approach enables the optimization of 3D food printing, making it a more viable and efficient method for producing personalized, nutritious, and appealing food products.

Conclusion

In the food sector, 3D food printing has become an innovative technology, providing unmatched possibilities for producing foods with modified textures and enhanced nutritional value. This review has demonstrated the vast potential of 3D food printing in producing foods with enhanced nutritional content and tailored textures, catering to diverse consumer nutritional needs and preferences. However, despite its numerous benefits, 3D food printing also poses significant challenges, including texture consistency issues and consumer acceptance hurdles. Future studies should focus on optimizing printing parameters, developing new food materials, and conducting sensory evaluations to ensure the quality and acceptability of 3D-printed foods. The applications of 3D food printing are vast

and varied, ranging from healthcare and space exploration to sustainable food production and culinary innovation. As this technology develops further, it has the potential to completely alter the food sector by offering individualized, sustainable, and nutrient-dense food options to a world that is expanding in population.

Ultimately, 3D food printing has the potential to redefine the future of food production, and its impact will be felt across various sectors. By embracing this technology and addressing its challenges, we can unlock new possibilities for creating healthier, more sustainable food experiences.

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