3D Food Printing and its Applications: A Review

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ABSTRACT

Novel developments in robotics and other software are adding convenience to our day-to-day lives. 3D printing is one such emerging field, worked on digital fabrication of material using deposition of layer one over the other in 3D space. In recent years, the spotlight on 3D printing has been shifting, to encompass a large number of areas, especially the food industry. 3D food printing brings revolutionary change in the food sector by creating ease in developing personalized food with specific nutritional compositions at low cost. It also has multiple benefits including personalised food design and individualized nutrition as well as allows the use of nutrient-dense ingredients which are not acceptable as it is, by the consumers. This leads to an economical method for delivering sustainable nutrition, and simplifying the supply chain. This paper aims to give a brief introduction on the relevance of 3D food printing in today's world, including its principle, techniques used in 3D food printing, its application in various food sectors and challenges that need to be overcome.

Key Words: *Fabrication; Customized food; Sustainable; Revolutionary; 3D Food Printing; Personalised food.*

1. Introduction

Charles Hull invented 3D printing in the year 1983 and is known as the father of 3D printing (Jordan *et al.*, 2019). The first 3D object to be printed in 1983 was incidentally a tiny cup to be used for eyewash (Lipson and Kurman, 2013). Initially, this technology was used only in the military field. However, a growing amount of research in this field has shown this technology to be useful in various sectors, including the development of 3D prints of human bone for anatomy education in medical field (Hashem *et al.*, 2015), production of apparels and ornaments in fashion industry (Yap *et al.*, 2014), biomedical implants, aircraft, and dental as well as tissue engineering (Mpofu *et al.*, 2014; Yap *et al.*, 2014). 3D printing technology has also found usability in food production i.e., in Food layered manufacture (Wegrzyn*et al.*, 2012). This technology has made it possible to use a mix of ingredients, which have limitations due to using conventional manufacturing processes, were pre-viously considered to be incompatible in the same dish. This technology has also made it possible to explore novel shapes and structures for the processing and presentation of these foods. The food prepared by using this technology have totally unique flavors and textures which are impossible to achieve with traditional cooking methods. So, this technology

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can bring out the 'digital age' in food processing technologies. During printing, various culinary ingredients can be mixed automatically based on the selected recipes and can be done simply by giving a command.

In recent years, there is an emerging market for higher degrees of personalization of food according to taste, appeal and nutritional requirements of the consumers (Milen*et al.*, 2012). There are two options to manufacture the tailored food. One is by the use of a large material set that is sufficient to give satiety value to all consumers and another one is by the use of a material set that is small, and can be combined in varying proportions (Milen *et al.*, 2012). The cost for such food products is relatively high. Three-Dimensional (3D) food printing, also referred as Food layered manufacture is a possible cheaper alternative (Wegrzyn*et al.* 2012; Attarin*et al.*, 2020). Food printing is a method in which the food is customized according to the needs of the consumer (Sun *et al.*, 2015). The main aim is to create 3D tailored food objects layer by layer, without the need of object-specific tooling, moulding, or human intervention shown in Figure. 1 (Sun *et al.*, 2015). As a result, this technology has the potential to improve production efficiency while also lowering manufacturing costs for the fabrication of custom food products (Sun *et al.*, 2015). 3D food printing also provides various advantages, including the customization of food according to the consumer's need, automatic production of food, production of unique structures and silhouettes, eco- friendly as it helps in reduction in food waste or also use alternative source of nutrients (Yang *et al.*, 2017; Dankar *et al.*, 2018).

3D food printing is the frontline application of additive manufacturing technology. When printing food, careful selection of edible inks and production processes are required to be chosen by the food designer (Pallottino *et al.*, 2016). For 3D food printing, food material has to be printable, means they have to carry their structure formed by the 3D printer even after formation in all aspects of structural, material and nutritional

Figure. 1 Printing of Veggie burger with Foodini (Sher et. al., 2015).

characteristics and the prepared food must be resistant to any processing required for finishing of the food product like cooking, baking etc. (Godoi *et al.*, 2016). Extrudable materials like chocolate, frosting, Cheese (Periard *et al.* 2007), edible hydrogels (Cohen *et al.* 2009), and cookie dough were initially employed as inks for 3D food printing, with outliers such as celery, which could be pureed and blended with hydrocolloids (Lipton *et al.* 2010).

It is essential for food researchers to understand the properties of the food ingredients. For 3D food printing various foods are appropriate, such as confectionery foods like chocolate and candy, and dough-based foods like pizza, pasta and crackers. 'Foodini printer', is the classic example of the 3D food printing machine shown in Figure. 2 (Sher and Tuto, 2015). It was developed by the Barcelona-based organization 'Natural Machines' and is intended to be used in the home to prepare a variety of cuisines such as pizza, chocolate, biscuits, and vegetable purees and its working shown in Figure. 3 (Natural Machines, 2013). For some people, the use of 3D food printing technology to prepare traditional foods such as pizzas or chocolates is like an over skill for an ordinary process (Yang *et al.*, 2017). But in reality, 3D food printing technology gives an opportunity to traditional foods to not only personalise the food's shape but also produce unique flavors and textures that have been never known by the consumers (Portanguen*et al.*, 2019). As a result, 3D food printing technology is

Figure. 2: Printing of Veggie burger with Foodini (Sher et. al., 2015).

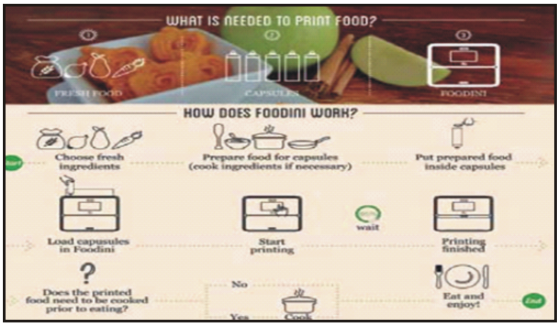

Figure. 3: Printing of Veggie burger with Foodini (Sher et. al., 2015).

a novel concept with the potential to generate low-cost, higher-quality-control, eco-friendly, and energy-efficient food products. (Yang *et al.*, 2017).

2. Principle & Techniques of 3D Food Printing

The technical term used for a process of '3D printing' or 'rapid prototyping' is 'Additive Manufacturing' (AM). It is defined as the process of "binding materials to create objects using 3D model data, layer by layer" (ASTM International, 2012). The principle of 3D food printing is solid free-form (SFF) method (Yang *et al.*, 2017). On the basis of 2 dimensional shapes, the SFF method formed a three-dimensional print with controllable silhouette by assembling Computer-Assisted Manufacturing (CAM) and Computer Aided Design (CAD) (Lee *et al.*, 2010). This method consists of Stereolithography Lasing (SL), Fused Deposition Modelling (FDM) and Selective Laser Sintering (SLR) (Yang *et al.*, 2017). The main method used in 3D food printing is Fused Deposition Modelling (FDM) (Kollamaram*et al.*, 2018). This is used for printing a variety of foods, including molten state in liquid form such as chocolate, sugars etc (Godoi*et al.*, 2016). In preparation of purees, doughs and gels no structuring agent is required. They are directly deposited on the surface. To support the structures of the purees, doughs and gels, structuring hydrocolloids are used as the deposited material (Lipton *et al.* 2010).

To build 3D structures, various kinds of layer deposition are used, including Stereolithography Apparatus (SLA), Selecting Laser Sintering (SLS), Powder Binder Printing (PBP), Fused Deposition Modeling (FDM) and Three-Dimensional Printing and Gluing (Yang *et al.*, 2017). Arduino IDE and Repetier-Host are the computer software which are used to control the system that prints the articles as per the 3D drawings. (Luimstra, 2014). Because of the printer's great accuracy and resolution, printed models are of fine quality. According to the specificity of the product, the 3D food printing technology requires suitable materials or ingredients as ink and printers (Yang *et al.*, 2017). 3D food printers are not the same as regular printers. They use a variety of things as ink, including architectural materials and food items (Godoi*et al.*, 2016).

The most basic component of a food printer is a syringe (syringe's one end is connected to an electric engine and another end is connected to one or two nozzles), plastic clips (that fix the nozzle in place). To mix and keep all of the materials, several barrels or reservoirs are required. (Yang *et al.*, 2017). To deliver the ingredients, syringes or nozzles are used. The electric motor is used to push or extrude the ingredients from the syringe, and the system is acknowledged as an extruder. The printer can be outfitted with multiple extruders. Dual-feed extruder can also be used which pushes two seperate ingredients of different colours from the syringe to create a variant colour by altering the ingredients mixing ratio. 'Builder' (a Holland manufacturer) developed this food printer with colour mixing and dual-feed extrusion (Builder

Ltd., 2015). The components are deposited one layer over another on the planar heating platform, which also cooks the raw material (Yang *et al.*, 2017).

On the basis of the fabrication, the 3D printers are categorized into four categories, including triangle-structure printers, triangle-claw-structure printers, rectangle-cassette-structure printers and rectangle pole-structure printers (Luimstra, 2014). Triangle and rectangle–cassette structure printers are the utmost popular among all in the market due to their best performance (Luimstra, 2014). Triangle shape printers are simple in structure, convenient in maintenance and have low cost. They have poor design and low accuracy whereas rectangle – cassette shape printers have higher accuracy and good designs. But they have complicated installations and are expensive. According to their respective features, the triangle structure is primarily used in the DIY fabrication field, whilst the rectangle-cassette structure is primarily found in the market. Table 1 compares the structures of three-dimensional printers. (Yang *et al.*, 2017). The general components of 3D printers are the frame, control circuit, mechanical seals and the motor. The control circuit is the very important component of the 3D printer. Basically, it controls the printer's operation and serves as a bridge between the machine and the computer (Yang *et al.*, 2017).

3. Applications of 3D food printing

Rapid increase in global population leads to increase in food demand which creates challenges to provide sustainable nutrition without creating any negative social, economic and environmental impacts (Lindgen*et al.*, 2018). With the evolution of 3D food printing technology, we may be able to use new nutrient-dense food sources, including unusual foods such as insects, which are not consumed as a food by the bulk of the population but may be used as an ingredient to manufacture food to feed the world population. (Luimstra, 2014). Also, 3D food printing served as a new way of cooking.

The two aspects of application of 3D food printing in food products are as follows:

1. Novel nutrient enriched and possible usage of any food ingredient
2. Texture and appearance of traditional food products can be improved by regulating food ingredients at the macro and micro-structural levels (Luimstra, 2014).

4. Application of 3D Food printing in various fields:

Military Foods

The US Army pays a great attention for the manufacturing of 3D printed military foods because:

Table 1: Table Showing the Comparison of structures of the main kinds of 3D printers

Structure	**Triangle**	**Triangle-claw**	**Rectangle pole**	**Rectangle cassette**
Typical Machines	Prusa	Rostock	Printrobot	Replicator, Ultimaker
Advantage(s)	Simple structure, convenient maintenance, low cost	Higher printing speed, simple installation, convenient maintenance	Simple structure, higher accuracy, lower cost, convenient maintenance	Higher accuracy, good design
Disadvantage(s)	Lower accuracy, bad design	Difficult adjustment, occupy too much space	Bad design	Installation is very difficult, high cost

Source: Yang et al., 2017

1. By the use of this technology, we can prepare food as per requirement on the battleground.
2. Depending upon the nutrition and energy requirement of each and every soldier, meals can be individualized and customized.
3. We can also enhance the storage life of the food ingredients by using this technology, by storing the food ingredients in raw material instead of the final product (Jennifer, 2014).

In ultrasonic agglomeration, the food particles are subjected to fuse together by shooting ultrasonic waves at them. By using this, they can prepare variety of meals. Hence, soldiers have more food options. They also plan to transform the forage plant material like tree bark, leaves and berries etc. into food by the use of 3D compact units (Sher and Tuto, 2015).

Space Food

Systems and Materials Research Corporation (SMRC) was funded by NASA to investigate 'the feasibility and application of 3D food printing for food production during long space missions' (Lin, 2015). NASA wanted to apply this technology to fulfil the needs of nutritional stability, food safety and acceptability of meals intended for long space missions by the use of the minimum number of assets from spacecraft. In NASA, individual packaged food prepared using typical cooking methods causes micronutrient deterioration over time. Therefore, NASA may be able to achieve the nutritional stability and shelf-life criteria for long missions. (Sher and Tuto, 2015). For the preservation of food prepared by the traditional methods, they require the refrigeration system but it uses much spacecraft resources. Individualized energy and nutritional requirements of astronauts is not considered by the current space food system (Lipton *et al.*, 2015). To deliver the macronutrients (carbohydrates, proteins, and fats), rheological properties in food, 3D food printing may be used. Micronutrients, aroma and flavors are incorporated by the inkjet printing to upgrade the nutritional stability and shelf life of the food product reported by the SMRC in their proposal. Macronutrient stocks will be stored in a dry sterile container. Flavors and micronutrients will be stored in the sterile packs in the form of liquid, dispersions or aqueous solutions. During food processing the macronutrient stock will be combined with oil or water and directly fed to the printer and blended with flavours and texture enhancers at the print head. By the use of extruder desirable shapes and structures will be prepared from the mixture. This technology not only enhances the shelf life and nutrition of food but also fulfil the individualized dietary requirements and pleasure of eating (Irvin, 2013).

For Dysphagia patients

Aging problem is faced by various countries, including Canada, Japan and Sweden. About 15%-25% of people over the age of 50 and 60% residents of nursing homes have difficulty in chewing and swallowing (dysphagia) (Sun *et al.*, 2015). Patients of dysphagia are frequently feed unappealing 'porridge-like food' which causes less or no desire to eat and various nutritional deficiencies in patients. To resolve the above problem, the PERFORMANCE project was started and funded by the European Union (EU). The aim of this project is to design an automatic manufacturing technique to provide an individualised and texture modified food by the use of 3D food printing technology (PERFORMANCE, 2012). Scientists who are working in this project have designed stimulated foods, including peas and gnocchi with imitated texture and taste. Elder people will love to eat this designed food because it has a soft, pulverized texture which is quite easier for them to swallow (Liu *et al.*, 2017). Customized meals can be prepared for individuals according to their age, nutrition and energy needs and their physical condition (Severini&Derossi, 2016). Team PERFORMANCE conducted a survey regarding the acceptability of 3D printed food in care homes in which they found that 54% of participants felt the texture of food was so good, 79% thought that the printed food is similar to the food prepared by the traditional cooking method and 43% preferred printed food when they have difficulties in chewing and swallowing (Lunardo, 2016). Some nursing homes in Germany served printed soft and pureed foods to the patients of dysphagia (Wiggers, 2015). Mashed potatoes, broccoli and peas were used to made 3D printed food for the dysphagia patients and this product was commercialised successfully into the market (Wiggers, 2015).

Confectionery Market

Sweets are widely consumed around the globe. Due to the high consumption rate of sweets, various research centres of 3D food makers and foremost food industries, including Hershey are more focusing on 3D printed sweets. 3D Systems and Hershey work together and developed 'Cocojet' an extruder chocolate printer, which prints different shapes in chocolates (Milen, 2012). 'Choc Creater' was the first commercialised chocolate printer designed by the scientists of the University of Exeter (Sher and Tuto, 2015). Eight nozzle Cheetah chocolate 3D printer was invented by Hans Fouche. This system was used to prepare variety of chocolates (Victor, 2015). Melt-extrusion technology is used in 3D printers to develop numbers of 3D printed chocolates. 'Chocolatiering' a cheaper selective laser sintering based printer designed by University of Waterloo. This printer is use to design 3D chocolate silhouettes using cocoa powder (Victor, 2015). In 2007, the first 3D structure made up of sugar was developed by the CandyFab which was a selective sintering-based printer under the CandyFab project. Under CandyFab project, they also designed a technique named as 'SHASAM' (Selective Hot Air Sintering and Melting), in which particles were fused together by the use of a heating source to develop the complex silhouettes (CandyFab project, 2007).

By the use of Chef Jet Pro, variety of food ingredients, like sugar, cheese and chocolate are used to prepare different types of sweetmeats or food embellishment, including sugar showpieces, wedding cakes and interlocking sweets. The printed sweets are tasty and appealing in nature. This system is armed with four print nozzles therefore, capable to produce polychromatic structures, including multi-colour cocktail decorations (Liu *et al.*, 2017).

Two London-based students established a project named 'The GumLab' and designed a GumJet 3D printer for printing of an attractive chewing gum. Printing of layer-by-layer flavoured gum resins was done by the use of extrusion technology-based printer (Liu *et al.*, 2017). Wacker, created a 3D printer for chewing gum, which prints gum filled with fruit juice, plant extracts and coconut. He also developed a novel technique to convert existing candy into gum, called Candy2Gum (Corey, 2016).

5. Challenges of 3D food printing

3D food printing is an extremely sophisticated technique. Various parameters in 3D food printing must be optimised, such as careful creation of the digital recipe, appropriate feeding materials, and proper use of mechanical force. Different pressures are applied on the different formulations of food. The flow rate of the food combination via the nozzle may also be affected by room temperature (Lipson, 2013). For the rate of resolution and deposition both, the size and diameter of the syringe are very important. Sometimes, there is nozzle blockage due to oil, or the food which was deposited may deformed (Lipson, 2013). Many people misunderstand the process of 3D food printing can immediately generate a fried chicken breast or a loaf of bread directly through the nozzle of the printer (Lipson, 2013).

Optimization of this printing process is also a very difficult task as it needs a proper evaluation of specific personalized requirements of any person. For the computer numerical control, several settings, including line distance, layer thickness and shape, diameter of nozzle, number of layers, writing speed, control of printing temperature, laser power and rapid cooling, should be considered. When developing food recipes for 3D food printing, food components with high strength should be considered in order to meet the need for good printability (Liu, 2017).

Color, flavor and texture are the very important parameters for the acceptability of any food product. Therefore, it is important to create the 3D edible silhouette with all these desired characteristics. Various attempts have been made to use this technology to produce colourful, textural, and varying flavour food products, but they have not been widely utilised (Hasseln, 2013). Hence, special attention should be taken to create a variety of coloured, tasted, and textured foodstuffs.

6. Conclusion

3D food printing has several benefits, including personalized food layout, individualised nourishment, printed attractive or appealing food products, used nutrient dense food materials and fulfil the increase in food demand etc. 3D food printing has been investigated in the food sector. 3D food printing has been used in a variety of culinary industries, such as military foods, space foods, dysphagia patient meals and sweets. Though research into 3D food printing is currently expanding, a few hurdles remain, including printing speed, the production of food with multiple quality and nutritional attributes, and printing precision and accuracy. Once these hurdles are overcome, 3D food printing is expected to become more common.

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