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Research Article

FOOD LAYERED MANUFACTURING: A POTENTIAL CATALYST FOR CUSTOMIZED FOOD FABRICATION

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ABSTRACT

Food Layered manufacturing is a digitally controlled food construction process which can build up complex 3D food products layer-by-layer to make an object from a 3D model data, as opposed to subtractive manufacturing methodologies. Different from robotics-based food manufacturing technologies designed to automate manual processes for mass production, 3D food printing as it is popularly called, integrates 3-D printing technologies and digital gastronomy techniques to manufacture food products with customization in shape, colour, flavor, texture and even nutrition (Sun *et al.,* 2015). Most notable printing technologies with current applications in the food industry include Sinitering Technology, Fused Diffusion Modeling, Binder Jetting and Inkjet Printing. Three types of printing materials (i.e. natively printable materials, non-printable traditional food materials, and alternative ingredients) are currently been used for customized food fabrication. The various types of platform for food printers include self-developed, commercial and user-interface. Eventually, the potential prospects of food printing on personalized nutrition, on-demand food fabrication, food processing technologies, process design, modification of traditional recipes, among others, cannot be over-emphasized. Their applications in bespoke food manufacturing, 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 (Sun *et al.,* 2015).

INTRODUCTION

In the movie of *Star Trek: The Original Series* in the 1960s, a 24th century advancement named a "food synthesizer" was envisioned and described. It was a "replicating machine" that could synthesize meals based on the personal requirements. However, the working mechanics of this device was not explained in the movie. Perhaps, the scriptwriter did not have concise ideas about how this machine could technically work. In spite of this, the movie formed a basis that there has earlier been a desire of instantly making personalized meals and replicating exiting food designs. In 1942, George O. Smith in his *Venus Equilateral* sci-fi series also portrayed similar novel duplications and new manufacturing technologies [1]. At that time, it could have indeed be fair to say that such manufacturing revolution described in all these science fictions had unlikely feasibility but the recent advances made in the field of additive manufacturing have begun to make widespread, fundamental changes in layered manufacturing and all of these imaginations seem less far-fetched. In addition, the recent proliferation of low-cost desktop 3D printers is gradually establishing the springboard of "mini-factories" with 3D printing from the comfort of everybody's home. An increasing trend towards the domestication of manufacturing is happening. This localization of production disrupts the economies-of-scale model and completely breaks down the barriers to mass-customization.

According to ASTM, 3D printing is the process of joining material to make an object from a 3D model data, usually layer by layer as opposed to subtractive manufacturing methodologies. 3D printing is also called additive manufacturing; a method of basically making a three-dimensional object from a package model. It is also known as rapid prototyping; a mechanized method whereby 3D objects are quickly made on a reasonably sized machine connected to a computer containing blueprints for the object. The 3D printing concept of custom manufacturing is exciting to nearly everyone. It portrays an innovative manufacturing process where objects are built up layer by layer, from a 3D computer design using a variety of printing technologies and typically works by converting a software-based design into distinct 2D layers or slices, which are "printed" and bounded to each other

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in order to create a 3D product. Before now, it typically processes plastics, ceramics and metals but recently there has been an upsurge other materials which can be worked into a 3D objects such as food and materials like metals of various sorts and organic matter like carbon and its varied derivatives

The method of making these objects in largely additive. Within the additive method, an object to be written is built from the base-up by in turn adding it to layers of the development material. The additive method may be contrasted with the subtractive process, where material is removed from a block by methods such as sculpting or drilling. This revolutionary method for creating 3D models with the use of inkjet technology saves time and cost by eliminating the need to design; print and glue together separate model parts. The basic principles include materials cartridges, flexibility of output, and translation of code into a visible pattern.

Three-dimensional (3D) food printing, also known as Food Layered Manufacture (FLM), can be one of the potential alternatives to fabricate customized food products. It integrates additive manufacturing and digital gastronomy techniques to produce 3D custom-designed food objects without object-specific tooling, molding or human intervention. It is widely regarded as a digitally controlled, robotic construction process which can build up complex 3D food products layer by layer [2].The technique can increase production efficiency and reduce manufacturing costs for mass customization in food fabrication. Its inception has brought about a revolution in cooking by precisely mixing, depositing, and cooking layers of ingredients, so that users can easily and rapidly experiment with different material combinations. With this technology, food can be designed and fabricated to meet individual needs on health condition and physical activities through controlling the amount of printing material and nutrition content.

The first generation food printer concept designs were introduced to the general public more than 10 years ago. Nanotek Instruments, Inc., patented a rapid prototyping and fabrication method for producing 3D food objects [3], such as a customer-designed birthday cake; however, no physical prototype was built. Nico Kläbe came out with a Moléculaire concept design in the Electrolux Design Lab 2009 competition, which could print a multi-material customized meal using a small robotic arm.

Working Principle of An Edible 3d Printer

As shown in Fig. 1, the current food printing process starts with designing a virtual 3D model. Slicing software translates this model into individual layers and finally generates machine codes for printing. After uploading the codes into a printer and choosing a preferred food recipe, the food printing starts. Numerous efforts have been put into recipe modification, food printing process tuning, and equipment modification. Currently, selective sintering [4], hot melt extrusion/room temperature extrusion [5]; [6] power bed binder jetting [7] and inkjet printing [8] applied to food-related printing. A number of articles and papers pertaining to food printing have been published over the past few years. Most of them focused on the fabrication of customized food items. Researchers from Netherlands Organisation for Applied Scientific Research (TNO) had started to explore more fundamental topics such as converting ingredients into tasty products for healthy and environmental concerns.

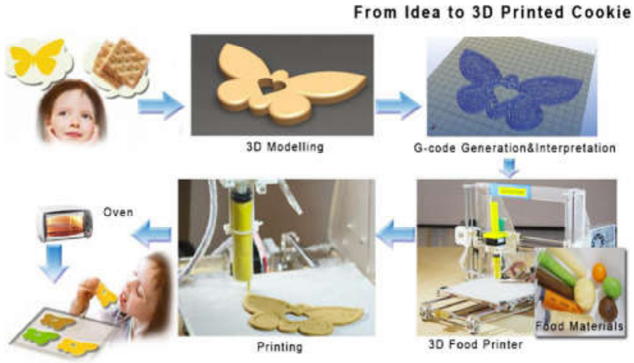

Figure 1 Overview of 3D food printing process

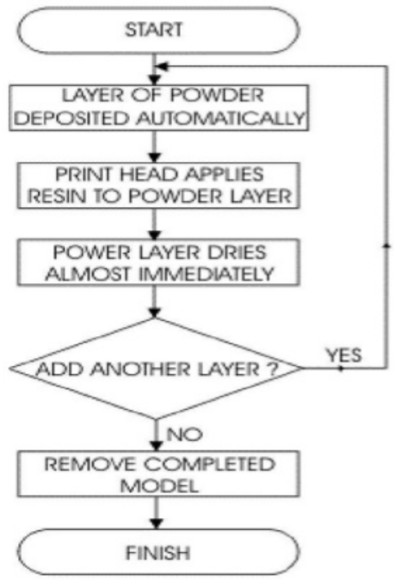

Figure 2 A Typical 3D Printing Process Flow Chart

Current Food Layered Manufacturing Technologies

The most predominant 3D technologies used in the food industry include the following:

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 Figure 3(A) or laser in Figure 3(B)) moves 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 until the 3D object is completed. TNO's Food Jetting Printer [9] 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. The Candy-Fab also 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 among layers. An advantage of selective sintering is that it offers more freedom to build complex food items in a short time without post-processing. It is basically suitable for sugar and fat-based materials with relatively low melting points. A peculiar limitation associated with selective sintering includes a complicated fabrication operation since many variables are involved.

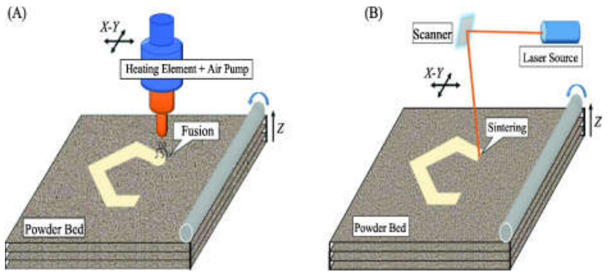

Figure 3 (A) Selective hot air sintering and (B) Selective laser sintering

Hot melt extrusion

Hot-melt extrusion, also called fused deposition modeling (FDM), was firstly described in [10] in Fig. 4, melted semisolid food polymer is extruded from a movable FDM head, which solidifies almost immediately after extrusion, and welds to the previous layers. Hot-melt extrusion has been applied to create customized 3D chocolate products [11]. MIT researchers used hot-melt chocolate as a dispensing liquid and developed a functional prototype Bdigital chocolatier [12]. In this project, compressed air was applied to push the melt chocolate out of chambers for customized candy fabrication. Using the hot-melt extrusion method, 3D Food-Inks Printer printed 3D color images on an extruded base [13], while a post-cooking step was required to fuse layers together.

Some natively printable materials like cheese, frosting e.t.c can be extruded smoothly at room temperature [14]. The material flow rate is adjusted by controlling solenoid valves, and this setup was tested using creamy peanut butter, jelly and Nutella. This extrusion method can fabricate complex confections using a single material with high repeatability, which is difficult using manual hand techniques [14]. The food printers designed based on the extrusion method usually have a compact size and low maintenance cost but greatly limited by material choices, long fabrication time, and delamination caused by temperature fluctuation.

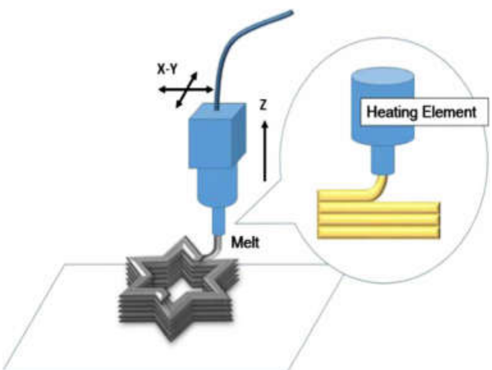

Figure 4 Hot Extrusion

Binder Jetting

In binder jetting shown in Fig. 5, each powder layer is distributed evenly across the fabrication platform, and a liquid binder is sprayed to bind two consecutive powder layers [15]. Before fabrication, a layer of water mist is sprayed to stabilize powder material and minimize disturbance caused by binder dispensing. In an edible 3D printing project, [16] utilized sugars and starch mixtures as the powder and a Z Corporation powder/binder 3D printer as the platform to fabricate customized shapes. In 2013, Sugar Lab used sugar and different flavor 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. However, food items with high sugar content and little nutritional value may not be attractive, which are often linked to obesity, type 2 diabetes and heart disease. This greatly limits this technology's market potential. However, Binder jetting offers advantages such as fast fabrication and low material cost but suffers from rough surface finish and high machine cost.

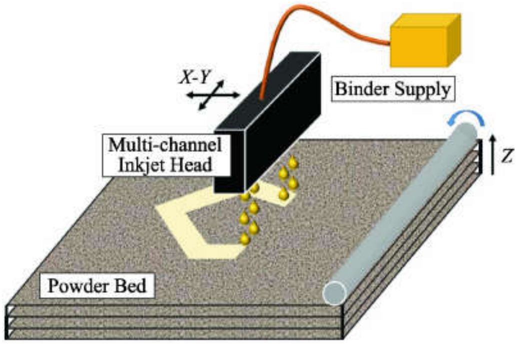

Figure 5 Powder Bed Binder Jet

Inkjet printing

As shown in Fig. 6, inkjet food printing dispenses a stream of droplets from a syringe-type print head in a drop-on-demand way for cookie, cake, or pastry fabrication. De Grood Innovations' FoodJet Printer [17] used pneumatic membrane nozzle jets to deposit drops onto pizza bases, biscuits, and cupcakes. The drops fallen under gravity and formed a two and a half-dimensional digital image as decoration or surface fill on substrates.

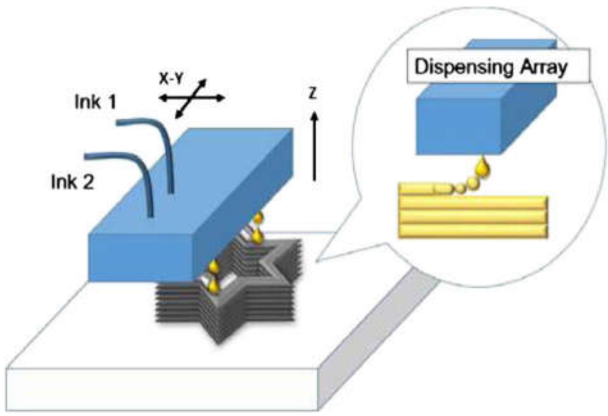

Figure 6 Ink jet Printing

Multi-material and Multi-print head

Applying multiple materials is a common in food design and fabrication, and the diversity of printing materials empowers consumers to take charge of food design. Most of food printer projects such as *ChocALM* and *Insects Au Gratin* were developed using single print head extrusion for a mixture of multiple materials.

Table 1 Comparison of Food Layered Manufacturing technologies in food printing

	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, corn flour, flavours, and liquid binder	Low viscosity materials such as paste or puree
Viscosity	$10^3 \sim 10^5$ cP	Not applicable	1 ~ 10 cP (Binder)	$5\times10^2 \sim 5\times10^3$ cP
Platform	• Motorized stage • Heating unit • Extrusion device	• Motorized stage • Sintering source (laser or hot air) • Powder bed	• Motorized stage • Powder bed • Inkjet printhead for binder printing	• Motorized stage • Inkjet printhead • Thermal control unit
Printing Resolution*	Nozzle diameter: 0.5 ~ 1.5 mm	powder size:100 µm	nozzle diameter≤ 50 µm Powder particle ≤100 µm	nozzle diameter≤50 µm
Fabricated Products	Customized chocolates	Food-grade art objects, toffee shapes	Sugar cube in full color	Customized cookies, Bench-top food paste shaping
Pros	• Cost effective • Fast fabrication	• Better printing quality • Complex design	• More material choices • Better printing quality • Full color potential • Complex design	• Better printing quality
Cons	• Low printing quality	• Expensive platform • High power consumption • Limited materials	• Slow fabrication • Expensive platform	• Slow fabrication • Expensive printhead • Expensive platform • Limited materials
Machine	Choc Creator	Food Jetting Printer	Chefjet	Foodjet
Company	Choc Edge	TNO	3D Systems	De Grood Innovations

To choose a suitable print head, [18] compared a bathtub-type gel printer and an inkjet type food printer in meso-decorated gel and agar printing. When one print head 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, multiple print heads are allocated to print supporting or fabrication materials. The data from each layer are directed to a platform controller, which activates the associated motors to move the corresponding dispensing head and control its feeding rate and deposition area.[19] fabricated a variety of food products with overhanging geometries using dual-material printing (silicon and betty crocker easy-squeeze frosting). In this study, the two materials were tested on fabricating a silicone bridge and a bouncy ball toy, either as a fabrication material or supporting material. Generally, this process may deliver multi-material fabrication with geometric complexity easier than manual operation. Printing multi-material from multi print-head is a highly attractive feature which permits switching among material sources for fabricating complex food constructs. It can be applied to testing various nutrition/ingredient combinations in a food product development process or tailor nutrition for individual preference.

Researchers tried multiple printhead using Fab@Home 3D printer and tested with frosting, chocolate, processed cheese, muffin mix, hydrocolloid mixtures, caramel, and cookie dough [20]. Dual-material printing was only achieved for a limited material set. A secondary material was utilized to support the fabrication and was removed after fabrication. Figure 7 shows two examples of multi-printhead food printing samples fabricated at the National University of Singapore. The basic materials in this biscuit recipe consist of flour, butter, sugar and egg white. Food dyes are used to color the same recipe for different layers and patterns.

material may generate multi-scale ingredients after processing. [9] proposed using electrospinning to produce multiple food sub-components at a micro-scale and further assemble them into multi-component composite structures. This is a new solution to shape non-traditional food materials under multi-scale into appealing edible structures.

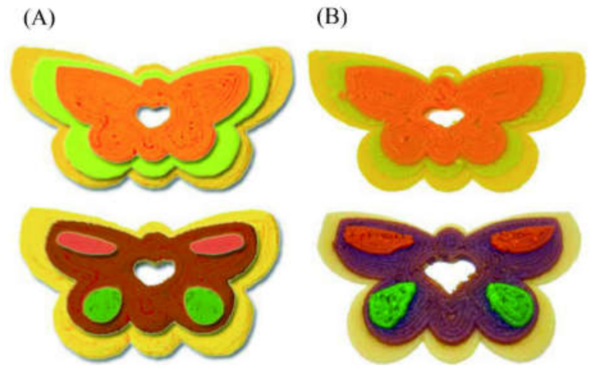

Figure 7 (A) Multi-material food design (B) Fabricated food samples

Classification of Food Printing Materials

The available materials for food printing can be classified into three categories: natively printable materials, non-printable traditional food materials, and alternative ingredients.

Natively Printable Materials

Natively printable materials like hydrogels, cake frosting, cheese and chocolate can be extruded smoothly from a syringe [6]. Final products are fabricated with diverse taste, nutritional value, and texture. However, none of them is served as main courses in meals. Some of these natively printable materials are stable enough to hold the shape after deposition. For example, the mixture of sugars, starch, and mashed potato was used as powder materials in Z Corporation powder/binder 3D printers [18] to fabricate sugar teeth. The fabricated teeth were strong enough without further post-processing. Other composite formulations such as batters and protein pastes may require a post-cooking process [20] resulting in fabricated structures difficult to retain their printed shapes.

Non-printable Traditional Food Material

Printability tests for traditional food materials were judged by viscosity, consistency, and solidifying properties [21], and the most successful printable material was pasta dough. Food like rice, meat, fruit, and vegetables, largely consumed by people every day, is not printable by nature. To enable their capability of extrusion, adding hydrocolloids in these solid materials has been utilized in many culinary fields. Although some solid and semisolid foods have already been manipulated to become printable by gastronomic tricks, it is difficult to test and modify the entire list. One potential solution is to create an element set using a small group of ingredients which can generate a high degree of freedom on texture and flavor. [6] investigated on fine tuning concentration of hydrocolloids (xanthan gum and gelatin) and achieved a very wide range of textures (i.e. mouthfeels). After printing process, the majority of traditional edibles need post-deposition cooking, such as baking, steaming, or frying. These processes involve different levels of heat penetration and result in non-homogenous texture. [20] experimented on modifying cookie recipes for both printing and post-cooking. He managed to find one recipe which can print 3D models with complex internal geometries and retain their shape after deep frying.

Alternative Ingredients

Alternative ingredients extracted from algae, fungi, seaweed, lupine, and insects are novel sources for protein and fiber. In the BInsects Au Gratin project, insect powders mixed with extrudable icing and soft cheese were used as printing materials to shape food structures and make tasty pieces. Residues from the current agricultural and food processing can be transformed to biologically active metabolites, enzymes, and food flavor compounds, as sustainable and eco-friendly printing material sources. Available food processing technologies can further scale down the size of alternative food material molecules, create more particles for an overall greater surface area, and improve food nutrition absorption and stability. Briefly, introducing alternative ingredients into food printing would aid in developing healthier (e.g., low fat) food products.

Platform for Food Printing

The recent expansion of low-cost desktop 3D printers has led to food printing development since they utilize very similar printing platforms. Food printer platform consists of an *XYZ* three-axis stage (Cartesian coordinate system), dispensing/sintering units, and user interface. With computer-controlled, three-axis motorized stage and material feeding system, these platforms can manipulate food fabrication process. A food design model, after being translated into machine path planning language (G-code, M-code, etc.), can be easily defined in terms of printing speed, deposition speed, and other geometric parameters. Food composition can be deposited/sintered essentially point-by-point and layer-by-layer according to computer design model and path planning. At least four functions are proposed in order to invent and personalize new recipes rather than simply automate traditional food fabrication process. The proposed functions are: metering, mixing, dispensing, and cooking (heating or cooling) [22]. 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 have 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 [23]. Fig.8 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

Figure 8 (A) Food printing platform and (B) Printhead

With the modified commercial platform, researchers can quickly create complex food shapes, and compare the properties and fabrication processes of various food materials. However, these platforms are not flexible for further improvement and are only applicable for a limited range of materials, and therefore they 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 [24] building cheese and chocolate 3D objects from edible ingredients [5], or reducing cost associated with freeform fabrication of sugar products with open-source hardware. 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.

Mixing Techniques

Even with multiple printheads, it is not possible to develop a platform compatible with all food material printing. An alternative solution is to combine and mix a small group of ingredients to produce a relatively large material matrix. Two types of mixing techniques are explored to vary material composition and create more combinations of flour-based semi-solid viscoelastic materials. They are, namely, the static and agitated mixing techniques.

The static mixing fully relies on the driving force from material feeding and friction force between materials and the mixer's built-in structure. It comes as a static mixer concept for two-part epoxy adhesive resin mixing and dispensing. This technique is suitable for a continuous food flow mixing. However, a few technical issues need to be overcome like consistency of food flow inside a helical structure, and the associated cleaning process for food residue within the structure.

The agitated mixing can adjust mixing ratios dynamically so that the extruded food materials can continuously change color or composition. [23] designed two rigs for agitated mixing: oscillating mixing from periodic motion in a linear way, and conical surface mixing with a large contact area and friction force. The former achieved an acceptable result in two color mixing experiments. With further improvement, they can be more appropriate for discontinuous food flow mixing.

Potential technologies Applicable to Food Printing

Besides the above described 3D printing technologies, there is a need to bring in more established technologies to further enhance the printing process, such as electrospinning and microencapsulation. They have been embedded into bio-printer design for structural coating and microsphere fabrication [24] [25]. In food science, the applications of electrospinning and microencapsulation include extracting fibers and encapsulating nutrition, thus providing additional material sources for printing. The two technologies can also be directly integrated into the food printing process through multi-printhead platform, to control fibers and nutrition dispensing. This may be a potential way to fabricate on-demand food.

Electrospinning

Electrospinning is capable of producing thin, solid polymer strands ranging from 10 to 1000 nm in diameter. It can generate antimicrobial nanofibers from chitin [27] and biopolymer zein nanofibers to encapsulate beta-carotene [28] for bioactive food packaging. Electrospinning can produce food materials with controlled size and structure, thus generating healthier foods (lower fat and lower salt) with desirable sensory properties and ingredients with improved properties [29]. It is also capable of shaping non-traditional food materials under multi-scale into appealing edible structures. An integration of electrospinning and food printing may offer a possible all-in-one solution to fabricate food products with personalized nutrition, i.e. extracting fibers out of materials, encapsulating nutrients, controlling their dispensing volume, and constructing food structures with a controlled release of the nutrients. [9] proposed using electrospinning to produce multiple food sub-components at micro-scale and further assemble them into multi-component composite structures for a variety of materials. Micro-scale fibers can provide structure and texture to food products with a pleasant taste experience, such as muscle fibers in meat, cellulose fibers in vegetables, and citrus fibers in low-fat full-taste mayonnaise. From a technical perspective, the current challenge is to integrate and manipulate electrospinning process in food printing platform.

Microencapsulation

Simply adding ingredients to food products can improve nutritional value but may compromise aroma, taste, color, and texture. Also, the bioavailability of ingredients may suffer due to slow degradation, oxidation, and reactions between ingredients and other food components. Microencapsulation can pack minerals, vitamins, flavors, and essential oils within another material for the purpose of shielding active ingredients from the surrounding environment. One of the microencapsulation approaches, electro-hydrodynamic atomization has been incorporated into bioprinter design to generate double-walled microspheres for a bioactive drug delivery system [24].

Integrating such technology into food printing can be achieved by using a multi-printhead system, where at least one printhead generates and dispenses microcapsules in the fabricated food products. This would help fragile and sensitive materials survive in processing and packaging conditions, stabilize the shelf life of active ingredients, and create appealing aroma release, taste, odor, and color masking. In other words, microcapsules containing flavor or nutritional elements would remain dormant in the food and will only be released when triggered by consumers [30]. This method simplifies the current functional food manufacturing process, enhances functional ingredient stability (e.g., probiotics and bioactive ingredients), and realizes controlled release of flavorings and nutrients.

Benfits of 3d Food Printing

Customized Food Design

Food manufacturing techniques are mainly developed for mass production, while creativity on shapes, structures, and flavors are usually compromised. Previously, customized food involves specifically handmade skills with low production rate and high cost. Food printing technologies could potentially overcome these barriers and provide a platform to experiment food design on shapes, colors, and flavors. More design solutions are generated such as customized chocolate shaping [11] and personalized full color images onto solid food formats [13]. The quality of fabricated food products depends on the fabrication process rather than operator skills. As such, production can be easily synchronized with customer demands. Some problems from traditional food production processes are virtually eliminated because complex food pieces are produced in a single process. The need for warehousing, transportation, and packaging can be reduced significantly. With a proper supply chain configuration, it is possible to improve cost efficiency of customized food products while maintaining customer responsiveness.

Personalized Nutrition

Besides existing nutritional preferences, the concept of personalized nutrition care according to a person's dietary needs, allergies, or taste preferences is on the research agenda of food industries [31] Studies have shown that individuals respond differently to various nutrients, and they may experience more or less benefit/risk associated with particular dietary components. Only personalized nutrition can meet the needs and preferences in terms of an individual's health status and body type requirement. [32] developed a 3D edible gel printer using a syringe pump and dispenser to make soft food for the elderly who cannot swallow the food well. Under the traditional food supply chain, foods with personalized nutrition are produced with additional cost. Marketing and distributing such foods may not be financially viable. Furthermore, foods with controlled ingredient formulation will be much more challenging to produce from a technical perspective. Food printing can personalize nutrition in two ways: controlling the amount of food to be printed and calibrating natural/nutritional ingredients during design. Since food in house or service store, the additional cost for distribution can be minimized.

the problem of a high food product failure rate at around 75 % [32]. To improve the communications between food scientists, food engineers, marketing people, distributors, and consumers during the product development stage, food producers need to explore ingredient combination and fabricate new design samples. However, it is always difficult to find suitable equipment with simple design and reliable performance for a small batch production. A promising solution is to further develop the food printer as a prototyping tool to conduct small batch production in a cost-effective and time-efficient way. It can help to fully understand comprehensive technical requirements, explore ingredient combination, taste, and mouthfeel prior to starting mass production. The fabricated food products may be used to verify consumer interest in a proposed design and ingredient stability of specific designs. This could also help filter out a large number of design candidates that do not meet the requirements in a short time at acceptable cost.

Customized Food Supply Chain

Food printing targets a build-to-order strategy with higher production efficiency and lower overriding cost. Under an e-commerce platform, consumers may configure or transact food designs and fabricate physical products using a nearby

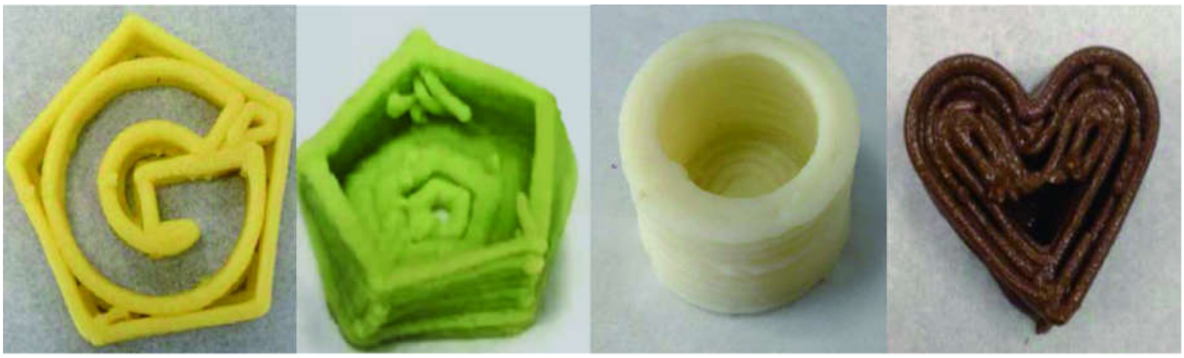

Figure 9 Customized food design and fabrication samples

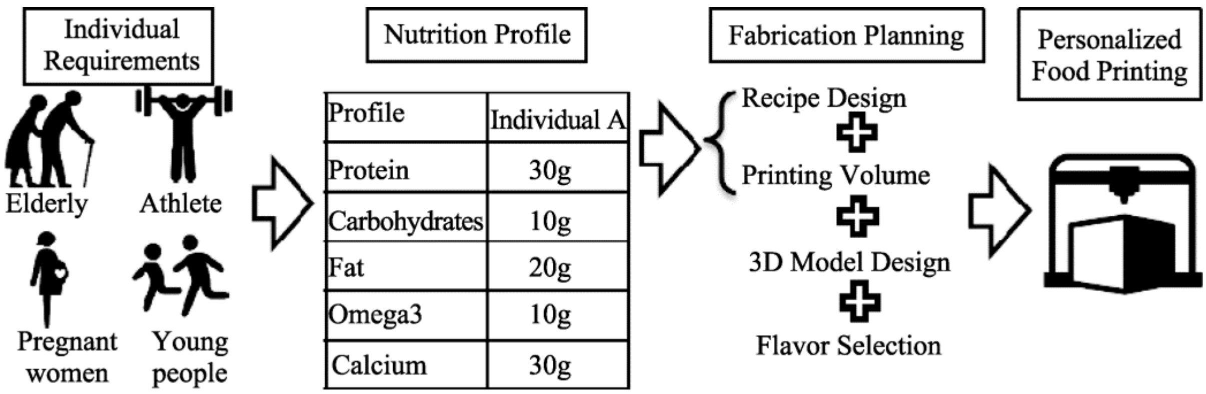

Figure 10 Customized food with personalized nutrition

Rapid Prototyping Tool for Food Product Design

In the food industry, consumer demands on improving food safety, shelf life, and nutritional value and reducing wastage create a complicated scenario for food product design. The food industry preferred to re-develop the existing products with incremental changes, rather than creating a radical change in products [31] This apparently "be safe" approach perpetuates

To achieve zero lead-time from design to market, plenty of innovative food design websites and mobile apps can assist users on design and order customized food products. All of them will result in a great change in customized food supply chains, reduce the distribution costs, simplify customized food service, and bring products to consumers in a shorter time. A description of this new, customized food supply chain is shown in Figure 11. It starts with customers searching for an online food design platform based on their needs, and selecting a food design. The corresponding design data is transferred to a neighborhood Printing Service Bureau. The selected food designs are fabricated at this Bureau and are eventually delivered to the customers.

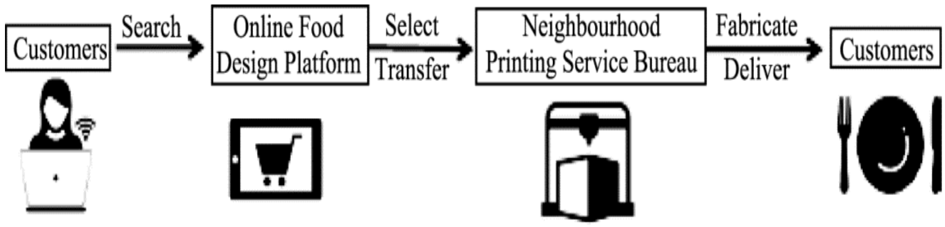

Figure 11 Customized food supply chain

Reformulating Food Processing Technologies

Most of the food processing technologies associated with chemical and physical changes may not match the 3D printing process. This applies to composition (ingredients and their interactions), structure, texture, and taste. Ingredient formulations with varied combinations and fabrication 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. In other words, conventional food processing technologies are unlikely to fit into such a complicated scenario, and they should be reformulated, such as pre-conducting some processes (e.g., gluten formation and leavening) and replacing remaining processes (e.g., shaping and baking).

Process Model and Digitalization

To model the relationship between inputs and outputs, data quantification for each process (ingredients metering, mixing, printing, baking, etc.) and communication protocols between different functions or processes should be established. Key process parameters such as temperature, moisture, and food properties (such as density, thermal, electrical conductivity, printing viscosity, and permeability) are often coupled. It is crucial to digitalize a comprehensive fabrication into steps and combine them together to formulate a simulation model for manipulation. The data on food properties can be obtained from measurement, computerized database, handbook and theoretical calculations. Since food properties often vary from batch to batch, this simulation model should be able to predict the result of a particular for a range of properties. It can also calculate the total amount of materials required to construct the final products, the construction time, as well as calorie intake.

Innovative Food Products

Buddhist cuisine applies soy-based or gluten-based materials for cooking meat analogue or mock meat dishes for vegetarians and Buddhists, which taste very similar to meat. The research [33] also proved the concept of creating a wider range of textures and tastes by mixing small group of hydrocolloids and flavor additives. In other words, it is feasible to create a wide range of food items with very similar taste and shape by using a limited number of raw materials/ingredients. If such knowledge is embedded into the food printing process, more innovative food products and unique dining experiences can be created.

Incorporation of Alternative Ingredients

In an era where foods sources are being endangered in some parts of the globe, to create more food products with different kinds of ingredient substitutions can be one of the solutions.

As it has been studied by designer Susanna Soares and Food Bio-scientist Dr. Kenneth [34]. insects can be used to make food products with the help of 3D printing to serve as an alternative for protein intake. When compared with conventional meat products, the protein concentration inside insects is slightly higher and 3D food printing can greatly contribute to making unpleasant aesthetics and cultural background of insects become more “digestible” to consumers.

Besides, food printing can make use of alternative food ingredients with longer shelf life. Raw materials usually have longer shelf life than the final food products. If food products can be quickly fabricated on the spot based on users’ requirements, users would be able to have their meals fresh all the time. That is actually one of the reasons why NASA has poured $125,000 into the research and development of food printing to explore the capability of this new application and discover a variety of foods with shelf stable ingredients [35].

Professional Culinary in Daily Life

With a 3D food printing platform, designs from culinary professionals can be fabricated at any place by downloading the original data files. Users can reproduce an original work by importing the corresponding fabrication files that carry culinary knowledge and artistic skills from chefs, nutrition experts, and food designers. After downloading design files, the products can then be built in front of the customers using their personal 3D food printer. It is a new context of household product making, which would be impossible to achieve using the existing methods.

Challenges of 3D Food printing

Although the 3D Food Printing may offer tremendous opportunities and the projection of food printing future is beautiful and attractive, it also comes with a few challenges. These are the barriers that development of food printing needs to overcome for popularization and serious applications.

- The major issue is the food materials development. To enlarge the pool for printable food materials with both stable features and similar flavor and texture as compared to the traditional products. To enable the full customization in shape, flavor, color and nutrition. Typically for the nutritious customization, it is a big challenge to make progress in the dynamic and adjustable compositions of food nutrition combination in food printing.

- Another challenge can be the cleaning process and maintenance of the machine. If refilling is a necessary, how to ensure the food materials throughout the whole process not to get contaminated by the machines needs to be carefully considered and designed. Food is related to people's safe and health. Therefore, additional requirements increase the complexity of the design and no mistakes are allowed.
- In addition, a potential limitation can be the front-end modeling for the food products. Corresponding parameters and standards for food printing are highly dependent on the selected food materials. How to ease the operation of the customers during the configuration of food printers and make the whole interface user friendly will directly determine the final acceptance of the food printing technologies in public.

Other challenges can be the validation of the market desirability and the perception and acceptance of the public. To discover the compelling applications of food printing is not easy. Currently based on the capability of food printing, useful applications are still narrow and specified.

Sustainability and Ethical Issues

An increase of global population results in growing demand for food. Alternative ingredients extracted from algae, fungi, seaweed, lupine, and waste from the current agricultural and food production can be utilized as printing materials in the future. All of them may ease the growing demand for food production in an environmentally friendly and efficient manner. Using other advanced technologies, these food materials can be scaled down to a greater extent, which makes nutrients more stable and more absorbable in the human body. The most controversial ethical issue is in regard to printing meat. 3D printed meat could provide high-quality proteins without increasing stress on arable land or fishing farm. For vegetarians, printed meat somewhat circumvents concerns about harmful or destructive use of animals for food. Australia has sponsored an ethical research program for uncovering and articulating community concerns about this emerging technology [34].

Future work

At this point in the time the possibilities of this emerging technology are being explored with respect to the type of products that can be made from a materials and technology point of view. However, the potential is clear. To realize the prospects offered by 3D food printing, research has to be continued. Various companies are looking for business partners in several industries including food manufacturers, the food (service) industry and developers of 3D food printing equipment for industrial or domestic use. Currently, few food printers (such as *Foodini*) only print the food, which must be then cooked as usual. But future models will also cook the preparation and produce it ready to eat. On the other hand, Sugar Candies and Desserts etc. printed using *ChefJet* printer are ready to eat. The 3D printing of food is something which may take a while to catch on. Although there are several companies, including *3D Systems*, working on this type of technology, it's only been within the candy/desert space where such techniques have actually taken off. With this said, changes within the industry are happening at such a rapid rate that we may see widespread 3D food printing take hold sooner rather than later

CONCLUSION

3D food printing has demonstrated its capability of making personalized chocolates or producing simple homogenous snacks. Currently, these applications are still primitive with limited internal structures and monotonous textures. It is necessary to develop a systematic way to investigate recipes, 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. Food printing technologies apply digital technologies to manipulate food forms and materials. This versatility, applied to domestic cooking or catering service, will allow efficient delivery of high-quality, freshly prepared food items to consumers. It can also deliver personalized nutrition, new flavors, textures, and shapes of food products. With the development of an open web-based media interface, food printers may form ecology of networked machines that can order new ingredients, prepare favorite food on demand, and even collaborate with doctors to develop healthier diets.

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