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The future of 3D food printing: opportunities for space applications

Rachael E. Enfield

Janam K. Pandya

Jiakai Lu
University of Massachusetts Amherst

David McClements
University of Massachusetts Amherst

Amanda J. Kinchla
University of Massachusetts Amherst

Title: The future of 3D food printing: opportunities for space applications

Authors: Rachael E. Enfield, Janam K. Pandya, Jiakai Lu[a], David Julian McClements[a], Amanda J. Kinchla[a]

Affiliations: [a] *University of Massachusetts Amherst, Amherst, Massachusetts*

Corresponding Author: Amanda Kinchla kinchla@umass.edu 102 Holdsworth Way, Amherst, MA 01003

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Abstract

Over the past decade or so, there have been major advances in the development of 3D printing technology to create innovative food products, including for printing foods in homes, restaurants, schools, hospitals, and even space flight missions. 3D food printing has the potential to customize foods for individuals based on their personal preferences for specific visual, textural, mouthfeel, flavor, or nutritional attributes. Material extrusion is the most common process currently used to 3D print foods, which is based on forcing a fluid or semi-solid food "ink" through a nozzle and then solidifying it. This type of 3D printing application for space missions is particularly promising because a wide range of foods can be produced from a limited number of food inks in a confined area. This is especially important for extended space missions because astronauts desire and require a variety of foods, but space and resources are minimal. This review highlights the potential applications of 3D printing for creating custom-made foods in space and the challenges that need to be addressed.

Keywords: 3D printing; additive manufacturing; food; space; astronauts

Introduction

The concept of three-dimensional printing (3D Printing, 3DP), also known as additive manufacturing, was first developed more than three decades ago (Gibson, Rosen, and Stucker 2015). 3DP is the process of creating a physical object by laying down multiple layers of a material in succession, typically assisted by a three-dimensional digital model. The initial applications of this technology were mainly in the printing of synthetic substances, such as plastics and metals, to create custom-made innovative materials with novel properties. 3DP has also been applied in the medical field to assemble artificial organs or tissues from living cells, such as skin and hearts (Gu et al. 2020). A recent example of this approach has been the 3DP of personal protective equipment (PPE), such as face masks and shields, for medical professionals combating the coronavirus pandemic (Erickson et al. 2020; Tino et al. 2020; Wesemann et al. 2020). Recently, 3DP has been finding increasing applications in the food industry (Liu et al. 2017). This technology can create foods with specific appearances, textures, flavors, and nutritional profiles. Recent advancements in automation and computation have led to affordable commercial 3D printers that consumers can utilize at home to create customized food products (Lansard 2020).

In general, 3D printers are based on several different technologies. However, only a few of them are suitable for food printing applications due to the unique physicochemical attributes of foods and food ingredients, as well as the costs involved. Specifically, the material extrusion technique is the most common method used in commercial 3D food printers. A major focus of researchers in this area of 3D food printing has been on developing a range of standardized raw materials that can be used to fabricate food inks, such as hydrocolloid solutions, emulsions, and crystallizing lipids, to increase the versatility of the technique (Yang, Zhang, and Bhandari 2017).

3D food printing has several potential advantages for some applications, including customizable food production, reduced manufacturing costs, reduced food transport requirements, reduced packaging needs, and a lower environmental impact (Chen 2016; Liu et al. 2017; Jia et al. 2016). For instance, food inks could be shipped as a paste or a powder that is added to the device prior to printing. 3D printing may also reduce post-harvest and post-processing food waste and can increase the shelf life of foods (Galdeano 2015). This use of 3DP may also be used to improve the sustainability of the food supply by creating high-quality foods from alternative protein sources (such as plants, microbes, or insects) rather than using proteins from animal sources (such as meat, fish, eggs, or milk) (Severini, Azzollini, et al. 2018; Feng, Zhang, and Bhandari 2019). Moreover, 3DP can be used to create foods with nutritional profiles tailored to an individual's specific needs, which is important for personalized nutrition applications. Furthermore, 3D food printing could facilitate long-term space expeditions by increasing food diversity, improving food quality, reducing storage requirements, and extending shelf life (Derossi et al. 2018; Severini, Azzollini, et al. 2018; Sun et al. 2018).

This article aims to provide an overview of currently available 3D food printing technologies and opportunities. In particular, we discuss different 3D printing approaches, the parameters that affect 3D food printing, and the formulation of food inks. Additionally, we provide a comprehensive overview of current applications of 3D food printing, the future opportunities and challenges for its application in personalized nutrition and long-term space missions.

3D Printing Processes

The 3DP processes currently available can be grouped into seven main categories: vat photopolymerization, material jetting, binder jetting, powder bed fusion, material extrusion, directed energy deposition, and sheet lamination (Calignano et al. 2017; Gibson, Rosen, and Stucker 2015; vs. SLA vs. SLS 2020; "Additive Manufacturing Research Group | Loughborough University"; Dassault Système). However, the material extrusion approach is the most suitable for food applications based on material properties and costs. It should be noted, however, that research has also been conducted on the use of powder bed fusion, material jetting, and binder jetting to form certain kinds of foods. In this section, we briefly discuss different kinds of 3DP processes and their potential applications in 3D food printing. Table 1 shows a side-by-side comparison of important 3DP techniques used for food printing.

Material Jetting

Material jetting processes dispense droplets that contain photopolymers that are then cured by UV light (Figure 1A). The material jetting process has similar features to 2D inkjet printing because both fire ink dots of ink at the target at a continuous interval or on-demand to create a final product. Some of the potential advantages of material jetting include high precision printing; the capability of printing layers less than 20 microns thick; and the ability to print different materials and colors simultaneously with a smooth surface finish. However, material jetting printers are typically expensive, require a long time to print an object, and use photopolymers that can undergo degradation and deformation over time, thereby reducing their mechanical properties. Currently, this method has been widely used to create realistic anatomical models for training in the medical field.

Material jetting may be utilized to print foods, which is typically carried out either as continuous jet printing or drop-on-demand printing. The material jetting technique is capable of printing low viscosity materials, which makes it challenging to maintain the final 3D structure of the food object. For this reason, it is primarily used for producing 2D images on the surfaces of foods, for instance, printing icing on a cake or patterns on edible films or coatings. The compatibility between ink and substrate surface, viscosity and other rheological properties of the ink, temperature and printing rate are important printing parameters that significantly affect the printing precision and accuracy of objects produced using this approach. The contact angle, a quantitative measurement of the ability of a liquid to maintain contact with a surface, is important for the compatibility and adhesion between the ink and the surface and should be less than 30°. For good deposition and surface compatibility, the viscosity of the ink should be between about 2.8 to 6 mPa.s and the surface tension should be below 3.5×10^{-6} N/m (Liu et al. 2017). FoodJet is an example of a commercial 3D food printer that is based on this principle, which has been used for creating patterns on the surfaces of foods. This type of printer uses various food materials as food inks, including chocolate, butter, cream, doughs, batters, sauces, purees jams, and jellies ("FoodJet" 2020). The process involves inkjet depositors situated over a product line and depositing the food ink onto the food as it passes on a conveyer belt (Molitch-Hou 2020).

Binder Jetting

Binder jetting is a non-thermal process that uses a liquid binding agent deposited onto a platform to bond layers of powder material together (Figure 1B). It is often used to print powdered metals, sands, and ceramics. Due to the relatively weak bonds formed between the particles, binder jetted materials tend to have relatively weak mechanical properties. For this reason, the objects produced using binder jetting often require post-processing to increase their mechanical strength. The binder jetting process does not involve heat, which reduces the stresses on thermally labile materials. Binder jetting for printing metal may be 10-fold more economical than other 3D printing processes. For this reason, it has found widespread utilization in some industries to replace metal injection molding.

The binder jetting approach can also be used to print foods using edible powdered materials (such as sugar, starch, or cornflour) and edible liquid binders (such as sugar solutions or xanthan-based binders) that hold the powder particles together within the 3D structure formed (Holland et al. 2018b). The nature of the materials produced using this process is therefore greatly dependent on the properties of the powdered material, the liquid binder used, as well as the operating conditions used. The binder must have suitable viscosity, surface tension, and density to prevent it from spreading from the nozzle after injection. The particle size, flowability, bulk density, and wettability of the powder material all affect the precision and accuracy of the final printed objects. It is particularly important that the powder can flow freely without clumping or caking. Additionally, the wettability of the powder surfaces is also a critical property affecting the overall print quality. If the wettability is too low, then the binding is poor, which affects the structural integrity of the object formed. Conversely, if the wettability is too high, then the resolution and precision of the printed object may be poor. Researchers have reported that a powder moisture content below 6% and an angle of repose less than 30° were also important for producing high-quality printed objects using this approach (Liu et al. 2017). Processing parameters such as head types, printing velocity, droplet path, nozzle diameter, layer thickness, and resonance frequency of the head have also been reported to play a role in the resolution of the printed object and, therefore, should be considered for optimization.

Edible objectives have been produced using this method using semi-crystalline cellulose as a powder and a xanthan gum solution as a liquid binder (Holland et al. 2018a). The cellulose powder was ball-milled to reduce the particle size and dried to different relative humidity levels. Xanthan gum solutions were prepared using different solvents, including pure water, ethanol, and a non-ionic surfactant (Tween 20). The quality of the printed objects formed depended strongly on the chain length of the xanthan gum molecules used, with smaller polymers improving the print quality. The relative humidity and temperature were controlled to recrystallize the objects after printing. Additionally, the rheological properties, surface tension, and material density were manipulated to create desirable printable materials. Sugar Lab® prints unique treats using the binder jetting method in a commercial application. The process includes adding water to the dry ingredients such as sugar and maltodextrin to create a type of fondant ("The Sugar Labs"). Here water, glycerol, and ethanol are mixed to form the liquid binder, while sugar, maltodextrin and a gum blend form the powder base. Powder and liquid binder are jetted in alternating layers, building up a print. Binder jetting offers the ability to create complex and innovative food prints using simple ingredients, although there are still many areas to explore with binder jetting technology ("The Sugar Labs"; Holland et al. 2018a).

Powder Bed Fusion

The powder bed fusion process uses either a laser or an electron beam to melt and fuse powdered materials (Figure 1C). This printing technique can create complex material geometries due to its high precision. However, PBF printers can be expensive and time-consuming due to the need for preheating, vacuum generation and cooling periods during each print. Many methods such as electron beam melting (EBM), selective heat sintering (SHS), and selective laser melting (SLM) can be categorized as PBF processes, but the latter is the most commonly used technology. In non-food applications, Powder Bed Fusion techniques are used to print specialized parts with high precision in industrial manufacturing operations.

3D printers with PBF technology can be used for food printing using powdered materials such as sugar, fat, or starch granules (Liu et al. 2017). However, it is still not widely used for research or commercial applications. The precision and accuracy of foods produced using the PBF process depend on the powdered materials' particle size, flowability, bulk density, and wettability of the powdered materials (Godoi, Prakash, and Bhandari 2016). Moreover, the operating conditions, such as laser type, diameter, power, and scanning speed also play an important role. A commercial organization, CandyFab has investigated the viability of PBF as a food printing technology by printing pure sugar using a selective hot air sintering and melting process. The hot air caused the sugar crystals to melt and then sintered together, creating edible 3D objects (Table 2). More research needs to be conducted to explore further the applications of Powder Bed Fusion techniques in specialty food manufacturing.

Material Extrusion

Material extrusion is the most popular 3DP process utilized for research and commercial applications due to its ease of use and affordability. In a typical material extrusion 3DP, a nozzle extrudes material, normally using thermal energy, on a platform and builds the object layer-by-layer with each layer fusing to the one below it (Figure 1D). For non-food applications, common printing inks for material extrusion 3DP include to create replacement parts for home-goods applications, industrial manufacturing prototypes, and biomaterials in the medical field. Material extrusion is currently the most commonly researched 3DP technology for food printing because a wide variety of food ingredients can be used as suitable food inks. The most widely researched food inks for food applications include hydrogels, sugar frostings, cheeses, and chocolate due to their ability to extrude smoothly through the syringe and then hold their shape after printing (Sun, Peng, Yan, et al. 2015). Foods printed from such materials have been customized for their taste, texture, and nutritional profiles. In some cases, foods can be created without the need for any additional post-printing processing steps prior to consumption. In other cases, it may be necessary to use additional processing steps, such as heating or chilling, to obtain the final food. Extrusion is often used to produce foods with relatively simple structures (such as snacks and desserts), but it is more difficult to make foods with complex structures (such as meat, fish, fruit, or vegetables) (Lille et al. 2018; Derossi et al. 2018; Keerthana et al. 2020). It is often necessary to include additives that enhance their textural attributes for relatively firm food materials. For instance, meat purees can be hardened after printing by using the enzyme transglutaminase to crosslink proteins (Lipton 2010). Similarly, mashed potatoes with the required textures can be produced by including additional potato starch in the formulation (Liu et al. 2018). The textural attributes of fish surimi gels were improved by adding NaCl to promote protein crosslinking (Wang et al. 2018). Moreover, the texture and stability of 3D printed fruit-puree-based snacks have been improved by utilizing pectin in the formulation (Derossi et al. 2018).

Several rheological attributes of food inks must be optimized for the production of high-quality 3D printed foods, including their shear viscosity, consistency index, flow behaviour index, melting temperature, gelling temperature, elastic modulus, and yield stress (Yang et al. 2018; Pérez et al. 2019). In particular, the shear modulus of a food ink after printing influences the shape of the objects produced, whereas the yield stress and elastic modulus influence the structural integrity and resolution after printing (H. W. Kim, Bae, and Park 2017). Successful 3D food printing also depends on optimizing operating parameters, such as nozzle moving speed, extrusion rate, nozzle diameter, layer height, nozzle height, and temperature (Pérez et al. 2019). The nozzle moving speed is one of the most important printing parameters as it directly influences print quality, as well as printing time. The extrusion rate is usually governed by the rheological and other physiochemical properties of the food ink and the printer's design. The extruder nozzle diameter also affects the print quality and production time: the smaller the nozzle, the higher the resolution, but the longer the printing time. Optimizing layer height and printing height is critical to achieving good print quality. In general, increased height reduces print quality but increases printing speed. Finally, the extruder's temperature influences the rheology of the food ink, altering its extrusion and setting behaviour. Overall, optimizing all the printing conditions is important to obtain a good compromise between print quality and production time.

Several food ingredients exhibit material properties that make them suitable for application as food inks. Researchers have investigated a variety of food ingredients for their potential to produce food inks suitable for material extrusion printing, including animal proteins, plant proteins, fruit purees, vegetable purees, starches, and emulsions (Derossi et al. 2018; Lille et al.

2018; Dankar, Pujolà, et al. 2018; Hamilton, Alici, and in het Panhuis 2018; H. W. Kim, Bae, and Park 2017; Le Tohic et al. 2018; Wang et al. 2018; Liu et al. 2018; Severini, Derossi, et al. 2018). Gelatin has been widely utilized for this purpose because of its ability to form low viscosity fluids at high temperatures and form hydrogels at low temperatures (Rapisarda et al. 2018). Potato starch can produce semi-solid edible materials with textures like mashed potatoes when used at an optimum concentration. One study reported that 2% potato starch was optimum for 3D printing purposes: a lower concentration meant that the material did not hold its shape after printing. In comparison, a higher concentration indicated that it could not be extruded (Liu et al. 2018). Rheological properties, such as yield stress, consistency index, and elastic modulus, have been identified as necessary for potato starch-based inks (Pérez et al. 2019).

Miscellaneous Processes

Apart from the 3DP processes discussed above, sever other approaches have also been developed for 3D print materials. Vat photopolymerization processes use a narrow heat source (mainly UV lasers) that is direct into vats, or tanks, of liquid photopolymer resin to selectively cure materials layer by layer (Figure 2A). Currently, the Vat photopolymerization technique is most commonly used for medical modelling, especially in dentistry; however, it has somewhat limited application for food printing. Directed energy deposition (DED) is another 3D printing technique where the material is melted as it’s being deposited via a laser or electron beam. (Figure 2B). DED is generally fast and can handle large print areas at the cost of resolution. It is one of the more complex processes and is mainly used to repair or add additional material to existing components. This type of 3D printing is likely to be unsuitable for food applications. Sheet lamination is rarely used in the 3D printing process that uses sheets of material bound together

(Figure 2C). It is less accurate but relatively fast and inexpensive. Laminated object manufacturing (LOM) uses paper as its material and adhesive as its binding agent. Other sheet lamination technologies use metal sheets as materials and lasers to bind them. Neither of these technologies is currently used for 3D food printing.

Edible Inks for 3D Printing

One of the most important factors impacting the successful application of 3DP for the fabrication of food products is the availability of food inks with the required functional attributes. 3D printers based on extrusion are currently the most suitable for broad application within the food industry, so we focus on them here. A 3D ink must be capable of flowing through a nozzle but then solidifying after it has been deposited onto a surface and creating a robust structure to support the weight of the subsequent layers (Sun et al. 2018; Joshi and Sheikh 2015). Only a limited number of food materials exhibit this kind of behaviour while also having the desirable organoleptic and nutritional properties. This section provides a brief overview of some of the most important food components that can create food inks.

Composition

In general, foods are comprised of water, carbohydrates, lipids, proteins, minerals, vitamins, and additives (such as colors, flavors, and preservatives). Edible 3D inks capable of flowing through a nozzle and then solidifying can be created using a combination of these ingredients. Lipids are a diverse group of organic compounds that are typically insoluble in water but soluble in certain organic solvents. In foods, triglycerides, which consist of three fatty acids attached to a glycerol molecule, are the most common type of edible lipid. The fatty acids in triglycerides vary in the number of carbon atoms and the number and position of double bonds they contain, as well as their position on the glycerol backbone, which impacts the physicochemical and nutritional profile of lipids. Food inks can be formulated from bulk or emulsified lipids.

In the case of bulk lipids, it is important that triglycerides with an appropriate melting profile are selected, *i.e.*, a solid fat content *versus* temperature profile. Typically, the triglycerides should be fluid inside the nozzle but crystallize after printing to form a 3D network of aggregated fat crystals that give a semi-solid texture. This can be achieved using a nozzle held at a temperature above the melting point of the triglycerides but then having a printing platform at a temperature below the melting point. After deposition, it may be important to control the size, number, and interactions of the fat crystals formed, as this determines the optical and mechanical properties of the material (Pérez et al. 2019). Chocolate is often 3D printed using this approach, known as hot-melt extrusion. The triglycerides in cocoa butter crystallize into six primary polymorphic forms (I to VI), which influences the properties of the printed solidified material (Godoi, Prakash, and Bhandari 2016; Pérez et al. 2019). Moreover, the polymorphic form may change after printing, altering the printed chocolate's surface gloss, texture, taste, and shelf life (Pérez et al. 2019).

Researchers have reported that controlling the cooling profile of printed chocolate is critical for creating self-supporting layers with desirable quality attributes (Molitch-Hou 2020; Yang, Zhang, and Bhandari 2017; Godoi, Prakash, and Bhandari 2016; Pérez et al. 2019; Lanaro et al. 2017; Lanaro, Desselle, and Woodruff 2018).

In the case of emulsified lipids, the triglycerides can be converted into an oil-in-water emulsion. Then solidification can be achieved after printing using a gelling agent such as gelatine in the aqueous phase. This would produce a fluid emulsion at high temperatures but semi-solid below the gelling point of the gelatin. Alternatively, a highly concentrated emulsion could be used that exhibits plastic-like behavior. As a result, it can flow through the nozzle when high pressure is applied (above the yield stress) but will form a solid after printing when the pressure is reduced. High internal phase emulsions are particularly suitable for this purpose because the droplets are so closely packed together that they give strong semi-solid behaviour. The 3D printing of mashed potatoes is another example of this approach. As mentioned earlier, researchers found that mashed potatoes tended to sag after 3D printing, but this effect could be avoided by adding 2% potato starch to increase their yield stress (Liu et al. 2018).

Other food hydrocolloids, such as proteins and polysaccharides, can be gelled by altering solution composition or environmental conditions (Gu et al. 2020). For example, gelatin, agar, and carrageenan can form gels when cooled below a specific temperature (cold setting). In contrast, biopolymers, such as methylcellulose, egg protein, and whey protein, can form gels when heated above a specific temperature (heat-setting). This type of food ink may therefore be induced to go from fluid in the injector to a semi-solid on the printing platform by controlling the temperature of the nozzle and platform. In these cases, the sol-gel transition temperatures and final gel properties (such as appearance, texture, and water holding) are important factors to consider.

Some food biopolymers can be made to form gels in the presence of gelling agents, *e.g.*, alginate forms gels in the presence of calcium, carrageenan in the presence of potassium (Godoi, Prakash, and Bhandari 2016), and proteins in the presence of some salts and transglutaminase (Wang et al. 2018). In these cases, it is possible to co-extrude the gelling biopolymer and gelling agent together to induce gelation using coaxial nozzles (Ko et al., 2021). For instance, an alginate solution can be extruded through the inner nozzle. In contrast, a calcium solution is simultaneously extruded through the outer nozzle, which is designed to ensure rapid crosslinking during printing to increase the final print quality (Gu et al., 2020). Several researchers have explored the application of coaxial printing with edible materials (Gu et al. 2020; Ko et al. 2021; Jeon et al. 2021; S. M. Kim, Kim, and Park 2021). For instance, it has been used to create imitation crab meat from surimi and potato starch (S. M. Kim, Kim, and Park 2021) and to develop structures that simulate muscle fibers using various hydrocolloids (Ko et al. 2021). It should be noted again that the biopolymer and ion types and concentrations must be carefully controlled to obtain a 3D ink with the appropriate flow and gelation properties.

Printing Factors

The printability of a material relates to its ability to be handled and deposited by the printer and maintain its structure after printing (Godoi, Prakash, and Bhandari 2016). One of the most important factors influencing the printability of food inks is their rheological properties. Fluids can be described by their shear viscosity *versus* shear rate profile, which a simple mathematical model can often describe:

$$\eta(\gamma) = K\gamma^{n-1} \quad (1)$$

Here, η is the apparent shear viscosity (Pa s) and γ is the shear rate (s^{-1}). Whereas K is the flow consistency index and n is the flow behaviour index. The flow consistency index measures how viscous a fluid is, and the flow behaviour index describes how the viscosity changes when it is sheared. For $n = 1$: the viscosity does not depend on shear rate; for $n < 1$: shear thinning occurs where the viscosity decreases with the shear rate, and for $n > 1$: shear thickening occurs where the viscosity increases with shear rate. Typically, strongly shear-thinning fluids are most useful as printing inks because they will easily flow when a force is applied during extrusion and will flow slowly after they have been deposited onto the printing platform (Liu et al. 2018), which provides time for gelation to occur using a suitable mechanism (Wang et al. 2018).

Edible materials that exhibit plastic-like behaviour are particularly suitable for food inks (Pérez et al. 2019). This type of material behaves like a solid below a critical applied stress but like a fluid above this value. This critical stress above which flow first begins is the yield stress, which is a particularly important parameter for food inks. To a first approximation, the rheological properties of plastic material can be described by two equations that apply below and above the yield stress. Under shear conditions, these equations are:

$$\tau = G\gamma \qquad (\text{for } \tau < \tau_Y) \qquad (2)$$

$$\tau - \tau_Y = \eta \dot{\gamma} \qquad (\text{for } \tau \geq \tau_Y) \qquad (3)$$

Here, τ is stress, $\dot{\gamma}$ is the shear rate or rate of strain, G is the shear modulus, η is the shear viscosity above the yield stress, and τ_Y is the yield stress. The above equations describe the rheological properties of an ideal plastic material. In practice, food materials often exhibit non-ideal plastic behavior and so more sophisticated equations. For example, some flow may be observed over a range of shear stresses rather than at single yield stress, or the viscosity may depend on the shear rate above the yield stress.

The rheological properties of materials must be carefully controlled when designing food inks. The shear modulus, yield stress, and viscosity are important properties determining its printability. The shear modulus determines the hardness of the final printed material, which will influence its ability to hold its shape as well as its perceived texture and mouthfeel. The yield stress should be high enough so that the material does not collapse after printing; however, it should also be small enough to be pumped out of the nozzle (Liu et al. 2018).

The design and operation of the 3D printer are also important when selecting an appropriate food ink. In particular, the nozzle diameter, nozzle height, nozzle moving speed, and extrusion rate impact the quality and production time for a 3D printed food, as discussed earlier. To produce a wide range of food products from a limited range of 3D inks, it is essential to direct future research towards the formulation, characterization, and application of edible materials suitable for extrusion/solidification. These materials may contain colors, flavors, preservatives, micronutrients, and nutraceuticals, as well as structure-forming components, such as lipids, proteins, or polysaccharides. Emulsion technology, which involves homogenizing oil and water together to form either oil-in-water or water-in-oil emulsions, is particularly suitable for developing the next generation of 3D inks. A major advantage of emulsions is that oil-soluble, water-soluble, and amphiphilic functional ingredients can all be incorporated into the same system so that multifunctional 3D inks can be created.

Opportunities of 3D food printing

Customization

Food choices are based on personal preferences, influenced by various factors, including geography, culture, gender, health status, lifestyle, and age (Sun, Peng, Zhou, et al. 2015). Therefore, identifying new approaches that maximize the customization of consumer preferences while catering to their dietary needs is becoming increasingly important. One of the ways this can be achieved is by altering the composition and structural organization of foods using 3DP

(Dankar, Haddarah, et al. 2018). About 1 in 4 people above the age of 50 are reported to have difficulty chewing and swallowing food, which often makes it difficult to obtain the nutrients they require to stay healthy through commercially available food choices (Sun, Peng, Zhou, et al. 2015; Hamilton, Alici, and in het Panhuis 2018). As an example, research by the Netherlands Organization for Applied Scientific Research (TNO) aimed to print customized pureed foods that provide all the nutritional requirements of the elderly (Dankar, Haddarah, et al. 2018). 3DP of foods could also benefit people with certain health conditions, such as food allergies, diabetes, heart disease, hypertension, and compromised immune systems (Dankar, Haddarah, et al. 2018). 3D printers can be used by people at home or in institutions (such as care facilities) to create foods that meet their individual nutritional needs depending on their health status. For instance, foods could be printed that contain specific combinations of nutrients (fats, proteins, carbohydrates), micronutrients (vitamins or minerals), or nutraceuticals (carotenoids, curcuminoids, or polyphenols). Customization can be enhanced with the availability of diverse food inks and printing software to expand its applications.

Past research has investigated the customizability of 3D-printed foods. Derossi et al. created a functional kid snack from fruit puree customized that contained calcium, iron, and vitamin D. The study aimed to create nutritional snacks for children ages 3-10 that would meet their nutritional requirements and would be in a form that they found desirable to consume. The researchers created a food formulation and evaluated the rheological and other physicochemical characteristics required to print the personalized snacks successfully. Although consumer studies were not performed on any of the snacks, the ability to create a food formula and print it effectively provides a strong foundation for further research (Derossi et al. 2018).

In other applications, researchers have successfully produced fiber-enriched printable snacks in the shape of butterflies using mushrooms as a fiber source and a material extrusion as a printing technology (Keerthana et al. 2020). It was reported that dough containing 20% mushroom powder resulted in optimal print quality. Moreover, the possibility of using insect powder as a protein supplement in cereal-based snacks has also been examined (Severini, Azzollini, et al. 2018). The researchers formed a dough from mixtures of yellow mealworm flour and wheat flour, which resulted in a significant improvement in the amino acid profile of the snacks without compromising product quality after printing. Studies have also reported the application of 3D food printing as a tool to educate young children about science, *e.g.,* by printing savory spreads (Vegemite and Marmite) on “breadboards” as edible circuits (Hamilton, Alici, and in het Panhuis 2018).

Sustainability

Food waste is a critical problem that occurs at every step of the food supply chain and reduces the sustainability of global food production. As much as half of all food grown across the globe results in a postharvest loss (Papargyropoulou et al. 2014). Avoidable food waste includes food that is still edible but wasted because it is no longer considered desirable (Papargyropoulou et al. 2014), are still safe to consume, and leftovers from prepared meals. In developing and underdeveloped countries, food waste is generated due to inefficient supply chain and inadequate distribution systems. 3D food printing can be used to address these problems in several ways.

3D printing technology can be utilized to print the food on-demand and in precise quantities using shelf-stable food inks with extended shelf lives, such as powders and pastes (Feng, Zhang, and Bhandari 2019; Jiang et al. 2019). Additionally, 3DP foods can reduce the amount of packaging materials required by the food industry (Godoi, Prakash, and Bhandari 2016; Galdeano 2015; Jiang et al. 2019). Food ink cartridges can be re-used, thereby encouraging recycling and further reducing waste. Many researchers have been engaged in sustainable packaging materials, such as edible films made from proteins, polysaccharides, lipids, and their composites, that can be used to reduce the environmental impact associated with the storage of foods (Jiang et al. 2019). These edible films can store food inks, thereby reducing their environmental impact. Alternatively, 3D printing technology can also be used to create these edible films. Cellulose is one of the most promising materials for creating edible films due to its abundance, affordability, biodegradability, and properties (Escursell, Llorach-Massana, and Roncero 2021). Previous research has shown that 3D printed foods can reduce the cost and energy associated with food storage, transportation, and distribution (Galdeano 2015).

Another area where the application of 3DP may have environmental benefits is the production of plant-based alternatives to animal-based products, such as meat, fish, egg, and dairy products. Indeed, livestock production is a major source of greenhouse gas emissions, land use, water use, pollution, and biodiversity loss ("Sources of Greenhouse Gas Emissions"; K. Handral et al. 2020). Consequently, replacing animal-based foods with plant-based versions could have a major environmental impact. The application of 3DP is exploring high-quality meat analogs from food inks containing alternative proteins such as those derived from plants, microbes, or insects (Portanguen et al. 2019). In addition, 3D printing could also be used to create cell-based or cultured meat (K. Handral et al. 2020). In this case, the 3D printer is used to form a scaffold that contains living cells taken from an animal. These cells grow and multiply, eventually leading to meat-like structures and textures. This process faces unique challenges concerning appropriate culture media, stem cells, growing conditions, and traditional challenges such as speed and scalability. The utilization of 3DP to form meat and fish is similar to its application in the biomedical industry to create artificial organs from living cells. Indeed, it uses many concepts and techniques first developed in this field. a significant potential of the 3DP technology, further research is needed to explore successful applications.

Shelf life and food safety

The safety and shelf life of foods are determined by the potential of microbial growth, contamination with toxins, quality degradation, and nutrient loss. Many intrinsic or extrinsic factors affect the shelf life of foods (Jiang et al. 2019). The intrinsic factors include the nutrient profile, structural organization, water activity (a_w), pH, redox potential, and preservative content of foods. In contrast, the extrinsic factors may include storage temperature, relative humidity, oxygen levels, and environmental microorganisms.

The shelf life of powders used as 3D printing materials could be relatively long because of their low water activity, inhibiting microbial growth and chemical reactions. Conversely, the shelf life of pastes used as food inks could be limited due to their relatively high-water activity. Nevertheless, the shelf life of pastes can be extended using various processing techniques such as thermal processing, pH control, cold storage, or the introduction of preservative systems. As an example, it has been reported that the optimal pre-print formulation of a mushroom-based food ink had a relatively low water activity (0.6-0.66), indicating that food safety can be managed by controlling food formulation. However, it should be noted that very little research has been carried out on the safety of 3D printed foods. One study reported that bacterial levels of 4.28 Log

CFU/g were found in the food inks used, which indicates that the process of 3DP requires sanitization methods (Severini, Derossi, et al. 2018).

Therefore, there is a need for more research to evaluate the safety of 3D-printed foods. In particular, it will be essential to identify the factors impacting the safety of food inks and possible contamination of the 3D printer so that successful strategies can be developed to improve their storage and cleaning (Zhang et al. 2021). For the commercial food manufacturing application of 3D printing technology, further research in developing effective cleaning and sanitation procedure is essential. This begins with the sanitary design of the commercial 3D printer. The commercial 3D food printed must be manufactured with high-quality, food-grade stainless steel material. The equipment must be manufactured in such a way to avoid rough surfaces, unnecessary curves and turns, dead legs and must include sanitary welding when necessary. Such a 3D printer must be equipped with an automatic Cleaning-In-Place (CIP) system with sanitary valves that effectively clean the lines, pipes, nozzles, and other hard-to-clean surfaces. The cleaning and sanitation chemicals' type, concentration, and flow rate must be explicitly validated to the kind of food inks used. The effectiveness of the CIP system must be verified by collecting and monitoring the microbial swabs data. Additionally, the COP (cleaning out of place) system must be defined for the food contact surfaces that the CIP system cannot reach. A comprehensive food safety plan must be prepared by conducting a hazard analysis of each process during 3D printing operations. The critical control points must be identified, and critical limits must be determined, monitored, and verified to ensure the safety of food produced through the novel manufacturing process. Overall, further understanding of food safety and quality procedures is essential for further development and expansion of 3D food printing applications, including at home, restaurants, institutions, and astronauts on space expeditions.

3D Printing in Space

Non-food Applications

An important application of 3DP technology is in the space industry. This includes its application for printing parts and components of a spacecraft before and during a mission. On-the-ground applications of 3DP technology for the space industry have several advantages including its ability to rapidly produce specialized parts for space crafts and space suits. Moreover, it can be used to create prototypes for research purposes, which can significantly reduce the cost and time associated with the design, development, testing and application of new components (Sacco and Moon 2019). Furthermore, space voyages have limited access to resources therefore 3DP may enhance self-sustainability through on-demand printing. Researchers have been studying printing with metal and polymer materials for in-space applications. Creating spare parts on demand allows for adaptive and rapid responses to unforeseen circumstances. Although various 3D printing technologies can be used for space applications, some can even print in a zero-gravity environment with little difference in quality from those printed on the ground (Sacco and Moon 2019). The International Space Station (ISS) has utilized two different 3D printers: 3DPrint and Additive Manufacturing Facility which has printed at least 115 parts in orbit (Johnson 2019). The research on non-food applications highlights the potential of 3DP technologies in space.

Food Applications

Space food should be compact, lightweight, easy to store, and convenient to eat. Early space expeditions, including the Mercury and Gemini missions, focused on food research and development to deliver calorie-dense, nutritious, and palatable foods (Cahill and Hardiman 2020; Jiang et al. 2019). Initially, the food was packaged in tubes or bite-sized cubes, but retort pouches, cans, and food bars were developed later. These foods were relatively safe and nutritious but were often unappealing. Moreover, the initial space missions were relatively short flights, and therefore the unappetizing nature of the food could be endured, but the need for more advanced space food for more extended missions was recognized (Perchonok and Bourland 2002). In these longer missions, food safety and shelf life are additional challenges. Foods taken on a mission to Mars require at least five years of shelf life (Jiang et al. 2019; Cahill and Hardiman 2020). A recent study reported that only 7 out of 65 (<11%) thermostabilized foods tested for their potential utilization in space missions were palatable after 5 years of storage (Jiang et al. 2019). Consequently, new approaches are required to create a diverse range of space foods with expected shelf-life requirements. Additionally, desirable food products should also supply essential nutrients for astronauts to stay healthy during long-term missions. But the limited amount of storage space on a spacecraft restricts the amount of ingredients and food processing/ preparation equipment that can be brought on a mission. Food is not only essential to the physical health of astronauts; it is also important for their mental health. Research has found that the mental health of astronauts is strongly impacted by the quality and diversity of foods available. In particular, foods’ limited variety or palatability can increase stress (Sirmons et al. 2020).

3D food printing can create a wide range of customized foods from a small range of food inks. The potential applications of 3D food printing in space have been highlighted by several researchers, but little actual research has been reported (Hamilton, Alici, and in het Panhuis 2018; Liu et al. 2017; Joshi and Sheikh 2015; Jiang et al. 2019). NASA has funded research to explore the utilization of 3D food printing to overcome problems with micronutrient degradation from dried and prepackaged foods (Irvin and Prouty; Torrez, Douglas, and Irvin 2013; NASA 2019). In 2013, a project was carried out to design protein and starch pastes with varying textures and demonstrate test recipes, including a nutritionally appropriate blend of protein, starch, fat, flavors, and micronutrients. In addition to food design, the project also examined the design of a storage system to preserve and transport the nutrients, a mixing station that worked in low or microgravity, and a modified 3D printing system. Phase I of the project was completed and demonstrated a cheese pizza created by a prototype food printer (Irvin and Prouty; Torrez, Douglas, and Irvin 2013). Researchers have identified research opportunities to advance 3D food printing for in-space applications and have highlighted the advantages such as nutritional stability, shelf life, and acceptability of meals availability on space missions (Liu et al. 2017). Printing food for space is often mentioned in future work sections or conclusions as a potential application (Hamilton, Alici, and in het Panhuis 2018; Liu et al. 2017; Joshi and Sheikh 2015; Dankar, Haddarah, et al. 2018). Nevertheless, more systematic research is necessary for this area.

Potentially, several aspects of food in space can be improved using 3D printing technology. Currently, food developed and packaged for space has a limited shelf life, typically only lasting for about three years, as shown in table 3 (Jiang et al. 2019). The potential to make powdered shelf-stable ingredients can decrease the risk of spoilage of the raw materials in space. The environment on a spacecraft can be carefully controlled, allowing for regulated extrinsic factors that affect shelf life, such as temperature, relative humidity, and oxygen levels. Intrinsic factors can then be tested for the optimum compositions to extend shelf life. Alternative protein sources could also create meat-like products with good shelf life and quality. These proteins could be stored as powders and then printed into a range of desirable products when needed. Nevertheless, ensuring the shelf life and safety of food inks and 3D printed foods is critical. As discussed in previous sections, more research is required in order to study the food safety and shelf life of food inks and 3D printed foods.

Currently, 3D food inks need to be prepared and packaged on Earth. However, there is potential to grow some of the materials used in food inks aboard a spacecraft using agricultural or fermentation technologies (Cahill and Hardiman 2020; Cohu et al. 2014; Finetto, Lobascio, and Rapisarda 2010; Menezes et al. 2015). Which then could be utilized as food ink for 3D food printing. A proposed manned mission to Mars suggests a 2.5-year voyage. Each crew member requires about 1.83 kg of food mass per day, thus for a 916-day mission with six crew members, at least 10,060 kilograms of food mass would be required (Menezes et al., 2015). Grown food could be processed onboard, thereby expanding the food options further. The diversity in food prepared using 3DP technology can improve the mental and physical health of the astronauts by increasing their dietary choices, adding shapes and colors, and bringing the familiarity of fresh ingredients.

Sustaining the health and wellness of astronauts during long space voyages is critical. 3D printing could customize the nutritional profiles of foods intended for each astronaut, depending on their precise dietary requirements. Nutrients could be stored in the form of powders that could be used to fortify 3D printed foods. These powders could be formed by spray drying nutrient-enriched emulsions or nanoemulsions specially designed to increase the bioavailability of the vitamins, minerals, and nutraceuticals they contain. Foods can be tailor-designed to meet the daily nutritional requirements of all the astronauts and meet the personal nutrition requirements of each astronaut (Cahill and Hardiman 2020). Currently, dietary supplements ensure that astronauts meet nutritional requirements needs. However, the bioavailability of the micronutrients in supplements is often relatively low, which means their health benefits are not being fully realized. Incorporating these nutrients directly into astronauts' meals could significantly improve their bioavailability. (Cahill and Hardiman 2020).

Potential for Space Dining

In principle, 3D printing has many advantages for application in space missions since a wide variety of foods can be produced from a limited range of ingredients. However, much of the work in this area has been rather abstract. Research on food printing has not focused on producing entire meals or creating long-term balanced diets. Instead, researchers have typically focused on building individual parts of meals, such as mashed potatoes, cookies, or fruit snacks (Liu et al. 2018; Derossi et al. 2018; Dankar, Pujolà, et al. 2018; Yang et al. 2018). This is mainly because these foods can most easily be printed with existing 3D printing technologies and food inks. This section highlights 3DP technology and the food ink requirements using a hypothetical example of a meal designed for astronauts. Such an application will require the spaceship to be equipped with an extrusion-based 3D printer with multiple nozzles (single or coaxial) to simultaneously print several different 3D inks. Moreover, the nozzle's temperature, diameter, and position would need to be controlled (which could be achieved by having a series of different nozzles that can be automatically changed).

For example, several parameters need to be considered for printing a typical breakfast consisting of egg (sunny side up) with bacon and toast (Figure 3). The egg consists of an irregular disk shape with a yellow viscous fluid in an opaque white gel. In principle, the egg white could be printed by extruding a solution of heat-set proteins, such as egg, whey, or soy proteins, through a nozzle onto a hot plate. The protein solution's concentration and mineral composition must be carefully controlled to produce a gel with the required optical, textural, sensory, and nutritional properties. The hot plate would have to be held above the thermal denaturation temperature of the proteins used to allow the protein to denature, aggregate, and form a gel. On the other hand, the egg yolk could comprise an oil-in-water emulsion with carotenoids (for color and eye health) in the oil phase and proteins, polysaccharides, and minerals (for texture and nutrition) in the aqueous phase.

The other breakfast component, the bacon, should be thin and crispy with fatty and meaty regions that have a whitish and pinkish color, respectively. This kind of material may be printed by having two nozzles, one containing a fat-rich 3D ink and the other with a protein-rich 3D ink. The fatty regions in the bacon could be printed using a fat-rich ink consisting of a heat-set oil-in-water emulsion containing large fat droplets (to simulate adipose tissue) suspended in an aqueous phase containing heat-set proteins or other types of gelling material. The meaty regions in the bacon could be printed using a protein-rich ink consisting of heat-set proteins dissolved in water, along with dyes, flavors, and salts to provide the desired appearance, texture, and flavor profile. Powdered meat or plant-based proteins could be used for this purpose.

The final component of the breakfast, the bread, could be printed using a starch-based 3D ink that forms a heat-set gel when it is extruded onto a hot plate. Alternatively, starch-based inks could be used that gel at room temperature forming a bread-like structure, then baked using a heating device to produce toasted bread. So far, the most common starch printed is potato starch, often in the form of mashed potatoes. Most researchers have printed it at room temperature, while some have included a post-processing step.

In this scenario, each food item requires the utilization of food inks that contain different ingredients. With current technology, it would be necessary for someone to prepare each of the inks and then feed them into the 3D printer. For instance, a separate powder could be utilized to prepare each food ink by mixing it with water. In the future, it may be possible to create a limited number of powders that are mixed in different combinations to create a wide variety of food inks with other attributes. Moreover, this process could be fully automated. The astronaut would just enter the type of food that was required, and then the computer attached to the 3D printer would determine the best combination of different powders to mix together to obtain the necessary final properties for each food ink. However, further research is required to identify the minimum number of powders used and their compositions and properties. Another key issue would be the time required to print the food and then clean and sanitize the 3D printer afterward. As discussed earlier, this depends on the number and type of food inks used and the 3DP operating parameters, such as extrusion rate and nozzle size, shape, speed, and height.

Future Research Needs for Space Foods

3D food printing has great potential for space applications. However, much more research is required before its potential can be fully realized. For example, the effects of zero-gravity, limited space, and long-term storage need to be assessed. Material extrusion printers widely used for on-ground food printing must be faster, more accurate, and more versatile for space food applications. In particular, for in-space printing of complex foods, further research is required to develop multiple extruder printers with multiaxial feeds that can handle various food inks simultaneously. Current extrusion printers typically rely on air pressure to extrude materials through nozzles. However, for in-space printing, the safety and temperature of the airflow system need to be evaluated. Indeed, it may be more advantageous to utilize electrical-driven pumps for this purpose. The printer's compatibility with in-space environmental temperature also needs to be assessed for the storage, extruder, print bed, printer enclosure, operational accuracy, quality, and food safety.

Further research is also needed to understand food inks' structure-function relations better. For instance, the relationships between composition, physicochemical properties, functional attributes, nutritional profile, and sensory properties of 3D printed foods need to be elucidated. Furthermore, the potential degradation of nutrients and other components in food inks over time needs to be studied, and effective methods of inhibiting degradation identified to allow for the consistent formulation of healthy and desirable foods throughout the mission. More studies are also needed to determine the origin of the specific nutritional requirements of different astronauts so that foods personalized for each one’s individual needs can be formulated and printed.

Notably, much more research is required on the safety aspects of 3D printed foods. Studies are needed to identify potential food safety hazards, develop effective strategies to mitigate these hazards, to create 3D food printers and food inks that remain safe throughout the mission.

Potential food safety hazards could be in the form of biological, chemical (including allergens), or physical hazards, and could be from food-ink preparation on earth, contamination during travel, printing in space, improper sanitization of equipment, as well as storage of inks in space (Devlieger et al. 2016). A robust food safety plan for the processing, transportation, and storage of food inks will be critical on earth and in space. Similarly, sanitary design of the printers, protocols for their effective cleaning and sanitation, and reliable safety verification strategies need to be developed.

Conclusion

Food printing has already been successfully used to create various kinds of foods from many different types of edible materials (food inks). Nevertheless, numerous hurdles still need to be overcome before it is routinely used for food production on earth and in space. In this article, we highlighted the potential of 3D food printing for space applications. One of the biggest hurdles for more extended space missions is the limitations on how much food and processing equipment can be carried. Having a diverse range of delicious and nutritious foods is essential to astronauts' physical and mental health. 3D food printing has great potential to create these types of foods under the stringent constraints required for space missions. But research and innovation are still needed to improve and optimize 3D printing technologies and food inks to produce a wide range of delicious, healthy, and safe foods.

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Declaration of Interest

The authors have no conflict of interest to declare.

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Tables

Table 1. Currently available 3D Printing Processes ("Additive Manufacturing Research Group | Loughborough University"; Calignano et al. 2017; "3DEXPERIENCE Platform"; Gibson, Rosen, and Stucker 2015)

Printing Process	Technology	Advantages	Limitations
Vat Photopolymerization (VP)	Stereolithography (SLA)	- Accurate - High resolution - Versatile	- Structurally weak - Expensive - Lengthy postprocessing - Limited materials
Material Jetting (MJ)	Inkjet	- Accurate - Speed - Full color	- Expensive - Structurally weak - Limited materials
Binder Jetting (BJ)		- Speed - Range of colors - Large build volumes - Complex parts - Recyclable powder	- Structurally weak - Low resolution
Powder Bed Fusion (PBF)	Selective Laser Sintering (SLS)	- Functional parts - Good mechanical properties - Complex geometry	- Speed - Expensive raw materials - Rough surface finish
Material Extrusion	Fused Deposition Modeling (FDM)	- Range of materials - Range of price - Accessible - Easy to use	- Accuracy - Speed
Directed Energy Deposition (DED)		- Good for repairs - Speed - Fully dense parts - Large build area	- Complex technology - Accuracy - Low resolution
Sheet Lamination (SL)	Laminated Object Manufacturing (LOM)	- Low material cost - Large build area - Easy material handling	- Limited geometry - Low resolution - Material waste - Lengthy postprocessing

Table 2. Currently available 3D Food Printing Processes

Printing Processes	Material Jetting	Binder Jetting	Powder Bed Fusion	Material Extrusion
Materials	Cake icing, low viscosity toppings	Liquid binder, powdered materials: sugar, starch, corn flour	Powdered materials: sugar, chocolate	Proteins, fruit and vegetable purees, starches, emulsions, gelatin
Material Properties	Compatibility, rheological properties: viscosity, surface properties	Density, flowability, particle size, wettability, rheological properties, surface properties,	Density, flowability, particle size, wettability	Rheological properties: viscosity and flow behavior
Printing Properties	Temperature, printing rate, contact angle	Head type, printing velocity, nozzle diameter, layer thickness, resonance frequency	Laser type, laser diameter, laser power, scanning speed	Extrusion rate, layer height, nozzle diameter, nozzle height, temperature
Advantages	Fast, full color	Fast, complex geometry, full color	Complex geometry	Range of materials, accessible,
Disadvantages	Limited to 2D designs	Limited materials	Slow, limited materials	Slow
Prints*				
Reference				

*Images from websites: Material Jetting – foodjet.com(“FoodJet” 2020), Binder Jetting - brill3dculinarystudio.com (3D Systems), Powder Bed Fusion – candyfab.org (Oskay and Edman 2009), Material Extrusion – naturalmachines.com(Natural Machines)

Table 3. Currently Utilized Food Processing Technology (adopted from Jiang, Zhang and Bhandari)(Jiang et al. 2019)

	Process	Earliest Application	Advantages	Limitations	Shelf-life	References
Previous advance food technology (AFT)	Freeze-drying	Mercury (1961-1963)	Odor, color and flavor of food is usually natural; light in mass	High cost, about four times more than conventional dehydration	1.5-2.5 years	(Perchonok and Douglas 2018; Casaburri, Gardner, and George 1999; Perchonok et al. 2012; Lane et al. 1995; NASA 1995)
	Retort thermostabilization	Apollo (1968-1972)	Good taste, easy to eat and less residue	The added weight of package is large	2-3 years	
	Irradiation	Apollo (1968-1972)	Using a certain dose of ionizing radiation to destroy the microbial structure of food	Irradiated food may have some undesirable sensory characteristics	2-3 years	
Emerging joint thermal technology	Pressure assisted thermal sterilization (PATS)	Still in the development stage	Less damage to vitamins A and C, thiamin, and folic acid	May have a negative effect on meat color; may exacerbate certain biochemical reactions leading to indirect nutrient destruction	Target for 5 years shelf life	(Maya, Grace, and Michele 2015; Michele 2011; Perchonok 2014; Perchonok and Douglas 2018; Barbosa-Cánovas et al. 2014; Balasubramaniam et al. 2016)
	Microwave assisted thermal sterilization (MATS)			Non-uniform distribution of electromagnetic field; possible edge overheating effect		
On-orbit food preparation technology	3D printing	International Space Station (2000-present)	Can customize according to the nutritional needs of different people; reduce mass needed for food	Printable materials need to be developed in depth; need to develop faster and more accurate printer	Product has no long shelf life requirements	(Liu, Min, Bhandari, and Yang 2017; Liu, Min, Bhandari, and Wang 2017)

Figure Captions

Figure 1. Four of the seven 3D printing processes: A) Material jetting, B) Binder jetting, C) Powder bed fusion, D) Material Extrusion (Dassault Système)

Figure 2. Three of the seven 3D printing processes: A) Vat photopolymerization (top-down), B) Directed energy deposition *(Dassault Système),* C) Sheet lamination *("Sheet Lamination| Additive Manufacturing Research Group | Loughborough University" 2019)*.

Figure 3. 3D modelled breakfast of bacon, egg and toast to demonstrate a potential 3D created meal