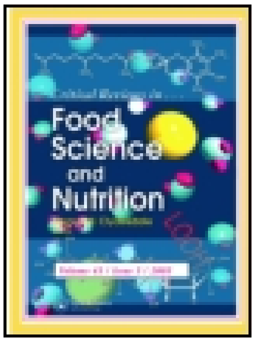

Critical Reviews in Food Science and Nutrition

ISSN: 1040-8398 (Print) 1549-7852 (Online) Journal homepage: http://www.tandfonline.com/loi/bfsn20

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CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
https://doi.org/10.1080/10408398.2018.1514363

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REVIEW

3D food printing: main components selection by considering rheological properties

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ABSTRACT

3D printing, also referred to as additive manufacturing, offers a wide range of new processing possibilities to the food industry. This technology allows a layer by layer (bottom to top) printing of predefined slices of designed and desired objects. 3D printing potentially allows rapid manufacturing of complex objects, which are unhindered by design complexity, thus providing substantial liberty to create new and untested geometric shapes. In terms of food manufacturing, the potential that 3D food printing technologies can bring may revolutionize certain aspects of food manufacturing, providing the convenience of low-cost customized fabrication and even tailored nutrition control. The most common materials suitable for 3D food printing are carbohydrate, fat, protein, fiber and functional components. In the present study, the characteristics of raw materials or additives used during 3D printing, and requirements for estimating and improving their printing performance and self-supporting ability in extrusion-based printing regarding rheological characteristics of 3D food printing materials are reviewed. As an innovative process, 3D food printing may induce a revolution in certain areas of food manufacturing.

KEYWORDS
3D printing; food; rheological properties; components; manufacturing

Introduction

3D printing refers to processes in which material(s) is/are joined or solidified under computer control to create a 3D object. It is also known as additive manufacturing (AM), and defined as a technology, which is controlled using computer-aided design (CAD) software and instructs a digital fabricating machine to shape 3D objects by successive addition of material layers (Lupton and Turner 2016). The most early additive manufacturing equipment and materials were developed in the 1980s by Hideo Kodama (1981) of Nagoya Municipal Industrial Research Institute, who invented two additive methods for fabricating 3D plastic models. In 1984, Chuck Hull of 3D Systems Corporation filed his own patent for a stereolithography fabrication system, in which photopolymer layers were added, and followed by curing with ultraviolet light lasers (Lipson and Kurman 2013). In 1992, Scott Crump and his company, Stratasys, invented and commercialized its first fused deposition modeling machine (Lipson and Kurman 2013). After one year, Massachusetts Institute of Technology invented the first “Inkjet printing” 3D printing equipment, which was commercialized by Soligen Technologies (Yang, Zhang, and Bhandari 2017). Decades later, 3D printing was beginning to demonstrate great potential and in some cases flourish in areas, such as medical science, manufacturing, aerospace, clothing, socio-cultural sectors and also foods (Table 1).

3D printing allows a layer by layer (bottom to top) printing of predefined slices of the designed and desired objects (Ivanova, Williams, and Campbell 2013). This new technology results in fast manufacturing of complicated objects, especially unhindered by design complexity, thus providing substantially potential in new and untested geometric designs (Kalsoom, Nesterenkoa, and Paull 2016). As previously described, 3D printing allows the construction of predesigned and sometimes complex objects in a layer by layer fashion (Ivanova, Williams, and Campbell 2013) providing the industry with new manufacturing methods for established companies and new possibilities for do-it-yourself commodities. With such the techniques we can process a wide range of products, including human skeleton (cranium) (Perry 2014), house, aircraft engine parts, football shoes, firearms, or foods for elderly, children, astronauts and athletes (Simmons 2015; Feng, Zhang, and Bhandari 2018). Late coming to the technology may do much of their own equipment manufacturing rather than engage purchasing off the shelf products. It was possibly for this reason that the futurologist Jeremy Rifkin claimed that 3D printing signaled the beginning of the third industrial revolution (Rifkin 2012).

The earliest evidence relating to 3D printing of food was a U.S. patent (Yang, Wu, and Liu 2000). 7 years later, Prof. Hod Lipson and his colleagues from Cornell University also reported the utilization of 3D food printing in 18th Solid Freeform Fabrication Symposium (Periard et al. 2007). At

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Table 1. Comparison of main kinds of 3D printers.

Type	Description	Materials
Fused deposition modeling	Producing by extruding small beads or streams of materials that harden immediately to form layers	Polycarbonate (Salazar-Martín et al. 2018), sodium caseinate (Schutyser et al. 2018), acrylonitrile butadiene styrene (ABS) (Gautam, Idapalapati, and Feih 2018), dough, mashed potatoes, and cheese (Yang, Zhang, and Bhandari 2017, Yang, Zhang, Fang, et al. 2018)
Selective laser sintering	Completely melting the powder using a high-energy laser to create fully dense materials in a layer-wise method that has mechanical properties similar to those of conventional manufactured metals	Porcelain (Danezan et al. 2018), nylon (Yan et al. 2017), polystyrene (Sun et al. 2017), sugar, and chocolate powder (Liu et al. 2017).
Binder jetting	Applying liquid binder to the selective areas of a spread layer of powder material	Stainless Steel powder (Miyanaji, Momenzadeh, and Yang 2018a), titanium alloy (Miyanaji, Momenzadeh, and Yang 2018b), copper (Kumar et al. 2017), tungsten carbide (Enneti et al. 2018), sugar powder (Liu et al. 2017)
Inkjet printing	Using pneumatic membrane nozzle-jets to deposit drops onto a moving object to form an appealing surface	Carbon nanotube (Eshkalak et al. 2017), silver nanoparticle (Vaithilingam et al. 2018), pharmaceutical (Edinger et al. 2018), and sauce (Liu et al. 2017)

the present time, 3D printing of edible items has become an area of great interest to many organizations. As proposed by Lipton et al. (2015), many of these organizations view 3D food printing as having two key strengths, geometric complexity and economy efficiency at low production volumes. The potential for the creation of objects with geometric complexity allows for the generation of intricate 3D shapes, which can be used for artistic presentations and complex textures. Many researchers are extending the idea of developing by squeezing out food, layer by layer, into three-dimensional objects. A large variety of foods are suitable for printing, with current successes cases, including chocolate, cake, cookie, ice-cream and hard candy (Figure 1). In addition to 3D food printing's ability to produce items in small batches, it allows customization, not only of shapes but also of compositions. This potential opens the possibility of adapting the content of a food to an individual's health and activity level as well as their personal taste preferences, and offers new opportunities for companies to instantly manufacture customized foods at the point of sale and in a cost efficient manner.

Indeed, in the area of food product design and production, 3D printing represents a technology with immense potential and provides low cost, simple and rapid prototyping advantages over traditional methods for the fabrication of food materials and objects. However, a fact that must be faced is that some food materials do not lend themselves as suitable for 3D printing since their structural stability is weak, or alternatively it is difficult to integrate the different components into each other or the printed food itself proves difficult to cook in kitchen. The company may feel challenged by difficulties associated with the fabrication of traditional food by 3D printing as the intrinsic characteristics, such as mouth feel and flavor, may not live up to consumer expectations. Another problem is how to avoid the impact of variability in raw material composition or suitability for processing by printing. Generally in the overall field of food science, challenges but also opportunities coexist when it comes to 3D printing of food.

Knowledge of the rheological properties of food materials is important to estimate and necessary to improve their printing performance and self-supporting ability for use in extrusion-based printing. Food materials for extrusion printing should be pseudoplastic fluids with suitable shear-thinning behavior and be easily extruded from the printer nozzle under an appropriate shear force and be capable of rapid structural recovery solidification following extrusion. To predict the effect of extrusion through the nozzle, rheological properties, including yield stress ($\tau 0$), storage modulus (G'), loss modulus (G'') flaw behaviour index (K) and flow characteristic index (n), are commonly used, while $\tau 0$ and G' are a critical indicator of the ability of the matrix to self-support while K and n play an important role in extrudability and printability. A good balance must be made to ensure that the printed object is as strong as possible and will maintain its printed shape while still printable and capable of adhering to previously deposited layers (Liu, Zhang, Bhandari, et al. 2018).

To improve the quality of 3D printed food, exogenous substances are often added to the carbohydrate, fat, protein and fiber raw materials to enhance their processability, aroma, nutritive value or storability (pre and/or post printing). The primary aim of this review is to analyze the impact of a change in raw material composition during 3D printing and explore the effect of the carbohydrate, fat, protein and fiber composition on 3D printing of food while also proposing future trends and recommendations for further implementations of 3D printing in the food industry.

Essential constituents and feasibility of food components for 3D printing

Carbohydrate

In the context of printing, extrusion through the printing nozzle is the action of forcing mouldable materials through a die opening to create objects with desired cross sections based on their deposition and post extrusion fusion with their geometry determined by appropriate modeling methods. Syringe screw and air pressure are the most common parameters to force the raw materials through the extruder die (Figure 2). The ideal end result of extrusion-based 3D food printing is to achieve a comparable or superior

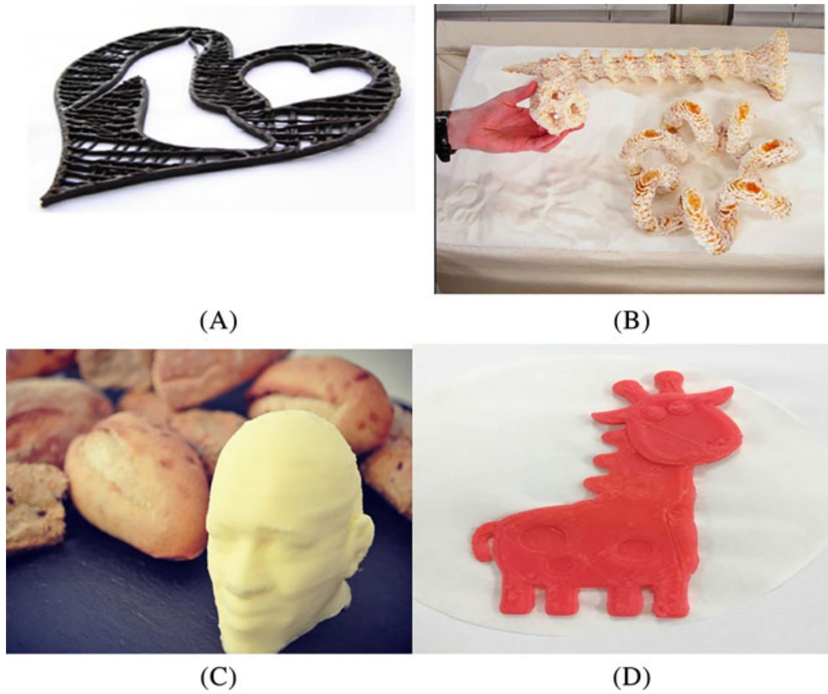

Figure 1. Various 3D printed food (A) Chocolate (Lipton et al. 2015), (B) dough, available at https://candyfab.org/#intro, (C) mashed potato available at https://www.naturalmachines.com/, and (D) starch gel (made by author's lab-mates).

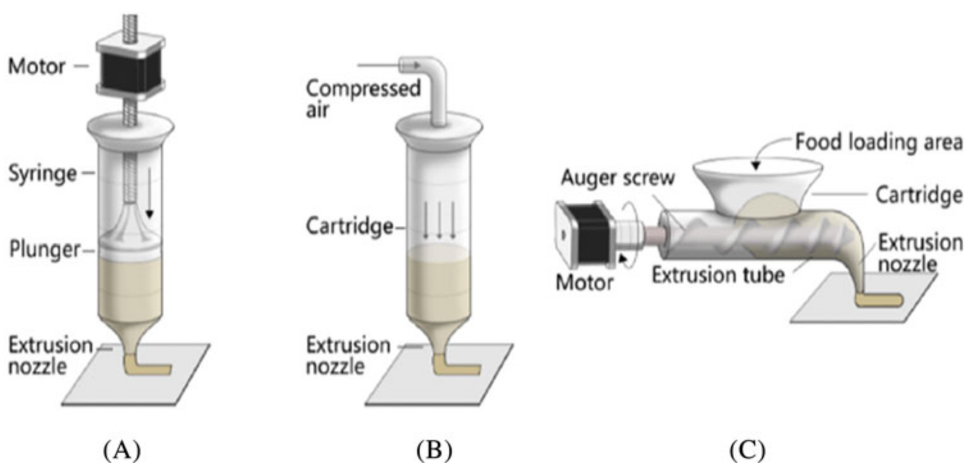

Figure 2. Extrusion mechanisms: A. Syringe-based extrusion, B. Air pressure driven extrusion, and C. Screw-based extrusion (Sun et al. 2018).

geometric output to that attainable with conventional food extrusion processing but with this output obtained through digitalized design while also incorporating personalized nutrition control (Sun et al. 2018). Single or multi nozzles can be used to hierarchically print products to meet consumer demands generating unique tastes, extrinsic features and tailored nutritional profiles. Extrusion 3D printing is suitable for producing carbohydrate based food, such as bread, pizza and cookies. Work from Cornell University (Lipton et al. 2010) reported customized cookies made by additive manufacturing technologies and illustrated the probability in 3D printed baking, slow cooking, frying, etc. Zoran and Coelho (2011) presented a new concept of digital gastronomy pasta produced by 3D printing technology. Van der Linden (2015) from TNO summarized the mass of samples based on 3D printed food (Figure 3). A company called Natural Machines® created an air pressure driven 3D printer for baking materials such as customized pizza and cookies (Natural Machines 2016). BeeHex® used a commercial 3D printer (air pressure with multi nozzles) to process customized pizza (BeeHex 2016). These examples have proven the potential of high precision and industrialization in carbohydrate based 3D food printing (Figure 4).

The food materials should be flowable (liquid or powder) during extrusion and also support its structure during or after the extrusion. Flowability can be achieved by plasticization and melting. However, the subsequent self-supporting structure is achieved by dehydration or gelation under a controlled temperature regime and/or through the inclusion of appropriate additives (Godoi, Prakash, and Bhandari 2016). Additives including starches, polysaccharides or proteins have a definite effect on melting behavior, glassy state and plasticization of the food-materials during liquid- and

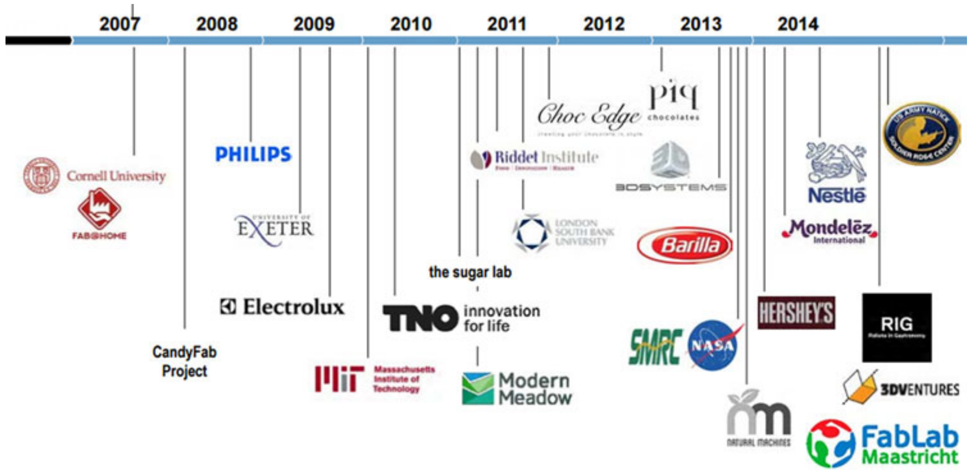

Figure 3. Development track of 3D food printing (van der Linden, 2015).

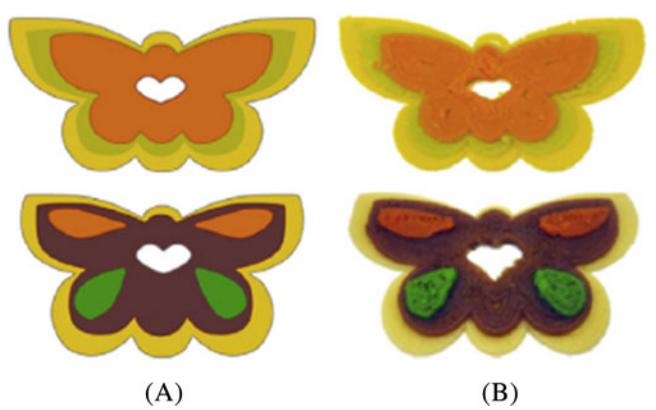

Figure 4. Food design and fabrication samples with A for 3D model and B for actual printed cookies (Sun et al. 2018).

powder-based 3D printing processes (Bhandari and Howes 1999).

One of the most successful materials for 3D food printing is dough (with or without additives) as judged by its consistency, rheology and solidifying properties following printing. Yang, Zhang, Fang, et al. (2018) studied the physical properties of 3D printed dough and the influence of variation in the composition of the raw material. These works used the rheological characteristics to calculate the product qualities. From the data they obtained they concluded that the flow behavior and viscous modulus of a dough affect its extruding action, while its elastic modulus, gel strength, rupture strength and adhesiveness influence its ability to support the 3D structures or subsequently maintain the shape of structure of the initially printed products. The rheological characteristics indicated that dough can be easily extruded because of its pseudoplastic behavior with its viscosity decreasing as the shear rate increases. They also found that the storage modulus was higher than the loss modulus in the linear viscoelastic range assessed, suggesting the potential to form an elastic gel or gel-like structure and an enhanced structural strength following 3D printing. Many treatments to alter the rheological properties of materials are also showing the influences on 3D printing. For instance, the level of added polysaccharose, such as flaxseed gum, basil seed gum, xanthan or guar gum (Ahmed and Thomas 2018; Israr et al. 2018; Martin-Alfonso et al. 2018) can raise the apparent viscosity of the raw material, which made the extruded product harder and the gum–material mixtures showed gel-like behavior since the storage modulus was much larger than the loss modulus. As the storage and loss modulus of the gum–starch mixtures was increased by increasing the concentration of flaxseed gum, the results suggest that gum may ultimately reinforce the structural strength of 3D printed products. Even if two kinds of flour are mixed or sucrose is added, this can also alter the rheological properties of the raw materials and promote the gel microstructure stability, which altered the subsequent properties of the 3D printed products (Moreira, Chenlo, and Torres 2013; Yang, Zhang, Prakash, et al. 2018). Martínez, Oliete, and Gómez (2013) investigated the effect of addition of expanded wheat flour on dough evaluated by a rapid viscosity analyzer. It was found that adding expanded flours decreased dough extensibility but increased in dough plasticity. These characteristics are good for forming sharp geometric 3D printed objects.

Be an emerging food processing method, it is important to develop more 3D food printing compatible materials. Quantifying the printability of a material remains a challenge as this parameter is influenced by several factors, such as raw material temperature, composition, inclusion of stabilizing additives and so on (Lipton et al. 2010). Kim, Bae, and Park (2018) compared the 3D printability of 8 hydrocolloids, of which agar, guar gum, locus bean gum, xanthan gum and gellan gum can be classified as carbohydrate. The conclusion of their work is summarized in Table 2. In their tests, the Methylcellulose was selected as a suitable reference material for its capability to simulate the printability of various types of food applications. Other materials were categorized into grades A, B, C, and D according to the dimensional stability and degree of handling compared with Methylcellulose. The rheological properties of mashed potatoes with the addition of potato starch and its impact on their 3D printing behavior were investigated by Liu, Zhang, Bhandari, et al. (2018). They found that mashed potato with 2% added potato starch displayed excellent extrudability and printability. Under such conditions, the printed objects possessed smooth shape, good resolution and could maintain

Table 2. Mean values (±standard deviations) of the TPA parameters of the hydrocolloids produced with various concentrations (8%, 10%, and 12%) (Kim, Bae, and Park 2018).

Hydrocolloids Texture	Concentrations (%)	Texture attributes: Hardness (N)	Factorability (N)	Springiness (mm)	Suitability/reason
Gellan gum	8	68.64 ± 7.86	68.46 ± 11.59	1.00 ± 0.08	Unsuitable/Factor-ability observed
	10	84.99 ± 7.37	86.05 ± 8.91	1.19 ± 0.15	
	12	76.79 ± 3.60	79.60 ± 11.69	1.15 ± 0.28	
Guar gum	8	5.76 ± 0.24	–	0.96 ± 0.00	Considerable/Wide gel strength range
	10	7.85 ± 0.46	–	0.95 ± 0.02	
	12	11.47 ± 1.20	–	0.95 ± 0.04	
Locus bean gum	8	3.39 ± 0.56	–	0.93 ± 0.00	Low suitability/Narrow gel strength range, high springiness
	10	6.02 ± 0.93	–	0.92 ± 0.00	
	12	8.73 ± 0.31	–	0.90 ± 0.03	
Xanthan gum	8	1.96 ± 0.29	–	0.88 ± 0.00	Considerable/Low springiness
	10	2.21 ± 0.17	–	0.87 ± 0.00	
	12	2.72 ± 0.13	–	0.87 ± 0.00	
Agro	8	5.62 ± 0.22	5.18 ± 0.34	0.79 ± 0.01	Unsuitable/Factorability observed
	10	6.43 ± 0.17	7.10 ± 0.34	0.97 ± 0.03	
	12	10.55 ± 0.84	12.15 ± 0.45	0.99 ± 0.02	

Table 3. Typical chocolate 3D printing based technologies.

Inventor	Source	Technology
Hao et al. (2010)	Proceeding	Fused deposition modeling
Grood and Grood (2009)	Patent	Ink Jet Printing
Diaz, Noort, and Van (2015)	Patent	Binder jetting
3D Systems®	Commercial products	Binder jetting
Choc Edge®	Commercial products	Fused deposition modeling
Fouche Chocolates®	Commercial products	Fused deposition modeling
Porimy®	Commercial products	Fused deposition modeling
3D Cloud®	Commercial products	Fused deposition modeling
Shinnove®	Commercial products	Fused deposition modeling

that shape following printing. Holland et al. (2018) used xanthan gum as a glue to agglutinate the cellulose. Food inks based on xanthan gum have been formulated to enable successful jetting onto amorphous cellulose powder using a FujiFilm® Dimatix ink jet printer. Although the products were coarse, they still provided evidence to suggest the potential to manufacture food using 3D inkjet printing, which was prone to popularize 3D food printing.

Fat

Fat, or lipid, which are often referred to triglycerides, are one of the three main macronutrients, along with carbohydrate and protein and is formed by the esterification of three fatty acid molecules (long, straight chain carboxylic acids) along with a glycerol molecule to yield a triglyceride. However, adding the triglyceride composition and structure can affect the mixtures formulation for 3D printing technology and consequently, the functional properties of the end product material, including its melting point range, solid fat index, and crystal structure (Godoi, Prakash, and Bhandari 2016). For instance, fatty acids with a larger number of carbon atoms generally have a higher melting point. As the saturation of fat also influences the material characteristics, saturated fats have more desirable physical properties, and they melt at a desirable temperature (30-40 °C) and are stable during storage. Therefore, the composition of triglyceride in the raw material can help to regulate the melting point of the deposited layers and ultimately determine their self-supporting properties pre- and post-processing. This is of particular importance in the melting of extrusion-based 3D printing materials, which are melted upon application of heating and solidified by cooling.

Chocolate is a good material for extrusion-based 3D printing as the cocoa butter (the main structuring material in chocolate) can be easily melted and form the self-supporting layers upon cooling. Many companies have developed 3D chocolate printing machines (Table 3). The excellent mechanical properties of chocolate also allow chocolate form a complex but stable structure (Figure 5). To optimize the technological conditions, Lanaro et al. (2017) evaluated the characteristics of a 3D printer with dark chocolate using a DSC (Differential Scanning Calorimeter) and a rheometer. These works found that the melting point of chocolate occurred between 29 and 31 °C while the solidification occurred between 23.5 and 31 °C. They found it was important to ensure that the temperature was kept above the solidification point of 30 °C and above a certain pressure as the chocolate is a shear thinning material with shear rates below 6 rad/s at temperatures from 32 to 40 °C. The rate of movement was shown to have the negligible effect on the formation of self-supporting layers and an extruded chocolate volume to translation speed ratio of 0.8–0.9 resulted in superior performance. They also figured out that it was important to fix a cooling accessory into the 3D printer that enabled the solidification of the extruded self-supporting layers, which were critical for producing complex 3D geometries. Mantihal et al. (2017) discussed how structure strength relied on the 3D modeling, demonstrating that the inclusion of support structures during the design of the 3D printable model played an important role on snap quality and self-support properties. Cross-supports were more effective than parallel-supports in creating more stable hexagonal shaped constructs, a phenomenon which was demonstrated by a snap force using a texture analyzer.

Rheological properties and polymorphic forms play important roles in the physical characteristics of the final chocolate products. Hao et al. (2010) studied the extrusion behavior of chocolate with 3D printing technology and the results indicated that the viscosities of the chocolate were relatively constant when the temperature was maintained

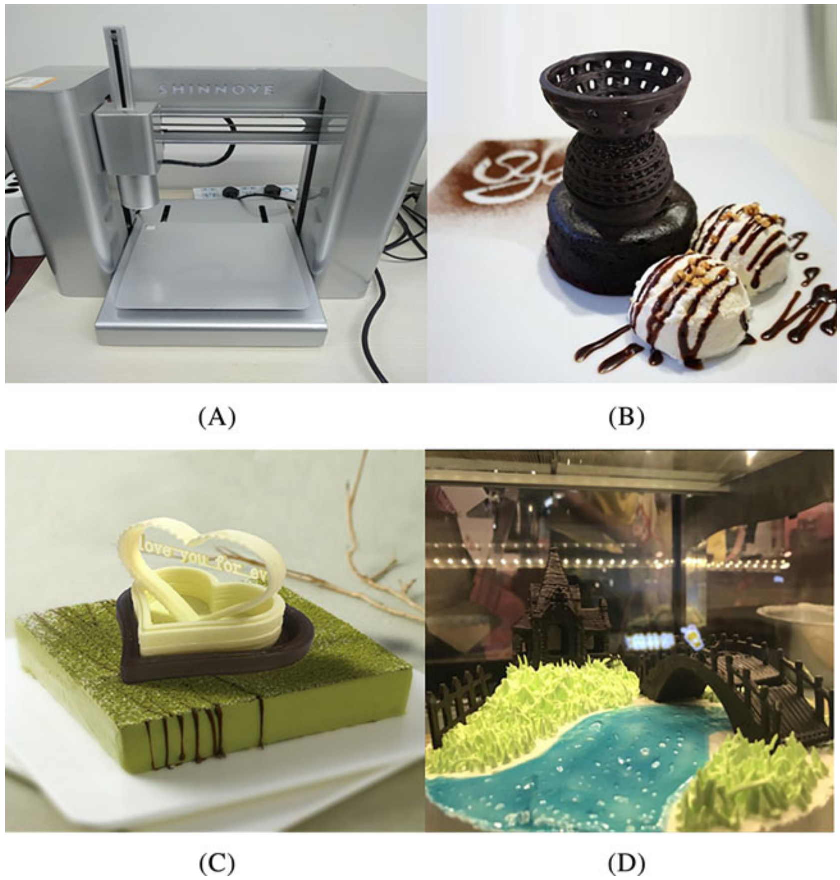

Figure 5. Abundant of 3D printed chocolate. A: Shinnove® S2 3D food printer, B, C, D: chocolate manufactured by Shinnove® S2 3D food printer (Lab made).

between 32 and 40 °C and the pressure was between 3.5 and 7.0 Pa, while higher temperatures and pressures made the chocolate difficult to shape. Chocolate with different components (milk, white and dark chocolate) displays different and printable characteristics. In particular changing the formulation to include different amounts of fat (from milk or cocoa butter) involves changes in the particle–particle interaction. The addition of fat and lecithin during processing, covering the sugar and cocoa particles, reduced interactions and caused a significant ($p < 0.05$) decrease in all rheological, textural and thermal parameters. Chocolate showed marked shear thinning behavior with yield stress from extrusion. Lower cocoa butter concentrations, in parallel with high solid particle fractions, such as in dark chocolate formulation, promote particle–particle interactions, leading in higher rheological characteristic values. On the other hand, higher amounts of cocoa butter, even if in presence of higher amounts of non-fat particles (such as sugar), together with milk fat (from milk powders), reduce resistance to flow. This effect was proven in white chocolate samples (higher milk and sugar), made up of smaller particles having the highest distance between chocolate particles. Dark chocolate samples presented the highest and significantly different textural parameter values of hardness and frangibility. These results were further confirmed when dark chocolate samples were characterized by a very aggregate and dense structure that offered more resistance to probe return during a back extrusion test. Milk and white chocolate samples showed the lowest consistency and cohesiveness values, suggesting the presence of a structure with weaker interactions between particles (Table 4) (Fernandes, Müller, and Sandoval 2013; Glicerina et al. 2013, 2015, 2016). These results also can be used on 3D printing that chocolate with less fat content would make printed products tough, stable but hard to extrude. Furthermore, there are six crystallizations which exist during chocolate melting to reforming. With repeated melting and reforming the crystal structure would alter. The crystallization of chocolate also had a relevant impact on its thermal properties, rheological behavior and the physical characteristics of the final products (self-supporting layers, gloss and blooming during storage) (Marangoni and McGauley 2003).

Table 4. Consistency and cohesiveness indexes of dark, milk and white chocolate samples (Glicerina et al. 2016).

Samples	Consistency (N s)	Cohesiveness (N)
Dark	110.14 ± 13.96a*	16.07 ± 1.25a
Milk	1.22 ± 0.16b	3.16 ± 0.53b
White	0.87 ± 0.06b	1.83 ± 0.37b

*Values (mean ± standard deviation) in the same column followed by different letters are significantly different at $p < 0.05$.

Using fat as the additive can also change the performances of materials. Yang, Zhang, Prakash, et al. (2018) found that a butter content of 6.0 g/100 g would make 3D printed dough with the most irregular shape since butter can restrict the gluten formed to increase the adhesiveness and modulus of elasticity, which offered better gel network microstructure in samples and is beneficial to shape retention. Besides, for the same shear rate the viscosity increased as the content of sucrose, butter and flour increased in the formulations. Moreover, at the same angle frequency, G' and G'' (storage modulus and loss modulus) continuously and significantly increased as the content of sucrose, butter and flour increased. Jacob and Leelavathi (2007) compared the characteristics of dough added with bakery fat and sunflower oil. They found that dough containing oil after cooking had relatively harder texture and probably because of the poor entrapment of air during creaming. Oppositely, dough with bakery fat offered products with soft texture.

3D printing also can be used in cheese printing. Tohic et al. (2018) studied an extrusion-based food 3D printing in conferring structural changes pre- and post-processing to a cheese product. After fabrication success, they considered that 3D printing of food offers many possibilities for customized nutrition, including exceptional flexibility in geometries, textures and flavors.

Protein

Proteins are large biomolecules, or macromolecules, consisting of one or more long chains of amino acid residues. Proteins perform a vast array of functions within organisms, including catalyzing metabolic reactions, DNA replication, responding to stimuli, and transporting molecules. Most microorganisms and plants can biosynthesize all 20 standard amino acids, while animals (including humans) must obtain some amino acids from their diet. The amino acids that an organism cannot synthesize on its own are referred to as essential amino acids. Except for some gum-like protein (gelatin, for instance), most protein cannot be used as a 3D printing raw material directly. Protein denaturation under external stress (temperature or mechanical strength) or compounds (e. g., strong acid or base) is good way to prepare 3D printing adapted raw material. To enhance the printable of proteins, the methods used can be summarized as (1) chemical cross-linking; (2) ionotropic cross-linking; (3) complex coacervate formation. However, chemical cross-linking is rarely to be applied in the food industry, as many cross-linking reagents are heavy metals and must be completely removed from food components before they are suitable for consumption by humans. Conversely, ionotropic cross-linking and complex coacervate formation have been widely applied by food industry, for instance in tofu structuring. These methods ensure protein form a gel-like structure and enhance its self-supporting strength (Godoi, Prakash, and Bhandari 2016). Furthermore, isoelectric deposition also can be used to form 3D printing materials. At the isoelectric point, proteins may show aggregation, which is a very attractive feature for liquid-based 3D printing processes ruled by the protein based-gelation and hydrogel-forming mechanisms. Intercalated deposition and enzymatic modification protein also can form a self-supporting structure. Protein can be deposited with polysaccharide materials (for example, alginate) in a layer by layer assembly under the certain conditions. This behavior can be explained by the fact that the trans-glutaminase catalyses the formation of covalent bonds between lysine and glutamine residues in a calcium dependent reaction. Hence, the proteins present in a meat puree were enzymatically cross-linked, and gave rise to self-supporting hydrogels (Zheng, Monty, and Linhardt 2015). All these examples show the potential of protein as a material for 3D printing.

Gelatin is derived from collagen obtained from various animal body parts. It is commonly used as a gelling agent in food. Gelatin exhibits Newtonian flow in dilute solution except when extended by charged groups, which makes it a potential candidate, which is suited for use as an ingredient in 3D printer inks (Pang et al. 2014). However, the data from Kim, Bae, and Park (2018) indicated that gelatin without additives shows poor self-support features as the sample had higher hardness and fracturability, which gave rise to flaws in the samples. Hence, the gelatin used in 3D extrusion processes must bear in mind that charges on the molecules give rise to relevant effects on viscosity. A change in pH in either direction alters the ionization of the functional groups and increases the preponderance of either positive or negative charges. The mutual repulsion of similar charges extends the molecule and enhances the viscosity of the system. Shear rate is another important factor affecting the flow of proteins like gelatin in extrusion processes. Irreversible reduction in viscosity can be observed upon the application of shear forces. Extreme conditions of very high shear rate may lead to a non-Newtonian behavior (Kragh 1961). Lille et al. (2018) used protein (milk powder, oat protein, concentrate, and faba bean protein concentrate), starch and cellulose nanofibre as the materials for extrusion-based 3D printing. They found that the best printing precision and shape stability was obtained with a semi-skimmed milk powder which was mixed with starch and cellulose nanofibre. Rheological measurements revealed that the shape stability after printing was linked with the yield stress of the paste. In stress sweep measurements, G' typically showed constant plateau values at small stress values. As described before, the G' in this plateau region is a measure of the elasticity of a material under very small deformations and can be taken as a measure of the structural strength or mechanical rigidity of a material at rest. The results showed that all samples had a structure which was elasticity dominated and gel-like structure ($G' > G''$, phase angle ($\tan(\delta) < 45°$). As phase angle $= G''/G'$, the standard value at phase angle $=45°$ is 1, a value for $\tan(\delta)$ greater than unity indicates more "liquid" properties, whereas one lower than unity means more "solid" properties, regardless of the viscosity (Metzger 2006). Wang et al. (2018) investigated the effect of NaCl addition on rheological properties of fish surimi gel prepared for 3D extrusion printing. The data obtained indicated that the surimi gels were pseudoplastic fluids which were shear-thinning. Furthermore, an increase in NaCl concentration led to a general decrease in viscosity, which would be helpful to allow the slurry to flow from the printer nozzle and then get viscous post-deposition thereby holding its shape. By analyzing the data from rheological studies on surimi gels showed that products made with 1.5 g NaCl/100 g surimi mixture can be the most suitable for 3D printing. NaCl addition was helpful for the slurry to flow out from the nozzle in time and then get viscous post-deposition for holding its shape. Rapisarda et al. (2018) redesigned the 3D printer to measure the gel characteristics, including strength, fracture and compression properties.

Dietary fiber

As the description of AACC (American Association of Cereal Chemists), dietary fiber consists of the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine, which undergoes complete or partial fermentation in the large intestine. It consists of non-starch polysaccharides, such as arabinoxylans, cellulose, and many other plant components (i.e. resistant starch, dextrins, inulin, lignin, chitins, pectins, beta-glucans, and oligosaccharides).

Dietary fibers are found in fruits, vegetables and whole grains and are beneficial for human health. However, dietary fiber cannot be used as the raw materials for 3D printing as most insoluble dietary fiber showed no plasticity and poor self–support abilities. These properties make them usually used as additives or mixed with other ingredients during 3D printing. Some fiber rich materials have been used for 3D printing. Severini et al. (2018) mixed vegetables-fruits paste (carrots, pears, kiwi, broccoli raab leaves and avocado) and fish collagen together to process 3D printed edible objects. They declared that the printing did not modify significantly the sensorial characteristics of the resultant samples or the antioxidant capacity and total phenolic content. But the geometric differences between model and products were significant. In the research of Holland et al. (2018), semi-crystalline cellulose was modeled by powder binding deposition technique. To process the edible objects successfully, semi-crystalline cellulose was mechanically treated by ball milling to produce an amorphous powder, and the food inks based on xanthan gum were formulated to enable successful jetting with a FujiFilm® Dimatix ink jet printer. It was found that only depositing one layer of droplets was not sufficient to produce a cohesive powder layer that could be lifted cleanly. Three, five and ten ink layers were applied to the powder produced structures that were able to withstand transfer onto glass microscope slides to varying degrees (Figure 6). 3D printed fruit-based snacks for children were developed by Derossi et al. (2018). They used fresh bananas, dried mushrooms, canned white beans, dried non-fat milk and lemon juice mixed with pectin. The effects of print speed and the flow level on the shape, dimension and microstructure of the snacks were evaluated. In Australia, Vegemite and Marmite are popular food spreads made by yeast and contain mass of dietary fiber. Hamilton, Alici, and Panhuis (2018) investigated the suitability of vegemite and marmite processing onto bread by food layered manufacturing (3D extrusion printing, FLM). They found that both the yeast jams were shear-thinning materials and exhibited pseudoplastic behavior. Less pressure was required to start the extrusion process of Vegemite compared to Marmite as Vegemite had lower yield stress than Marmite. The results

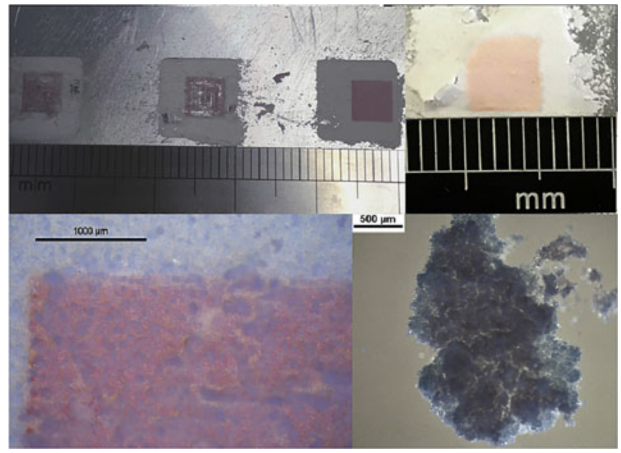

Figure 6. Clockwise from top left: Ball milled cellulose powder in recessed plate with varying printed ink layers; Ball milled cellulose with 10 ink layers on glass microscope slide; Optical microscopy of ball milled cellulose with printed ink particle; Optical microscopy of square printed pattern on cellulose powder (Holland et al. 2018).

showed that printed FLM designs were suitable in outreach activities to teach young learners about electronic circuits and 3D printing. The applicability investigation of protein and fiber-rich food materials for baking in extrusion-based 3D printed structure was carried out by Lille et al. (2018). Post-processing by oven drying was most successful at high initial solid contents (<50%) in the printed samples.

The rigidity of materials would be raised during the addition of insoluble dairy fiber. However, as materials used for 3D printing directly or as food components (Elleuch et al. 2011), soluble dairy fiber content was related to the ability to absorb water and form a gelatinous mass having effects on viscosity or gel-forming capacity. The viscosity of soluble dairy fiber decreased with the increase in shear rate. The shear stress showed a practically linear dependence on shear rate and particle size. Due to the larger particle size of soluble dairy fiber powder, networks were more easily formed, resulting in more particle interactions and thus higher apparent viscosity and yield stress (Mueller, Llewellin, and Mader 2009). Magnitudes of G' and G'' increased with the rise of frequency and were almost frequency-dependent. All samples exhibited a liquid-like behavior at low frequencies, where G'' was higher than G'. At high dynamic frequencies (approximately over 1.0 rad/s), G' became greater than G'' and the system showed a gel-like behavior (Peressini and Sensidoni 2009). Many articles agreed that the viscosity of materials regardless of whether it was starch, dough or chocolate would be raised as the shear rate increasing (Martínez, Oliete, and Gómez 2013; Bonarius et al. 2014; Lundberg et al. 2014; Shiau, Wu, and Liu 2015; Liu et al. 2016; Graça et al. 2018). However, soluble dairy fiber can be used in some special conditions, such as increasing the water binding capacity of products.

Emerging functional components

One of the characteristics of 3D food printing is the personalized nutrition design. For this reason, the functional components were also applied on the 3D food printing, including fruits juice, insect powder, vitamin and algae. In particular, personalized nutrition refers to specific print recipes based on the nutritional needs of athletes, pregnant women, and the elderly. The can also be one of the main development direction of 3D food printing.

The properties and compositions of materials have been considered as the most important factors in 3D printing process. These functional materials should be homogenous, have appropriate flow properties for extrusion, and can support its structure during and after printing process (Shao et al. 2015) or can be mixed with the structural materials harmoniously. Yang, Zhang, Bhandari, et al. (2018) used starch mixed with lemon juice for 3D food printing, and studied the influence of printing parameters (nozzle height, nozzle diameter, extrusion rate and nozzle movement speed) on the quality of printed products. In this printing system, the 1 mm nozzle diameter, 24 mm^3/s extrusion rate and 30 mm/s nozzle movement speed were found to be the optimal parameters to print 3D constructs matching the target geometry with fine resolution, more smooth surface texture, and fewer point defects with no compressed deformation. Azam, Zhang, Bhandari, et al. (2018) and Azam, Zhang, Mujumdar, et al. (2018) examined the 3D printing characteristics of vitamin D enriched orange concentrate wheat starch blends. The rheological data suggested that steam cooking of orange concentrate–wheat starch mixture for 16 ± 0.5 min exhibited shear-thinning behavior, which was essential for extrusion-type 3D food printing of food mixtures. A variation of 5% wheat starch with orange concentrates significantly increased in the yield stress ($\tau 0$) and viscosity (n). However, the structure would be enhanced if orange concentrate–wheat starch mixture could be mixed with different gums. The 3D printing characteristics revealed that the objects printed using *k*-carrageenan gum containing blend possessed maximum fidelity to the target geometry and good loading bearing capacity, preventing collapsing over time due to the proper G' value. At tan(δ) of 0.238, orange concentrate-wheat starch-*k*-carrageenan gum mixture achieved the best printing condition. An et al. (2018) used *Nostoc sphaeroides* as the materials to mix with pre-gelatinized potato starch for 3D food printing. They believed that the elasticity and viscosity balance is an essential parameter to achieve printability. The best printing outcome was observed at 40 g kg^{-1} potato starch additive amount. Liu, Zhang, Yan (2018) also investigated the characteristics of extrusion 3D printing of mashed potatoes/strawberry juice gel using a dual extrusion. In this test two methods were evaluated, while method A is to create a multi-part model and assign each of them to one extruder, method B is to create a single part model and assign different roles to each extruder. It was hard to judge which method was better. However, method B took shorter process time than method A when printing the same modal.

Challenges and trends of 3D food printing

Impact of rheological properties on 3D food printing

As described above, the rheological properties of raw materials showed huge impact on the quality of printed products and the 3D printing processing. The information was summarized in Table 5. It is important to make clear the rheological properties of raw materials including viscosity, fluid behavior, G'/G", yield stress and tan(δ), which can determine the self-supporting abilities, storage characteristics, extrudability and printability.

Consumer attitude on 3D food printing

3D food printing offers a wide range of new possibilities within the food industry. From the realization of complex food designs to the automated preparation of personalized meals, 3D food printing provides many innovations in the food manufacturing, catering and retail sectors.

However, consumers usually view novel food technologies and their resultant products with suspicion. By consulting the relevant articles published by Brunner, Delley, and Denkel (2018), Lupton and Turner (2016), Siegrist (2008) and Bruhn (2007), the perceived benefit, risks and naturalness are important factors for the acceptance of new food technologies (Siegrist 2008). These factors can be classed as flavor, potential health risk, nutrition, price and personal preference. Any suspicion of the presence of harmful byproducts and more generally, any potential health risk associated with the consumption of novel food would undoubtedly preempt consumers' acceptance of interest. Chemical transformation (e.g. modification of the food composition) is an additional factor that similarly jeopardises people's acceptance of new foods and new technologies. In developing/less developed countries (e.g. China), price of food also plays the determinant role in food selection of consumer (Yu 2018).

Very limited research about the consumers' attitudes and acceptance of 3D printed food has been carried out to date. In 2016 Lupton and Turner first attempted to understand how customers might respond to food produced by 3D printing technology. The investigation results were disappointed since a considerable number of consumers have feared food produced with an inedible, unsafe or at least nutritionally depleted material. The questionnaire survey carried by Brunner, Delley, and Denkel (2018) in Switzerland revealed that respondents' initial attitudes toward 3D-printed food were rather negative. Hopefully, the attitudes of consumers towards 3D printed food could be improved significantly after extensive advertisements and introductions on theories and benefits of 3D food printing are delivered. Fun, convenience, health and personalized nutrition should be the major factors to promote the applications of 3D printing technology in food production.

Superiorities of 3D food printing

The superiorities of 3D food printing have been emphasized by all 3D food techniques related researchers. However, conclusions obtained from the attitude of consumers to 3D food printing listed above are still insufficient. It is important to understand the core value and

Table 5. Rheological properties of various materials applied on 3D food printing.

Materials	Rheological properties
Chocolate (Hao et al. 2010)	Viscosities of chocolate were relatively constant when the temperature was maintained between 32 and 40 °C and the pressure was between 3.5 and 7.0 Pa, while higher temperatures and pressures made the chocolate difficult to shape.
Chocolate (Lanaro et al. 2017)	Below 6 rad/s at temperatures from 32 to 40 °C, chocolate showed to have the negligible effect on the formation of self-supporting layers
Dark chocolate (Fernandes, Müller, and Sandoval 2013)	Dark chocolate presented the highest and significantly different textural parameter values of hardness and frangibility.
Dough (Yang, Zhang, Fang, et al. 2018)	G′ and G′′ continuously and significantly increased as the content of sucrose, butter and flour increased.
Dough (Yang, Zhang, Prakash, et al. 2018)	Dough can be easily extruded because of its pseudoplastic behavior with its viscosity decreasing as the shear rate increases.
Gum (carbohydrate) (Ahmed and Thomas 2018; Israr et al. 2018; Martin-Alfonso et al. 2018)	Using gum as the additive agents can raise the apparent viscosity of the raw material, which made the extruded product harder.
Expanded wheat flour mixed with dough (Martínez, Oliete, and Gómez 2013)	Flour decreased in dough extensibility but increased in dough plasticity, which are good for forming sharp geometric 3D printed objects.
Fish surimi gel NaCl addition (Wang et al. 2018)	Surimi gels were pseudoplastic fluids, which were shear-thinning. Furthermore, an increase in NaCl concentration led to a general decrease in viscosity.
Gelatin (Pang et al. 2014)	It exhibited Newtonian flow in dilute solution except when extended by charged groups, which make it a potential candidate to be suited for use as an ingredient in 3D printer inks
Gelatin (Kim, Bae, and Park 2018)	Gelatin without additives shows poor self-support features as the sample had higher hardness and fracturability, which gave rise to flaws in the samples.
Gelatin (Kragh, 1961).	Extreme conditions of very high shear rate may lead to a non-Newtonian behavior.
Milk powder mixed with starch and cellulose nanofibre (Lille et al. 2018)	The shape stability after printing was linked with the yield stress of the paste. In stress sweep measurements, G′ typically showed constant plateau values at small stress values. All samples had a structure which was elasticity dominated and gel-like structure.
Milk and white chocolate (Glicerina et al. 2013)	The lowest consistency and cohesiveness values suggest the presence of a structure with weaker interactions between particles
Soluble dairy fiber powder (Mueller, Llewellin, and Mader 2009)	Networks were more easily formed, resulting in more particle interactions and thus higher apparent viscosity and yield stress.

potential applications for the food industry, market and consumer. It is also necessary to follow up with technological progress and the relevant applications in order to make it clear how this new technology may satisfy the customers' needs and how it changes people's lifestyle. The advantages of 3D food printing versus traditional food manufacturing mainly include:

1. Customized food design: 3D food printer provides a platform for home experimentation with foods extrinsic features and flavours.
2. Personalized nutrition design: 3D food printing can enable a precise control of people's diet, and ensure fresh and healthy dishes that exactly meet the needs and preferences of individuals. Moreover, functional components or drugs can be mixed easily with meals by 3D food printing.
3. Simplifying customized foods supply chain (Sun et al. 2015): It is economical to design the supply chain for 3D food printing raw materials as compared to traditional one.
4. Processing digitalization: consumers can pre-view their products during manufacture on computer monitors, or modify the model ready for printing by computer.

Future of 3D food printing

As an emerging food processing technique, there is huge progressive space existing in 3D food printing. The following suggestions could be proposed.

1. Improving equipment and materials prepared for 3D printing

   As the technologies develop, the accuracy, convenience and size may result in a reduction in the price of 3D food printers. However, printing speed is still limited and cannot satisfy consumers' needs. Besides equipment cleaning, nozzle blockage and consumable materials need to be improved. Moreover, professional training is still necessary before using 3D food printer. The simple operation and management of 3D food printers would be required if the technology is to reach the popularity of the microwave oven.

   To date the amount of commercially available 3D food printing relevant raw materials is insufficient though materials adapted for 3D food printing are a research hotspot. The most popular commercial 3D food printing material is still chocolate without any special additives. Other materials are referred to in articles or patents, but are not available commercially. There is an urgent need in dedicated materials for 3D food printing to be developed, such as pre-prepared special dough, which requires knowledge of the raw materials and their properties in a printing formulation.

   Single material can hardly satisfy the demand of 3D printing, while multiple materials can integrate the advantages of mono-materials. For instance, using mashed potato as materials for 3D food printing directly is defective because the mechanical strength was not enough. After adding gums the self-supporting ability of printed product gets better and the surface becomes smoother (Liu, Zhang, Bhandari 2018; Liu, Bhandari, et al. 2018). However, how to mix different materials harmoniously and make clear the characteristics of mixed material still needs more explorations.

2. Identification of an appropriate business model
A new food technology may become an issue when consumers are convinced that this technology provides no additional benefit to them or to society and may only have advantages for producers and the industry (Siegrist 2008). The distance to popularize 3D food printing similar to the microwave oven is still a long-term objective, but now researchers and businessmen should make close cooperation to develop the path to popularize this new technology. An off-line consumer experience center could be a good commercial promotion model for 3D food printing. Food companies also can cooperate with the special unit, such as hospital or bread houses, to promote the implementation of this technology.
3. Strengthen the propaganda
Successful product development is driven by customer needs, and customer acceptance is a key factor. Customers have very limited information about new technologies, and may have difficulties assessing risks associated with a novel food but also they may be unable to estimate possible benefits. Commonly consumers trust in the food industry, the media, the scientists and the government, the best communication strategy might be a propaganda campaign for the new technology widely to change the public's view about a novel food when its content does not match pre-existing knowledge and values. It is also a good strategy to fabricate the traditional food by 3D food printing to raise the consumers' acceptance.

Acknowledgements

This research was conducted in the College of Mechanical and Electronic Engineering, Northwest A&F University, and supported by research grants from National Key Research and Development Program of China (2016YFD0401004), National Natural Science Foundation of China (No. 31601485), China Postdoctoral Science Foundation (No. 2016M602866), Shaanxi Postdoctoral Science Foundation (No. 2016BHSEDZZ101) and the Fundamental Research Funds for the Central Universities (Z109021620). We also appreciate constructive comments and suggestions from Prof. James G. Lyng in University College Dublin during manuscript preparation and revision.

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