Accepted Manuscript

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PII: S0924-2244(17)30082-1

DOI: 10.1016/j.tifs.2017.08.018

Reference: TIFS 2074

To appear in: *Trends in Food Science & Technology*

Received Date: 11 February 2017

Revised Date: 20 June 2017

Accepted Date: 30 August 2017

Please cite this article as: Liu, Z., Zhang, M., Bhandari, B., Wang, Y., 3D printing: Printing precision and application in food sector, *Trends in Food Science & Technology* (2017), doi: 10.1016/j.tifs.2017.08.018.

3D printing: printing precision and application in food sector

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Abstract

Background: Three dimensional (3D) food printing is being widely investigated in food sector recent years due to its multiple advantages such as customized food designs, personalized nutrition, simplifying supply chain, and broadening of the available food material.

Scope and approach: Currently, 3D printing is being applied in food areas such as military and space food, elderly food, sweets food. An accurate and precise printing is critical to a successful and smooth printing. In this paper, we collect and analyze the information on how to achieve a precise and accurate food printing, and review the application of 3D printing in several food areas, as well as give some proposals and provide a critical insight into the trends and challenges to 3D food printing.

Key findings and conclusions: To realize an accurate and precise printing, three main aspects should be investigated considerably: material properties, process parameters, and post-processing methods. We emphasize that the factors below should be given special attention to achieve a successful printing: rheological properties, binding mechanisms, thermodynamic properties, pre-treatment and post-processing methods. In addition, there are three challenges on 3D food printing: 1) printing precision and accuracy 2) process productivity and 3) production of colorful, multi-flavor, multi-structure products. A broad application of this technique is expected once these challenges are addressed.

Key words: 3D food printing; printing precision; process parameters; productivity

Introduction

3D printing, also known as additive manufacturing (AM), solid freeform fabrication (SFF), was firstly introduced in food sector by researchers from Cornell University using an extrusion based printer (Fab@home) (Periard, Schaal, Schaal, Malone, & Lipson, 2007). This technology is characterized by a layer by layer material deposition mode based directly from a pre-designed file (Pinna et al., 2016; Rayna & Striukova, 2016).

There are many potential advantages of 3D printing technology applied to food sector, such as customized food designs, personalized and digitalized nutrition, simplifying supply chain, and broadening the source of available food material. Using this technology, some complex and fantastic food designs which cannot be achieved by manual labor or conventional mold can be produced by ordinary people based on predetermined data files that comprise culinary knowledge and artistic skills from chefs, nutrition experts, and food designers (Sun, Zhou, Huang, Fuh, & Hong, 2015). It also can be used to customize confectionery shapes and colorful images onto surface of solid edible substrates (Young, 2000; Zoran & Coelho, 2011). In addition, 3D food printing permits to digitize and personalize the nutrition and energy requirements of an individual person according to their physical and nutrition status (Severini & Derossi, 2016; Sun, Zhou, Huang, Fuh, & Hong, 2015; Wegrzyn, Golding, & Archer, 2012; Yang, Zhang, & Bhandari, 2015). Conventional food supply chain can be simplified by 3D food printing. The universal application this technique will make the manufacturing activities slowly moving to the places closer to the customers and will lead to the reduced transport volume, thus reducing the packaging, distribution and overriding costs (Chen, 2016; Jia, Wang, Mustafee, & Hao, 2016; Sun et al., 2015). Food printing technology will also broaden the source of available food material by using non-traditional food materials such as insects, high fiber plant based materials, and plant and animal based by-products (Payne et al., 2016; Severini & Derossi, 2016; Tran, 2016).

Currently, 3D printing techniques available in food sector generally include four types: extrusion based printing, selective sintering printing (SLS), binder jetting, and inkjet printing. Extrusion based printing is usually used in the extrusion of hot-melt chocolate or soft-material such as dough, mashed potatoes, and meat puree (Engmann & Mackley, 2006; Yang, Zhang, & Bhandari, 2015). Researchers from Cornell University studied the fabrication of cake frosting, processed cheese, and sugar cookies using extrusion based printing (Lipton et al., 2010; Periard, Schaal, Schaal, Malone, & Lipson, 2007). This technology has also been applied by Netherlands Organization for Applied Scientific Research (TNO) to fabricate various kinds of foods using traditional materials and non-traditional ingredients such as algae and insects (Daniel, 2015; Sol, Linden, & Bommel, 2015). Another extrusion based printer (Foodini Printer) has been created by Natural Machines to be used for surface filling and graphical decoration (Galdeano, 2015). Camille et al. (2017) studied the effect of 3D printing on quality of processed cheese. Results showed that the printed cheese was significantly less hard, by up to 49%, and exhibited higher degrees of meltability (21%), compared to untreated cheese samples (not 3D printed samples) (Camille et al., 2017). The hot-melt extrusion of chocolate using 3D printing was firstly operated using a Fab@home printing system. They studied the deposition of chocolate and the processing factors affecting the printing accuracy during chocolate fabrication (Hao et al., 2010). The chocolate extrusion printing has been commercialized by Choc Edge's Choc Creator, 3D System's ChefJet, Hershey's CocoJet, and Chocabyte (Millen, 2012; Zhuo, 2015). SLS has been utilized to fabricate complex structures using sugar or sugar-rich powders. Delicate and complex 3D structures has been created by researchers from TNO using sugars and NesQuik powders (Gray, 2010). Using SLS, CandyFab Project has successfully created various attractive complex structures using sugar powders which could not be produced by conventional ways (CandyFab 2007). Binder jetting offers advantages such as fast fabrication, building of complex structures and low material cost (Sun, Peng, Yan, Fuh, & Hong, 2015). Based on binder jetting, Southerland and Walters (2011) investigated the fabrication of edible constructs using sugars and starch mixtures. Researchers from 3D System have created a binder to produce a wide variety of colorful and flavors edible objects, such as various kinds of complex sculptural cakes by varying flavor and colorful binders (Izdebska & Tryznowska, 2016). Inkjet printing generally handle low viscosity materials, thus it is mainly used in the area of surface filling or image decoration (Pallottino et al., 2016). Grood and Grood (2011) created an drop-on-demand inkjet printer to dispense edible liquids onto food surfaces to create appealing images (Grood & Grood, 2011). The FoodJet printer uses pneumatic membrane nozzle-jets to deposit edible drops onto a moving object to form an appealing surfaces (FoodJet, 2015). Willcocks, Shastry, Collins, Camporini, and Suttle (2011) created a kind of edible ink to fabricate high resolutions of images on edible substrates, such as biscuit, cake, and crackers.

3D printing is being widely investigated in food sector. However, few studies have focused on how to achieve an accurate and precise printing, though it is critical to a successful and smooth printing of the food objects. The aims of this review paper are to collect and analyze the information regarding how to achieve a precise and accurate food printing, and to review the application of 3D printing in several food areas, as well as to give some proposals and provide a critical insight into the trends and challenges faced by 3D food printing.

2 3D food printing technologies and factors influencing printing precision and accuracy

As mentioned earlier, the quality and precision of printed objects depend on the material properties, processing factors, and post-processing treatments. Each 3D food printing technique has its own advantages and limitations. Tab. 1 shows the comparison of different 3D printing techniques, and factors affecting the printing precision and accuracy. This is discussed in detail in the following section.

2.1 Extrusion-based printing and factors influencing printing accuracy

The extrusion-based printing, also known as fused deposition modelling (FDM), was firstly introduced to fabricate plastics products (Ahn, Montero, Odell, Roundy, & Wright, 2002). During food printing process the melted material or paste-like slurry is extruded out continuously from a moving nozzle, and welds to the preceding layers on cooling. The extrusion based printing can be applied into chocolate printing and soft-materials printing, such as dough, mashed potatoes, cheese, and meat paste (Lipton et al., 2010; Yang, Zhang, & Bhandari, 2015). Though this technique has been applied in the deposition of a wide variety of soft-materials, the deposition of them into complex and delicate shapes are inherently limited as they are fundamentally prone to distortion and warping. To fabricate delicate and complex shapes during soft-material extrusion process, it is necessary to print the additional structural objects to support the product geometry. The supporting constructs must be manually removed in the final stage. This is a time consuming process and will slow printing speed and raise material costs (Hasseln, 2013; Hasseln, Hasseln, & Williams, 2014; Von, Von, Williams, & Gale, 2015b). Therefore, it is necessary to fully understand the material properties and relevant technologies, thus to be able to construct 3D structures. The printing precision and accuracy are critical in the production of an appealing object, and there are several factors which may be responsible for this: 1) extrusion mechanism 2) material properties, such as rheological properties, gelling, melting and glass transition temperature (Tg) 3) processing factors, such as nozzle height, nozzle diameter and extrusion speed 4) post-processing treatments.

Three extrusion mechanisms have been applied in 3D food printing: screw-based extrusion, air pressure-based extrusion and syringe-based extrusion. In the screw-based extrusion process, food materials are put into the sample feeder and transported to the nozzle tip by a moving screw. During the extrusion process, food materials can be fed into the hopper continuously thus realizing the continuous printing. However, the screw-based extrusion is not suitable for the food slurry with high viscosity and high mechanical strength, thus the printed samples do not attain proper mechanical strength to support the following deposited layers and result in the compressed deformation and poor resolution (Liu, Zhang, Bhandari, & Yang, 2017). The air pressure-based extrusion, during which food materials are pushed to the nozzle by air pressure, is suitable to print liquid or low viscosity materials, (Sun, Zhou, Yan, Huang, & Lin, 2017). The syringe-based extrusion unit is suitable to print food materials with high viscosity and high mechanical strength, so that it probably can be used to fabricate complex 3D structures with high resolution. However, it should be noted that the air pressure-based extrusion and syringe-based extrusion do not allow the continuous feeding of food materials during printing

In extrusion based printing, the properties of food material, such as the moisture content, rheological properties, specific crosslinking mechanisms and thermal properties, are critical to a successful printing. In the 3D printing of biomass of *Nostoc aphaeroides*, the moisture content affected the printing behavior greatly, and the slightly higher moisture content was helpful to form a smooth structure (An, Zhang, Godoi, & Zhong, 2017). The viscosity of the soft-material should be both low enough to be easily extruded through a fine nozzle and high enough to hold the subsequently deposited layers (Godoi, Prakash, & Bhandari, 2016). Wang and Shaw (2005) concluded that dental porcelain slurries with shear thinning behavior are beneficial to the construction of objects, as they can be easily extruded out from the nozzle with the application of shear stress and become rigid and solidifies upon the departure from the extruder (Wang & Shaw, 2005). In our previous work (Liu, Zhang, Bhandari, & Yang, 2017), we investigated the impact of rheological properties of mashed potatoes (MP) on 3D printing by addition of different concentrations of potato starch (PS). We concluded that the highly desirable materials for 3D food printing should not only possessed suitable yield stress (τ_0) and elastic modulus (G′) to be capable of maintaining printed shapes, but also had relative low consistency index (*K*) and flow behavior index (*n*) to be easily extruded out from nozzle in extrusion-based type printer. MP with addition of 2% PS displayed excellent extrudability and printability, i.e., shear-thinning behavior, *K* of 118.44 (Pa•s^n), and strong enough mechanical strength with yield stress (τ_0) of 312.16 Pa and proper elastic modulus (G′), therefore the objects could withstand the shape over time and possessed smooth shape and resolution. No addition of PS induced a drop in τ_0 (195.90 Pa) and G′, thus printed objects deformed in time because of sagging. Although MP with addition of 4% PS represented good shape retention due to proper τ_0 (370.33 Pa) and G′, the poor extrudability made it difficult to print due to high *K* (214.27 Pa•s^n) and viscosity. The printed samples are illustrated in Fig. 1 (Liu, Zhang, Bhandari, & Yang, 2017).We also investigated the printing behavior of MP with addition of different hydrocolloid, and Fig. 2 illustrates several sample pictures. In addition, our research group studied the fish surimi gel as potential food material for 3D printing (Wang, Zhang, Bhandari, & Yang, 2017). Results indicated that the surimi with high viscosity and low loss tangents (tanδ= G″/G′) could not extruded smoothly with large amounts of broken deposited lines. NaCl could be used to adjust the viscoelasticity of surimi and the printed objects using surimi with addition of 1.5g/100g NaCl displayed a smooth surface structure, better matching with the target geometry and no compressed deformation. Printed samples are shown in Fig. 3 (Wang, Zhang, Bhandari, & Yang, 2017). In the previous work of 3D printing Vegemite and Marmite, Hamilton, Alici, and Marc (2017) indicated that the *n* and *K* were critical in determining whether a material is suitable for 3D printing and determining the desired extrusion rates. Zhang et al. (2015) also reported that the gel with higher τ_0 and G′ revealed better performance to support the additional deposited layers in the printing of dual-responsive hydrogels. An, Zhang, Godoi, and Zhong (2017) studied 3D printing behavior of three types of biomass (*Nostoc aphaeroides),* that is fresh biomass, rehydrated biomass powder and rehydrated biomass powder with addition of starch. They studied the correlation between rheological behavior and printability, and pointed out that elasticity and viscosity balance is an essential parameter to achieve printability. The increase of elasticity went against smooth 3D print-running, but could help to strength of the construct (An, Zhang, Godoi, & Zhong, 2017). To achieve an ideal rheological properties to be capable of holding the 3D structures, rheological modifiers, such as hydrocolloids and soluble protein, can be added but must comply with food safety standards. In addition, the crystallization state and glass transition temperature (Tg) of material is also critical to make the deposited material to support its own structure after printing (Godoi, Prakash, & Bhandari, 2016). In hot-melt extrusion of chocolate, understanding the properties of the chocolate is critical to the quality of the printed objects due to the complex compositions and six different crystalline phases for cocoa butter (Marangoni & McGauley, 2003). Hao et al. (2010) investigated the material characterization on the quality of printed objects. During this process, a seed was added in the pre-melted chocolate to generate more V crystals which was desirable in the deposition of "good" chocolate. Chocolate slurries with pseudoplastic property at different temperatures was highly desirable in the deposition of 3D constructs (Hao et al., 2010).

The processing parameters, such as nozzle diameter, nozzle height, extrusion rate and nozzle moving speed, are also critical to the quality of the resulting printed constructs. Previous work (Hao et al., 2010) on the deposition of chocolate showed that the distance between the nozzle tip and build platform played an important role in the quality of built objects, and an equation was developed regarding the critical nozzle height:

$$h_c = \frac{V_d}{v_n D_n} \qquad \text{Equation 1}$$

Where, *hc* is the critical nozzle height, V_d the volume of slurries extruded out per unit time (cm^3/s), v_n the nozzle moving speed (mm/s), Dn the nozzle diameter (mm) and h_c the optimal nozzle height. This study showed that when a lower nozzle height than h_c was applied, the volume of the extruded chocolate would be too large for the space between the building platform and nozzle. Thus, the slurry was forced to spread in the directions perpendicular to the deposited slurry line and the resultant extruded objects displayed a squeezing effect and poor accuracy. Conversely, the application of a larger nozzle height resulting in parts of the chocolate not reaching the marble build surface in time, leading to massively inaccurate parts (Hao et al., 2010). Effects of nozzle height on the printing behavior was studied in our group. Results indicated that the application of a nozzle height lower than *hc* led to the thicker extruded lines than intended. The application of a nozzle height higher than *hc* led to parts of the extruded surimi lines not reaching the build surface before the nozzle turned a corner and thus resulted in massively inaccurate sections (Wang, Zhang, Bhandari, & Yang, 2017). The effect of various nozzle diameter on the built construct was simple to determine. A safe rule of thumb is to select the smallest nozzle tip that allows for easy material extrusion, as it is helpful to construct the object with the finest resolution and smooth surface during printing (Periard, Schaal, Schaal, Malone, & Lipson, 2007). Wang, Zhang, Bhandari, and Yang (2017) concluded that the nozzle diameter affected the printing precision and surface smooth considerably. The 3D printing of fish surimi displayed that the application of a small nozzle diameter (0.8mm, 1.5mm) led to relatively poor models due to the inconsistent extruded surimi filament in its diameter along the length. Conversely, the use of a larger nozzle diameter could extrude consistent lines, but the resolution and accuracy of the objects were poor (Wang, Zhang, Bhandari, & Yang, 2017). Generally, a small nozzle diameter is beneficial to print objects with fine resolution, but it should be noted that the printing time required increased greatly when using a small nozzle size. A good balance must be made with the printing productivity and the printing precision. The extrusion rate and nozzle moving speed are also important in extrusion based printing. It was suggested that the critical nozzle movement rate can be determined by the following equation derived from Equation 1 (Khalil & Sun, 2007):

$$v_N = \frac{4Q}{\pi D_N^2} \qquad \text{Equation 2}$$

Where v_N is the optimal nozzle speed (mm/s), Q the material flow rate (cm^3/s) and D_N the nozzle diameter. It was shown that a nozzle velocity greater than v_N would result in a smaller diameter material bead than that of the nozzle, whereas a nozzle velocity less than v_N would lead to a greater diameter material bead than that of the nozzle. Neither of them was desired in printing (Khalil & Sun, 2007). Wang, Zhang, Bhandari, and Yang (2017) suggested that the alteration of nozzle speed would affect the critical nozzle height when all other parameters were kept constant. Too high speed (32 mm/s) resulted in the dragging effect causing breaking of the extruded slurry filaments. While too low moving speed (20mm/s) resulted in the occurrence of flow instabilities of slurry and the formation of coils (Fig. 4). They also suggested that there is a linear relationship between the extrusion rate and the diameter of surimi lines. Too high extrusion rate (0.004 cm^3/s) gave a larger extruded lines' diameter than desired due to the extrusion of greater volume of material. Too low extrusion rate (0.002 cm^3/s) led to an inconsistent surimi slurry (Wang, Zhang, Bhandari, & Yang, 2017). In the 3D printing of chocolate, it was revealed that the printing accuracy was seriously affected by the extrusion rate and nozzle movement rate, due to the bead diameter of chocolate track decreased with the nozzle movement rate while increased with the extrusion rate, as shown in Fig. 5 (Hao et al., 2010). Similar results was also reported in the creating of detailed and complex ceramic parts using extrusion based printing (Rueschhoff, Costakis, Michie, Youngblood, & Trice, 2016). In the previous work (Zhuo, 2015) on the development of 3D food printer, a positive linear relationship between nozzle moving speed and extrusion rate was studied. As shown in Fig. 6, the blue region represents the acceptable prints and any values outside the region led to bad prints (Zhuo, 2015).

The printing temperature should also be fine-tuned, as the viscosity of the food material is directly correlated with the temperature. The temperature should be low enough so that the extruded chocolate harden rapidly on the substrate without flowing too much (Periard, Schaal, Schaal, Malone, & Lipson, 2007). In the previous work of 3D printing Vegemite and Marmite (Hamilton, Alici, & Marc, 2017), the viscosity decreased when the temperature increased. 172 kPa of pressure was used to extrude both materials at 25°C but it should be decrease to 103 kPa at 45°C. The application of a 172 kPa pressure to fabricate objects at 45°C led to too large flow rate and the formation of a puddle of material. With a further increase of temperature to 65°C, too quick extrusion of the material was formed even with the application of a very low pressure (<34 kPa) (Hamilton, Alici, & Marc, 2017).

Ideally, the 3D food structures should resist to post-processing (baking, cooking, frying, etc), as most of foods consumed in daily life must go through these processes. The deposition of various kinds of soft-material, such as cookie dough, cheese and cake frosting, have been done via extrusion based 3D printing technique (Lipton et al., 2010). However, these objects were not suitable for conventional food processing techniques and would greatly deformed after post-processing treatments. In order to realize the wide application of 3D printing process on foods, this technique must be easily compatible with traditional food processing steps (Lipton, Cutler, Nigl, Cohen, & Lipson, 2015). Two main ways that have been applied to maintain the shape stability of objects after post-processing are recipe control and addition of additives (Lipton et al., 2010). Additives of various concentrations of transglutaminase was blended with lean beef paste to maintain printed shape stability after cooking. It was shown that addition of 0.5% of transglutaminase by weight significantly increased the structure stability after cooking. This was because that the addition of transglutaminase led to the formation of new protein matrix over time. The extrudates survivability of scallop through deep fried and turkey meat through sous-vide cooking were investigated, and excellent performances were obtained (Lipton et al., 2010). In another study, the composition of the cookie recipe was found to have significant effects on the printability and shape stability of the cookie. It was shown that increasing the butter content increased the printability but decreased the shape stability after baking. The increase of yolk concentrations increased the shape stability, which can be seen in Fig. 7 (Lipton et al., 2010). The method of varying recipe formulation of cookie dough to achieve desired printability and shape stability after baking has also been investigated (Zhuo, 2015). Godoi, Prakash, and Bhandari (2016) believe that the 3D printed structures which can resist post-processing can be achieved by controlling the physical-chemical, rheological, structural and mechanical properties of the materials.

2.2 Selective laser sintering based printing and factors influencing printing accuracy

Selective laser sintering (SLS) is a technology that applies a power laser to selectively fuse powder particles together layer by layer finally into a 3D structure. The laser scans cross-sections on the surface of each layer and selectively fuses the powder. After scanning each cross-section, the powder bed is dropped and a new layer of powder is covered on top. This process is repeated until the desired structure is finished. Finally, the unfused powder is removed and reclaimed for next printing (Noort et al., 2016). SLS has been widely applied in the metal and ceramic industrial manufacturing, however, there are several hurdles for using SLS in food sector: (1) suitable powdered material which can fuse together without decomposition of the material itself during fabricating process (2) the construction of various edible objects using a wide range of food materials (Diaz, Van, Noort, Henket, & Brier, 2014). Generally, SLS allows for the production of free standing complex 3D structures with high resolution, but the available material is limited to powder material, such as sugar, fat or starch granule. It is necessary to expand the available range of food ingredient thus to broaden the application of this technology in traditional food. In SLS, the material properties and processing factors (laser types, laser power, laser spot diameter, etc), are both critical to the printing precision and accuracy of fabricated parts (Shirazi et al., 2015).

Material properties, such as particle size, flowability, bulk density and wettability of powder material, have a great impact on the printing precision and accuracy of objects in SLS (Godoi, Prakash, & Bhandari, 2016). Powder density and compressibility are also important in SLS, as they seriously affect the powder flowability inside the vessel which, in turn, contributes for the formation of patterns when the laser source is applied to the powder bed (Berretta, Ghita, Evans, Anderson, & Newman, 2013; Schmid, Amado, Levy, & Wegener, 2013). The preferred edible powder in SLS should be a free-flowing powder which can be poured without substantial clumping. In addition, the powdered material should not be sticky, and thus has no or any tendency to agglomerate or to adhere to contact surfaces (Diaz, Van, Noort, Henket, & Brier, 2014). The particle size affects the printing precision and resolution of fabricated objects (Duan et al., 2010; Sun, Peng, Yan, Fuh, & Hong, 2015). A smaller layer thickness results in a stronger mechanical strength and a decrease in the porosity of fabricated constructs, while the minimum layer thickness that can be used in SLS is determined by the maximum particle size of the powder (Fred, Lohrengel, Neubert, Camila, & Czelusniak, 2014). Diaz, Van, Noort, Henket, and Brier (2014) invent a method for the production of edible objects with a high degree of resolution and precision using SLS. In this invention, the multi-material structures were created by using a powder composition comprising a structural element and a binder component. The structural element provided bulk and scaffold function and the binder component acted as particle-particle sintering helping bind the powder into the desired structure. Typically, the melting temperature (Tm) or glass transition temperature (Tg) of the binder component ranged between 10-200°C. The binder should undergo melting and glass transition in less than five seconds, while the structural component should be non-melting at the temperatures below 200°C (Diaz, Van, Noort, Henket, & Brier, 2014). In addition, they concluded that the binder comprising at least two compounds that differ in their Tg or Tm, such as the palm oil powder with a Tm of 30°C and maltodextrin with a Tg of 62°C, demonstrated excellent performance in aspects of the printing precision and accuracy of printed objects.

The processing factors, such as laser types, laser diameter, laser power, and scanning speed, should also be fine-tuned to get a desired outcome. The interaction between the powdered materials and laser beam is critical to the quality of fabricated constructs in SLS process, as the strength of interaction depends on the laser types and the fusion of material is affected by the laser energy density (Gu, Meiners, Wissenbach, & Poprawe, 2012). A higher laser energy density, which can be obtained by adjusting the scanning speed and laser power, leads to denser parts with stronger mechanical strength due to longer interaction time. A porous and brittle structure will be obtained when a lower laser energy density is applied (Fred, Lohrengel, Neubert, Camila, & Czelusniak, 2014). The CandyFab uses hot air to selectively sinter and melt sugar powder due to the low melting temperature of sugar powder. The interaction time between the hot air gun and sugar powder was one to three seconds, determined by the air temperature and layer thickness. Larger laser spot diameter made the constructs less likely to break, and a higher rate of fabrication was obtained by turning up the heat and speed, while the resulting object's precision and resolution were poor. Changing the laser diameter from 5 mm to about 1.6 mm improved the printing resolution and precision, but at the expensing of lowering the constructing rate and reducing the mechanical strength of the printed object (CandyFab, 2009). In the fabrication of an colorful and detailed edible object, the SLS procedure was performed by Diaz et al. (2014) using a carbon dioxide laser with laser spot diameter 0.6 mm, and specific process parameters (layer distance of 0.1 mm, writing speed 1250 mm/sec, laser power 50% and layer thickness 0.3 mm).

The printed objects in selective laser sintering may require further post processing, such as the removal of the excess food material powder to improve the surface smooth and further heating to enhance the mechanical strength.

2.3 Binder jetting based printing and factors influencing printing accuracy

Binder jetting printing, also known as inkjet 3D printing (3DP), was firstly introduced by Sachs, Haggerty, Cima, and Williams (1994), during which powdered materials were deposited layer by layer and the binder was selectively ejected upon each material layer at certain regions based on the data file for the object being produced. The binder fuses the current cross-sections to previous and afterwards fused cross-sections. The un-fused powdered support the fused parts at all times during the fabrication process, allowing for the production of intricate and complex structures. Finally, the unbound powder is removed and recycled for further use (Sachs, Haggerty, Cima, & Williams, 1994). Binder jetting technology can be used to fabricate complex and delicate 3D structures, and have the potential to produce colorful 3D edible objects by varying binder composition. However, the structural material is only limited to powder stuff, and the edible binder affects its wide application in food sector, especially in the field of traditional food consumed in daily life.

In binder jetting process, properties of powdered material and binder are critical to the successful fabrication of parts. The binder must have suitable viscosity, surface tension, ink density, and suitable properties to prevent spreading from nozzles. The binder concentration was also important to the successful fabrication of parts with desired dimensional precision (Peters et al., 2006). In a successful fabrication process, the bound structures should possess adequate product strength with minimal shrinkage or expansion and minimal 'bleeding' of the binder into neighboring voxels (Hasseln, 2013; Hasseln, Hasseln, & Williams, 2014; Von, Von, Williams, & Gale, 2015a). Flowability of powder is important. The powder with suitable flowability permits the roller to easily build up thin layers, which facilitates the fabrication with high precision and accuracy. Conversely, poor flowability reduces the resolution and accuracy of fabricated parts due to insufficient recoating (Lanzetta & Sachs, 2003). A free-flowing powder with suitable spreading and packing properties is preferred in binder jetting. It means that the powder should be not sticky, and thus has hardly any or no tendency to agglomerate or to adhere to contact surfaces. Typically, the angle of repose of the powder should be low, e.g. smaller than 30° (Diaz, Noort, & Van, 2015). The wettability of powder is another affecting factor in accurate printing. It has been suggested that too-low wetting of powder material leads to the rearrangement of powder bed that is detrimental to subsequent printing. Too-high wetting and slow reaction between powder and binder reduce the resolution of and precision of fabricated objects (Hogekamp & Pohl, 2004; Shirazi et al., 2015). The moisture content of edible powder used in binder jetting should be less than 6% based on the powder material composition (Von, Von, Williams, & Gale, 2015b). In addition, wetting methods has also been applied to reduce the unbound powder migration during the fabrication process (Hunter, Kasperchik, Nielsen, Collins, & Cruz-Uribe, 2008). The particle size and distribution of powders also affect the printing precision and accuracy, as the variation of particle size influences the pore size distribution within the powder bed and thus affects the binding behavior of a water-based binder (Hapgood, Litster, Biggs, & Howes, 2002; Von, Von, Williams, & Gale, 2015a). To achieve an edible powder with suitable spreading and packing qualities, coarse powder particles can be mixed with fine powder particles (Von Hasseln, 2013; Von Hasseln, Von Hasseln, & Williams, 2014; Von, Von, Williams, & Gale, 2015a).

The processing factors, such as head types, printing velocity, droplets path, nozzle diameter, and resonance frequency of the head, also affect the precision of printed objects. In general a larger nozzle diameter helps to increase printing speed but reduce the resolution and precision of fabricated objects (Shirazi et al., 2015). In order to realize a successful printing, the processing factors mentioned above should be properly adjusted.

The fabricated objects in binder jetting may require further post processing, such as baking, heating, or removal of the excess food material powder to improve the mechanical strength or precision (Von Hasseln, Von Hasseln, & Williams, 2014; Von, Von, Williams, & Gale, 2015a). Making use of the adsorbability of pores within the printed parts, an additive can be sprinkled over the surface of the edible constructs to add different flavors or colors to improve the appearance of the food (Lai & Cheng, 2008).

2.4 Inkjet printing and factors influencing printing accuracy

Inkjet printing dispenses a stream of droplets from a thermal or piezoelectric head to certain regions for the surface filling or image decoration on food surfaces, such as cookie, cake, and pizza (Kruth, Levy, Klocke, & Childs, 2007). There are two types of inkjet printing methods: continuous jet printing and drop-on-demand printing. In a continuous jet printer, ink is ejected continuously through a piezoelectric crystal vibrating at a constant frequency. To get a desired flowability of the ink, it is charged by the addition of some conductive agents. In a drop-on-demand printer, ink is ejected out from heads under pressure exerted by a valve. Generally, the printing rates of drop-on-demand systems are slower than that of continuous jet systems, but the resolution and precision of produced images are higher. A typical maximum resolution for a single print head continuous jet printer image is about 70-90 dots per square inch (dpi) (Willcocks, Shastry, Collins, Camporini, & Suttle, 2011). Generally, inkjet printing handles low viscosity materials that do not possess enough mechanical strength to hold 3D structure. Therefore, it is usually used to print two-dimensional images. From the point of view of printing precision and accuracy, the compatibility between ink and substrate surface, viscosity and rheological properties of ink, temperature and printing rate, are important to a successful printing.

The compatibility of the printed image with surfaces of substrates play a critical role in determining the final image quality and resolution. The surface chemistry of the substrates and that of the ink influence the interaction behavior once the ink droplets are jetted onto the surface. Sometimes it is necessary to improve the compatibility of substrate's surface by coating the surface with a binder film or other compatibility-enhancing film before printing an image (Shastry, Ben, & Collins, 2006; Shastry et al., 2004; Willcocks, Shastry, Collins, Camporini, & Suttle, 2011). In the previous work (Mandery, 2010), a binder such as shellac or poly (1-vinyl-2-pyrrolidone), was added to the edible ink to increase the compatibility between the ink and the substrate (Mandery, 2010). Water-based glazes containing gums or other surfactants, such as polyglycerol oleates and polysorbates, were also used to modify the chocolate adequately to allow the printing of high-resolution images on surface. Moreover, the application of multi-layer of surfactant on the substrate surface before printing an image, the compatibility was significantly increased. Thus the printed images was better with high printing precision and resolution (Willcocks, Shastry, Collins, Camporini, & Suttle, 2011). The contact angle of ink droplet on surface, closely related with the compatibility and adhesion between the ink and the substrate, is desired less than about 50 degrees. Another indication of the compatibility, surface tension of the inks, is most preferred below 35 dynes/cm (Shastry et al., 2004). Shastry, Ben, and Collins (2006) also indicated that a low polarity material such as carnauba wax is typically coated on the surface of many hard panned sugar shell confections, which shows an adverse effect on the printing of an image with high precision and accuracy due to the low polarity surfaces. Thus a hydrophilic substance was usually coated to the surface of substrates to form a polarity-modified surface to improve the compatibility of water-based ink with the substrate (Shastry, Ben, & Collins, 2006).

The viscosity and rheological properties of edible ink is also critical to the printing precision and accuracy (Godoi, Prakash, & Bhandari, 2016). Generally, it is necessary that the edible inks possess low viscosity so that they can be easily ejected through the tiny orifices of the print-head (Shastry, Ben, & Collins, 2006). The desired inks in continuous jet have a narrow range of acceptable viscosity. The viscosity above 10 mPas easily leads to the pump's cavitation inside print-head during printing. The ink with viscosity below about 2 mPas is not stable. Thus the most desired viscosity of inks in a continuous jet printer should be between about 2.8 to about 6 mPas (Shastry et al., 2004). Willcocks, Shastry, Collins, Camporini, and Suttle (2011) also suggested that the inks should possess ideal viscosity to enable the proper flowability (Willcocks, Shastry, Collins, Camporini, & Suttle, 2011).

Temperature is another important factor in the ink jetting, as it can be used to modify the rheological properties and surface energy of the inks. A low temperature may be applied to lower surface energy and reduce the spreading tendency of inks across the chocolate surface (Shastry, Ben, & Collins, 2006; Willcocks, Shastry, Collins, Camporini, & Suttle, 2011). The temperature required to achieve desired viscosity also changes with the ink ingredients (Shastry et al., 2004).

The proper jetting rates and rapid drying of ink droplets are required for a precise and accurate inkjet printing. When too much ink is jetted to a given section, the ink droplets will coalesce into larger droplets due to the lack of sufficient time for the ink to completely dry, resulting in a loss of precision and a poor image quality. Application of a stream of dry gas and addition of alcohol to ensure the rapid drying of ink droplets can significantly increase the printing precision and accuracy (Shastry, Ben, & Collins, 2006; Willcocks, Shastry, Collins, Camporini, & Suttle, 2011).

3 Application of 3D food printing in some specific food areas

3.1 Military and space food

The US Army has shown a great deal of interest in the application of 3D food printing in military foods due to the several reasons. 1) this technology allows for the production of meals on demand in the battlefield; 2) meals can be personalized and customized depending on individual soldier's nutrition and energy requirements; 3) this technology could extend the shelf life of food material by storing them in raw material form rather than in final product form (Jennifer, 2014). The use of ultrasonic agglomeration to fuse particles together by shooting ultrasonic waves at them in 3D food printing in the US Army, have been experimented to produce a wider variety of meals and thus offering more options to soldier's food. US Army also intended to create a 3D compact unit which can transform forage plant materials (such as tree bark, berries) into food (Davide & Xavier, 2015; Jasmine, 2014).

NASA funded Systems and Materials Research Corporation (SMRC) to investigate the possibility and application of 3D printing for producing food during long space missions (Lin, 2015; Lipton, Cutler, Nigl, Cohen, & Lipson, 2015). NASA wanted to use 3D food printing to meet the requirements of food safety, nutritional stability and acceptability of meals for long space missions, while using the least amount of spacecraft resources. Currently, the food system in NASA could not meet the nutritional and five-year shelf life requirements for long missions, as the individual packaged foods processed with traditional cooking methods possess little micronutrients due to degradation over time. The refrigeration equipment will take up much spacecraft resources. In addition, the current space food system could not meet personalized nutritional and energy requirements of astronauts (Davide & Xavier, 2015; Lin, 2015; Lipton, Cutler, Nigl, Cohen, & Lipson, 2015). According to the proposal of SMRC, in order to design a food system to meet nutritional and personalized requirements for individual astronaut for long space missions, the 3D printing will be used to deliver macronutrients (carbohydrate, protein, and fat), structure and texture, and the inkjet printing to deliver micronutrients, flavor and smell. Dry sterile containers will be used to store the macronutrient stocks and sterile packs to store the micronutrients and flavors as liquids, aqueous solutions or dispersions. During the production of food, the macronutrient stocks will be fed directly to the printer by combining with water or oil and blending with flavors and texture modifiers at the print head. Then the mixtures will be extruded into desired structures and shapes. This technology could not only solve the uniform long term storage, sustenance, and micro-nutrition, but also could meet the personalized dietary needs and improve the pleasure of eating (Irvin, 2013).

3.2 Elderly food

Many countries are facing with the aging problem, such as Japan, Sweden, and Canada. About 15%-25% of elderly people over the age of 50 and up to 60% of nursing home residents suffer from chewing and swallowing difficulties (Sun, Peng, Yan, Fuh, & Hong, 2015). People suffering from this disease are often provided with unappealing ‘porridge-like food’, which cause the loss of appetite and even nutritional deficiencies. To address this issue, European Union (EU) has funded the PERFORMANCE project, aiming at designing an automated manufacturing method and offering personalized and specially textured food using 3D printing technology (PERFORMANCE, 2012). Scientists in the project have created simulation foods, such as peas and gnocchi, imitating their taste and texture. Not only the elderly will be fond of eating these foods, but also the soft, pureed texture is easier for them to swallow. Besides, personalized nutritional meals of each person can be produced based on individual age, physical condition, and nutrition and energy requirements (Davide & Xavier, 2015; Severini & Derossi, 2016). A survey done by the PERFORMANCE regarding 3D printing food in care homes have shown that 54 % of participants felt the food texture was good, 79% thought the printed food is equivalent to the one prepared by traditionally cooking method and 43% preferred to printed food when dysphagia occurred (Lunardo, 2016). In Germany, a few nursing homes served a printed soft food to elderly suffering from chewing and swallowing difficulties (Wiggers, 2015). The tastier 3D-printed foods made of peas, mashed potatoes, and broccoli have successfully entered the market and 1,000 of the country’s agencies supply this type of food daily (Wiggers, 2015).

3.3 Confectionery market

Sweets, accounting for a large proportion of the food market, are widely consumed in the world. Most of the leading companies and research centers of 3D food makers are focusing on sweets, such as Hershey, ChocEdge and 3D Systems. Tab. 2 shows the comparison of different confectionery or sweets printing machines.

One of the world largest manufacturers of industrial-grade 3D printers - 3D Systems, cooperating with Hershey (a leader in the production of chocolate and desserts), has developed an extrusion-based chocolate printer called Cocojet, which can print various shapes in chocolate (Millen, 2012; Zhuo, 2015). The first commercial chocolate printer called ChocCreator, was designed by the scientists in the University of Exeter (Davide & Xavier, 2015). Hans Fouche invented a 8 nozzle Cheetah chocolate 3D printer and used this system to experiment with different kinds of chocolates (Victor, 2015). Currently, most 3D chocolate is created using melt-extrusion based printer, while four students called 3D Chocolateering coming from University of Waterloo built a low cost selective laser sintering based printers to create 3D chocolate structures using chocolate powder (Victor, 2015). The CandyFab project was the first to create 3D dimensional structures using sugar in 2007 and introduced a selective sintering based printer, CandyFab. They created a technology SHASAM (selective hot air sintering and melting), in which a focused heat source was used to fused the particles together to create complex structures (CandyFab project, 2007). The 3D Systems ChefJet Pro is able to print both tasty and visually appealing sweets or food decorations using various kinds of food materials including sugar, chocolate and cheese. Complex structures such as interlocking sweets, various sugar sculptures and entire wedding cakes have been created using this system. Moreover, the ChefJet Pro equipped with four print heads was able to create multi-color structure, such as multi-color cocktail decorations (iReviews, 2014). Several examples of 3D customized sweets are shown in Fig. 8.

The GumLab project established by two London-based students, invented a GumJet 3D printer to print an appealing chewing gum. The extrusion based printer equipped with a Cartesian platform was able to print gum resin along with flavoring layer by layer (Krassenstein, 2015). Wacker has designed a chewing gum 3D printer, which could create gum with fruit juice, coconut and plant extracts thus allowing the production of gum with different mouth feel and flavor. In addition, Wacker also invented a new method called Candy2Gum to turn existing candy into gum. This technology can handle water-based and fat-containing ingredients while the traditional dry kneading method cannot (Corey, 2016).

4 Some proposals

3D food printing is an emerging technology in food sector, we emphasize that the aspects as shown below should be kept in mind to achieve a successful printing.

Rheological properties of food materials is important to improve the printing performance and self-supporting ability in extrusion-based printing. The food material for extrusion printing should be pseudoplastic fluids with suitable shear-thinning behavior and rapid structural recovery ability as it can be easily extruded out from the nozzle with the application of shear force and solidify rapidly again after leaving the nozzle. τ_0 and G′ are critical to the self-supporting ability, and *K*, *n* play an important role in extrudability and printability. A good balance must be made so that the mixture is as strong as possible to maintain the printed shape while still could be printable and capable of adhering to previously deposited layers (Liu, Zhang, Bhandari, & Yang, 2017). We emphasize that the rheological properties are critical to a successful extrusion printing.

The material's binding mechanisms and thermodynamic properties like Tm and Tg are important to a successful extrusion-based printing. Various kinds of additives can be added to achieve desired rheological properties. Thus, the binding mechanisms, such solidification upon cooling, cross-linking mechanisms, gel properties under different conditions (such as pH, ion, time, etc.) should be investigated to achieve desired properties suitable for 3D printing. Some additives like fat, blood plasma protein can be added to adjust the thermodynamic properties of material. The correlation between printing temperature and printing performance should be studied based on material's thermodynamic properties.

As pre-treatment methods (ultrasound, radio frequency, etc) and post-processing methods (drying, cooking, frying, etc) affect the gel formation mechanisms and the stability of printed objects, the impact of pre-treatment and post-processing methods should be studied, so as to determine the most suitable pre-treatment and post-processing method.

5 Challenges and trends

Recently, great efforts have been put by researchers aiming at applying 3D food printing into food industry. However, there are still many difficulties for this technology to be widely used in food sector due to several reasons 1) printing precision and accuracy 2) process productivity 3) production of colorful, multi-flavor, multi-structure products.

Printing precision and accuracy are critical to the application of 3D printing technology in food sector. One of the advantages of 3D printing is to fabricate an exquisite and fascinating structure of edible products to increase consumer's interesting and appetite. However, currently few works focused on printing accuracy are published. To achieve a precise and accurate printing, material properties (i.e. rheological properties, particle size, etc), process parameters (i.e. nozzle diameter, printing speed, printing distance, etc), and post-processing methods (i.e. baking, frying, cooking, etc) should be kept in mind. More efforts should be given in the achievement of precise and accurate printing.

Improving production efficiency can reduce production costs. A common example of enhancing process productivity is to increase the printing speed and to use large nozzle or laser diameter. However, this often leads the reduction of precision and resolution of printed objects, thus placing 3D food printing in an unfavorable circumstance. We emphasize that under the premise of ensuring acceptable printing accuracy, a large nozzle diameter and fast printing speed should be adopted. Another potential way to improve printing productivity is to use multi-nozzle printers to fabricate multiple objects simultaneously. However, this will surely increase the complexity of control system and technical challenge, thus it is necessary to carry out considerable studies to achieve both accurate printing and high process productivity.

As the color, flavor, and texture of food are critical to the experience of people, it is necessary to fabricate a 3D edible structure with these desired attributes. Several attempts have been made in the production of colorful, varying flavor and texture of food products using 3D printing technology (Hasseln, 2013; Hasseln, Hasseln, & Williams, 2014; Von, Von, Williams, & Gale, 2015a), but they have not been widely applied. Thus, more attention should be given to the production of varying color, flavor and texture food products.

Conclusion

3D food printing has several great advantages, such as customized food designs, personalized nutrition, simplifying supply chain, and broadening of the available food material. 3D printing has been recently investigated in food sector. However, few studies have focused on how to achieve an accurate and precise printing. Material properties, process parameters, and post-processing treatments are three main aspects affecting the printing precision and accuracy, which should be kept in mind in order to produce a delicate and complex edible structures. 3D printing has been applied in food areas such as military and space food, elderly food, sweets food, and chewing gum. Though the investigation of 3D food printing has been expanding at the moment, there are still a few challenges that need to be addressed such as printing precision and accuracy, printing speed and production of food with multiple quality and nutritional attributes. Wider application of 3D food printing are expected once these challenges are overcome.

Acknowledgments

The authors acknowledge the financial support from the China State Key Laboratory of Food Science and Technology Innovation Project (Contract No. SKLF-ZZA-201706), Jiangsu Province (China) “Collaborative Innovation Center for Food Safety and Quality Control” Industry Development Program, Jiangsu Province (China) Infrastructure Project (Contract No. BM2014051), which have enabled us to carry out this study.

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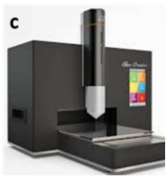
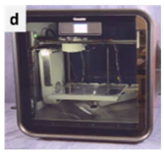
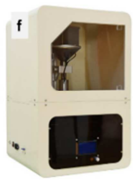
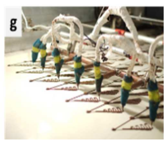
Tab.1 Comparison of different 3D food technologies

		Extrusion based printing	Selective laser sintering	Binder jetting	Inkjet printing
	Available material	Chocolate, soft-material such as dough, cheese, meat puree	Powdered materials such as sugar, chocolate, fat	Liquid binder and powdered materials such as starch, sugar, protein	Low viscosity material such as pizza sauce
Factors affecting printing precision	Material properties	Rheological properties, mechanical strength, Tg	Melting temperature, flowability, particle size, wettability, Tg	Flowability, particle size, wettability and binder's viscosity and surface tension	Compatibility, ink rheological properties, surface properties
	Processing factors	Printing height, nozzle diameter, printing rate, nozzle movement rate	Laser types, laser power, laser energy density, scanning speed, laser spot diameter, laser thickness	Head types, printing rate, nozzle diameter, layer thickness	Temperature, printing rate, nozzle diameter, printing height
	Post processing	Additive, recipe control	Removal of excess parts	Heating, baking, surface coating, removal of excess parts	No
	Advantages	More material choices, simple device	Complex 3D food fabrication, varying textures	Complex 3D food fabrication, full color potential, varying flavors and textures	More material choices, better printing quality, fast fabrication
	Limitations	Incapable of fabricating of complex food designs, difficult to hold 3D structures in post-processing	Limited materials, less nutritious products	Limited material, less nutritious products	Simple food design, only for surface filling or image decoration
	Products				

*The products images were reproduced from website: (a) Natural Machines Co., available at https://www.naturalmachines.com/ (b) TNO (Linden, 2015) (c) 3D Systems Co., available at https://www.3dsystems.com/culinary/gallery (d) FoodJet Printing Systems, available at http://www.foodjet.com/

Tab.2 Comparison of different sweets printing machines

Company	CandyFab Project	3D Systems	Choc Edge	3D Systems	3DCloud	Porimy	Fouche Chocolates
Machine	CandyFab-6000	ChefJet	Choc Creator	CocoJet	QiaoKe	3D Food Printer	Fouche Chocolate printer
Materials	Sugar	Chocolate, sugar, starch, protein	Chocolate	Chocolate	Chocolate	Chocolate, soft-material	Chocolate
Technology	Selective laser sintering	Binder jetting	Extrusion based printing	Extrusion based printing	Extrusion based printing	Extrusion based printing	Extrusion based printing
Machine image							

*The machine images were reproduced from website: (a) CandyFab Poject (CandyFab, 2007) (b) 3D Systems Co., available at https://www.3dsystems.com/culinary/gallery (c) ChocEdge Co., available at http://chocedge.com/ (d) 3D Systems Co., available at http://www.3dsystems.com/de/node/7563 (e) 3DCloud Co., available at http://www.3ders.org/articles/20150811-china-3dcloud-unveils-new-qiaoke-chocolate-3d-printer-with-a-unique-solid-feed-system.html (f) KunShan Porimy Co., available at http://www.porimy.com/product.asp?plt=370 (g) Fouche Chocolates, available at http://www.3ders.org/articles/20140102-south-africas-3d-printed-chocolate-factory.html

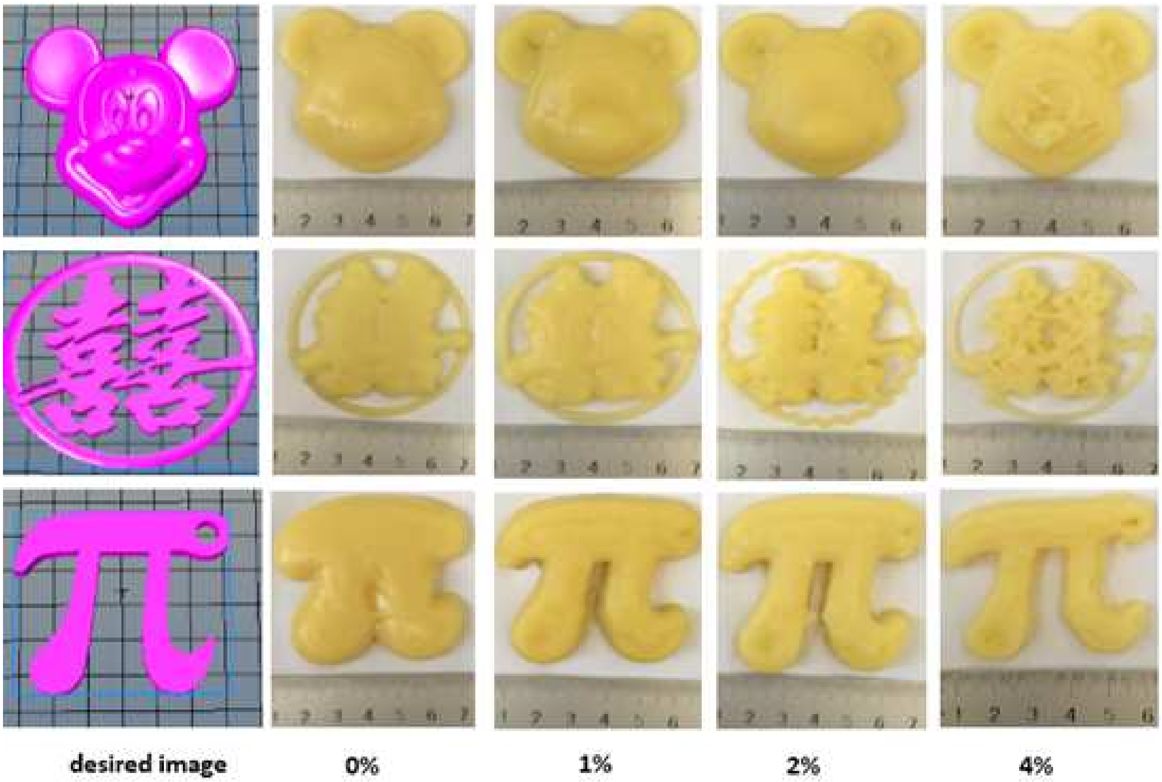


Fig. 1 Desired images and printed objects using mashed potatoes with addition of different concentrations of potato starch (Liu et al, 2017)

Fig. 2 Printed objects using mashed potatoes (our research group)

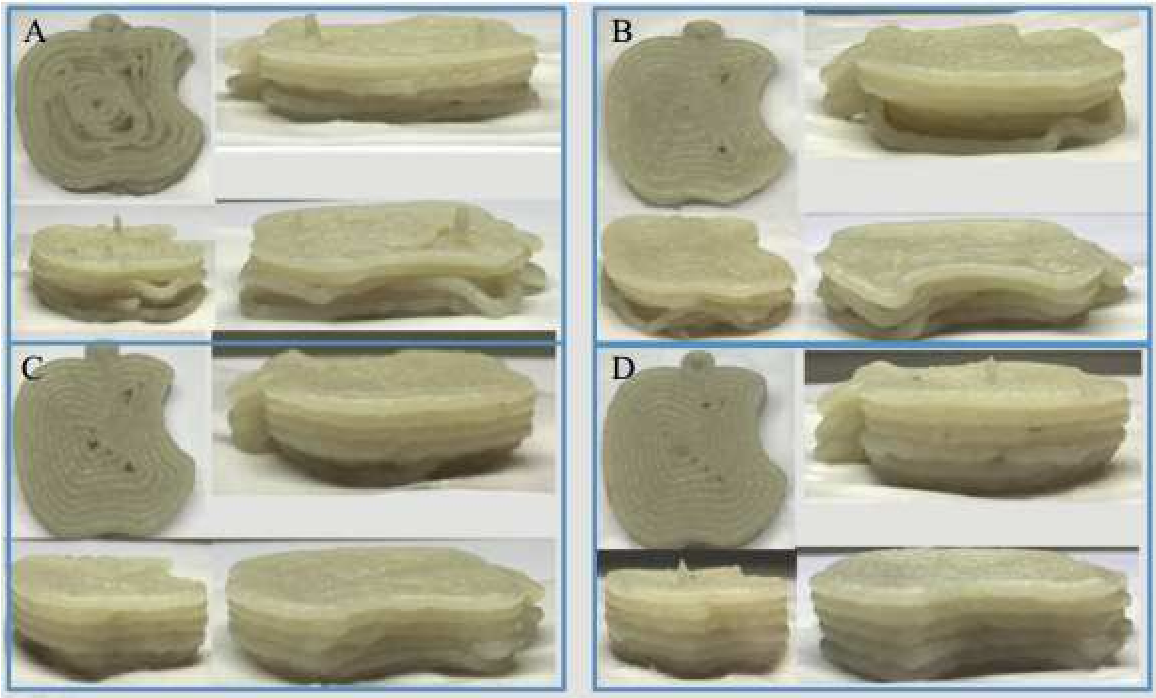


Fig.3 Different geometrical shapes of 3D printed surimi gel samples by the addition of three different levels of NaCl (A=Control, B=0.5 g/100 g, C=1.0 g/100 g, D=1.5 g/100 g).Extrusion parameters are nozzle diameter 2.0 mm, nozzle height 5.0 mm, nozzle moving speed 28 mm/s and extrusion rate 0.003 cm^3/s (Wang et al., 2017).

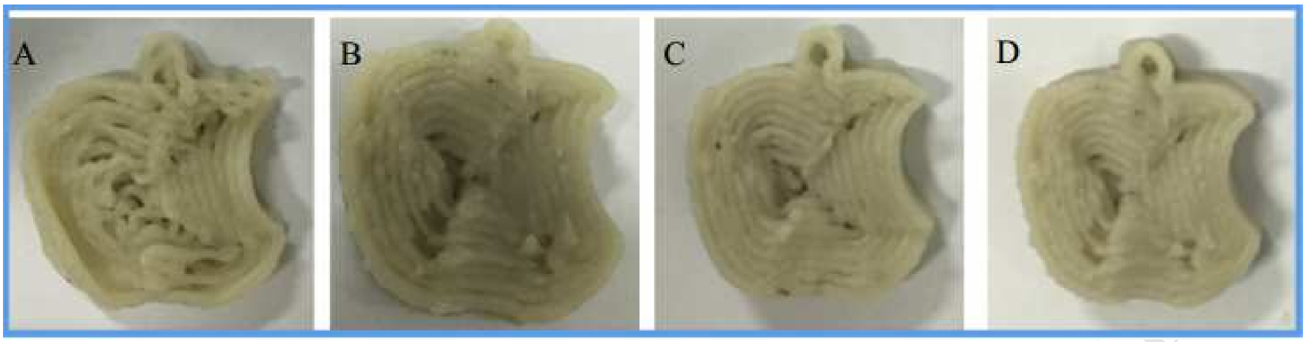


Fig. 4. Geometry shape of printed surimi gel samples (NaCl content 1.5 g/100 g) with different nozzle moving speed (A=20, B=24, C=28, D=32 mm/s). Other extrusion parameters are nozzle diameter 2.0 mm, nozzle height 5.0 mm and extrusion rate 0.003 cm^3/s (Wang et al., 2017).

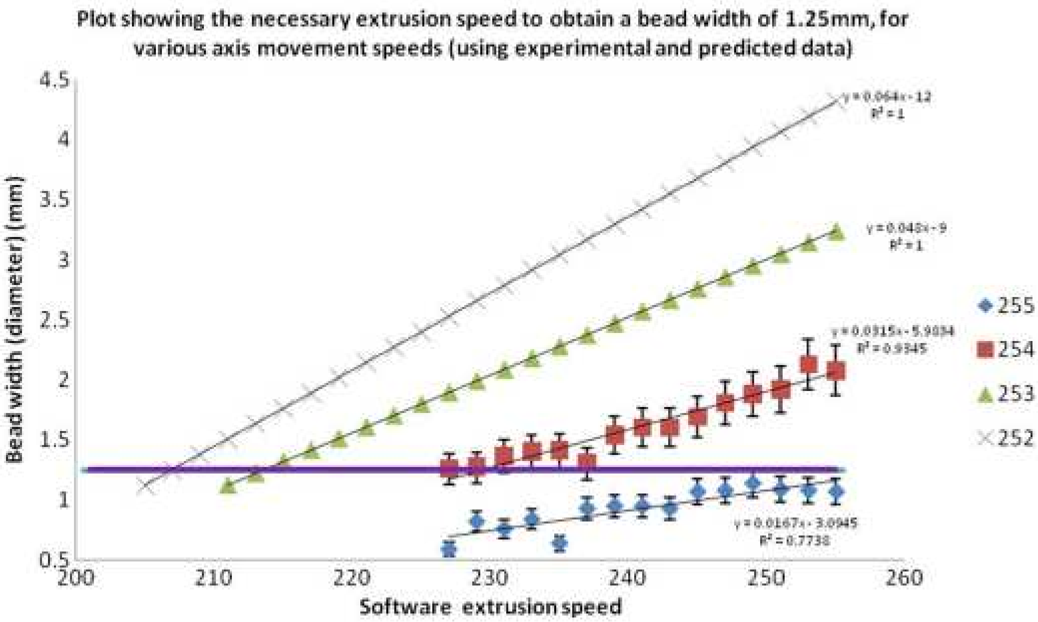


Fig. 5 Relationship between software extrusion rate and resulting bead diameter in chocolate printing (Hao et al., 2010)

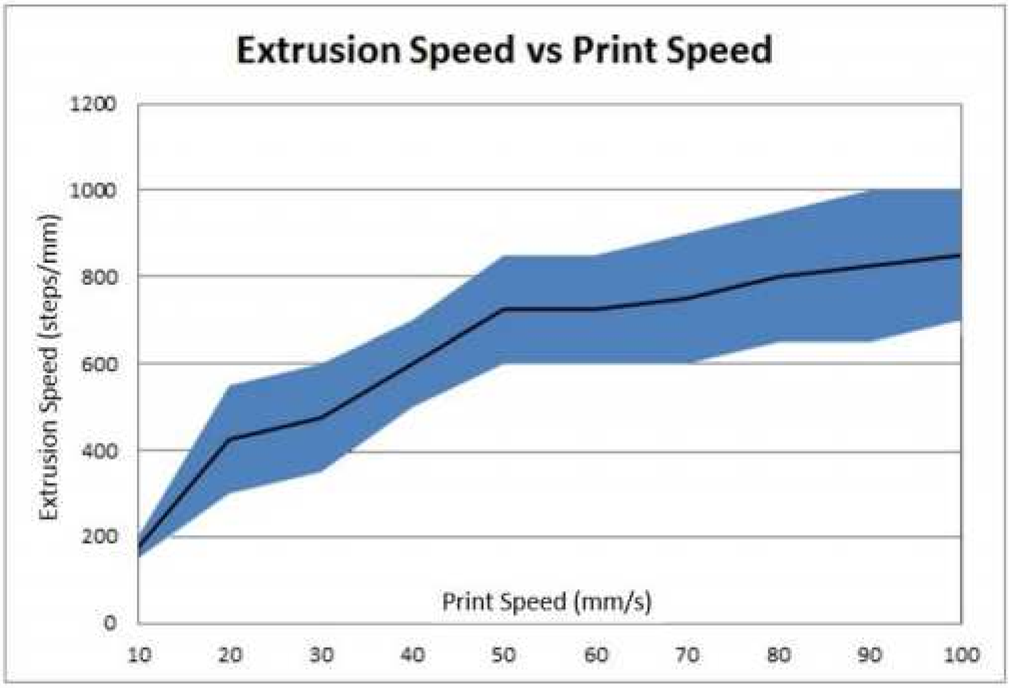


Fig. 6 Graph of the relationship of extrusion speed and print speed in cookie printing (Zhuo, 2015)

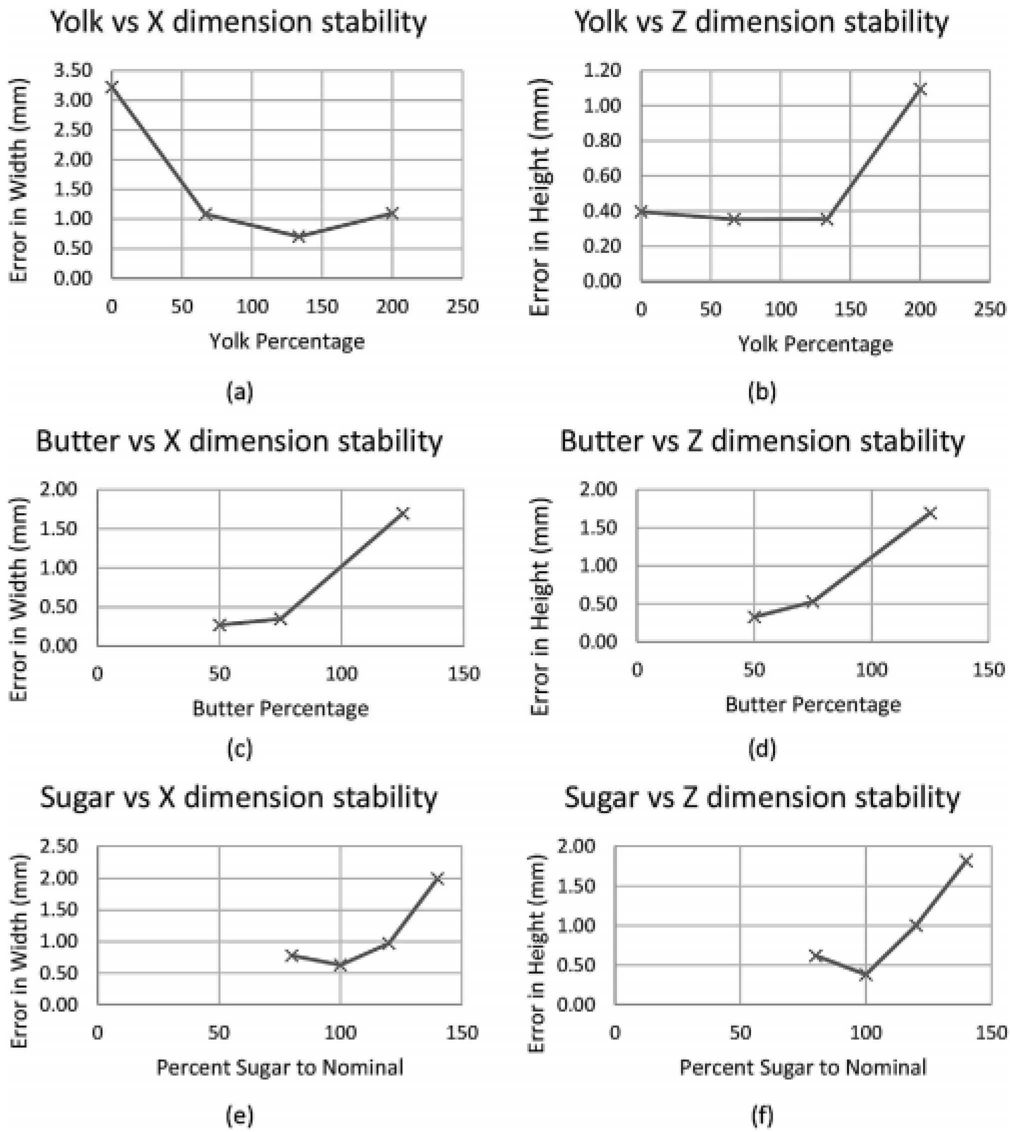


Fig. 7. Variations in the amount of butter, yolk, and sugar relative to the nominal cookie recipe effect the shape stability. Yolk concentration can improve stability in the X direction (in the plane of the backing pan) at the expense of stability in the Z direction (height). This creates a narrow band, between two thirds and one and a third normal, where yolk concentration can be varied and still printed. For each data point, ten cubes were made and measured in 3 places along the X and Z directions (Lipton et al., 2010)

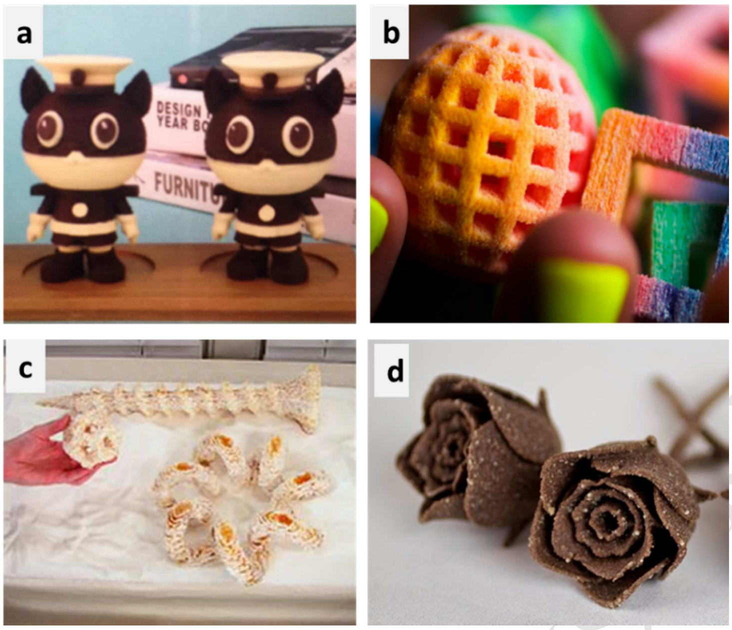


Fig. 8 Examples of customized sweets reproduced from website: (a) chocolate “Mr. Black”, KunShan Porimy Co., available at http://www.porimy.com/product.asp?plt=370 (b) colorful sweets, 3D Systems Co., available at https://www.3dsystems.com/culinary/gallery (b) sugar structures, CandyFab Project (CandyFab, 2007) (d) chocolate rose, 3D Systems Co., available at https://www.3dsystems.com/culinary/gallery

3D printing: printing precision and application in food sector

Highlights

- Factors affecting 3D food printing precision were discussed.
- Applications of 3D printing in food sector were reviewed.
- Challenges to 3D food printing were proposed.