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Three D Food Printing and its Applications—A Review

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ABSTRACT

3D food printing (3DFP) has the main objective of tailored food manufacturing, both in terms of sensory properties and nutritional content. Additionally, global challenges like food-waste reduction could be addressed through this technology by improving process parameters and by sustainable use of ingredients, including the incorporation of recovered nutrients from agro-industrial by-products in printed nourishment. The aim of the present review is to highlight the implementation of 3DFP in personalized nutrition, considering the technology applied, the texture and structure of the final product, and the integrated constituents like binding/coloring agents and fortifying ingredients, in order to reach general acceptance of the consumer. Personalized 3DFP refers to special dietary necessities and can be promising to prevent different non-communicable diseases through improved functional food products, containing bioactive compounds like proteins, antioxidants, phytonutrients, and/or probiotics.

Keywords: 3D food printing, binding agents, by-products, coloring agents, fortifying constituents, personalized nutrition

3D printing is "the manufacturing of solid objects by the deposition of layers of materials in accordance with specifications that are stored and displayed in electronic form as a digital model". In addition, 3D printing can integrate materials, structures, and functions (Yang *et al.* 2021) i.e. the capability of depositing two distinct materials having different behaviors during heating enables the generation of dynamic shape changes during dehydration (Kang *et al.* 2023). Similarly, color modulation of 3D-printed food has been triggered by depositing layers of materials having different colors when in contact with acidic solutions (Qiu *et al.* 2024).

3D printing, also known as additive manufacturing technology (AM), rapid prototyping technology (RP) or solid free form fabrication (SFF), is a technology based on digital models to produce pre-designed 3D objects by layering adhesive materials (Dankar *et al.* 2018; Godoi, Prakash, and Bhandari 2016; Liu *et al.* 2017). Its different from traditional manufacturing methods, 3D printing technology has been evolved tremendously in recent years due to its potential advantages, such as customized geometry, reduced production cost, shortened manufacturing cycle and almost unconstrained complexity of appearance, which have been regarded to potentially promote the third industrial revolution (Liu *et al.* 2017; Sun *et al.* 2018; Wang *et al.* 2017). Currently, Yang *et al.* (2001) has been reported to be the first time using the

extrusion based technology to produce a complex 3D cake. Since then, 3D printing technology has gradually developed in food sector.

Types of 3D Printing Technologies

Currently, there are four types of 3D printing technologies for food processing: extrusion-based printing, selective laser sintering, binder jetting and inkjet printing (An *et al.* 2019; Izdebska and Zolek-Tryznowska 2016; Liu *et al.* 2017). Fig. 1 shows the classification of 3 D food printing. Among them, extrusion-based 3D printing is the most widely used, which can be further classified into room temperature extrusion, fused deposition manufacturing and gel forming extrusion, according to different printing material states (Godoi, Prakash, and Bhandari 2016; Liu, Bhandari, Prakash, Mantihal, *et al.* 2019; Sun *et al.* 2018). Room temperature extrusion is carried out without temperature control and phase transition, and the extrusion of dough falls into this category (Yang, Zhang, Prakash, *et al.* 2018). To achieve successful printing, appropriate viscoelasticity of the material is the key property, which allows the material to be extruded through a fine nozzle and support the product structure after deposition. For melt extrusion molding, the molten paste is extruded from a nozzle and almost immediately solidifies and is welded to the previous layer, and this technique has been widely used to create customized 3D chocolate products (Liu *et al.* 2017; Mantihal *et al.* 2017). Different from the former two types of extrusion molding, the application of gel extrusion molding is much broader, such as the printing of hydrogel (Cohen *et al.* 2009), meat (Wang *et al.* 2017), mashed potatoes (Liu, Zhang, and Bhandari 2018; Liu, Zhang, *et al.* 2018), cheese (Kern, Weiss, and Hinrichs 2018), and fruits and vegetables (Severini, Derossi *et al.* 2018).

Extrusion-based food printing is the most popular method used in food printing due to its simplicity and the fact that extrusion is commonly used in conventional food processes (He, 2020). Fig. 2 shows the extrusion-based printing technologies. This technique can be further classified into room-temperature extrusion, fused deposition manufacturing, and gel-forming extrusion, according to different printing material states (Zand *et al.* 2022). Fig.3 shows the FDM Printing Technique. In extrusion-based 3D printing, the ability of the material to be squeezed out of the nozzle in a continuous manner (called extrudability) and the stability of the printed shape are the two main concerns (Schwab *et al.* 2020). Fig.4 shows the Direct ink writing. Extrudability refers to the initiation of flow and the formation of a stable filament during printing, while stability relates to shape fidelity and shape reservation over time after printing. The process has been outlined to follow the steps below (Sun *et al.* 2018). The first
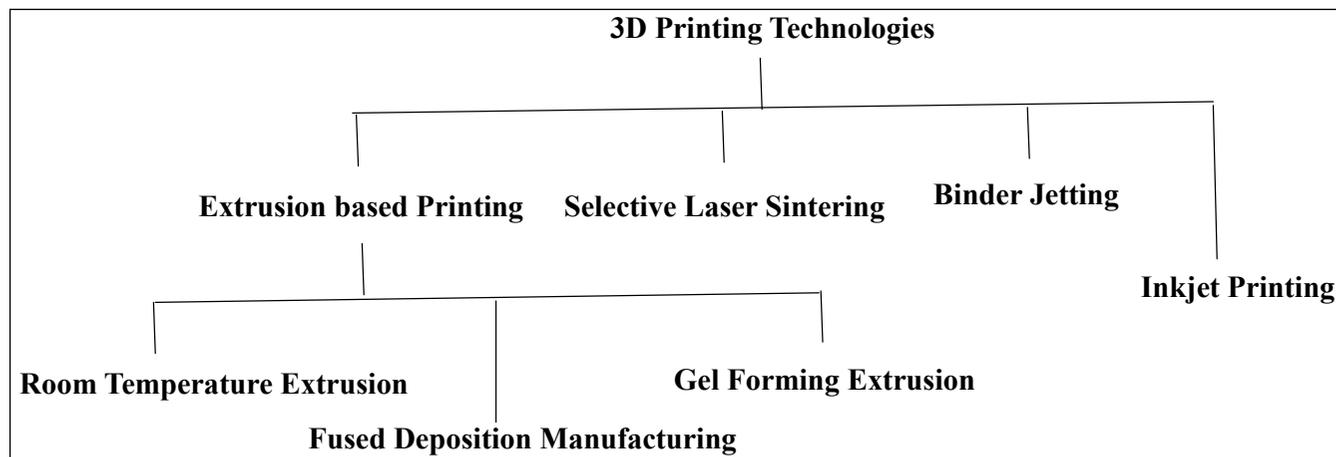

Fig. 1: Classification of 3 D printing Technologies (An *et al.* 2019; Izdebska and Zolek-Tryznowska, 2016; Liu *et al.* 2017)

step involves designing a virtual 3D model. This model is translated into individual layer patterns and ultimately generates machine codes for printing (second step).
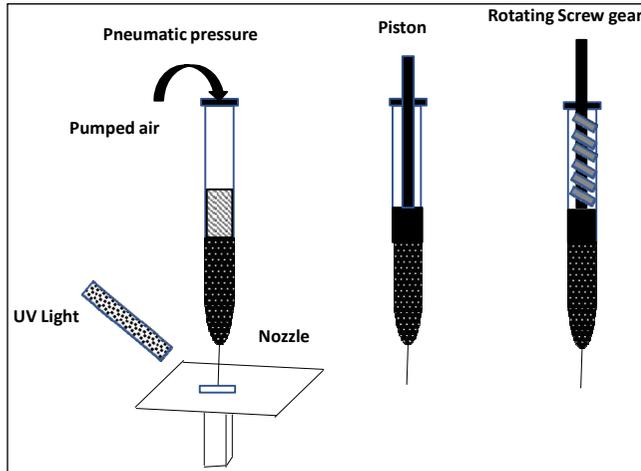

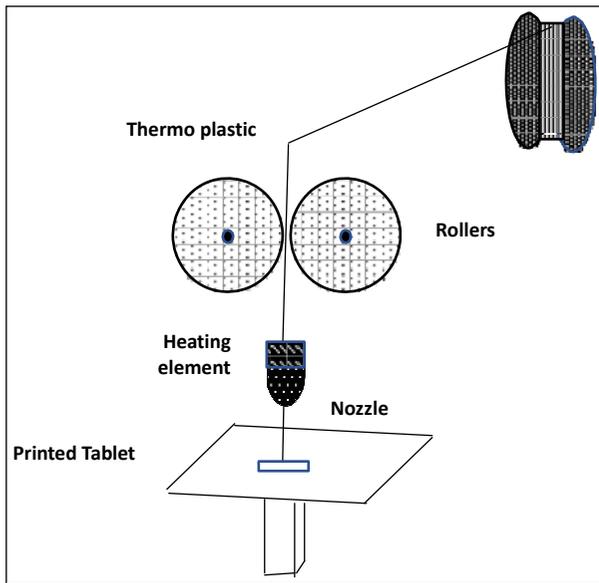**Fig. 2:** Extrusion based printing technologies

Fig. 3: FDM Printing Technique

The third step involves selecting a food recipe, and during the fourth step, the actual printing starts. The extruded material is dispensed either by moving the nozzle over an automatic platform or by moving the platform under the nozzle to form a layer. This platform can be heated for extra adhesion. Once the first layer is completed, the extruder and the platform

are parted away, and the second layer can then be directly deposited onto the growing object. One layer is deposited on top of a previous layer until the object's fabrication is complete (fifth step). Finally, the food after deposition can undergo cooking (baking, frying, or drying).
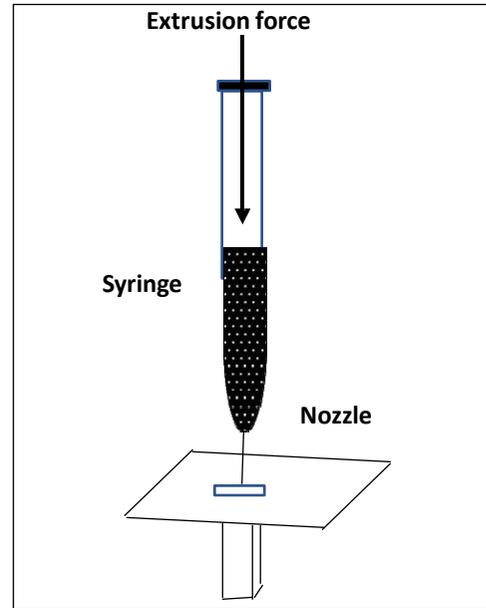

Fig. 4: Direct ink writing

In contrast, selective laser sintering (SLS) is a technique in which power lasers are used to selectively fuze powder particles into a three-dimensional structure layer by layer. Fig. 5 shows the Schematic diagram of Selective Laser Sintering. The laser scans the cross section of each layer surface to selectively fuze the powder. After scanning each section, the powder bed is lowered and covered with a new layer of powder, and then repeat this process until the desired structure is completed. Finally, the untreated powder is removed and recycled for the next operation (Liu *et al.* 2017; Noort *et al.* 2017). The SLS is widely used in the manufacture of cermet industry, but there are certain restrictions in the application of food because it is only used for the printing of powdery ingredients with low melting point (chocolate powder, sugar-based materials, fat-based materials, etc.) (Diaz *et al.* 2016; Godoi, Prakash, and Bhandari 2016; Liu *et al.* 2017; Sun *et al.* 2018). However, it is interesting
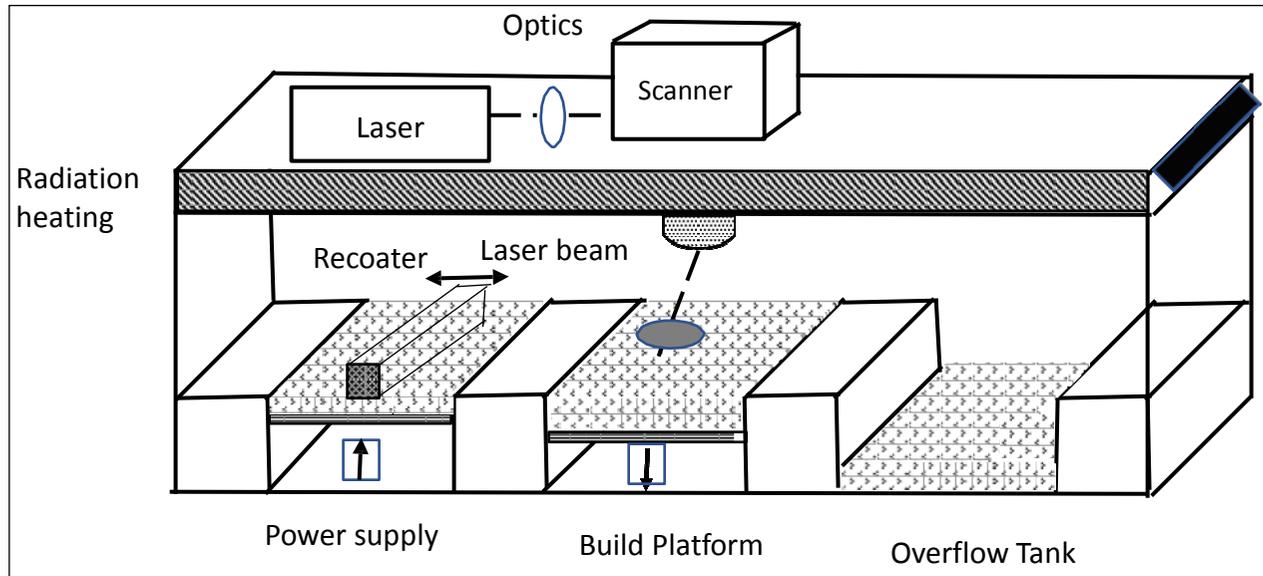
Fig. 5: Schematic diagram of Selective Laser Sintering

to note that the method is completed by layer-by-layer laying of powder, so the powder of each layer can be different, which is beneficial to the balanced processing of foods (Liu *et al.* 2017).

Selective laser sintering (SLS) is an additive manufacturing process that belongs to the powder bed fusion group. This method can be applied to create multiple layers of the food matrix where each layer contains different food material components. It uses a laser as the power and heat source to sinter powdered material. A presentation of this technology is depicted in Fig. 5. Firstly, a layer of powder is deposited on a build platform and levelled by a roller or blade. Secondly, powder particles are locally fused by a laser which is directed automatically at points predetermined by a 3D model. The next step after the first layer reaches a certain thickness is to lower the platform to start depositing the second layer and so on until all layers are deposited and the final 3D object is created.

Binder jetting is similar to SLS in principle. In the printing process, layers of powdery material are deposited, and the binder is selectively sprayed onto each layer of material in a specific area. Fig. 6 shows the Binder jetting 3D printer. The binder melts the

current section onto the sections before and after the weld. In the manufacturing process, the unmelted powder always supports the molten parts, resulting in complex structures. Finally, the unbonded powder is removed and recycled (Sun, Zhou, Huang *et al.* 2015). Binder jetting has the advantages of fast processing speed and low cost, but the smoothness is not enough, which requires post-treatment operations such as high-temperature curing (Sun, Peng, Yan, *et al.* 2015; Sun, Peng, Zhou, *et al.* 2015). This technique usually fabricates food using sugar and starch powders.

In Hot air Sintering (HAS) the raw material is mixed under the influence of a low speed and regulated flow of hot air passing through a narrow beam, thus creating the first two-dimensional (2D) form of a homogeneous powder. At first, the powder bed is slightly lowered, a thin flat layer of particles is spread to the top of the bed, and the fused powder is selectively fused in the new layer. The newly printed 2D object is actually merged with any overlapping connected regions in the first layer. By repeating this procedure, a 3D object is progressively formed. When the construction of the 3D structure is completed, the bed returns to its original position, the molded product is separated, and the unused raw material

(powder) is not discarded but retained to be used in the next manufacturing cycle.

In Liquid Binding the printer head ejects a liquid binder (ink) which is precisely deposited onto a thin layer of powder following a cut 2D profile created by a 3D computer model. The binder joins adjacent particles, thus creating a three-dimensional structure. Cohesion is due to different mechanisms such as sintering, chemical reaction, and the formation of liquid bridges (Mueller, 2012). The liquid (such as flavor liquids and colors) is vital in this method as it binds certain areas of a given layer of the powdered material (such as sugar) (ASTM, 2023). A diagram of this technique is depicted in Fig. 4. As shown in the figure, there are two chambers: one is filled with construction material powder which is fed into the second chamber by a leveling roller, and the second

chamber is used to implement the 3D model. The 3D model is made by gluing the building material into powder using the liquid binder. The powder is poured on top of the building platform which has been lowered to a depth equal to the height of the first layer to be created. The liquid adhesive binder is supplied through an inkjet print head at a controlled rate while the head moves along the horizontal plane. After the first layer is spread, the platform is lowered again to a depth equal to the height of the second layer, and more powder is rolled out from the first chamber.

Inkjet printing uses a drop-to-drop method to print food. Compared with the previous methods, it is commonly used for surfaces filling or image decoration on food surfaces (Liu *et al.* 2017; Pallottino *et al.* 2016), suitable for printing of low-viscosity
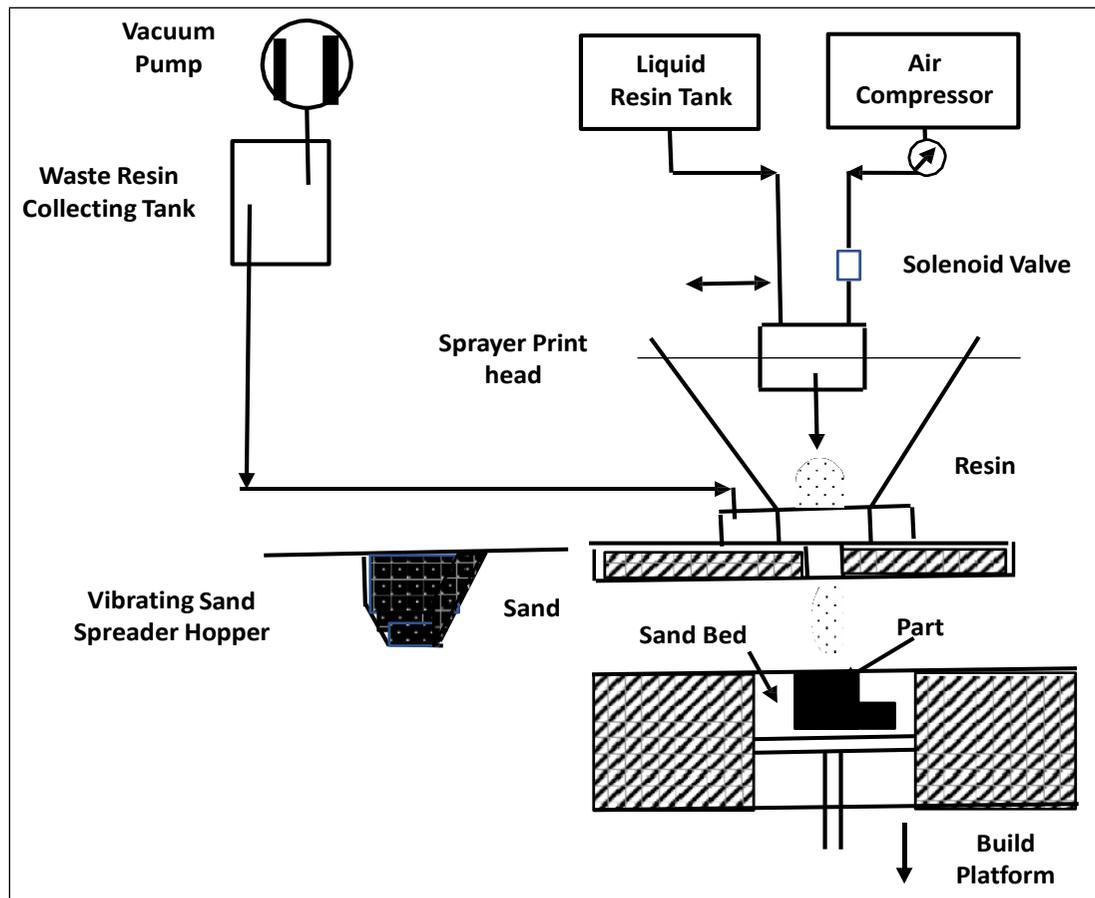

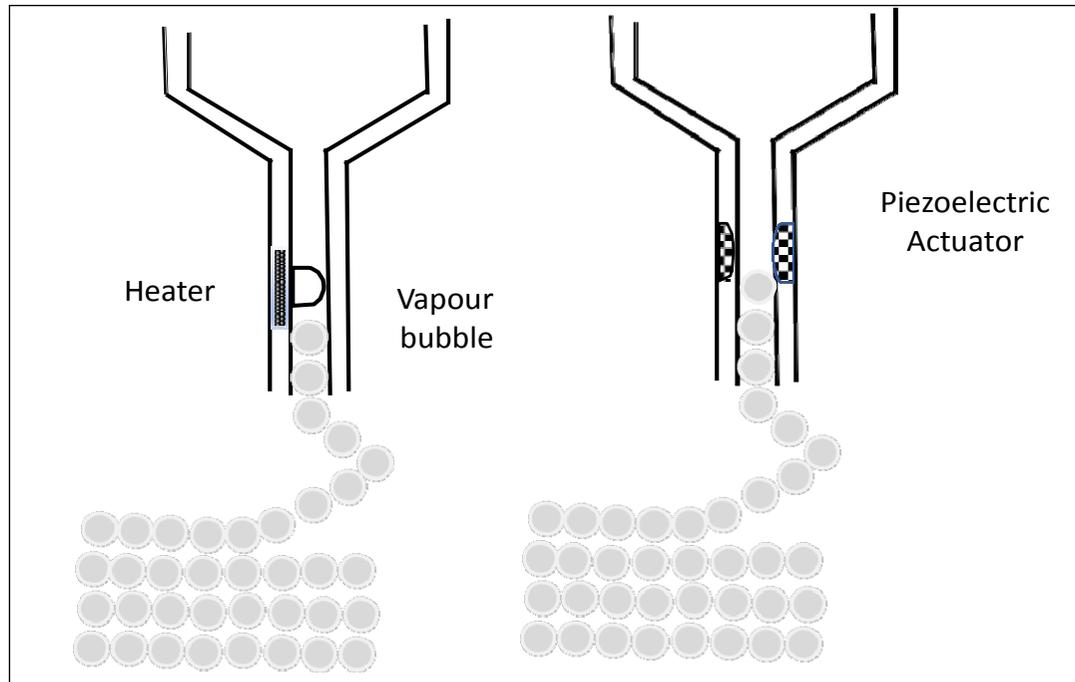**Fig. 6:** Binder jetting 3D printer

Fig. 7: Inkjet Printing

materials such as pulp or paste (Liu *et al.* 2017; Sun, Peng, Yan, *et al.* 2015). Fig. 7 shows the Inkjet Printing.

3D printing has been garnering increasing attention from different industries for its revolutionary impact in the field of manufacturing. It is set to gain mass adoption for its sustainable and efficient system of creating a variety of objects layer by layer using a 3D printer (Dizon *et al.* 2018). This technology greatly reduces waste and lead time in contrast to conventional manufacturing which includes subtractive manufacturing where a portion of a material is removed/subtracted from its greater part to produce a desired by-product. One of its advantages over formative manufacturing is its ability to produce complex shapes. The burden of high costs from traditional manufacturing is also considerably minimized through additive manufacturing (Dizon *et al.* 2020). Table 1 shows the applicability of 3D printing of novel foods and functional foods.

Table 1 shows the applicability of the 3D Printing of novel foods and functional products.

3D Printing Applications in Food

Printing Technology and Materials

Extrusion-based 3D printing, also known as Fused deposition modeling (FDM), is the most common printing technology in the food sector. 3D printing allows rapid manufacturing such as in making a cake layer by layer using a cake decorating robot (Wolf *et al.* 2021). Purees manufactured using 3D printing are mixed with a certain amount of thickening additives such as gelatin for the meat slurry (Liu, 2018) and pectin for the fruit-based snack in order to increase its print quality (Derossi *et al.* 2018). Mashed potato is printed from potato flakes with gelatinized starch, known as an ideal ingredient for the manufacturing of finished products for its lesser requirement in post-processing. Vegetables such as carrots, peas, and corn can also be 3D printed as they are relatively easy to prepare and are inexpensive food inks (Pant, 2021). Pizza (Anonymous, 2021), pasta (Liu *et al.* 2018), and dessert (Liu *et al.* 2017) can also be created directly using extrusion-based 3D printing. Table 2 shows the

Table 1: Applicability of 3D printing of novel foods and functional products

Sl. No.	Snacks	Method	Product	Characteristics	Reference
1	Yam powder with added high-fiber potato by-products	Dual-nozzle 3D printer	Freeze-dried yam and potato processing by-product at varying ratios	Addition of potato by-products reduced extrusion swelling and increased WAI and G'	Feng *et al.* 2020
2	3D printed functional food with antioxidant properties	Focus 3D food printer with paste printing head and 1.6 mm aperture nozzle	3D printed cookies fortified with freeze-dried microalga *Arthrospira platensis* encapsulated in alginate microbeads	Cookies were obtained with good shape fidelity with low water activity for high microbiological stability; addition of microalga increased antioxidant activity	Vieira *et al.* 2020
3	Fruit-based food formulation nutritionally designed for children to build 3D snacks	3D Printing	3D printed snack consisting of bananas, dried mushrooms, canned white beans, lemon juice, non-fat milk, pectin powder, ascorbic acid	Fruit-based formula estimated to contain 5–10% of required energy, calcium, iron and vitamin D for children ages 3–10. Flow of material affected the dimensional and microstructural properties of the product	Derossi *et al.* 2018
4	Printability of fiber-enriched foods with acceptable organoleptic characteristics, using button mushrooms	3D food printing	Snacks prepared with freeze-dried white button mushrooms, wheat flour, potassium metabisulphite, sodium chloride, calcium chloride, post-processed as sweet or spicy snacks	Freeze-dried powder was not printable but addition of wheat flour improved printability	Keerthana *et al.* 2020
5	Printability of cereal-based food structures with probiotics	3D food printing	Wheat dough with different flour/water ratios, optimized for printing, supplemented with *Lactobacillus plantarum*	Following baking, 3D printed structure was maintained and acceptable viability of the probiotics was obtained;	Zhang *et al.* 2018
6	3D-printed cereal-snack bar	3D printer	Cereal-snacks	Cereal-snacks with different texture properties (porosity fraction, hardness) by means of 3D-printing technology.	Derossi *et al.* 2020
7	Mixture of 50% native wheat starch + 40% maltodextrin + 10% palm oil powder	Selective laser sintering	Brittle 3 D foods	3D-printed samples were mechanically characterized by means of compression testing. The observed phenomena are captured in a constitutive model that describes the large deformation behavior and the brittle failure of the material.	Jonkers *et al.* 2020

Table 2: Various materials used in 3D Printed foods with varied applications

Sl. No.	Materials used	3D Printed food	Application	Reference
1	Frosting	Cake	Rapid manufacturing	Wolf (2021)
2	Gelatin and meat	Meat slurry	Increase food intake	Liu *et al.* (2018)
3	Carrots, peas and corn	Vegetables	Increase food intake	Pant *et al.* 2021
4	Banana, lemon juice etc	Fruit based snack	Personalized Nutrition	Derossi *et al.* 2018
5	Dough and tomato sauce	Pizza	Rapid manufacturing	Anonymous, 2021
6	Traditional pasta	Pasta	Rapid manufacturing	Liu *et al.* 2018
7	Chocolate	Chocolate	Customized dessert	Liu *et al.* 2017

information of 3D printing technique used in various food products i.e., cake, meat slurry, vegetables, fruit based snacks, pizza, pasta and chocolate manufacturing by using extrusion based 3 D Printing of foods. Table 2 shows the various material used in 3D printed foods with different applications in the Food.

Three-dimensional (3D) printing is an innovative and disruptive additive manufacturing technology that uses digital pre-designed files to guide a layer-by-layer material deposition process, creating complex 3D structures (Wu *et al.* 2024). Significant advantages of 3D printing include the ability to produce personalized food and nutritional options tailored to diverse and programmable tastes, textures, dietary needs, and physical conditions (Zhao *et al.* 2021). Additionally, 3D printing can enhance food flavors and visual appeal, making it an attractive option and awakening the desire for consumption in the elderly, children, adolescents, and individuals with swallowing difficulties (Chao, Yan, & Fan, 2024; Portanguen *et al.* 2019). 3D printing in food preparation was humorously predicted by the 1960s cartoon "The Jet-sons", where characters could select and print their meals in minutes. Although this "futuristic" scenario is not yet feasible and only a limited number of food systems are currently suitable for 3D-food printing, research in this field is rapidly expanding (Y. Chen *et al.* 2022). In reality, consumers in the UK have already shown a willingness to pay more for 3D-printed chocolate bars (Califano & Spence, 2024). Also, the interest in new foods has been found to increase the purchase intention of 3D-printed foods in Japanese consumers, especially when combined with digital marketing strategies, environmental awareness, and perceived benefits (Seo & Shigi, 2024). One of the challenges faced by 3D food printing technology is the use of food matrices which present high printability efficiency, influenced by the physicochemical proper-ties (Z. Guo, Chen, & Meng, 2023). Consequently, research and development of printable formulations have skyrocketed, with food gels being a primary focus of current research.

CONCLUSION

It is important to select materials with appropriate physical and chemical properties, such as particles size, fluidity, rheology, and mechanical properties. The food materials should have appropriate fluidity, viscosity, rapid recovery performance and proper mechanical strength, so that they can easily flow out from the nozzle tip and are capable of self-supporting and maintaining the shape after printing. Therefore, pre-treatment of food ingredients to meet these properties, like proper fluidity, rapid recovery behavior and appropriate mechanical strength, are very critical to achieve successful printing. Three-dimensional printing has emerged as a noteworthy manufacturing approach with potential in various fields, including the food industry. The versatility of design offered by it allows rapid and flexible prototyping for customized food. This prompts the manufacturing of innovative food products with customized nutritional values, textures, and sophisticated structures with multiple food

ingredients using different methodologies. Among these, extrusion-based printing is the most commonly used for Food 3D Printing (F3DP). At present, food 3D printing materials can be divided into three categories: powder, gel system and "dough". Different material states during 3 D printing; For powder Fused deposition manufacturing; Selective laser sintering; Binder jetting; Inkjet printing can be used. For gel system Extrusion based printing; Binder jetting; Inkjet printing can be used. For Dough system, Extrusion based printing can be used.

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