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Review

3D printing: Printing precision and application in food sector

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ABSTRACT

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

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

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

1. Introduction

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

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

Currently, 3D printing techniques available in food sector generally include four types: extrusion based printing, selective sintering printing (SLS), binder jetting, and inkjet printing. Extrusion based printing is usually used in the extrusion of hot-melt chocolate or soft-material such as dough, mashed potatoes, and

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meat puree (Engmann & Mackley, 2006; Yang et al., 2015). Researchers from Cornell University studied the fabrication of cake frosting, processed cheese, and sugar cookies using extrusion based printing (Lipton et al., 2010; Periard et al., 2007). This technology has also been applied by Netherlands Organization for Applied Scientific Research (TNO) to fabricate various kinds of foods using traditional materials and non-traditional ingredients such as algae and insects (Daniel, 2015; Sol, Linden, & Bommel, 2015). Another extrusion based printer (Foodini Printer) has been created by Natural Machines to be used for surface filling and graphical decoration (Galdeano, 2015). Camille et al. (2017) studied the effect of 3D printing on quality of processed cheese. Results showed that the printed cheese was significantly less hard, by up to 49%, and exhibited higher degrees of meltability (21%), compared to untreated cheese samples (not 3D printed samples) (Camille et al., 2017). The hot-melt extrusion of chocolate using 3D printing was firstly operated using a Fab@home printing system. They studied the deposition of chocolate and the processing factors affecting the printing accuracy during chocolate fabrication (Hao et al., 2010). The chocolate extrusion printing has been commercialized by Choc Edge's Choc Creator, 3D System's ChefJet, Hershey's CocoJet, and Chocabyte (Millen, 2012; Zhuo, 2015). SLS has been utilized to fabricate complex structures using sugar or sugar-rich powders. Delicate and complex 3D structures has been created by researchers from TNO using sugars and NesQuik powders (Gray, 2010). Using SLS, CandyFab Project has successfully created various attractive complex structures using sugar powders which could not be produced by conventional ways (CandyFab, 2009). Binder jetting offers advantages such as fast fabrication, building of complex structures and low material cost (Sun, Peng, Yan, Fuh, & Hong, 2015a). Based on binder jetting, Southerland and Walters (2011) investigated the fabrication of edible constructs using sugars and starch mixtures. Researchers from 3D System have created a binder to produce a wide variety of colorful and flavors edible objects, such as various kinds of complex sculptural cakes by varying flavor and colorful binders (Izdebska & Tryznowska, 2016). Inkjet printing generally handle low viscosity materials, thus it is mainly used in the area of surface filling or image decoration (Pallottino et al., 2016). Grood and Grood (2011) created an drop-on-demand inkjet printer to dispense edible liquids onto food surfaces to create appealing images (Grood & Grood, 2011). The FoodJet printer uses pneumatic membrane nozzle-jets to deposit edible drops onto a moving object to form an appealing surfaces (FoodJet, 2015). Willcocks, Shastry, Collins, Camporini, and Suttle (2011) created a kind of edible ink to fabricate high resolutions of images on edible substrates, such as biscuit, cake, and crackers.

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

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

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

2.1. Extrusion-based printing and factors influencing printing accuracy

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

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

In extrusion based printing, the properties of food material, such as the moisture content, rheological properties, specific cross-linking mechanisms and thermal properties, are critical to a successful printing. In the 3D printing of biomass of *Nostoc aphaeroides*, the moisture content affected the printing behavior greatly, and the slightly higher moisture content was helpful to form a smooth structure. The viscosity of the soft-material should be both low enough to be easily extruded through a fine nozzle and high enough to hold the subsequently deposited layers (Godoi, Prakash, & Bhandari, 2016). Wang and Shaw (2005) concluded that dental porcelain slurries with shear thinning behavior are beneficial to the construction of objects, as they can be easily extruded out from the