Journal of Food Engineering 179 (2016) 44–54

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Review

3d printing technologies applied for food design: Status and prospects

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ARTICLE INFO

Article history:
Received 28 October 2015
Accepted 28 January 2016
Available online 6 February 2016

Keywords:
3D printing
Additive manufacturing
Food design
Material properties
Printability
3D-food construct

ABSTRACT

The use of 3-Dimensional (3D) printing, also known as additive manufacturing (AM), technology in food sector has a great potential to fabricate 3D constructs with complex geometries, elaborated textures and tailored nutritional contents. For this reason, 3D technology is driving major innovations in food industry. Here, we review the use of 3D printing techniques to design food materials. Our discussions bring a new insight into how essential food material properties behave during application of 3D printing techniques. We suggest that the rational design of 3D food constructs relies on three key factors: (1) printability, (2) applicability and (3) post-processing. Especial emphasis is devoted to how the advantages/limitations of 3D printing techniques affect the end-use properties of the printed food constructs.

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1. Introduction

The design of food which meets the unique demand of special consumer categories, such as, elderly, children and athletes, has

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http://dx.doi.org/10.1016/j.jfoodeng.2016.01.025
0260-8774/

raised the need for new technologies usable in the processing of additives, flavours and vitamins with tailored chemical and structural characteristics, and longer shelf-life properties. Additive manufacturing (AM), also known as solid freeform fabrication (SFF), is one of these methods that involve techniques applied for building physical parts or structures through the deposition of materials layer by layer. This is also referred as a "3D printing" in a general term.

AM was originally invented to build 3D objects based on materials, such as, metals, ceramics and polymers aiming to perform the fabrication of complexes parts in a single step. In the very first studies, the fabrication of 3D objects from polymers relied on photo-polymerization processes in which ultraviolet curable polymers were used for printing layers upon layers of solid constructs (Hull, 1986; Kodama, 1981). AM technology using photo-sensitive materials is not suitable to design food. However, curable printing inks can be attractive in the field of food packaging where there is a continued need for safer, faster and cheaper inks, functional coating, and overprint varnishes. This technique can also be applied to make films and plastic containers with gas barrier coatings to protect flavour and extend the life of packaged food and beverages.

In the food sector, a relevant application of 3D printing techniques to design food constructs was firstly reported by researchers from Cornell University who introduced the Fab@Home Model 1 as an open source design 3D printer capable of producing forms using liquid food materials (Malone and Lipson, 2007; Periard et al., 2007). The operation system of the Fab@home printers is based on extrusion processes. In subsequent years many studies were carried out in an effort to adapt AM technology to the design of food constructs (Diaz et al., 2015a, 2014b; Grood et al., 2013; Hao et al., 2010a, 2010b; Schaal, 2007; Serizawa et al., 2014; Sol et al., 2015). This represents a challenge because AM is not easily applied to the complex food materials with a wide variation in physico-chemical properties.

The purpose of applying AM technology to print food materials does not rely on the concentration of manufacturing processes of product in a single step, but it is associated with the design of food with new textures and potentially enhanced nutritional value. This approach is achieved by the synergetic combination of the essential constituents of food (carbohydrates, proteins and fat), bearing in mind their intrinsic properties and binding mechanisms during deposition of layers. Another trend of the AM in the food sector is the design of complex structures which are not possible to design manually by an artisan, for example. This second strength generally uses sugars and other low nutritional ingredients to produce confectionary items (Yang et al., 2015).

In this review, we describe the current 3D printing techniques applied to design food materials. They are classified according to material supply: liquid, powder and culture of cells. The deposition of liquid-based materials can be performed via extrusion and inkjet processes. Powder-based structures are printed by deposition followed by application of a heat source (laser or hot air) or particle binder. A brief description of cell culture deposition (bioprinting) is also described, as this technique was applied to print meat analogue. Our discussions, however, are especially devoted on how the food constituents (not cell cultures) would behave during AM processes.

This review looks into three interactive factors which we consider essentials for the rational choice of 3D printing techniques in the design of food: (1) printability, (2) applicability and (3) post-processing feasibility. We emphasize that the profitable incorporation of AM technology by food industry relies on comprehensive studies of the materials properties and optimization of multicomponent systems containing carbohydrates, proteins and fat.

2. Additive manufacturing technologies

Depending on the fabrication principle, number of 3D printing techniques can be introduced in the food field and adapted to meet the demand of food design and materials processing. Table 1 summarizes the 3D printing techniques currently applied for food design. The processes are grouped by the type of material used: liquid, powder or cell cultures. Cell culture-based systems have been applied for printing meat. Particular attention was given to the techniques involving the essential constituents of food.

2.1. Extrusion processes

The application of extrusion processes into AM was introduced by the Fused Deposition Modelling (FDM™) method developed by Crump (Crump, 1991, 1992) and trademarked by Stratasys Inc (Batchelder, 2012). In this method a moving nozzle is used to extrude a hot-melt filament polymer as a continuous melted threat, fusing it to the preceding layer on cooling. While FDM is primarily used for prototyping plastics, the technology has been adapted to 3D food printing for few years. Fig. 1 shows a schematic diagram of 3D food extrusion processes which can be considered an adaptation of FDM into the sector of food design. In extrusion processes, formulated ink composed of food ingredients is loaded in a cylinder (extruder). The edible ink is extruded out of the nozzle by the force produced by an acting hydraulic piston. The consecutive deposition of layers is undertaken by directing the cylinder at points predetermined by a 3D model. Depending on the materials used in extrusion processes, the binding mechanisms may happen by the accommodation of layers controlled by the rheological properties of the materials, solidification upon cooling or hydrogel-forming extrusion.

2.1.1. Soft-materials extrusion

In AM, soft-materials extrusion has been applied to print 3D constructs by mixing and depositing self-supporting layers of materials such as dough, meat paste and processed cheese. The viscosity of the material is critical to be both low enough to allow extrusion through a fine nozzle and high enough to support the structure post-deposition. Rheological modifiers, or additives, can be used to achieve the desired rheological properties but must comply with food safety standards.

Periard et al. (2007) applied extrusion at room temperature to print cake frosting and processed cheese using the Fab@home Fabrication system (Periard et al., 2007). Using the same system, Lipton et al. (2010) tested a variety of recipes to print sugar cookies. Variations on the concentration of ingredients such as butter, yolk and sugar played an important role to form natively printable dough and resistant on cooking. The authors have also used transglutaminase and bacon fat as additives to make printable scallop and turkey meat-puree, respectively. The resulted meat-based products kept their shape after cooking (Lipton et al., 2010).

Extrusion-based processes have also been employed by the Netherlands Organisation for Applied Scientific Research (TNO) scientists to print a large variety of foods using essential carbohydrates, proteins, meat purees and other nutrients extracted from alternative sources, such as, algae and insects (Van der Linden, 2015). Most recently, TNO and Barilla (Italian pasta company) have presented the preparation of 3D printed pasta using classical pasta recipes (ingredients: durum wheat semolina and water, without additives) (Sol et al., 2015; Van Bommel, 2014; Van der Linden, 2015). Another example, a company called Natural Machines created Foodini Food printer which extrudes fresh food ingredients to design meals. The extruded ingredients are used for surface filling (e.g., pizza or cookie dough and edible burger from