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Recent Advances in 3D Food Printing: A Review with Focus on Personalized Nutrition and Functional Food Applications

Running title: Advances in 3D Food Printing Focusing on Personalized Nutrition

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SUMMARY

3D printing technique provides immense opportunities to manufacture foods of individual choices with added benefits to address malnutrition. Malnutrition has been identified as a major public issue that hampers the growth of developing nations worldwide. Fortification with functional ingredients is a promising approach to combat this disaster. However, consumer acceptance of fortified foods remains low due to their bland taste and unfamiliar formats. This scenario has created the demand for customized, fortified products made with novel technologies like 3D printing. The latest research report findings on 3D printing for the last 15 years have been collected and reported in this review. A detailed review on various technological options available for 3D printing, recent research reports with emphasis on functional food, has been compiled in this work. 3D Food Printing has been proven from previous works, as a highly promising novel technology capable of providing

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personalized nutrition. The 3D food printers primarily rely upon extrusion technology to fabricate nutrient-rich food products in multiple 3D designs, catering to both the aesthetic and functional preferences of consumers. This technology is expected to revolutionize the functional food industry in the near future, owing to its manifold applications.

Keywords: food printing; extrusion; 3D designs; personalized nutrition; nutrient-rich products

INTRODUCTION

Three-dimensional (3D) printing technique, which evolved around the early 1980s, as an outcome of the fourth industrial revolution (*1*), has been gaining momentum in the current era. This technique has immense applications in sectors like medicine, aviation, textiles, civil engineering, and the military (*2*). Raw materials like plastic and photopolymers were utilized predominantly for prototyping in 3D printing technology (*3*). The first 3D printer was constructed by 3D systems in the 1990s (*4*). The capability of developing prototypes rapidly, makes this technique unique, as compared to other printing techniques. Three-dimensional printing of foods is a later advancement of 3D printing, which has emerged of late. The conceptual patterns of first-generation 3D food printers were presented to the public around 18 years ago. Researchers from the United Kingdom have fabricated the earliest version of a 3D printer for printing chocolates, which was considered the first model of food printer. Afterwards, another 3D printer named 'Foodini' was launched by a Spanish Company, which paved the way for the onset of 3D printers. From 2011 onwards, the 3D printing technique has been employed in the food industry (*5*). In 3D printing of foods, foods are fabricated as layers additively (*6*), from multiple ingredients, in complex designs, as chosen by the end-user. This technique follows a clear-cut sequential set of operations (*7*), which involves a digital process that initiates the development of a 3D CAD model for the preferred design. A slicing software is used to slice the models into their respective layers. While slicing, machine codes are synthesized for sliced layers, which can be transferred to the instrument, for initiating printing of the chosen recipe (*8*). A good synergy between the hardware and software of the printer system is vital for the efficient operation of a 3D food printer.

Extrusion-based 3D printing

As 3D food printing offers numerous benefits, various types of printers differing in the principle of operation were developed over the last few decades. A detailed description of each type was highlighted in the following section. Fig. 1 shows the schematic diagram of a FoodBot food printer.

Fig. 2 represents the workflow of a 3D food printing machine. The four major techniques of food printing are extrusion-based printing, binder jet printing, inkjet printing and selective laser sintering. Among these technologies, the most commonly employed technique is extrusion printing (*9*). In this technique, food designs are formed through the process of extrusion using a nozzle at static pressure. Both solid materials and low-viscosity pastes are printed using this technique. Food materials to be printed are loaded in the machine and then forced through the nozzle to form layers of food material, one over the other. Foods usually printed by this technique are dough, meat, paste, cheese, *etc.* (*10*). Fish surimi gel was printed using an extrusion-type printer, and it was reported that the diameter and velocity of motion of the nozzle along with the rate of extruding have influenced the quality of 3D printing (*11*). Different types of sugar cookies were printed with an extrusion printer (*12*). Fig. 3a shows the schematic representation of extrusion-oriented 3D printer. Major advantage of this techniques is the low cost of the machine for the basic models, its ease of customization to adopt to a variety of raw materials. However, low level of printing precision and very long build time are its disadvantages.

Binder jet 3D printing

In binder jet technique, layers of food-grade powders are spread uniformly over the platform for fabrication (*13*). The layers of food-grade powders are often sprayed by a stream of water, to make them stable, minimizing the disturbances occurring because of binder jetting. Small binder droplets are dropped onto the surface of the powder bed from a printer head, which binds the adjacent powder layers. The powder surface is then heated using a hot lamp to provide mechanical strength to withstand the printing process. These steps are performed subsequently for all the layers (*13*). The properties of both the powder and the binder have a crucial role in printing efficiently. This process has some benefits like quicker fabrication, complex structure creation, and reduced cost of ingredients. With this technology, Sugar Lab fabricated sculptural cakes using sugar and different flavour binders. Fig. 3b shows the schematic diagram of the binder jet printer. Binder jet 3D printing is a versatile technique and its speed of production is greater when compared to other techniques. Another advantage is its possibility of inclusion of support structures in the fabrication of layers. This technique suffers from the disadvantage of rough or grainy appearance of the end product. Fine and soft textured products are very difficult to produce with this technique. This type of printing requires post-processing step to reduce moisture content and to improve the strength of the foods printed.

Inkjet 3D printing

In inkjet printing, food materials are dispensed from a heated head with multi-channels, to the selected regions of the food surface (*14*). The droplets are dispensed in a drop-on-demand manner. They fall upon gravitational force and are dried through solvent evaporation. These droplets can create two-and-a-half-dimensional images (*14*). This technique is commonly used for surface filling or decorating purposes. Baked items like cookies, cakes, pastries, and pizza are decorated through this technique (*15*). Food materials with complex structures are seldom printed by this method. Fig. 3c shows the schematic diagram of the inkjet printer. Inkjet printing offers various advantages like high resolution of the prints and accurate printing. In this technique, a variety of raw materials could be used for 3D printing. Damage occurring to the food after post-processing due to its delicate structure is the major disadvantage of this technique.

Selective sintering 3D printing

Selective sintering technology can be applied to powders, where they are sintered selectively to create any desired shapes (*16*). A sintering source like hot air or laser shall be made to pass over a bed of powdered food spread evenly. The source moves across both x and y axes of the powder bed, to bind them together. The sintering process is repeated continuously, so that the fused material attains 3D geometry, through simultaneous layering and binding of the particles (*16*). The food jetting printer from TNO (*17*) has employed lasers for fusing sugars and Nesquik powders in 3D designs. The unsintered material has been retained in the position as a supporting mechanism to the whole structure. A stream of hot air with minimal speed was utilized by Candy Fab (*18*), for sintering a layer of sugar. Application of heat to the bed, at a temperature lower than the melting point of the powdered material prevents thermal destruction occurring to the product and enhance the binding of particles. Both hot air and laser sintering methods facilitate rapid fabrication of foods, without requiring any post-printing operations. However, one limitation of this technique is that it could only sinter sugar and fat-containing particles having low melting points (*19*). Fig. 3d shows a schematic diagram of a selective sintering type 3D printer. The advantages and disadvantages of different printing techniques are summarized in Table 1.

Materials for 3D food printing

The materials used for printing are often grouped into three major classes. Natively printable materials are those that could be extruded with ease using syringes (*24*). Cake frosting, chocolates, and cheese are some examples of them. These materials could be personalized completely regarding the nutritional, textural, and sensory attributes. Some materials retain their shape for a long time after deposition so that the post-processing step is not necessary. Non-printable materials include food products, which are eaten in bulk amounts daily. They include meat, fish, rice, fruits and vegetables *etc.* They could be made printable only through the incorporation of some components like hydrocolloids. Xanthan gum and gelatine are usually used for this purpose (*25*). The addition of suitable additives to these types of materials, modifies their printing characteristics, resulting in a new formulation (*12*). Alternative ingredients comprise extracts from organisms like algae, fungi, seaweed, and lupines along with insects as the newer sources of protein and fiber. According to the "Insects Au Gratin Project", formulations containing insect powders, low-viscosity icings and cheese, were used as the raw materials for fabricating foods and creating tastier recipes (*26*). The leftovers from the current agriculture and food sector could be transformed into metabolites, enzymes and food-grade flavours, which are known for their biological activity. The advantages and disadvantages of the formulations used in printing are given in Table 2.

The key benefit of 3D-food printing is the rapid fabrication of customized food products having complex geometric patterns and novel textures (*25*). As 3D foods are categorized under soft foods, due to their high digestibility, they form a vital part of geriatric nutrition, especially for the dysphagic community (*31*). Apart from designing foods with customized patterns, 3D printing develops foods with tailored nutritional content through the incorporation of multiple ingredients. The capability of food printing to offer personalized nutrition makes the technology an exceptional solution for tackling the nutritional disorders associated with the deficiency of different nutrients. This review aims to throw light on the role of functional foods with bioactive ingredients in demolishing nutrient deficiency disorders, which mainly prevails in developing nations like India, Nepal and various parts of Africa. Also, the evolution of 3D food printers, numerous printing techniques employed and the novel 3D-printed functional foods, that could enhance and transform the realm of foods, both aesthetically and functionally, are also reviewed thoroughly in this article.

MALNUTRITION IN DEVELOPING COUNTRIES

Even though malnourishment is recognized as a global challenge, Asia and Africa are the major sufferers of all forms of under-nutrition (*32*). In India, a South Asian country, under-nutrition is one of the main contributors to disease burden and a major risk factor for the increased mortality rate among children below the age of five (*33*). Though the GDP of India has increased to 50 %, one-quarter of undernourished children live in India (*34*). The most important reason being the economic inequality, leading to consumption of diet lacking essential nutrients (*35*). According to the Ministry of

Women and Child Development, approximately ten lakh children in the country were deprived from acquiring proper nourishment. The disease burden caused by this condition, as well as the trends of the various malnutrition indicators viz low birth weight, stunting and wasting in children, anemia in children and women, in every state of India were evaluated (*36*). These trends spotlight the fact that the effects of these indicators have to be reduced to a greater extent to attain global 2030 targets, which in turn highlighted the need for an integrated nutrition policy *(36).* In a study conducted in a rural village in South India, calcium and iron consumption were observed to be low, especially in the population within the age group of 60 years (*37*). Around 96 % of the women and 84% of men were deficient in calcium. It was also observed that men's and women's diet had not met the recommended daily intake of iron. The deficiencies of calcium and iron could lead to disorders like anemia and osteoporosis. About 26 % of the people showed a low BMI. This study highlighted the relevance of community-based nutritional interventions (*37*). In another study conducted in a group of students from Ernakulam district, it was observed that anaemia was prevalent in children from 6 to 9 classes (*38*). Iron deficiency related anaemia continues to be one of the main health issues, among both children and teenagers in India. The prevalence of anaemia was more in adolescent women, and the intake of iron-containing diet was reported to be lower among the children (*38*).

In Nepal, malnourishment was observed to be a major health- hazard among children below the age of five years, particularly in rural regions (*39*). Under-nutrition is a major health concern, witnessed in Africa, particularly, in the Sub-Saharan region (*40*). The status of malnutrition in Africa presents a substantial public health and socioeconomic burden, warranting urgent attention and interventions (*41*)*.* About 264.2 million people were malnourished in the Sub-Saharan region, in the year 2020, which is about 24.1 % of the whole population. This percentage was the highest, as compared to other parts of the world (*42*). The state of under-nutrition represents a double burden with a higher percentage of under-nutrition as well as obesity. Both of these health hazards lead to diet-related non-communicable diseases. The occurrence of anemia due to iron deficiency was around 23 % in South Africa among children in the age range of 1–3 (*43*). Extreme anemia was responsible for more than 50 % of deaths among children infected with malaria in Africa. The prevalence of anemia was around 54 % in the study conducted in Edo camp, Nigeria. Children between 6-10 years and those affected with malaria were more prone to anemia. One in every two children suffers from a deficiency of iron in Nigeria (*44,45*). As per the estimates of the year 2020, of the total population in Africa, 21 % suffer from under-nutrition. This shows the intensity of the disaster, which needs proper addressing and prompt action, from the stakeholders including citizens, health workers, food producers and processors, and government officials (*40*). The necessity of campaigns to educate the younger generation regarding the impact of food processing strategies and the ingredients of a healthful diet has been emphasized in the study.

Even though the severity of disease burden of undernutrition in developed countries is relatively less, it does exist and has an impact on the population experiencing its various forms. In US, where availability of food is not a concern, detecting undernourished population is possible through relying on social and economic indicators, when compared to physiological indices (*46).* In Japan, malnourishment is a frequently occurring issue, the intensity of which increases with age. As per previous studies, undernourishment prevails to an extent of 1 to 10 % among elderly people, although 41 to 48 % are deprived from proper nutrition (*47-49*).

The Government of India had set up the National Nutrition Mission to address the challenges of under nourishment. This mission aims to compile the different nutrition-based schemes of Government Ministries and stakeholders, which comprises the diversification of dietary patterns to enhance the intake of iron and folic acid and to encourage food fortification endeavours in the private sector (*36*). To combat anaemia, which was highly prevalent among the younger generation, conduction of anaemia prevention programs in schools along with behaviour modification communication for modified diets and supplementing iron globally were the suggested remedies for anaemia among school-going children (*38*). In Nepal, eleven policy documents highlighted nutrition interventions comprising micronutrient supplementation, fortification of foods, feeding practices, and treatment of nutrient deficiency diseases (*50*). The provision of safe foods through a sustainable food pattern, has been categorized as a major policy area in Nepal (*50*). One cost-effective way to eradicate malnutrition among children in Africa, is to provide a completely balanced meal for primary and secondary school children through school feeding programs, which has been practiced in many countries (*41*). It has also been recommended that national as well as international policies along with nutritional intervention programs with the objective of prevention and treatment of undernutrition among the geriatric community would be effective in Africa (*51*). Since the role of dietary modification in the prevention of disease conditions associated with malnutrition has been quite apprehensible from the above studies, the administration of functional foods was considered as an ideal choice to eradicate malnutrition. Functional foods are known to satisfy the dietary requirements completely (*52,53*). Though only a few studies have been reported establishing the connection between malnutrition and functional foods, the role of these foods in eliminating the deficiency symptoms were highly evident (*54*).

The federal programs after the 1969 White House Conference on Food, Nutrition, and Health were observed to be fruitful in the 1970s in diminishing the burden of undernourishment in US (*46*). Based on the information gathered from nutritional and dietary requirements a “market basket” of cheap, frequently consumed foods that satisfy the Recommended Dietary Allowances (RDA) has been created which set the calculated minimum incomes through multiplying the price of an “RDA-based market basket” and the price of other needed commodities. This strategy could identify the undernourished population and allow targeting of food programs in a better way (*46*). In Japan, A nutritional risk screening tool, SCREEN II (Seniors in the Community: Risk Evaluation for Eating and Nutrition, version II) a validated, questionnaire with 14 items is used effectively. This is intended to analyze the nutritional disorders in community-dwelling population above the age of 65 years old. This tool accurately measures dietary habits, like food preparation, eating behaviour, and food composition (*55*).

THE ROLE OF FUNCTIONAL FOODS IN PREVENTING DEFICIENCY DISORDERS

The research interest in functional foods has gained momentum only in the early years of the 21st century. This interest had a great impact on their market growth, which showed a boom, and it is anticipated to attain 280 billion US dollars, by the year 2025, at 80 % growth rate annually (*56*). The definitions of functional foods have changed over time. In general, they are foods either natural or processed, which contain bioactive ingredients, incorporated in them, and can provide potential health benefits, other than merely fulfilling the satiety value. They have therapeutic effects, which were proven clinically (*57*). Some of these ingredients are antioxidants, probiotic organisms, essential fatty acids and polyphenols. The administration of foods fortified with iron decreased the occurrence of anaemia (*58*). The water-soluble extract from tomato (marketed as Fruitflow) was the first product in Europe to gain an authorized, proprietary health claim under Article 13(5) of European Health Claims Regulation 1924/2006 regarding nutrition and health claims made on foods (*59*). Efficient antiplatelet components were observed to be present in Fruitflow that strongly inhibited platelet aggregation and reduced the blood pressure (*59*). Although FDA does not have a clear-cut definition on functional foods, it has revised the definition of "healthy" foods of late, focusing more on the whole food groups. The current revision has aligned well with the present nutrition science and Dietary Guidelines for US population. The latest rule, which came into effect in December 2024, permits nutrient-rich foods like fruits, vegetables, and cereals to acquire "healthy" labels easily (*60*).

Plant-based functional foods

The bioavailability of iron has enhanced manifold in a beverage fortified with more than one mineral. Also, the enrichment of chickpeas rich in iron and zinc has increased its iron and zinc content by five times (*61*). Fortification with more than one nutrient increases the bioavailability of the fortified nutrients (*62*). An infant formula, with sweet potato as the base was developed in Africa. The formula had nutrients like vitamin A, Iron, and Zinc, which was of low cost and had attained the CODEX standards for all the micronutrients. The formula lacked calcium, which the author recommended to incorporate through the addition of dried powdered soft bones of fish. The amount of iron in the formula was in the range of 8–10 mg/100 g which was manifold greater than that present in the traditional weaning foods (*51*). Meat analogues with nutritional content comparable to that of meat were developed from plant sources, intended for vegetarians and vegan customers. To develop this, microalgae powder and soy protein concentrate were effectively combined through high moisture extrusion technology. The product developed had an appealing colour and a good nutritional profile with high levels of nutrients like vitamins A and B. The fibrous texture of meat, as preferred by the consumers was developed through the addition of 30 % microalgae powder (*63*). Noodles were prepared through the incorporation of mushrooms, which has the potential to impart various health benefits, as they are known to be proteinaceous and vitamin-rich foods. They are also excellent sources of micronutrients like iron calcium, copper, and zinc (*64*). They are low- calorie foods and are rich in dietary fibre. When mushrooms were incorporated to an extent of 5 %, the sensory tests yield good results. Also, the levels of nutrients protein, fibre, iron, calcium, and potassium in the final product was reported to be greater in comparison to the noodle brands available in the market (*64*). Konjac glucomannan is a polysaccharide and functional food ingredient consisting of glucose and mannose units, obtained from the tuber portion of *Amorphophallus konjac C* (*65*). This polysaccharide has the following applications in the food industry. They can be used as a thickener (*66*) stabilizer (*67*) and a gelling agent (*68*). Konjac glucomannan was selenized through the addition of the trace element selenium. Through fortification, a new glucomannan hydrolase enzyme was formed which can convert Konjac glucomannan to its corresponding oligosaccharides. Selenization was observed to be beneficial for providing synergistic biological activity and for developing a functional ingredient. The newly developed Konjac glucomannan oligosaccharides have antitumor activity (*69*). The base material for any baked product is refined wheat flour. Even though wheat flour provides, energy and protein, it was deficient in minerals like calcium, iron, and zinc (*70*). The popularity of bakery products like biscuits and cakes could be exploited, to develop healthier variants of these products. In an attempt to enhance the bio accessibility of minerals like calcium, iron and zinc in the product and to render a mineral-rich bread, wheat flour was replaced with sesame, cumin and moringa leaves in one combination, sesame and finger millet in the next combination and sesame seeds in the third combination. All the breads developed had higher amounts of the minerals and the enrichment had altered the quantity of total and bio-accessible part of the minerals (*71*). Wastewater from oil mills and olive paste, discarded from the olive oil industry are rich in bioactive ingredients like polyphenols (*72*). They were added to enrich cereal foods like bread and pasta (*73*). After enrichment, it was observed that the products containing water from the oil mill had a mild improvement in their chemical characteristics, but those enriched with olive paste showed a significant change in chemical properties. Also, products enriched with olive paste showed higher phenolic and antioxidant activity. From the whole quality index values of the products, it was reported that olive paste was more suited for fortification when compared to waste water from oil mill (*73)*.

Dairy-based functional foods

Milk and milk products were fortified with spices and herbs (*74*). Besides providing flavour to the foods, herbs, and spices offer protective action from oxidative, inflammatory, hypertensive, diabetic, and microbial infections, but exhibit favourable conditions for the growth of beneficial microorganisms (*74*). Cinnamon, when added to yoghurt, had resulted in enhanced growth of lactic acid bacteria. The yogurt had shown enhanced total phenolic content and radical scavenging (*74*). Milk from cow, buffalo and goat, fortified with ginger and beetroot extracts had exhibited enhanced antioxidant activity (*75*). A block of new cottage cheese was prepared with the addition of spices like pepper, parsley, garlic, dill, and rosemary (*76*). This cheese showed enhanced sensory properties, increased shelf life, and improved biological value (*76*). Fortification of butter with rosemary herb decreased the rate of lipolysis in butter (*77*).

Egg and meat-based functional foods

Table eggs were fortified with lipids from both microalgae and fish (*78*). The oil extracted from fish was rich in DHA (docosahexaenoic acid) and PUFA (polyunsaturated fatty acids). To retain the sensory properties of eggs, fish oil should be limited to the range of 1.5 % (*78*). The sensory properties, acceptability, and flavour of eggs supplemented with both oils were compared and it was observed that DHA supplemented by microalgae oil yielded better results in terms of sensory characteristics, overall acceptability, and flavor of eggs (*79*). Vegetable oils like sunflower oil in broiler chicken meat were replaced with PUFA (*80*). Soybean oil, mustard oil, fish oil, and linseed oil were used as the sources of PUFA. The meat was reported to be fortified with polyunsaturated fatty acids, with minimal variations in the sensory characteristics of the meat. The fortified meat showed enhanced levels of DHA and EPA (eicosapentaenoic acid) and lower levels of saturated fatty acids (*80*). Dietary recommendations for EPA and DHA based on cardiovascular risk considerations for European adults are between 250 and 500 mg/day (*81*). Supplemental intakes of DHA alone at 1 g/day do not raise safety concerns for the general population (*81*). Broiler chicken meat was enriched by feeding chicken with high oleic peanuts, instead of grains, canola seeds and soybean meal (*82*). The protein content of peanuts is two-fold higher when compared to grains. They are also rich in oleic acid (80 %). After enrichment, the meat showed enhanced amounts of polyunsaturated fatty acids and a low level of trans elaidic acid, which when present in large amounts can lead to cardiovascular diseases. Also, the protein and amino acid composition had remained unaltered after enrichment (*82*). When the feed of slow-growing chicken was enriched with linseed oil and tuna oil at the rate of 6 %, the chicken meat exhibited enhanced levels of PUFA with least alteration in the cholesterol content of the meat (*83*). The DHA content was observed to be 250 mg/100 g of meat, both in breast and thigh portions, which was adequate to meet the daily requirements of DHA, as per European Food Safety Authority (EFSA) (*83*). DHA is responsible for the proper functioning of the brain as well as vision according to EFSA (*84*). Mono and multilayered microcapsules were prepared from fish oil emulsions and they were added to meat products like sausages after operations like cooking and curing (*84*). They served as the vehicles of essential fatty acids which were known for their beneficial effects on health. The capsules were developed from two combinations, one from lecithin and maltodextrin and the other from lecithin and chitosan-maltodextrin. Through the addition of microcapsules, meat was fortified with EPA and DHA, and the products were analyzed to meet the labeling requirements for the source's omega-3 fatty acid content according to the European Union legislation guidelines. The lipid profile of the product developed as well as the percentage of fat loss remained after fortification. The combination of lecithin and maltodextrin and lecithin yielded better results than the other combinations, in terms of bioavailability of EPA and DHA (*54,84*). Besides all the healthful effects of fortified foods, they were seldom accepted by consumers wholeheartedly primarily due to their unfamiliar taste and inconvenient processing methods (*85*). With the evolution of a suitable, sophisticated processing technology like 3D food printing technology, both the acceptability and accessibility of functional foods are expected to be enhanced to a greater extent.

FABRICATION OF 3D PRINTED PERSONALISED FUNCTIONAL FOODS

3D food printing can play a critical role in addressing malnutrition. Since the technology is capable of constructing foods that can offer personalized nutrition, 3D-printed foods fulfil the individual nutritional requirements of the customers. Although multinational brands like PepsiCo, Barilla, Mazola, Hershey's, and Oreo have already launched their 3D products in the market (*86*), the literature has highlighted the fact that recent research direction in the area of 3D Food Printing should be towards the fabrication of newer 3D printed foods, with functional and bioactive components along with the basic nutrients (*87*). Table 3 shows 3D-printed products fabricated from different ingredients.

3D food printing with food grade inks

Customized, highly porous, aqueous,3D food simulants were developed with the food-grade ink pectin gel with low methylation (*93*). The incorporation of pectin yielded a firmer product after printing. Products that differ in properties were printed by altering the composition of the food inks and keeping the printing parameters as such. Calcium chloride was added in amounts required to form the cross-links of pectin contributing to the 3D structure. The incorporation of sugar resulted in a more viscous product with better printability and qualitative attributes. For printing formulations with a high pectin content, the amount of calcium incorporated to the formulation was reduced to yield products having desired flow properties. Through this method, customized food inks, having numerous applications, could be developed, to meet consumer choices. This study could be considered the initial step in the fabrication of 3-D printed pectin-incorporated porous products (*93*). A FujiFilm Dimatix inkjet printer with xanthan gum as the printing ink was used with powdered cellulose (*94*). Xanthan gum was dispensed over the powdered cellulose for binding. Optimization of material properties and other parameters was carried out to improve the effectiveness of binding. Cellulose was selected as the binding agent due to its low cost and the ability of cellulose to recrystallize after application. The newly formulated food-grade inks formed a firm structure with cellulose powder, which was used effectively for 2D inkjet printing. They could be successfully used for 3D printing after recrystallization of the powdered cellulose (*94*). The performance of a 3D extruder-type printer at ambient temperature was accessed with model components such as modified starch and xanthan gums (*95*). The food inks used include carrot puree, pastes from xanthan gum, and modified starch. Rheological tests were performed and the results were analysed to evaluate whether the inks developed were suitable for printing. Carrot puree yielded better results, to be used as the food ink (*95*).

3D-printed foods with functional ingredients and antioxidants

A study was made to assess the relationship between the printability of formulation and rheological properties, through the selection of tomato paste as the model (*96*). It was observed that the pressure for extruding the material increases with an increase in flow stress. The dispensing behaviour of the material also increased in proportional with the flow stress, except for fat containing products, which vary in their dispensing characteristics (*96*). A 3D-printed lemon juice gel was developed, incorporated with potato starch at different concentrations and the influence of potato starch addition at different levels on various characteristics of the gel was studied (*97*). Lemon gel, which was otherwise less transparent and chewy was made printable with the incorporation of potato starch gel, which exhibited anti-aging properties, transparency and ability to retain moisture. The impact of printing parameters (nozzle height, nozzle diameter, extrusion rate, and nozzle movement speed) as well as material properties on the quality of the final products was also investigated. When potato starch was incorporated at 15 %, the flow properties and mechanical properties of the gel were observed to be optimum. The printing parameters were optimum when the nozzle diameter is around 1 mm, the rate of extrusion is 24 mm/s and the nozzle movement speed is 30 mm/s. This work provided some insight towards the printing of gels in combination with starch (*97*). The impact of material composition on the quality of 3D-printed food were investigated using wheat flour, freeze-dried mango powder, olive oil and water (*90*). The optimum formulation with the best printing quality had flour and water in the ratio of 5:3. This formulation had no added freeze-dried mango powder and olive oil in it. For the formulation containing 2 % of olive, the printing quality was optimum with the flour: water: olive oil combination at the ratio of 55:2.75:30. When 2.5 g mango powder was incorporated to the formulation, optimum printing quality was observed for the formulation having flour: water: olive oil: lyophilized mango powder combination at the ratio of 57.5:30:3:2.5. Also, compressive pressure of 600 kPa, needle velocity of 6 mm/s, needle diameter of 0.58mm and internal filling ratio of 60 % was observed to be optimum. The foods printed with these printing parameters had numerous benefits like an organized packing structure, better interior texture profile and less deformation (*90*). Mashed potatoes were printed three dimensionally with different internal structures (*98*). The dimensional, structural and textural parameters were studied as a function of different infill patterns, in fill percentages and shell perimeters. From the results, it was observed that the 3D printed structures resembled the 3D designs greatly. Also, textural properties like hardness and gumminess was highly related to the infill levels. The microstructure analysis of the printed and cast material revealed that cast sample had a uniform internal structure, when compared to the layered structure and porous structure of the printed material in longitudinal section and cross- section respectively. And the textural analysis showed that the hardness of the printed sample was less, in comparison with the cast sample. This study had proved that 3D printing technology could alter the characteristics of foods, providing a novel path for customizing the textural properties through the fabrication of internal structures (*98*). A 3D printed smoothie was developed from mixture of fruits and vegetables which vary in colours (*27*). The ingredients used in formulation were carrots, kiwifruit, avocado, pears, and broccoli raab leaves. This study paved as a stepping stone towards the printability of fruits and vegetables-based formulations. The smoothie was printed in pyramid shape and the 3D printed smoothie had a better visual appeal as compared to its non-printed version. The sensory properties, antioxidant and phenolic content was unaltered after printing. The two defects noted while using the printer were the change in the actual and estimated position for the deposition of food and the improper sanitation of the areas of the printer which comes in direct contact with the foods. The study was explored the impact of printing variables like printing speed and flow level on the printability of food containing fruits (*27*). A snack food was formulated from fresh bananas, dried mushrooms, canned white beans, dried non-fat milk and lemon juice after 3D printing (*99*). After printing, the printed samples were observed to be similar to the 3D design. The material flow had a great impact on the microstructural properties. When the material flow was reduced, the interior structure of the snacks was irregular and the structure had large-sized pores but when the flow was higher, the internal structure became thicker, with a decrease in the porosity. The nutritional analysis of the printed snack revealed that 100 g of the snack was sufficient to meet the calorie requirement of children within the age range of 3-10 years. The printed snack was reported to be rich in calcium, iron and vitamin D (*99*). Another study explored the possibility of printing strawberry tree fruits, which have an exceptional nutritional profile, *viz.* vitamins, antioxidants, minerals, sugars and bioactive components (*100*). Hydrocolloids like wheat flour and corn flour were added to the fruit blend at various level, to make the formulation printable. The formulation developed was rich in polyphenols and exhibited anti-microbial activity. The type of hydrocolloids incorporated and the quantity and the choice of the printing program had a great role on the bioactive and functional properties of the formulation (*100*). A pickering emulsion rich in curcumin stabilized initially by pea protein isolate and k-carrageenan complex was 3D printed (*101*). From the printing results, it was observed that the emulsion containing k-carrageenan more than 0.3 % exhibited good extrusion, stability and shape retention. The bio accessibility and stability of curcumin was improved to a greater extent upon invitro digestion (*101*). 3D printed biscuits were fabricated from processed flours and multi-grain flours, which contain cowpea sourdough and quinoa malt (*102*). Traditional biscuits were also developed and these two types of biscuits were compared in terms of parameters like colour profile, hardness and image parameters to examine the structural deviations between the whole grain and composite flours (*102*). The 3D-printed biscuits were reported to be better owing to their multi-flour formulation, low values for redness, browning index and hardness. Traditional biscuits were observed to be harder than 3D-printed biscuits. The 3D-printed biscuits had exhibited similar quality characteristics with respect to their non-printed counterparts. A slight reduction was observed in the antioxidant activity, after 3D printing, but the levels of minerals like iron and phosphorous was seen enhanced in 3D biscuits (*102*)

3D-printed foods with cereals as the base material

3D-printed cereal foods containing probiotic microorganisms were constructed from wheat doughs by varying the amount of water and calcium caseinate (*30*). The doughs were printed in two designs-one a honeycomb structure and the other a concentric circle. It was observed that the printability of formulation was based on factors like water content, type of the flour used and the quantity of additives like calcium caseinate. After printing, strains of probiotic bacteria were incorporated and the prints were baked. The results of the study revealed that the viability of probiotic bacteria increased with increase in surface-to-volume structure. Among the two structures, the honey comb structure yielded maximum number of viable bacteria in comparison to the other structure (*30*). The gel formation properties and the physical characteristics of the dough alters with any alteration in the composition of the dough. The study investigated the effect of these changes on 3D printing of the dough (*103*). The results showed that pseudoplastic gel having high extrudability, gel strength, elasticity and low ductility was necessary to yield extruded samples of optimum shape. The formulation with water (29 g), sucrose (6.6 g), butter (6.0 g), flour (48 g) and egg (10.4 g) per 100 g yielded optimum results, in terms of shape, gel formation and physical properties. Apart from optimizing the formulation for a good dough, the physical properties of all the dough formulation were studied. It was observed that the ingredients sucrose, butter and flour were vital for the desired modelling results (*103*). A 3D pizza was developed from a gluten-free flour blend and the physical characteristics were compared with that of available in the market (*104*). Though the fermentation time required for the gluten-free pizza formulation was double as required by the commercial pizza dough, textural properties and colour of the 3D printed gluten-free pizza was comparable with the commercial pizza. The healthier version of pizza developed had the potential to replace the commercially available pizza from wheat flour (*104*).

3D-printed foods for geriatric and dysphagic population

Around 50 % of the aged population suffers from dysphagia, which is characterized primarily by difficulty in swallowing. To enable the dysphagic population to enjoy their meals, a 3D printer was developed to fabricate softer foods (*105*). A syringe pump was used to extrude the gel and a dispenser was employed to create 3D objects. Agar solution was used as the ink for printing. As Agar's gelation is influenced by temperature, the temperature of the gel should be regulated for optimum printing. Four types of soft foods were made using agar and gelatin with the developed printer. The compression tests and hardness of the printed foods were carried out, and the results indicated that all the printed agar gels had a soft texture resembling jelly, which is quite appropriate for dysphagic people (*105*). In order to meet the requirements of dysphagic diet which is highly challenging, novel edible formulations were developed from black fungus with the addition of gums like xanthan gum, Arabic gum, and k- carrageenan gum (*91*). It was reported that the formulation containing Arabic gum lacked self-supporting stability, and the results obtained for the International Dysphagia Diet Standardization Initiative (IDDSI) tests were observed to be poor (*91*). Also, though carrageenan gum incorporated formulation showed good self-supporting stability, the formulation failed in IDDSI tests, owing to its sticky nature, but the printed structure was found to be self-stable. The formulation developed with the incorporation of xanthan gum resembled very well with the level -5 minced and moist dysphagia food in the IDDSI tests (*91*). A dysphagia diet, suited for aged population was 3D printed in the study (*106*). The diet composed of cellulose nano crystal-based (CNC) protein/ polysaccharide edible inks, of which the protein sources were gelatin extracted from bovine skin and whey protein isolate along with xanthan gum which forms an essential ingredient of dysphagia food. The formulation having 2 % gelatin, 8 % whey protein isolate and 8 % xanthan gum was considered optimum, owing to their good printability and ability to retain the shape. The formulation with bovine gelatin, xanthan gum and 1.5 % CNC met the criteria of level-5 minced and moist dysphagia diet as per the IDDSI guidelines (*106*). The possibility of employing flax-seed gum as the texture-altered component to develop dysphagia diets using 3D printing technology was studied (*107*). The ink formulation also had mung bean protein and rose powder in it. The formulation containing 0.9 % flax seed gum yielded optimum results in terms of printing characteristics, and this was considered as level-4 pureed/extremely thick dysphagia food as per the IDDSI guidelines. This study fabricated cheap, dysphagia diet containing phenolics exclusively from plant sources (*107*). The impact of the incorporation of xanthan gum and guar gum was investigated on different properties of pork paste after cooking and 3D printing (*92*). The addition of hydrocolloids imparted a shear-thinning effect on the paste, which improved the extrudability of the formulation. The incorporation of gums after the post-printing operations had altered the texture significantly, making it suitable for people suffering from dysphagia. The final products could be grouped under transitional foods, after the IDDSI tests (*92*). The 3D printer developed by Liu had a peristaltic pump and a pressurized tank, instead of a syringe and piston employed in common printers (*108*). This modification was done to facilitate the printing of meat, which is complicated to print otherwise, due to its fibrous structure. The benefits of the modified meat printer were the improved storage capacity and material properties. The operation efficiency and productivity were increased. The chewing experience was enhanced after printing, facilitating easy intake by older people. This printing method could transfer the ingredients from the interior of the meat to the surface (*108*).

Protein- and fibre-enriched 3D-printed snack foods

3D-printed snack foods were fabricated from different ingredients like oat protein concentrate, faba bean protein, skimmed milk powder and starch (*109*). The study investigated whether extrusion-based 3D food printing could be applied for pastes rich in starch, protein and fibre. The printability of the pastes was assessed based on the factors like the ease of extrusion, printing precision and the print stability. The paste developed with semi skimmed milk powder yielded the optimum printing precision and shape stability. The results had showed that the applicability of the process was purely based on the material as well as their binding properties. Also, this study had exhibited that the optimization of different formulations was considered to be the initial point for developing snack foods in future (*109*). A 3D printed snack food was developed from wheat flour fortified with ground larvae of Yellow mealworms as a protein source (*110*). When insects were added at a rate of 20 %, a softer texture of the dough was obtained. The structural quality, nutritional characteristics were investigated and they remained unchanged after baking. To get a desirable product, baking process was optimized at 22 minutes and 200 °C. The incorporation of insects enhanced the nutritional value in terms of protein quality and essential amino acid score (*110*). A fibre-rich snack food was developed from button mushrooms using 3D printing technology (*88*). Lyophilized mushroom powder, which was non-printable in nature, was made printable with the incorporation of wheat flour, at different rates. The formulation containing 20 % mushroom powder yielded the best results, in terms of nutritional value and printability. Sensory evaluation of the savory products yielded better results as compared to the sweeter version of snacks (*88*). As a part of producing valuable by-products from industrial wastes, functional cookies were developed using 3D printing technology from grape pomace and broken wheat which were otherwise discarded (*89*). An increase in grape content had enhanced the viscosity of the formulation which resulted in reduced printing speed. The developed cookie had a good sensory profile, structural integrity and was rich in protein and fibre (*89*). Healthier 3D printed snacks were constructed using composite flour made from barnyard millet, green gram, fried gram and ajwain seeds (*111*). The printed products were subjected to different post-printing treatments. The printed snack had an attractive visual appeal and good overall acceptability. They also had protein and fibre in amounts needed to satisfy their daily requirements. Though the snacks developed through different post-processing methods yielded good sensory scores, microwave-dried snacks matched very well with the untreated samples and they exhibited better results in terms of nutritional and textural profile (*111*).

3D-printed foods from milk, eggs, meat and fish

A milk protein-based 3D food simulant was fabricated through the incorporation of whey protein isolate to the milk protein concentrate (*29*). The optimum formulation had milk protein concentrate and whey protein isolate at a ratio of 5:2, establishing the applicability of a simulative high protein system through extrusion technology. The prints based on this formulation resembled very well with the digital model. The viscosity and mechanical strength of this formulation were adequate to facilitate deposition and adhesion, which is an essential criterion in extrusion-based printing. This study would be beneficial to future works involving 3D printing of protein rich foods (*29*). The application of 3D printing to process cheese available in the market was investigated in a study (*112*). After printing, both printed and non-printed cheeses were compared in terms of hardness and meltability. The printed cheese had exhibited decreased hardness and increased meltability than the untreated cheese samples. The cheese samples after printing were observed to be highly flexible in terms of geometry as well as texture. This study emphasized the role of 3D printing in altering the material properties, thereby constructing tailored products (*112)*. The study by Anukiruthika *et al*. (*28*). 2020 investigated printability of both the white and the yolk fractions of eggs. As eggs are highly nutritious and exhibit numerous functional properties, 3D printing of egg-based formulations are highly relevant in the functional food industry. To make the egg fractions printable, rice flour was added as a filler at different proportions. The optimization of printing parameters including nozzle height, diameter, printing speed, extrusion motor speed, and the rate of extrusion was performed in the study. The incorporation of rice flour enhanced the strength and printing stability of egg whites and yolk. The printability of egg yolk was reported to be better than the egg white prints, with very little deformation. The optimum egg yolk formulation had egg yolk and rice flour in the ratio 1:2 (*28*). Chicken meat was printed through the incorporation of composite millet as a source of dietary fibre (*113*). The composite millet-based flour comprised barnyard millet, fried gram, green gram, and ajwain seeds. The optimum formulation had chicken meat and flour in the ratio of 2:1. This ratio was selected, based on the sensory results, as the incorporation of composite flour may adversely affect the sensory characteristics of the chicken meat. The printed product had good amounts of both protein and dietary fibre, so that the product could be consumed on a daily basis by the population belonging to all the age groups. This study had initiated the construction of meat products incorporated with dietary fibre, thus improving the health benefits (*113*). Lean meat-lard composite layers were 3D printed and the printed layers were cooked (*114*). It was reported that the structure of the products was unaltered after cooking. The study had investigated the impact of numerous fat content and infill densities on the physical and textural properties of meat. The high-fat content caused more cooking loss, shrinkage, cohesiveness, and lower fat retention, moisture retention, hardness, and chewiness. With an increase in infill density, high moisture retention, and a reduced rate of shrinkage and cohesiveness, an increase in hardness and chewiness was observed (*114*). A 3D fish surimi gel was developed and the result of the addition of sodium chloride was investigated on the physio-chemical properties of the gel including water holding capacity, gel strength, and network structure (*11*). An increase in the addition of sodium chloride caused an improvement in these properties and the gel having 1.5 % sodium chloride yielded the best result in terms of rheological parameters as well. In this study, the functional characteristics were observed to be the major criteria while printing surimi gel additively (*11*). Developing novel surimi products employing fat fortification and 3D printing technology was investigated in the study. The work was also aimed to render the PUFA rich-high internal phase emulsions stabilized with microbial transglutaminase (MTGase) cross-linked fish scale gelatin particles (FSG). Edible inks were developed through the incorporation of stabilized emulsion to surimi using 3D food printing and the impact of this addition on different characteristics of surimi gel was studied. When the oil phase volume was 80 %, the stability, flow properties and the structural characteristics of the emulsion were affected by FSG. The mechanical properties of the emulsion incorporated surimi was reported to be enhanced. The incorporation also had a profound influence on the printing accuracy. Incorporation of emulsions using 3D printing technology render cheap, healthy, PUFA enriched surimi products (*11*). Three-dimensional printing technique is now being used to print different types of food components, through proper selection of raw materials, pre-printing steps to make them extrudable, optimization of formulations, nozzle diameter and nozzle height. The ability to print multiple components and the innovations in both the software and hardware, make this technology to fabricate foods for the general public, regardless of age group, occupation, and lifestyle (*115*).

CHALLENGES AND FUTURE PROSPECTS OF 3D FOOD PRINTING

Even though 3D food printing technology has emerged as an invaluable technology, offering an array of possibilities in food processing, the constraints of the technology should not be ignored. As this technology rely on the machine completely, with least dependence on human labour, variables like formulation of the food, extrusion motor force and the choice of raw materials for printing has to be optimized prior to printing. The construction of 3D printed food depends on temperature, dimensions of nozzle, extrusion rate, speed of deposition. The inadequate mixing of ingredients in the material feed, stability of the material feed during the operation and the post printing factors often poses a problem (*8*). Fabrication of foods in large scale is another limitation of 3D food printing due to the lower capacities. Also, they have a very short shelf-life, since the formulation tend to be unstable, owing to the change in the rheological properties (*8*). Manufacturing, a reliable, least- cost, large scale printer, capable of developing rapid prototyping seems to be a challenge till date (*116*). Also, the piracy of the 3D files might be an issue in future, as the technology becomes more popular**.** The introduction of newer policies under IPR to prevent copying of digital designs could not be overlooked in future (*117).*

Food safety validation of customized formulations used in 3D food printing is necessary. The chances of food safety related hazards upon consumption of 3D printed foods should be taken into consideration. An important hazard arises from the interaction of the printing recipe and the parts of 3D printers, resulting in cross- contamination (*118,119*). Also, some printed foods require post-processing which might involves heating and re-heating steps after storage. These processes can activate the growth of pathogenic organisms (*119*). Moreover, printed foods may contain components like allergens, foreign objects, and ultrafine particles which are hazardous to health (*27,119,120,*). In future, in order to attain safety of 3D printed foods, a regulatory standard addressing known risk factors and their controlling mechanisms associated with raw materials, printers, post-processing conditions, and handling practices needed to be emphasized (*27,119*). Dankar *et al*. (*121)* emphasized the significance of framing exclusive legislations for 3D food printing. Apart from the presence of hazardous commodities and adulterants in 3D foods, their intake may lead to food poisoning outbreaks, unless fabricated and stored properly. The regulation of these issues requires national, federal, and international mandatory standards (*118*). In future, on a hypothetic note, this technique may be utilized to fabricate novel foods from chemical components in the context of famines or food unavailability. In such scenario, an explicit regulation will be mandatory. 3D-printed foods could be categorized as imitation foods and should be labelled distinctly from their non-3D counterparts. if the construction of traditional foods involves more cost, when compared to their 3D versions and both these foods could not be distinguished from one another, selling 3Dprinted foods lacking distinct label would result in food fraud (*122*). Even if, most of the 3D printed foods could be easily recognized due to their unique appearance, an explicit labelling would be highly recommended. A threshold (e.g.- below a particular level) could be fixed as the labelling cut-off (*122*). Despite the shortcomings identified for this technique, 3D food printing has a promising future owing to its ability to offer customization in every aspect related to food. The technology contributes to environment-friendly approach through efficient utilization of wastes as well as incorporation of sustainable resources. Providing viable dietary solutions in disasters and space nutrition are the two major areas where this technology could be applied well in future (*123*).

CONCLUSIONS

Three-dimensional (3D) printing of foods has evolved as a boon to the food processing sector since the technology was found ideal for developing customized food products, both in terms of geometry as well as nutritional profile. 3D food printing has immense potential to capture the future food market by taking advantage of the functional ingredients across the globe, be it on the surface, sub-surface or from the deep ocean, to provide a healthier choice to the consumer. Functional foods play a major role in the prevention and cure of diseases associated with dietary disorders, as proven by previous studies. Despite the highly health-conscious population of the current world, the functional food industry often fails to gain consumer acceptance. The acceptability of these foods could be enhanced to a greater extent through the fabrication of 3D-printed functional foods. Even though 3D printing of foods is still at its embryonic stage, the studies on 3D-printed functional foods have proven that this technology is capable of processing a wide variety of ingredients ranging from lemon juice gel to highly fibrous meat in infinite designs, thus offering personalized nutrition. Apart from the numerous challenges of operating a 3D printer, printed products are anticipated to conquer the processed food market in the near future, considering the healthy and personalized variants created within a short time.

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CONFLICT OF INTEREST

The authors declare that no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

DATA AND MATERIAL AVAILABILITY

Data supporting this study are available from the respective authors upon reasonable request.

AUTHORS' CONTRIBUTION

The data collection and curation, formal analysis methodology, as well as drafting the manuscript was led by Rasheeda M. Remya S contributed equally to the conceptualization and data curation, and played a leading role in validation and in writing and editing the review. She also shared equal responsibility in supervision. Mohan CO contributed equally to the conceptualization, data curation, and supervision. He took the lead in providing resources and managing the project, and shared equal responsibility in reviewing and editing the manuscript. Bindu J contributed equally to supervision, provision of resources, and reviewing and editing the manuscript.

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Table 1. Advantages and disadvantages of different printers

Sl no	3D food printing technique	Advantages	Disadvantages
1	Extrusion-Based	Machines at the initial stage was of least-cost (*10*) Availability of a wide range of ingredients (*10*). Ease of customization (*10*).	Lower printing precision (*10*). Longer fabrication time to manufacture sharp outer edges Anisotropic characteristic of food after printing (*10*). Difficulty in holding 3D structures during post printing (*10*)
2	Binder jetting	Lower printing time (*20*) Capability of fabricating foods with greater solid content Support materials are incorporated automatically during layer formation Developing products from versatile component constitution (*21*).	Limited to foods composed of sugar and starch powders (*21*). Rough surface of the developed foods, necessitating post-printing treatments including temperature curing (*22*) The products developed were of lower nutritive value (*22*)

		Ease of colour printing on various food parts (*21*).	
3	Ink- jet printing	Wastage of model component is nil (*10*). The resolution and accuracy are higher (*10*). Diverse components and colours could be used (*10*). Fabrication speed was higher (*10*).	Post-printing might destruct tiny and thin aspects (*10*). The materials used for support could not be reused leading to wastage (*10*). Simple design and used mainly for surface filling or decorative purposes (*10*).
4	Selective laser sintering	Complicated parts which cannot be fabricated by other technics can be created with ease (*23*). No need of external support. Ideal for bulk production. Highly accurate and precise (*23*).	The fabrication process is expensive (*21*) Needs post-printing step (*21*) Broader surfaces and small voids are challenging to fabricate with accuracy (*21*)

Table 2. Advantages and disadvantages of different formulations used in 3D food printing

Type of formulation	Advantages	Disadvantages	Reference
Fruit and vegetable based	Sensory features, antioxidant property and phenolic content remained un altered after printing Better visual appeal after printing	Difficulty in accurate replication of the computer made design, especially for large scale applications Sanitizing all the areas of the machine in contact with food was not easy	(*27*)
Egg- based formulations	Printing precision was high Greater layer definition	Requires the incorporation of filler like rice flour to enhance printability	(*28*)
Milk -based formulations	Simulative high-protein food system	Not reported	(*29*)

	The prints resembled the 3D designs well		
Fish- based	Higher degree of resolution Similarity to the 3D model Deformation is less	Requires addition of sodium chloride to reduce viscosity and improve printability	(*11*)
Cereal- based	Structural quality as well as nutritional profile was unaffected	Not reported	(*30*)

Table 3. 3D printed novel foods

Year	Category	Technology	Image	References	Nutritional goals	Target Customers
2020	Egg based	Extrusion		(*28*)	To understand whether eggs could be delivered in printable format. To compare the impact of printing technology on the yolk and white portions of egg. To investigate whether the physical and chemical attributes of eggs could be employed effectively in layer- layer manufacturing	All age group
2020	Cereal based	Extrusion		(*88*)	To fabricate healthier 3D food products from sustainable	

					alternative raw materials. To develop a scientific base for 3D printed mushrooms-based products	All age group
2018	Cereal based	Extrusion		(*30*)	To construct novel foods comprising functional ingredients. To study whether probiotic organisms could be survived after baking in foods containing wheat flour.	All age group
2021	Cereal based	Extrusion		(*89*)	To investigate how well the value addition of food processing wastes align with consumer acceptability. To ensure cleaner production procedures along with enhanced recovery of nutrients from industrial wastes To describe newer and sustainable approach towards utilizing	All age group

					food processing wastes.	
2018	Fish based	Extrusion		(*11*)	To investigate the possibility of fabrication of 3D printed surimi-based system. To explore whether surimi could be printed in complex 3D patterns	All age group
2019	Cereal based	Extrusion		(*90*)	To investigate the influence of material composition on the quality of 3D-printed food. To explore the relationship of compressive pressure with needle velocity of food printing to achieve optimum parameters for 3D printing	All age group
2018	Milk based	Extrusion		(*29*)	To construct protein- rich food simulants with 3D printing technique To demonstrate 3D printed simulant consisting milk protein and to	

					explore the impact of whey protein isolate incorporation on the printing behaviour of milk protein concentrate.	All age group
2022	Black fungus based	Extrusion		(*91*)	To develop 3D printed dysphagia food with improved visual appeal and altered texture.	Age above 60 years
2018	Fruit based	Extrusion		(*27*)	To explore the potential of printing formulation consisting fruits capable of providing energy, calcium, iron and vitamin D. To assess the sensory acceptability of foods with pyramid shape and their changes upon storing.	Children in the age group of 3-10 years

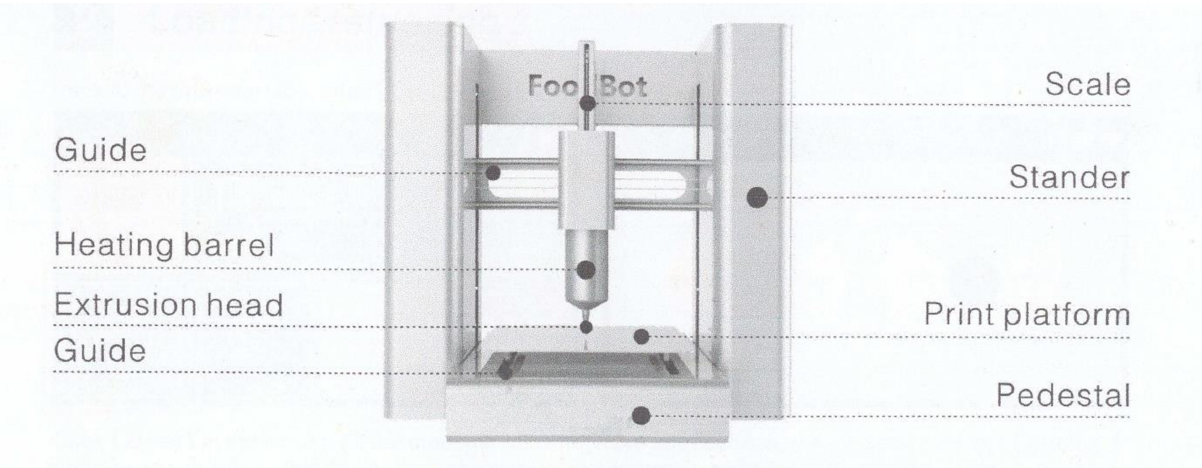


Fig. 1. Schematic diagram of a Food Bot 3D food printer (scanned image from the manufacturer's manual)

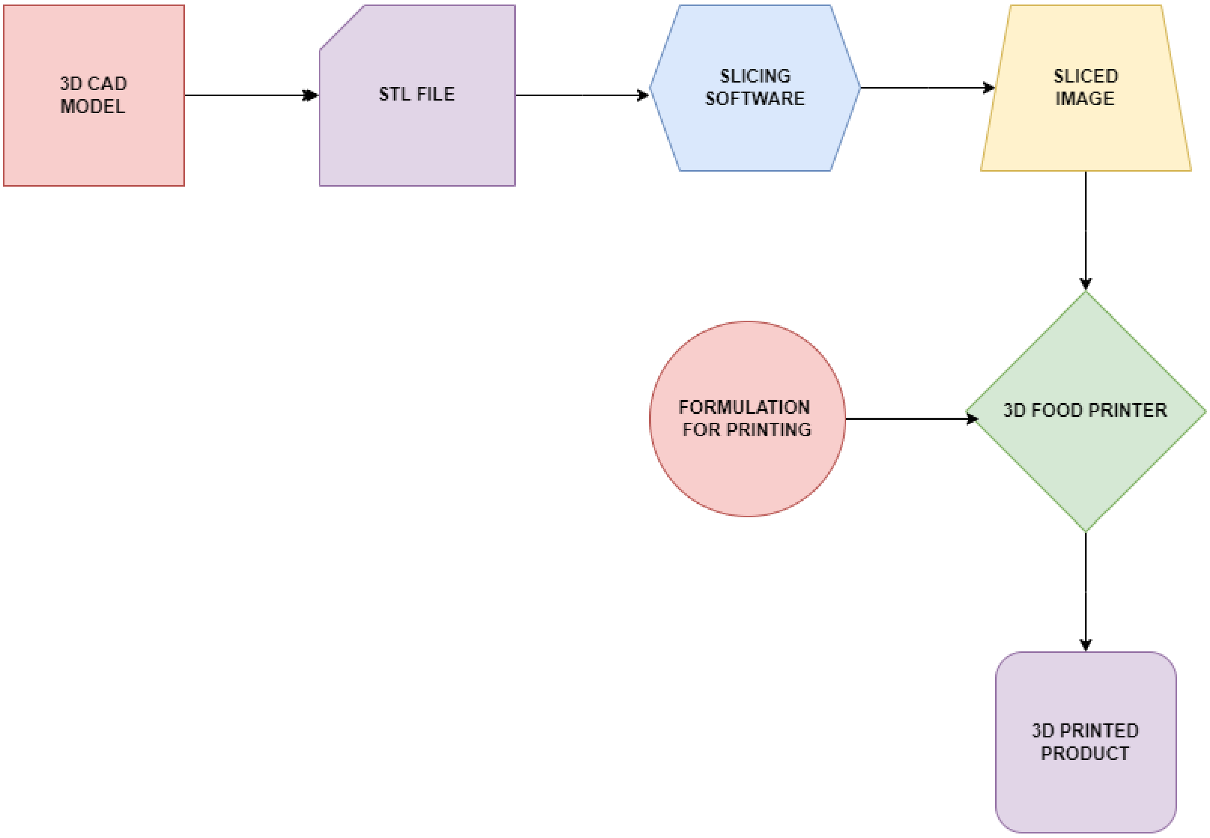
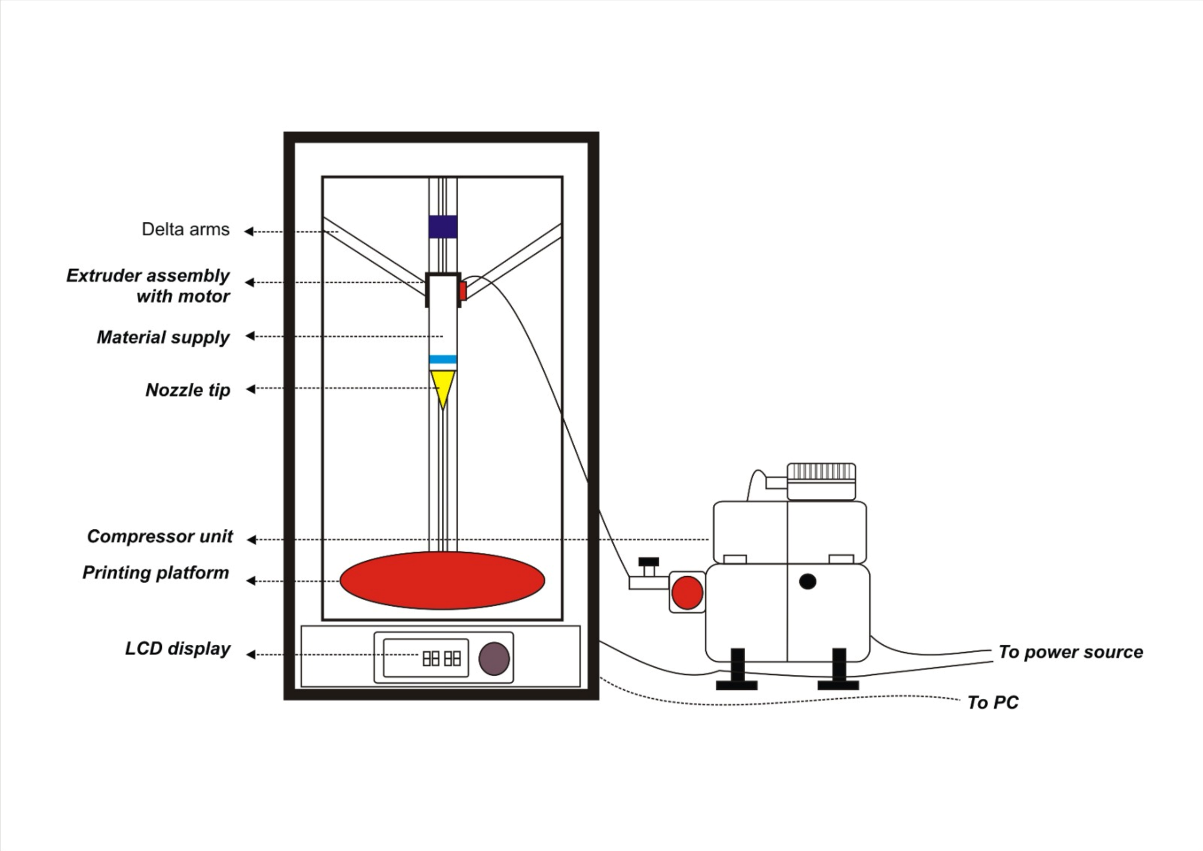
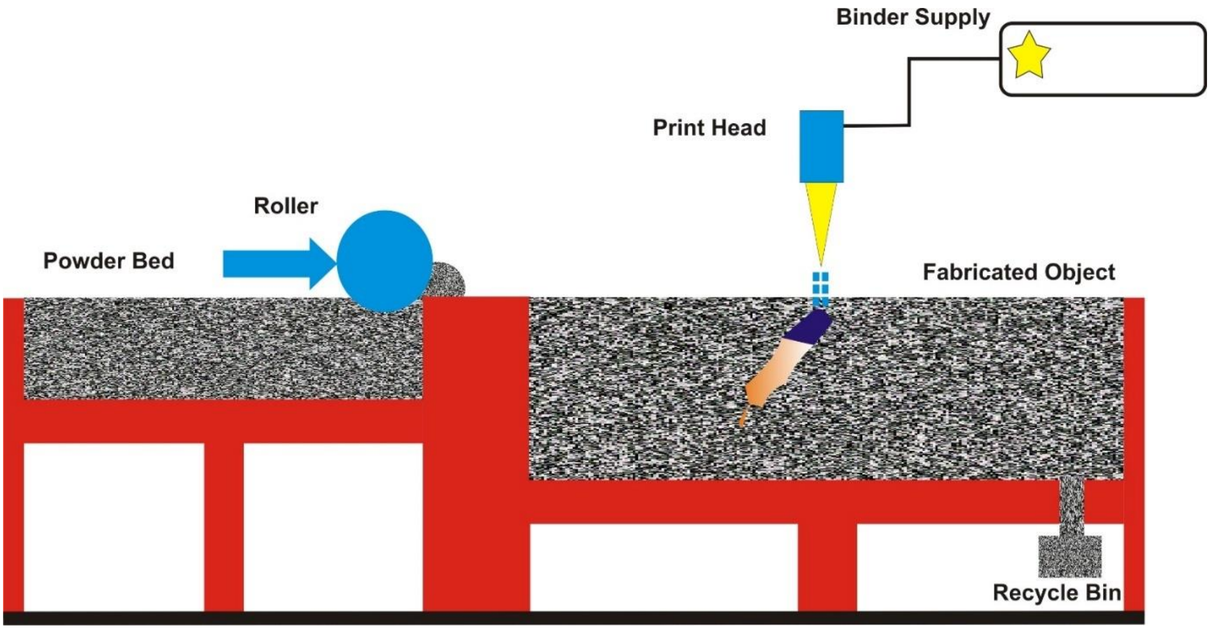


Fig. 2. Schematic diagram of basic workflow of a 3D food printer

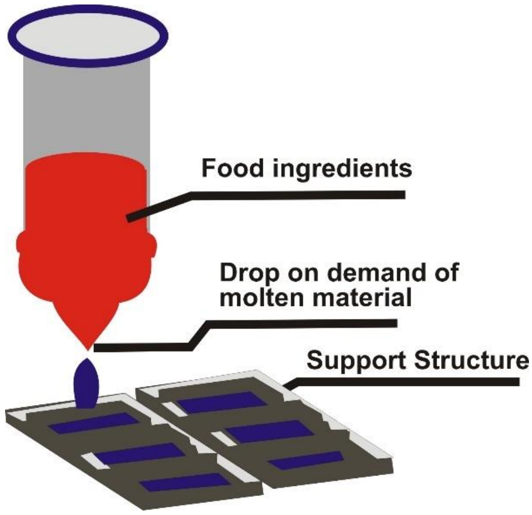
a)


Delta arms
Extruder assembly with motor
Material supply
Nozzle tip
Compressor unit
Printing platform
LCD display
To power source
To PC

b)


Binder Supply
Print Head
Roller
Powder Bed
Fabricated Object
Recycle Bin

c)



d)

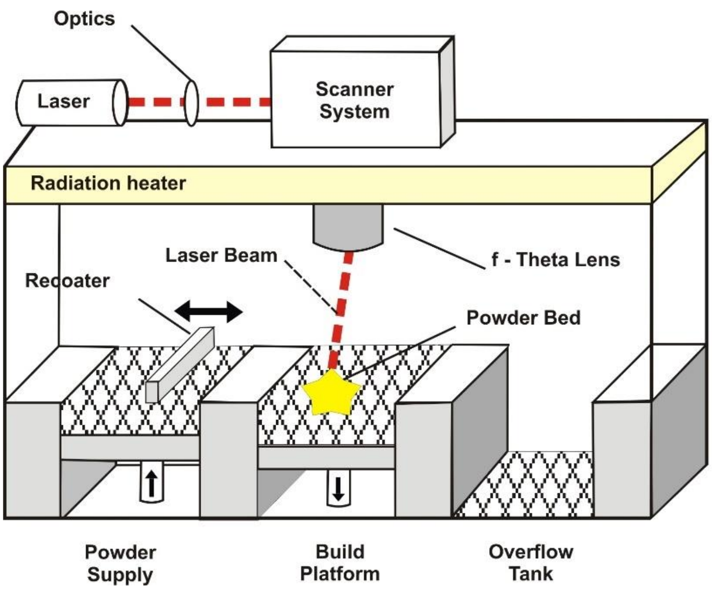


Fig. 3. Schematic diagram of: a) extrusion-type 3D food printer, b) binder jet printer, c) inkjet printer, and d) selective laser sintering 3D printer (Corel Draw graphics editor