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# A Review on 3D Printing for Customized Food Fabrication

Jie Sun[1,2*], Zhuo Peng [1], Weibiao Zhou [3], Jerry Y.H.Fuh[2,4], Geok Soon Hong [4], Annette Chiu[1]

[1]*Keio-NUS CUTE Center, National University of Singapore, Singapore.*
[2]*National University of Singapore (Suzhou) Research Institute, Suzhou Industrial Park, China.*
[3]*Food Science and Technology Programme,* [4]*Department of Mechanical Engineering, National University of Singapore, Singapore*
*sunjie_xjtlu@hotmail.com*

**Abstract**

This study introduces the first generation food printer concept designs and workable prototypes that target to revolutionize customized food fabrication by 3D printing (3DP). Different from robotics-based food manufacturing technologies designed to automate manual processes for mass production, 3D food printing integrates 3DP and digital gastronomy technique to manufacture food products with customization in shape, colour, flavor, texture and even nutrition. This introduces artistic capabilities to fine dining, and extend customization capabilities to industrial culinary sector.

The selected prototypes are reviewed based on fabrication platforms and printing materials. A detailed discussion on specific 3DP technologies and their associate dispensing/printing process for 3D customized food fabrication are reported for single and multi-material applications. Eventually, impacts of food printing on personalized nutrition, on-demand food fabrication, food processing technologies and process design are reported. Their applications in domestic cooking or catering services can not only provide an engineering solution for customized food design and personalized nutrition control, but also a potential machine to reconfigure a customized food supply chain.

*Keywords:* customized food fabrication, 3D food printing, platform design, multi-material

# 1. Introduction

There is an increasing market need for customized food products, most of which are currently designed and made by specially trained artisans. The cost for such a limited number of pieces is relatively high. Three-dimensional (3D) food printing, also known as Food Layered Manufacture (Wegrzyn et al., 2012), can be one of potential alternatives to bridge this gap. It aims to produce 3D custom-designed food objects in a layer-by-layer manner, without object-specific tooling, molding, or human intervention. Thus, this technology can increase production efficiency and reduce manufacturing cost for customized food products fabrication.


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## 1.1 Food Printing and Robotics-based Food Manufacturing

Cooking is one of the most important activities in our life, and a robotic chef capable of following recipes would have many applications in both household and industrial environments. For example, baking cookies robots can locate ingredients, mix them in correct order, and place a resulting dough in a baking tray of oven (Bollini et al., 2012). These robots equipped with libraries can perform everyday manipulation tasks, and basic actions such as picking up an object, putting it down or pouring (Beetz et al., 2011) These robotics-based techniques used in traditional food manufacturing for mass production, are generally designed to automate manual processes. They can greatly reduce workload, save labour cost, and improve food manufacturing efficiency. Food manufacturers are quite happy with such progresses, and are not clear about the reasons and motivation of developing food printing techniques and their unique features. Hence, a comparison between the two techniques is necessary.

Differentiated from such robotics-based technologies, food printing integrates 3D printing (3DP) and digital gastronomy techniques to manufacture food pieces with mass customization in shape, colour, flavor, texture and even nutritional value. 3DP is a digitally-controlled, robotic construction process which builds up complex solid forms layer by layer and applies phase transitions or chemical reactions to fuse layers together. Digital gastronomy is to implement cooking process knowledge in food fabrication so that our eating experiences go beyond taste to encompass all aspects oof gastrnomy (Van Bommel et al., 2011). Combining 3DP and digital gastronomy techniques can digitally visualize food manipulation, therefore creating a new space for novel food fabrication at affordable price. As a result, a customised food design in a form of digital 3D model will be directly transformed to a finished product in a layered structure (Levy et al., 2011).

## 1.2 Overview

A number of articles and papers pertaining to food printing have been published over the past few years. Most of them focused on fabricated novel food items. Recently, some researchers started investigating fundamental-level issues in food printing, such as converting ingredients into tasty products for healthy and environmental reasons. However, such information is scattered in various publications with different technical focuses. The objective of this paper is to gather, analyze, categorize, and summarize information pertinent to the technology and its impact to food processing. The rest of paper is organized as follows: section 2 discusses food printer concepts and platform designs, as well as diverse printing materials. Section 3 investigates the 3DP technologies for food printing from engineering perspective including dispensing and printing technologies, multi-material and multi-printhead printing mechanism. Section 4 discusses the impact of food printing on customized food design, personalized nutrition, on-demand food fabrication, food processing technologies and process design. Finally, a conclusion is presented in Section 4.

# 2. Food Printer Concepts and Platform Designs

The first generation of food printer concept designs and prototypes is emerging into the public domain. Within a short history, a few research projects were conducted from concept designs to in-depth research on material extrusion and deposition.

## 2.1 Conceptual Ideas

Nanotek Instruments Inc. patented a rapid prototyping and fabrication method for 3D food objects in 2001 (Yang et al., 2001), such as a custom-designed birthday cake. However, no physical prototype was built. Nico Kläber (Electrolux, 2009) came out a Moléculaire concept design in Electrolux Design

Lab competition, which incorporated molecular gastronomy into food printer design. This concept aimed to print multiple materials using a small robotic arm and created a fully customised meal using normal food. Philips Food Creation Printer introduced food cartridges to create custom-designed food product in a layer-by-layer manner (Philips, 2008). An interactive graphical user interface was proposed to select ingredients, quantities, shapes, textures and other food properties. This idea may be applicable for any type of customized 3D food printing. However, all of these concept designs seem vastly unrealistic and no implementation potential.

In digital gastronomy, ingredients can be determined according to on-line information on nutritional content, personal and social preference. Massachusetts Institute of Technology (MIT) introduced a digital gastronomy concept into food printer design and presented three conceptual designs as shown in Table 1 (Zoran et al., 2011). Each focused on different aspects of gastronomy from mixing, modelling to transformation. These concepts seem more realistic compared with previous conceptual designs but are still far away to be technically feasible.

| | Concept Focus | Design Platform | Difficulties |
|---|---|---|---|
| Virtuoso Mixer | combine and mix diverse ingredients to control their quantities, types and source. | • top layer: storage containers to monitor temperature, humidity and weight<br>• 2nd layer: processing chambers dedicated to mixing, whisking and crushing<br>• bottom layer: extrusion unit with thermo control | • distribution and metering design between the layers,<br>• machine cleaning<br>• waste minimization. |
| Digital Fabricator | model and cook ingredients combination into specific shapes with defined dimensions | • refrigerated canisters of food<br>• a three-axis mixing/printing head onto the printing surface<br>• a fabricator chamber | • refilling canisters<br>• machine cleaning<br>• material supply to mixing head and storage system |
| Robotic Chef | transform existing ingredients into new flavour and design pattern | • two five-degree of freedom robotic arms<br>• a tool head to localise transformations such as drilling, cutting and dispensing via syringes<br>• a heating bed for cutting/cooking/ sintering | • design and program to fabricate diverse food shapes<br>• complicated manipulation |

**Table 1:** Summary of conceptual designs on food printer

## 2.2 Platform For Food Printing

Food printer platform basically consists of a XYZ three axis stage (Cartesian coordinate system), dispensing/sintering units, and user interface. With computer controlled three axes motorized stage and material feeding system, such platforms can manipulate food in a real-time way. Food composition can be deposited/sintered essentially point by point and layer by layer according to a computerized design modeling and path planning. To invent and personalize new dishes rather than simply automate traditional food fabrication process, at least four functions are proposed: metering, mixing, dispensing and cooking (heating or cooling) (Zoran et al., 2011). Only the dispensing and cooking functions are available in the current commercial or self-developed food printing platforms.

- Food printers based on commercial platforms

To simplify development process and shorten development time, researchers modified commercial available open source 3D printing platforms for food printing purpose. One common modification is to replace original printhead with specially designed dispensing unit and an additional valve to control material feed rate, or replace standard inkjet binder with food grade material like starch mixtures.

The Fab@Home system was one of universal desktop fabricators compatible with food materials, although it is not specifically designed for food applications. Researchers also integrated Frostruder MK2 on MakerBot platform to extrude frost, where two solenoid valves were used to control the flow rate of creamy peanut butter, jelly and Nutella (Millen et al., 2012). Fig.1 shows a food printing platform with a printhead developed at National University of Singapore. The platform is built based on a modified Prusa i3 platform with a self-developed extrusion printhead.

(a) Food Printing Platform

(b) Printhead

**Figure 1:** The Food Printing Platform Developed at National University of Singapore

With modified commercial platform, researchers can quickly create complex food shapes, and compare various food materials' property and fabrication processes. While, those platforms lack of flexibility on further improvement, and are only applicable for a limited range of materials, which cannot support in-depth research.

- Food printers based on self-developed platform

Self-developed platforms are built based on specific requirements, such as creating 3D sugar structures with a computer controlled laser machine (Windell et al., 2007), building cheese and chocolate 3D objects from edible ingredients (Hao et al., 2010), or reducing cost associated with freeform fabrication of sugar products with open-source hardware (CandyFab, 2007). They provide more choices for material dispensing so that a suitable printhead can be designed and implemented among a few candidates, dispensing parameters and fabrication process can be more flexible and optimized.

In both commercial and self-developed platforms, mechanical movements of substrate and dispensing head(s) are achieved through computer controlled stage. In printing process, a digital 3D model can be converted into multiple layer data (STL files), and then these data will be interpreted into driving signals to stage driver motors through the regulated controller. The same procedures of moving and dispensing are repeated for each layer with its own characteristic shape and dimensions. The combination and consolidation of these layers forms a complete 3D object.

- User control interface design

User control means the full control of shape, ingredients and materials, which may significantly impact food creativity design. User control interface design involves three functions: 1) providing tools on shape design and material selection for customized food piece design, 2) transforming this design into a computerized 3D model, and 3) planning dispensing pathway and processing associated parameters. Thus, developing an interactive user interface linking with an open-access web-based template library is essential (Lipton et al., 2010).

With such interface, customers can design their own personalized food pieces, obtain design files online through a technology service provider or share their design with other users. The products can then be built in front of the customers using personal 3D food printer in a new context of household product making, which would be impossible to achieve based on existing methods.

## 2.3 Available Printing Materials

Substantial efforts have been made to pre-process materials suitable for 3D printing, and increase their thermal stability during post-processing. Printing pureed food proposed by TNO can help elderly people with chewing and swallowing problems (Gray et al., 2010). TNO has also suggested printing customized meals for seniors, athletes, expectant mothers through varying food component levels like protein and fat. Generally, the available printing materials can be classified into two categories based on their printability.

- Natively printable materials

Natively printable materials like hydrogel, cake frosting, cheese, hummus and chocolate can be extruded smoothly from syringe (Cohen et al., 2009). The mixture of sugars, starch, and mashed potato were tested as powder materials in Z Corporation powder/binder 3D printer (Walters et al., 2011). A number of sugar teeth were fabricated for demonstration. However, none of them is the main course of meals. Some traditional foods were tested for printability study using Fabaroni (Fabaroni et al., 2014), and the most successful material was pasta dough, judged by viscosity, consistency and solidifying properties. Food products made by natively printable materials can be fully controlled on taste, nutritional value, and texture. Some of natively printable materials are stable enough to hold the shape after deposition, do not require further post processing and can be reserved for medical and space applications. Other composite formulations such as batters and protein pastes may require a post-deposition cooking process. This will make food product structures more difficult to retain their shapes (Lipton et al., 2010).

- Non-printable traditional food material

Food like rice, meat, fruit and vegetables, largely consumed by people every day, are not printable by nature. To enable their capability of extrusion, adding hydrocolloids in these solid materials has been approved and utilized in many culinary fields. Lipton et al. (Lipton et al., 2010) used simple additives to modify traditional food recipes and created complex geometries and novel formulations. Although solid foods and semi-solid liquids have already been manipulated to become printable by gastronomic tricks, it is difficult to test and modify the whole list. One potential solution was to use a small group of ingredients to create a platform with many degrees of freedom on texture and flavor. By fine tuning hydrocolloids' concentrations, a very wide range of textures (i.e. mouthfeels) can be achieved. Cohen et al. (Cohen et al., 2009) experimented food texture using two hydrocolloid systems, and explored structural requirements for post-processing materials such as protein pastes and cake mixtures.

- Post-processing

Food printing process does not require a high energy source to completely remove liquid ingredient from food composition. Fabricated layers do not need to be completely solidified, but has sufficient rigidity and strength to support its own weight and the weight of subsequent layers without a significant deformation or shape change.

The majority of traditional edibles need post-deposition cooking after shapes are constructed, such as baking, steaming or frying. These processes involve different levels of heat penetration and result in non-homogenous texture. The printed complex internal geometries using a cookie recipe with cocoa modified material (Lipton et al., 2010) could retain its shape after baking process.

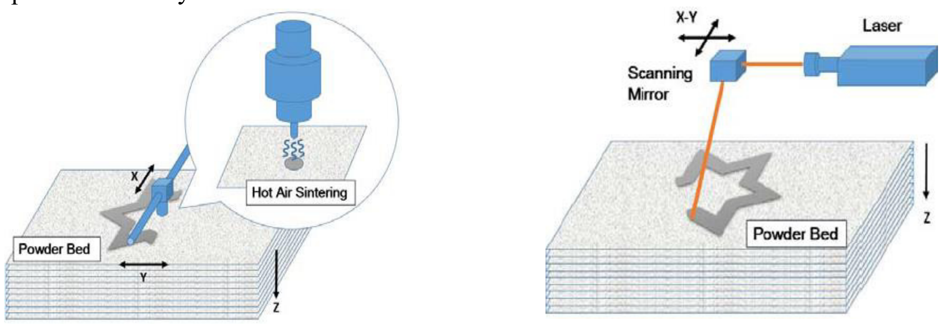
# 3. 3DP Technologies In Food Printing

3D food printing has significant advantages in high-value, low volume food fabrication, particularly for customized items in food service. Diverse printhead designs are applied to load and print food materials. Some used thermal energy from laser/hot air/heating element to sinter or melt powder, and others used inkjet-type printing heads to accurately spray binder or solvent. Below is a summary of applicable 3DP technologies.

## 3.1 Current 3DP Technologies' Applications

- Selective Sintering technology

Sugars and sugar-rich powders can be selectively sintered to form complex shapes. After a layer of fresh powder is spread, a sintering source (hot air in Fig. 2(a) or laser in Fig. 2(b)) will move along X and Y axes to fuse powder particles so that they can bind together and form a solid layer. This process is repeated by continuously covering the fused surface with a new layer of material particles until completing a 3D object (Deckard et al., 1988). TNO's Food Jetting Print (Gray et al., 2010) applied laser to sinter sugars and NesQuik powders. The sintered material formed the part whilst the un-sintered powder remained in place to support the structure which may be recycled. The CandyFab (CandyFab, 2014) applied a selective low-velocity stream of hot air to sinter and melt a bed of sugar. The fabrication powder bed is heated to just below the material melting point to minimize thermal distortion and facilitate fusion to the previous layer. Selective sintering offers the freedom to quickly build complex food items in a short time without post curing. This technology is suitable for sugar and fat based materials with relatively low melting points. However, the fabrication operation is complicated as many variables involved.




(a) Selective Laser Sintering (SLS)

(b) Selective Hot Air Sintering

**Figure 2:** Selective Sintering

- Hot melt extrusion

Hot-melt extrusion also called fused deposition modeling (FDM), was firstly described in Crump's work (Crump et al., 1991). In Fig. 3, melted semi-solid thermoplastic material is extruded from a movable FDM head and then deposited onto a substrate. The material is heated slightly above its melting point so that it solidifies almost immediately after extrusion and welds to the previous layers.

In food printing, hot-melt extrusion is applied to create personalised 3D chocolate products (Yang et al, 2001) (Hao et al., 2010; Causer, 2009). Hao et al. (Hao et al., 2010) compared the material properties among various food stuffs and printed 3D chocolate products with different shapes and sizes. MIT Researchers used hot melt chocolate as dispensing liquid and developed a functional prototype named "digital chocolatier" to fabricate customised chocolate candy (Zoran et al., 2011). In this research, the compressed air was applied to melt chocolate and force it out of the chambers. A '3D Food-Inks Printer' with embedded 3D colour images on extruded base material (Golding et al, 2011) may also fall into this category, while a post-deposition cooking step was required to fuse layers together.

The food printer designed based on hot-melt extrusion has a compact size, and low maintenance cost. The disadvantages such as seam line between layers, long fabrication time, and delamination caused by temperature fluctuation, need to be further investigated.

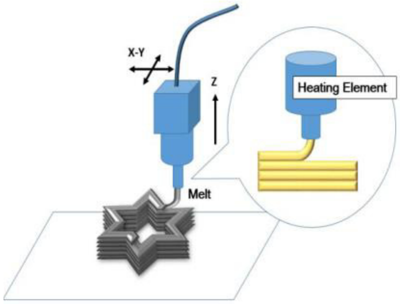



**Figure 3:** Hot Melt Extrusion (FDM)

- Binder jetting

In standard binder jetting technology, each powder layer is distributed evenly across the fabrication platform, and liquid binder sprays to bind two consecutive powder layers (Sachs et al, 1990). As Fig. 4, the powder material is usually stabilized through water mist to minimize disturbance caused by binder dispensing. In edible 3D printing project, Walters et al. (Walters et al, 2011) utilized sugars and starch mixtures as the powder material and a Z Corporation powder/binder 3D printer as platform to fabricate customized shape with complex structures. Sugar Lab (Yang et al, 2001) used sugar and different flavour binders to fabricate complex sculptural cakes for weddings and other special events. This fabrication adopted 3D Systems' Color Jet Printing technology, and the material and fabrication process met all food safety requirements. Binder jetting offers advantages such as faster fabrication and low materials cost, but suffers from rough surface finish and high machine cost. Post-processing may be required, such as curing at higher temperature to further strengthen the bonding.

- Inkjet printing

In Fig. 5, inkjet food printing dispenses stream/droplet from syringe-type printhead in a drop-on-demand way. 3D edible food products such as cookies, cakes, or pastries are created in a layer structure, which involves pre-patterning food items at multiple layers of processing. The De Grood Innovations' FoodJet Printer (Foodjet, 2014) used pneumatic membrane nozzle-jets to deposit selected material drops onto pizza bases, biscuits and cupcakes. The ejected stream/droplets fall under gravity, impact on the substrate, and dry through solvent evaporation. The drops can form a two and half dimensional digital image as decoration or surface fill.

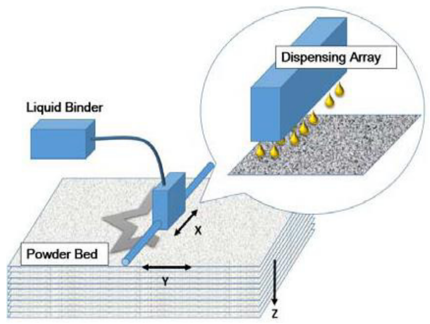



**Figure 4:** Powder Bed Binder Jetting

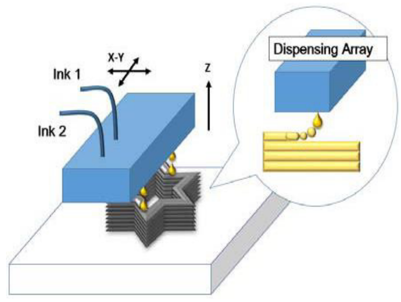



**Figure 5:** Inkjet Printing

Compared with manually customized food fabrication, 3D food printing does not require costly setup and hence is economical in small quantity production. The quality of fabricated food items depends on the process and planning rather than people's skill. As such, fabrication can be easily and accurately controlled based on customer demand. It plays increasingly important role in food processing as a complementing technology. Table 2 is a summary of current 3DP techniques' applications in food printing, with the comparison of applicable materials, fabrication platforms, and products.

| | Hot-melt extrusion | Sintering technology | Inkjet powder printing | Inkjet printing |
|---|---|---|---|---|
| Materials | Food polymers such as chocolate | Low melting powder such as sugar, NesQuik or fat | Powder such as sugars, starch, cornflour, flavours, and liquid binder | Low viscosity material such as paste or puree |
| Platform | • Motorized stage<br>• Heating unit<br>• Extrusion device | • Motorized stage<br>• Sintering source (laser or hot air)<br>• Powder bed | • Motorized stage<br>• Powder bed<br>• Inkjet printhead for binder printing | • Motorized stage<br>• Inkjet printhead<br>• Thermal control unit |
| Fabricated products | Customized chocolates | Food-grade art objects, Toffee shapes | Sugar cube in full-color | Customized cookies, Bench-top food paste shaping |
| Machine | Choc Creator | Food Jetting Printer | Chefjet | Foodjet |
| Company | Chocedge | TNO | 3D systems | De Grood Innovations |

**Table 2:** Comparison of 3DP technologies in food printing

## 3.2 Multi-material and Multi-Printheads

Applying multiple-material is quite common in customized food design and fabrication. Some of these materials are from traditional food recipes, additives and others are non-traditional edible materials (primarily non-food such as ingredients extracted from algae, beet or even insects. In the 'Insects Au Gratin' project, insect powders mixed with extrudable icing and soft cheese to shape food structures and make tasty pieces (Walters et al., 2011) . The diversity of printing material empowers consumers to take control of different materials design and fabrication.

Most of food printer projects such as ChocALM, Insects Au Gratin, are developed using single printhead extrusion for one material or a mixture of multiple material. When one printhead is used to print the mixture of food materials, it is not capable to control material distribution or composition within each layer or in a whole structure. To achieve controlled material deposition and distribution in a drop-on-demand way, more printheads are proposed. For multiple-printhead, the data from individual layer is directed to a platform controller (either in commercial or DIY platform), which selectively activates the motors to move the corresponding dispensing head, and control its feeding rate. Hence, food printers may deliver multi-material object fabrication with higher geometric complexity and self-supporting structure.

(a) Multi-material food designs (b) Fabrication sples

**Figure 6:** Multi-material food design and fabrication sample

Researchers tried multiple-printhead using Fab@Home 3D printer, and tested frosting, chocolate, processed cheese, muffin mix, hydrocolloid mixtures, caramel and cookie dough (Lipton et al., 2010) . Dual-material printing was only achieved using separated deposition heads for a limited material set, and the secondary material was utilized to support fabrication (Periard et al., 2001), which can be removed after that. Fig. 6 shows some three-material food samples fabricated by our group at the National University of Singapore. The basic biscuit recipe consists of flour, butter, sugar and egg white.

Multi-material may generate multi-scale ingredients after processing, and require corresponding fabrication techniques. Gray (Gray et al., 2010) proposed using electro-spinning to produce multiple food sub-components at micro-scale and further assemble them into multi-component composite structures for a variety of materials. This is a new solution to shape non-traditional food materials under multi-scale into appealing edible structures.

# 4. Impacts from 3D Food Printing

Food printers introduce artistic capabilities to fine dining, and extend mass-customization capabilities to industrial culinary sector. This benefits a high-value, low volume customization food fabrication process that would be impossible to achieve currently. It also provides research tools to manipulate structure development of solid food materials at multiple scales. This technology is still under development stage; hence, it is important to understand its core value and potential applications in the market. At the same time it is also necessary to follow up with technology progress and relevant applications in order to investigate how this new technology will meet the customers' needs and potentially change people's lifestyle.

- Customized food design

Most of food manufacturing techniques are developed for mass production, while food creativity and user control on shapes, structures and flavours are usually sacrificed. Food printer provides a platform for consumer experimentation with food forms and flavours (3D Systems, 2014) . Previously, this customization process involves specifically hand-made skills with low production rate and high cost. Food printing technologies could potentially overcome these barriers by offering more freedom in food customisation design on shapes, colors and flavours for home users. It may generate more design solutions such as customised chocolate shaping (Zoran et al, 2009; Causer et al., 2009), and personalized full-colour images onto solid food formats (Golding et al., 2001). Fig. 7 shows some customized food pieces samples fabricated by our group.

**Figure 7:** Customized food design and fabrication samples

- Personalised nutrition

Except existing nutritional preferences, individual dietary has highlighted the concept of personalised nutrition in terms of individual's health status and body-type requirement (Watzke et al., 2010). 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. It would significantly improve population wellbeing. In this case, food ingredients even with well-known material properties must be tailored to specific formulations under each fabrication. More efforts are required to bring such highly customized food products into every home.

- Simplifying customized foods supply chain

Food printers will facilitate the implementation of a build-to-order strategy with low overriding cost. It is economical to locate production facilities near the end customers. This can help to reconfigure the customized food supply chain and bring products to consumers within a shorter time, acceptable price while utilizing fewer resources.

- Reformulating food processing technologies

Most of food processing technologies associated with chemical and physical changes may not match requirements of 3D printing technologies. This applies to composition (ingredients and their interactions), structure, texture, and taste. Ingredient formulations with varied combinations and manipulation conditions can generate various textures in products, which may go beyond a manageable level. Also, printing material property should be rigid and strong enough to support the weight of subsequently deposited layers as well as the thermal effects from post-cooking process. Briefly, conventional food processing technologies are unlikely to fit into such a complicated scenario, and the whole processes should be reformulated. For example pre-conducting some process (e.g. gluten formation and leavening) and replacing remaining processes (e.g. shaping and baking).

- Process design and digitalization

To achieve a better understanding of 3D food printing processing, a mathematic model that can realistically describe this process with inputs, outputs and process type will be essentially useful. Customized food fabrication process and food printer design are the major driving force for developing such a model. Key process parameters such as temperature, moisture, and food properties such as density, thermal and electrical conductivity, viscosity, permeability are often coupled. It is very necessary to digitalize comprehensive cooking processes before mathematically manipulation, which greatly differs from traditional food processing models. Data on food properties can be obtained from measurement, computerized database, handbook and theoretical calculations. In reality, food properties often vary from batch to batch due to difference in formulations, etc. By varying the property data and geometry around the expected value in the simulation model, one can bracket the properties and predict the results of particular food processing for a certain range of properties.

To develop this simulation model, researchers will further explored to model specifically-designed printing process with the 3D object geometry, perform data quantification for each process (ingredients metering and mixing, printing, baking and so on), and determine communication protocols between different functions or processes.

# 5. Future Work And Conclusion

3D food printing has demonstrated its capability on making personalised chocolates or producing simple homogenous snacks. However, these applications are still primitive with limited internal structures or monotonous textures. It is necessary to develop a systematic way to investigate printing materials, platform design, printing technologies and their influences on food fabrication. Meanwhile, the food design process should be structured to promote user's creativity, the fabrication process should be quantified to achieve consistent fabrication results, and a simulation model should be developed to link design and fabrication with nutrient control. With the development of an interactive open web-based user interface, food printers may become part of an ecology system, where networked machines can order new ingredients, prepare favorite food on demand and even collaborate with doctors to develop healthier diets.

This paper reviews food printing development from conceptual design till available commercial machines. The two printing platforms are employed, and both natively printable materials and non-printable traditional food materials are used for printing experiment. Although quite a number of food printing technologies are available, there is still a long way to further develop them for commercial usage. From this technology review, it can be seen that food printing may exert a significant influence on various types of food processing, which allow designers/users to manipulate forms and materials with enhanced and unprecedented capability. This versatility, applied to domestic cooking or catering service, can improve efficiency to deliver high quality, freshly-prepared food items to consumers, deliver personalized nutrition and enable users to develop new flavors, textures and shapes to create entirely new eating experiences.

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