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Recent Development in 3D Food Printing

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ABSTRACT

Robots and softwares have been significantly improving our daily lives by rendering us much convenience. And 3D printing is a typical example, for it is going to usher in a new era of

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localized manufacturing that is actually based on digital fabrication by layer-by-layer deposition in three dimensional space. In terms of food industry, the revolution that three-dimensional printing technologies is bringing to food manufacturing is convenience of low-cost customized fabrication and even precise nutrition control. This paper is aimed to give a brief introduction of recent development of food printing and material property of food ingredients that can be used to design the 3D food matrix and investigate the relationship between process parameters and resulting printed food properties in order to establish a food manufacturing process with this new food production approach.

Keywords 3D printing; Food; New developments; Materials; Phase temperature

INTRODUCTION

3D printing is a method that can make a three-dimensional object based on layer-by-layer deposition. The designs of objects are created by Computer Aided Design (CAD) software and the 3D printer is connected and controlled by the computer by a USB cable. The products are produced based on 3D models or other electronic data source and can be made into any shape in theory. Distinct from traditional machining techniques, 3D printing mostly relies on the removal of material by subtractive processing methods such as drilling or cutting. Thus 3D printer can easily make intricate shapes and even used-to-be impossible internal structures.

The very first part of the 3D object was printed in 1983 by Chuck Hull who invented 3D printing (Hod Lipson, Melba Kurman, 2013). 3D printing technology is initially used in military field. With the efforts made by researchers this technology has been experimented to wider applications. Recently, 3D printing technology has also been experimented into various kinds of food systems, that is, Food Layered Manufacture (Wegrzyn et al. 2012). By using 3D printing technology, suitable ingredients can be mixed and then processed into the most intricate shapes and structures which are impossible to be made or are uneconomical to produce under traditional manufacturing process. These kinds of food can have entirely novel textures and flavors that are unimaginable to be produced through traditional cooking processes. Thus, it is predicted that 3D printing technology can bring the processing or food preparation technologies into the digital age. Wide variety of ingredients can be automatically mixed during printing on the basis of certain selected recipes and be made in the absence of operator by introducing advanced settings.

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The 3D food printing follows the principle of a Solid Free-Form (SFF) method. The SFF method includes Stereolithography Lasing(SL), Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS). Fused Deposition Modeling (FDM) is the main 3D printing method that can be used for food. FDM applies to 3D food printing of various foods such as molten materials in liquid state such as chocolate, gelatin, sugars etc. Purees, gels and doughs are all deposited directly without any structuring agent or added with structuring hydrocolloids as the deposited material to support their structures. A syringe, whose one end connects to an electric engine and the other end connects to one or two nozzles, normally appears in the most fundamental structure of a food printer. Plastic clips firmly fix the nozzle in place. Several containers or reservoir are used to mix and store all the ingredients and the syringe or nozzle is used to deliver the ingredients. The ingredients in the syringe are pushed or extruded onto the platform by an electric motor, and this system is called an extruder. The printer can be equipped with multiple extruders. The extruder can also be a dual-feed extruder that pushes two different materials with different colors from the nozzle to generate a third color by adjusting the mixing ratio controlled by a colormix generator (a computer application software). This type of color mixing dual-feed extrusion food printer has been developed by a Holland manufacturer called Builder (Builder Ltd., 2015). The heating platform where the materials are deposited can also perform the cooking of the raw food. Previously, Periard et al. (2007) used dual-material printing including Betty Crocker easy-squeeze frosting and silicon to print a bouncy ball toy and a silicone bridge, which in fact were much easier than manual work. Hence, it is definitely that printing multi-material from multi-printhead will create infinite potential combinations of gourmet in the near future, which is highly attractive and worthy of in-depth research.

3D printing technology also makes it possible to add certain ingredients and colors and flavors in every taste to produce delicious foods and to satisfy the need of personalized nutrition. Not only CAD but also scanner and other software that are freely available on the net allow people to touch and feel the designs. This can be a similar feeling as if one plays with digital clay and make everyone to be an expert designer and manufacturer of designed food.

With the improvement of the quality of 3D printers, the prices of these machines will be falling. As presented in Figure 1, person can download product data from the net and fine-tune it according to their own taste. The redesigned information will be sent to a 3D printer and fabricated. The physical products can be ready to use without further process, or need to be assembled into other forms or shape. Thus, as long as we have the design data, one can easily create the products according to own preference. Both aesthetic customization and functional customization can be achieved at the same time, for example scanning parts of certain bodies of objects and creating things that are produced to match everyone's original imagination.

In addition, there are four main kinds of 3D printers, including triangle, rectangle-cassette, rectangle-pole and triangle-claw. And triangle and rectangle-cassette are the most common ones of all in reality. Table 1 shows comparison of structures of these main kinds of 3D printers. And each of them has their own advantages and limitation. For instance, triangle structure has simple structure and convenient maintenance, low cost, but has lower accuracy and poor design; while rectangle-cassette structure has higher accuracy and good design, but has complicated installation and high cost. According to their own properties, the majority of triangle structure applies in DIY fabrication field, while most of rectangle-cassette structure appear in the market.

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For food researchers, understanding the food material properties is the most important things. A large variety of foods are appropriate ingredients for 3D printing, such as confectionery food such as chocolate and candy, and foods mainly used in dough such as pasta, pizza and crackers. For example, one of the food printing machines Foodini printer, made by the Barcelona-based company Natural Machines, is intended as a domestic device to make varieties of food shape and structures such as cookies, chocolate, vegetable puree and pizza (Natural Machines Ltd., 2014). Perhaps some people consider that using 3D printing technologies to make traditional foods like chocolates or pizzas seems like an overskill for a mundane application. But actually what 3D printing technologies bring to traditional food is not only customized shape but also novel textures and even flavors that people have never known before. Above all, 3D printing technology is a promising technology that has a potential to provide the opportunity to produce food products with better quality control, environment-friendly, higher energy efficiency and lower cost.

This article is aimed to overview recent developments in the 3D printing technology applied to food systems. It also examines the relative advantages of this technology in maintaining the quality of 3D printed foods and highlights prospects of further research and possible industrial applications.

PRINCIPALS AND METHODS OF 3D PRINTING

A 3D printing technology is actually one of the additive manufacturing methods. A 3D printer is a kind of machine which can rapidly prototype products. Different from traditional printers, 3D printers use various kinds of other materials such as architecture materials and food materials as ink. The products which come out of the machine can be parts or models or foods or machines. 3D printer makes products by various kinds of layer-by-layer deposition on the plane surface. There are several types of layer deposition that perform 3D structures: Fused Deposition Modeling (FDM), Stereolithigraphy Apparatus (SLA), Three Dimensional Printing and Gluing (3DP), Selecting Laser Sintering (SLS) and Powder Binder Printing (PBP). The computer softwares such as Repetier-Host and Arduino IDE control the machine to print products on basis of designs of 3D datas (Jelmer Luimstra, 2014). The printed models have fine quality because of the high accuracy and resolution of the printer. 3D printing technology will need suitable printers and material according to various specific purposes. There are four categories of 3D printers based on the shape they fabricate: triangle-structure printers, rectangle-cassette-structure printers, rectangle-pole-structure printers and triangle-claw-structure printers (Jelmer Luimstra, 2014). The former two types are the most common ones in the current market because of their better performance (Jelmer Luimstra, 2014). Usually, triangle-structure printers are mainly DIY-assembled ones, and their major features are convenience of maintenance but have lower accuracy. The rectangle-cassette-structure printers are primarily commercial available. They possess high accuracy but are inconvenient due to high cost of maintenance (Jelmer Luimstra, 2014).

In general, a 3D printer mainly comprises of the frame, mechanical seals, control circuit and the motor. The control circuit is the key part which is programmed to act as a medium to connect between the machine and the computer and to control the work of the printer.

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APLICATIONS OF 3D FOOD PRINTING

An ongoing problem that requires to be solved properly is to provide sustainable nutrition and appealing food to feed increasing global population. With the development of 3D printing technology, we may be able to avail the opportunity to use not only new nutrient-dense but nearly infinite food materials including exotic foods such as insects that are not accepted by the majority of people as ingredients to create new popular food to feed all the global population (Jelmer Luimstra, 2014). In addition, as 3D printing can also be serve as a new potential cooking way. Increasingly revolutionary changes is expected to happen on certain traditional foods such as chocolate, cookies, cakes and ice creams. Although the recipes of these traditional sweet food products do not change significantly, this new fabricating technique can innovate novel textures and flavors of food to strengthen the likeness of people to food products. Therefore, the applications of 3D printing food products can be based on two aspects. (1) New nutrient-dense and potential usage of any food materials (2) Improvement on traditional food products' appearance and texture by the control of food materials at macro- and micro-structural levels (Jelmer Luimstra, 2014).

Opportunity to Fabricate Nutrient-dense Innovative Food Materials

The benefits of printing of food can be several: (1) Food can be personalized on behalf of ingredients, composition, flavors, shapes and sizes to cater to different people's needs, health conditions, life style and appetites; (2) ingredients which are nutrient-dense can be incorporated, including exotic insects; (3) It will be convenient to freshly prepare food; (4) It will be free to create new designs for food with innovative shapes, textures and flavors.

Personalized food, which are produced by 3D printing machines, should consider composition (includes total calories, added macronutrients and added micronutrients), size and sensorial and textural attributes. For 3D printing, all the ingredients are made into puree or powders in advance, thus the building performance should be evaluated after completion of the printing such as looks, object strength and stability after heating (Hod Lipson, 2013).

Cornucopia design

For individuals, the source of economic healthier choices would be a new kind of digital information-based food culture. The environment-friendly property of this this new type of food manufacturing method is a possible trend for the future. Digital gastronomy is a recent novel concept that allows people to casually change types and volumes of ingredients based on their nutritional content as well as their own individual preferences (Amit Zoran, Marcelo Coelho, 2011).

One of the leading 3D printing companies The Fab @ Home project made first open-source DIY 3D printer and aimed to make the technology accessible to normal people (Jeffrey I Lipton, Daniel Cohen, Michael Heinz, Maxim Lobovsky, 2011). Marcelo Coelho and Amit Zoran describes a new concept of digital gastronomy—Cornucopia (Amit Zoran, Marcelo Coelho, 2011). They presented how to turn kitchen tools appeared in science fiction into reality by their new design for gastronomy. Their concept designs was classified under three different categories: the modeling of food ingredient combinations into unparalleled shapes with precisely defined dimensions; the chemical and physical transformation of existing ingredients into new combinations; combine and mix various kinds of ingredients and to completely control their quantities, types and sources. The Robotic Chef, the Digital Fabricator and the Virtuoso Mixer were the main concepts introduced by this digital kitchen. They presented the term digital gastronomy to show their focus that is on how 3D printing technology can be officially introduced into the kitchen so that it may influence the process of cooking and our eating experiences to bring a revolution in food's preparation, culture, economy, chemistry and physics. Relevant examples of ideas for future kitchens are the application of computer numerical controlled (CNC) laser machines to create 3D sugar structures and DIY 3D printers to model 3D objects from other edible ingredients such as chocolate and cheese. Various designs and materials with exceptional efficiency and capability lead to the development of new flavors, textures, scents and shapes which are not achieved through traditional cooking methods (Amit Zoran, Marcelo Coelho, 2011).

Insect food

Many experts believe that, in the near future, the global population will still keep growing while we risk not having enough food that can feed everyone. The European Union and the World Food Organization recognize the fact that making insects into proper food might be one of the ways to cope with this this problem, as insects could be abundant resources that can be made into flour in order to prepare various nutritious healthy meals (Kjeld van Bommel, 2014). Insects are rich in protein and fiber and other nutrients. For a long time, although insects are nutrient-

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dense, they are not accepted as food materials for the majority of people owing to their odd original looks and flavors. British scientists have been attempting to combine the "3D printing" and "insects" to develop a technique which can turn insects into appetizing meals (Jelmer Luimstra, 2014). This team has experimented mealworm beetle larvae in combination with fondant to produce icing for the top of cakes as well as cake decoration. In addition, Susana Soares (2011) has used this kind of insect flour to print food that has the shapes of butterfly wings and honeycombs. In addition, Kjeld van Bommel (2014) and Jelmer Luimstra (2014) are extracting basic carbohydrates, proteins and nutrients from algae or insects and then using them to print steak and chicken which requires far less labor and energy than does a chicken or a cow.

Improvement on Appearance and Texture of Traditional Food Products

In this digital age, researchers are confident that users would easily precisely control the nutritional value, quality, flavors and texture in each meal through a touch-screen interface and internet connectivity. Besides, as the food printer can be connected to Internet, the food printer will also be able to automatically order new ingredients if they are consumed.

There can be special and strict requirements to food ingredients for 3D printing. First, ingredients must be flowable to extrude from the nozzle. Second, ingredients also must be hold its structure to maintain shape after depositing on the printing platform. Understanding of glass transition, gelation, rheology and melting properties of the material will be important. Also, the inherent characteristics of various ingredients, heat resistance and cooking properties of the printed material need to be considered. In addition, material's biochemical and microbiological properties and biological variation should also be considered.

Though printability tests for food materials including detections of viscosity, consistency and solidifying properties, Cream, chocolate and starchy foods such as raw dough are all indeed ideal experimental materials used by scientists and engineers (Jelmer Luimstra, 2014). Raw dough is one of convenient and available ingredients which can be mixed randomly. Use of this dough can help researchers realistically simulate expensive rare material properties (Jelmer Luimstra, 2014). One available solution to enable the majority of appealing natural food material such as vegetables and meat to apply in 3D food printing is adding hydrocolloids such as xanthan gum and gelatin to achieve desirable textures and remain satisfying shapes after post-processing (Cohen, D. L. et al., 2009).

Chocolate

The melting and crystallization behaviors of fat present in chocolate will be important to understand from the point of view of deposition temperature and change occurring in deposited chocolate. The physical properties and mouthfeel of the 3D printed chocolate product will be dependent on the time and temperature history after deposition. Mulji and Mackley *et al* (2003) investigated microstructures and mechanical property changes in cold-extruded chocolate. The temperature rise above ambient condition is plotted against time after extrusion, showing that the process is essentially non-isothermal (Figure 2). The rise in extrudate temperature is believed to be due to the occurrence of phase changes (mainly crystallization of fat) within the chocolate with time after extrusion. Figure 2a shows that the magnitude of the temperature rise decreases with the die exit diameter (*D*). Figure 2b also shows the dependency of the temperature rise on the chocolate recipe, namely Milk, White and Dark. Dark chocolate, which contains less fat, showed the greatest temperature rise and milk the least. Figure 2c shows that varying the relative amounts of milk fat and cocoa butter in milk chocolate did not have any significant effect on the temperature profile.

The M_n data provides direct evidence for a decrease in LFC (Liquid Fat Content) with time after extrusion. Figure 3a shows that the amount of liquid fat formed due to extrusion increases with decreasing exit diameter. Figure 3b shows the evolution of M_n for different chocolate recipe, namely Milk, White and Dark. Dark chocolate which contains less fat showed the greatest decrease in LFC after extrusion and milk the least. Figure 5c shows that varying the relative amounts of cocoa butter and milk fat in milk chocolate did not have a significant effect on the M_n evolution. The T_2 data show the same trend as the M_n data and this is probably due to the change in LFC with time (Figure 3d-f).

J. Engmann and M.R. Mackley (2006) described the development and application of the model that has the ability to describe the extrusion behavior of semi-solid chocolate. L. Hao *et al* (2010) investigated the extrusion behavior of chocolate with advanced 3D printing technology. Figure 4, which is DSC thermogram, shows DSC analysis of the deposited chocolate product, indicating that the viscosities of the chocolate is can be relatively constant when the temperature is between 32 and 40℃ and the pressure is between 3.5 and 7 Pa.s.

Study on 3D printing of dental porcelain slurries (Jiwen Wang, Leon L. Shaw, 2005) shows that the distance between build plate and the nozzle is vital to the quality of the building plate or certain deposited material, suggesting that the nozzle height could be calculated by the equation below:

$$h_c = V_d / (v_n * D_n) \qquad (1)$$

where V_d is the volume of the material extruded per unit time (cm^3/s), v_n is the nozzle moving speed (mm/s), and D_n is the nozzle diameter (mm). The results showedthat the build heights will be different for different materials, and also that different material determines different extrusion height. The diameter of the nozzle is also very critical. Too small nozzle will lead to too slow extrusion speed, and too large nozzle will lead to a rough food surface. Jiwen Wang and Leon L. Shaw (2005) set the nozzle for three diameters: 1, 1.25 and 1.5 mm. By varying the extrusion rates and nozzle moving speed the best nozzle diameter found was 1.25 mm in terms of property of the deposited product.

Figures 5 and 6 suggest that the higher extrusion rate leads to the greater volume of extruded chocolate and extrusion rate becomes more even at the higher extrusion rate than at the lower extrusion rate. In addition, Figure 7 shows that axis movement rate and extrusion rate could be restricted when bead diameter is 1.25 mm. The data suggested that certain points of axis movement rate or extrusion rate have different optimal settings under the same condition.

All these reports indicate that there is a need to optimize the rate and resolution of deposition of the product during 3D printing. (J. Engmann and M.R. Mackley, 2006; Hod Lipton, 2010). To successfully create layer-by-layer structure, the physical properties of food material or ingredients, especially the melting and crystallization behaviors, are vital to be considered and continuously optimized. Also, some properties of 3D printers, such as speed (e.g. axis movement rate and extrusion rate) and accuracy have impact on the final products which are successful or not. Maybe some people think 3D printing of chocolate is perhaps not necessary, but at least this kind of simple 3D food printing research gives us an excellent demonstration how to illustrate 3D printer characteristics.

Cookies or starch-based polymers

Franz Nigl (2013) successfully made a cookie printing a message onto the top of each cookie. The same team created a new form of fried corn dough. At the same time, Jason Bowman (2013) successfully used raw dough to make high-resolution cookies by modifying the recipe of cookies to enable the cookies to maintain their shape after printing.

Lam et al (2002) developed a unique blend of starch-based polymer powders (cornstarch, dextran and gelatin) for specific 3D printing process. Cylindrical scaffolds of five different designs were fabricated and post-processed to improve their mechanical and chemical properties. The scaffold properties were characterized by scanning electron microscopy (SEM), differential scanning calorimetry (DSC), porosity analysis and compression tests. These experts applied such technologies to the standard of the quality of 3D printing products, and have achieved great success in medical field. However, biocompatibility of the set of materials used needs to be studied in the future.

Dough

The early attempts for 3D food printing were all made using simple dough that hardened when dried or cooled. These kinds of paste-based diet might suit certain specific consumers (such as astronauts), but it is too limited for the mass in their daily lives. If we want the food printers to be on the market, the printers will require a much larger range of ingredients, recipes

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and cooking temperatures (Jelmer Luimstra, 2014). Some researchers mixed gelling agents like carrageenan, xanthan gum and gum arabic with other ingredients including supplements and then mix them into the printer to create edible constructs like raspberry domes, mushroom-shaped bananas and cubes of milk (Jelmer Luimstra, 2014). Jeffrey Lipton (2015) successfully made deep-fried scallops, turkey and celery which have creatively customize food shapes. Turkey, scallop and celery were modified using transglutaminase to enable them to be hot processed after printing.

Frozen foods

There are also other 3D printing reports like printing of ice cream, cakes, cocktail and gum. Kyle et al. (2014), modified an existing 3D printer. They put a freezer inside the printer, and a liquid nitrogen cooling system to set the ice cream in place. In these experiments, Whippy-style soft ice cream, and voila - custom shaped chunks of ready-to-eat ice cream were printed. Fraguada (2014) also printed ice cream. This printer, which is called FoodForm, was also able to 3D print several various types of food, such as cake, honey, ice cream, fruit or vegetable puree, dough food and eggs. They also used Polyscience's Anti-Griddle, a machine which cools any plate to -34℃, which enabled them to print about 10mm and still get their top layers to be frozen and could freeze the ice cream directly after it is been extruded. MELT icepops, (a new company from Amsterdam) reported building a 3D food printer that produced particularly designed precise ice cream (Jelmer Luimstra, 2014). This machine could produce ice cream by own design,

TRENDS AND CHANLLENGES IN 3D PRINTING OF FOOD PRODUCTS

Challenges

3D food printing is far more complex than the way it looks. There are several conditions that needs to be optimized in 3D food printing, including proper use of mechanical force, careful design of digital recipe and suitable feeding ingredients. Different food formulations are necessary to be applied with different pressures. Sometimes room temperature maybe also affect the food mixture flow rate through the food nozzle (Hod Lipson, 2013). The size and diameter of the nozzle are both critical for the rate of deposition and resolution. Even if the nozzle has the right size and ingredients have the adequate velocity, some fresh ingredients in the syringe may not be stable. Sometimes the oil will form a block, or the food which are printed out are deformed and fall far short of the desired shape as water in the food ingredients mixture goes to the bottom of the syringe (Hod Lipson, 2013). People often misunderstand 3D food printing process that the nozzle can be directly emitted fried chicken breast or baked bread (Hod Lipson, 2013).

Optimization of 3D Printing Process Conditions with Both High-Quality and High-Efficiency

Optimization of 3D food printing process is a challenging problem that demands evaluation of specific customized needs of individuals. On behalf of computer numerical control, certain settings, such as line distance, nozzle diameters, writing speed, laser power, numbers of layers, shape and layer thickness, especially printing temperatures control and rapid cooling, should also be seriously considered. But unfortunately, few literature about phase transition temperature of ingredient mixtures has been reported yet. While determining the food recipes, the properties of

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food materials should be considered as the materials should have high strength to fit the needs of printability.

CONCLUSION

This review has showed some recent developments in 3D food printing technology, especially new personalized food, chocolate, starchy food and other traditional foods. Increasing number of novel food formulations with intricate and attractive shapes are continually developed. The trends and challenges for future can be listed as below: optimization techniques of 3D printing process and exploration of more new food materials or ingredient recipes suitable for printing and the cost of the printer.

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

Structure	Triangle	Rectangle-cassette	Rectangle-pole	Triangle-claw
Typical Machines	Prusa	Replicator, Ultimaker	Printrobot	Rostock
Advantage(s)	simple structure, convenient maintenanace, low cost	higher accuracy, good design	simple structure, higher accuracy, lower cost, convenient maintenance	higher printing speed, simple installation, convenient maintenance
Disadvantage(s)	Lower accuracy, poor design	complicated installation, high cost	poor design	complicated adjustment, too much occupied space

Table 2 Compositions and total fat content of the chocolates (N. C. Mulji et al., 2003)

	Chocolate recipe					
Component (wt%)	Milk	White	Dark	Added CB	Added MF	Added CB + MF
Sugar	46.9	43.5	49.9	45.9	45.9	45.9
Non-fat milk solids	16.9	22.9	0	16.6	16.6	16.6
Cocoa butter	7.7	20.2	1.9	9.4	7.4	8.4
Cocoa mass	14.3	0	45.3	13.9	1.9	13.9
Milk fat	7.9	8.1	2.5	8.1	10.1	9.1
Cocoa butter equivalents	4.9	4.2	0	4.8	4.8	4.8
Lecithin	0.5	0.1	0.4	0.4	0.4	0.4
Vanillin	0.04	0.05	0.01	0.03	0.03	0.03
Water	0.9	1	0	0.9	0.9	0.9

ACCEPTED MANUSCRIPT

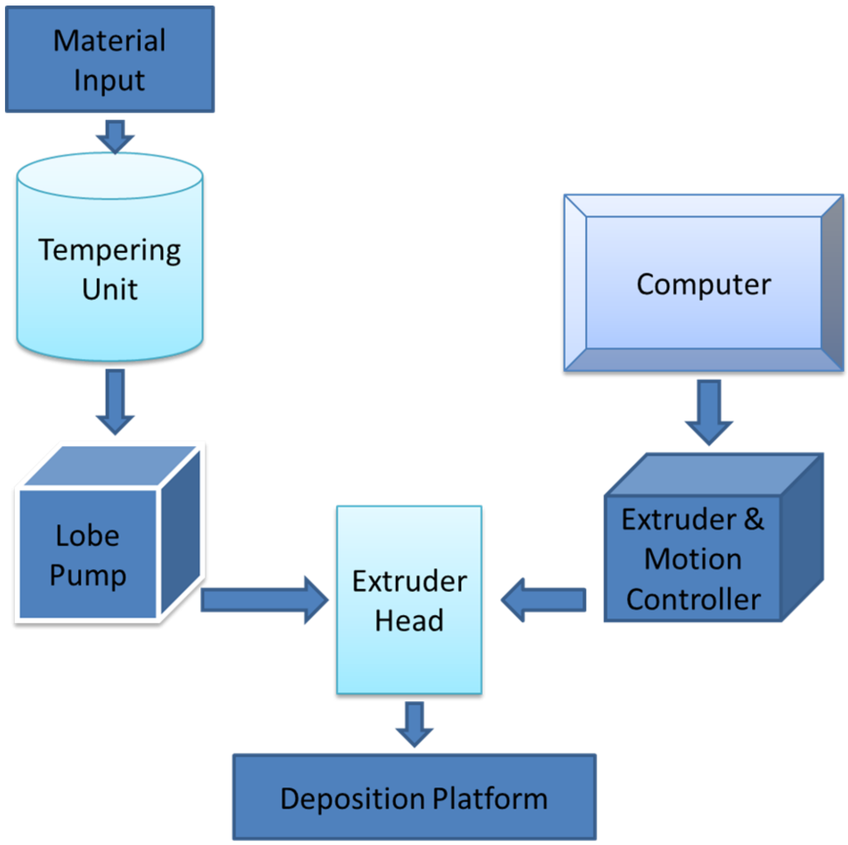

Fig. 1 A schematic diagram of food printing

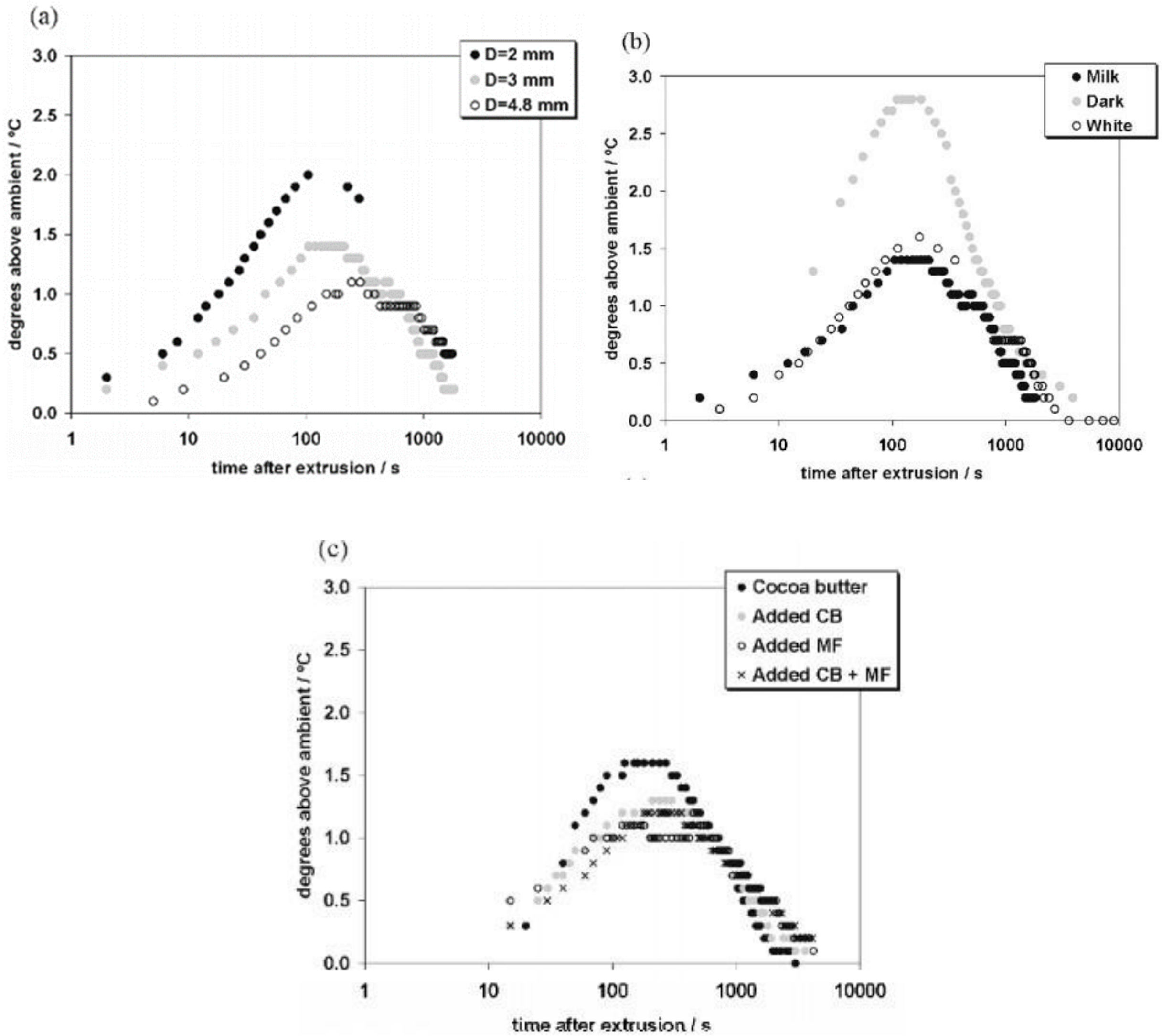

Fig. 2 Rise in extrudate temperature above ambient with time after extrusion: (a) exit diameter dependence for Milk; (b) recipe dependence for *D* = 3 mm; (c) fat content dependence for *D*= 3 mm. (N. C. Mulji et al., 2003)

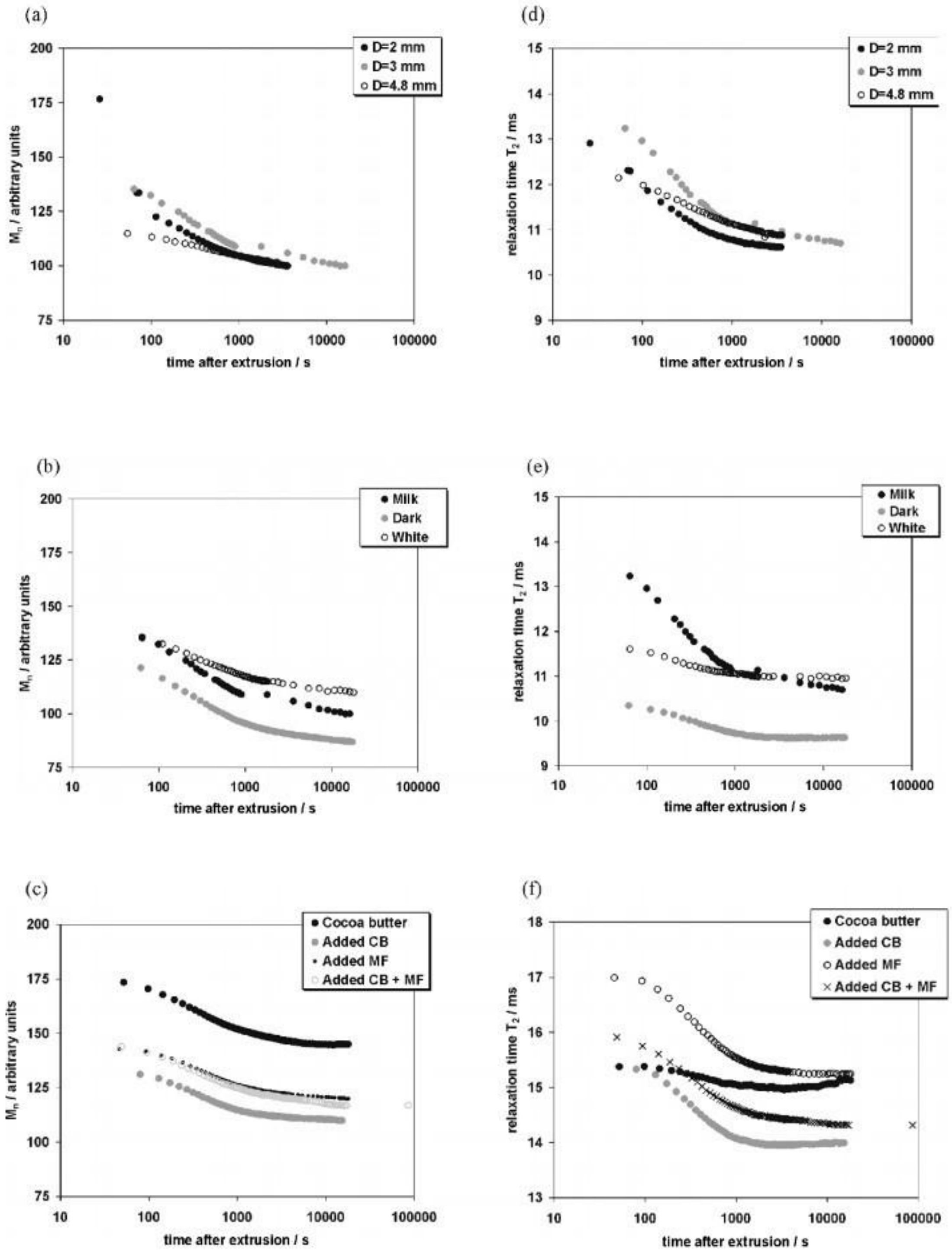

Fig. 3 (a) Decrease in signal intensity M_n with time after extrusion with diameter for Milk recipe; (b) Decrease in signal intensity M_n with time after extrusion with recipe for D= 3 mm; (c)

Decrease in signal intensity M_n with time after extrusion with fat content for D= 3 mm; (d) Decrease in relaxation time T_2 with time after extrusion with diameter for Milk recipe; (e) Decrease in relaxation time T_2 with time after extrusion with recipe for D= 3 mm; (f) Decrease in relaxation time T_2 with time after extrusion with fat content for D= 3 mm (N. C. Mulji et al., 2003)

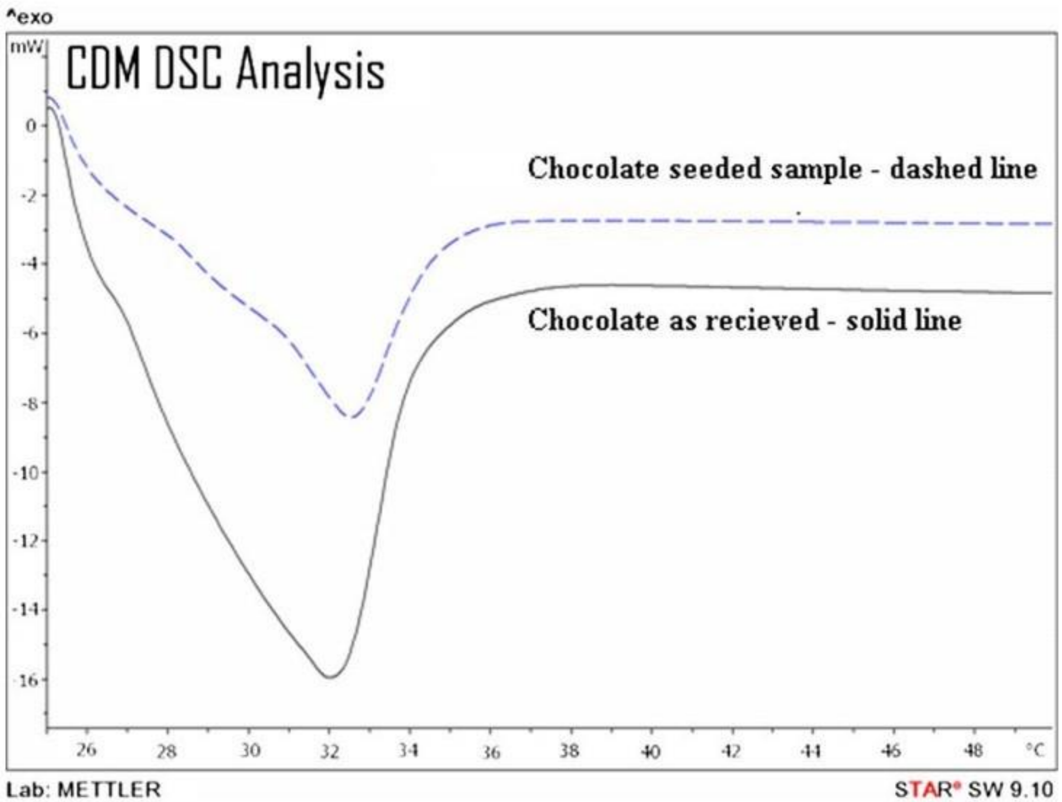

Fig. 4 DSC Analysis of as received and tempered by seeding CMC chocolate. (L. Hao et al., 2010)

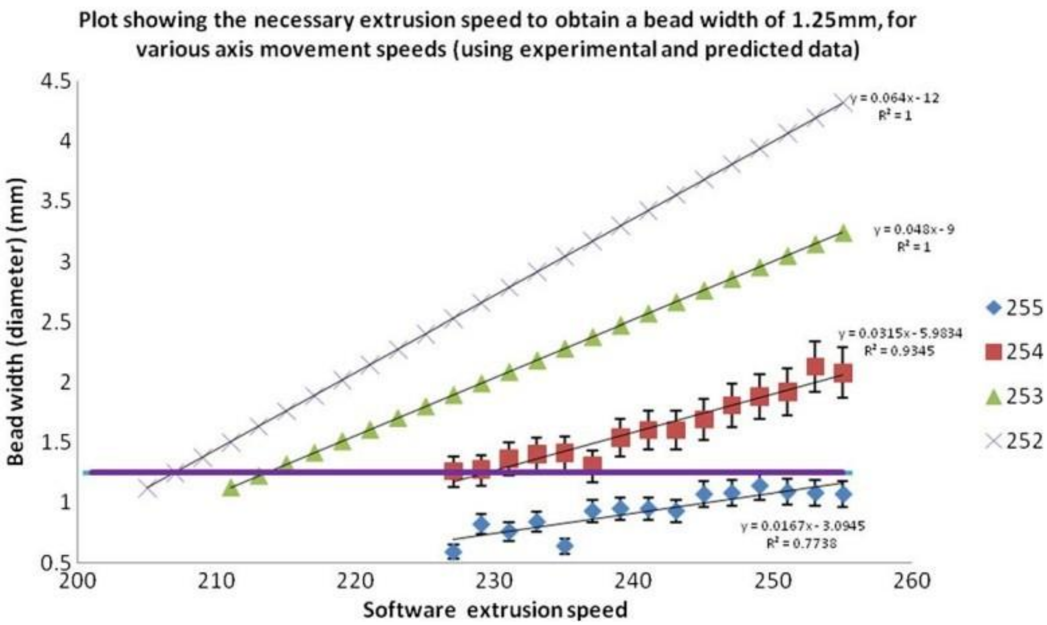

Fig. *5*. Relationship between software extrusion rate and resulting bead diameter (L. Hao et al., 2010)

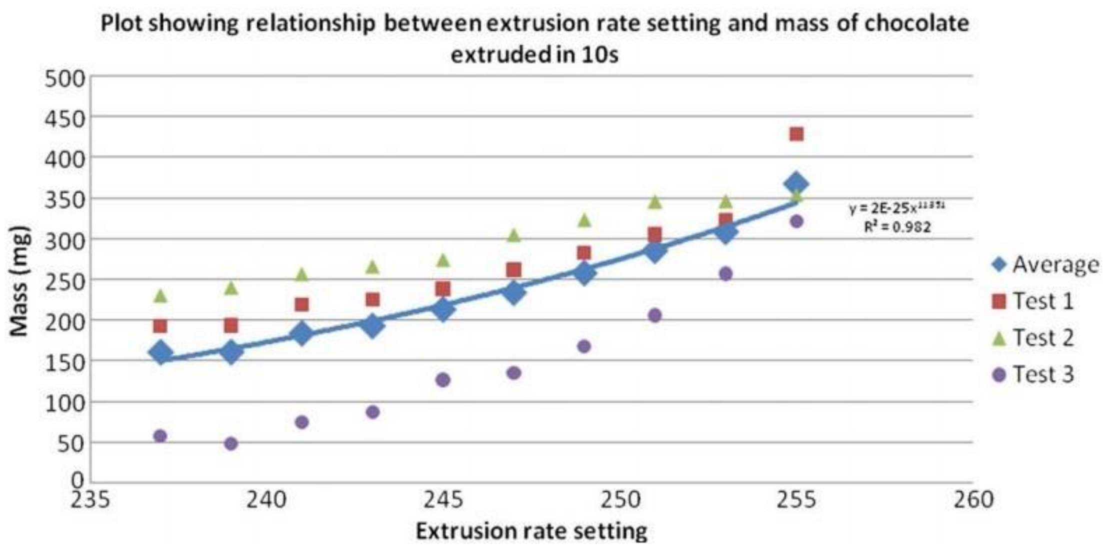

Fig. 6 Relationship between extrusion rate software setting and mass of chocolate extruded over a period of 10 s (L. Hao et al., 2010)

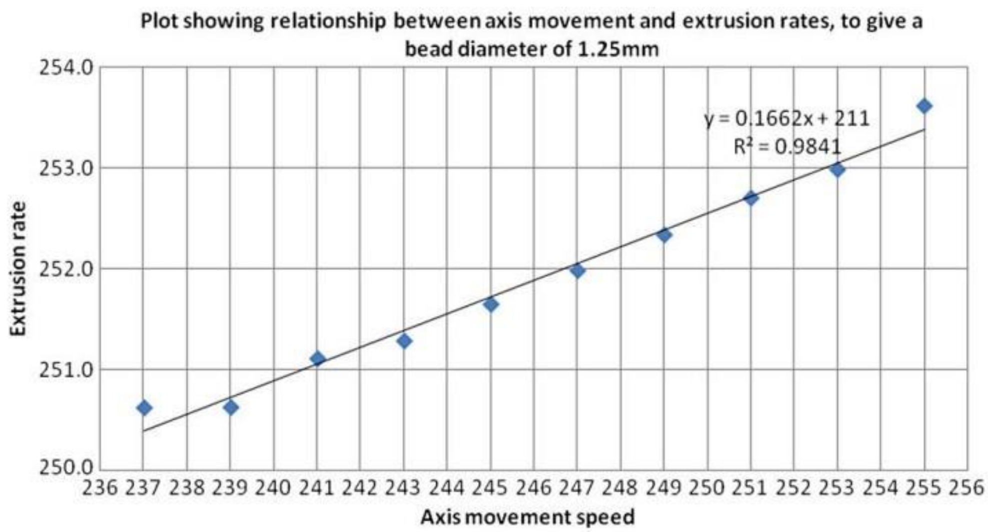

Fig. 7 The extrusion and *y*-axis movement rate required for the deposition of 1.25 mm bead diameter. (L. Hao et al., 2010)