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Variables affecting the printability of foods: Preliminary tests on cereal-based products

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ABSTRACT

3D printing technology was employed to obtain cereal-based snacks having a desired shape and dimension. The printability of the dough and the quality of cooked samples were studied as a function of two main variables: infill percentage and layer height. The obtained snacks well matched the designed structures but some dimensional changes were observed. The increase of layer height produced a reduction in the height of samples from 20 to 18 mm, as well as an increase of their diameter from 15.5 to 19 mm. This was attributed to the irregular deposition of the dough as the layer height increased. On the other hand, the infill level was more important for the changes in solid fraction of both raw and cooked snacks exhibiting values of ~84% and ~24%, respectively. The breaking strength of samples was strongly related to the infill level, although a significant variability resided in the level of layer height used during 3D printing.

Industrial relevance text: Recently, the interest in '*personalized food formula*' has been exponentially increasing. With this term we refer to the customization of food in terms of shape, dimension, internal structure, nutritional values, taste, etc. 3D printing is considered a very promising technology to produce 3D food structures with desired dimensional, sensorial and nutritional properties. However, before applying 3D food printing for catering services or large industrial scale, a better understanding of the effects of printing variables on the quality of 3D food structure is required.

1. Introduction

In the last 20 years the growing development in printing technology has enabled to overcome the gap between the traditional bi-dimensional surface and three-dimensional space. The so-called 'Additive Manufacturing' (AM), also known as rapid prototyping, is the process by which 3D objects are built through the deposition layer-by-layer of several cross-sectional slices. From an economic point of view, 3D printing technologies are at least of two types, the commercial 3D printers with a cost lower than $10,000 and rapid prototype machines of up to $500,000 or further. Additionally, 3D printers of lower costs usually necessitate a computer-assisted design (CAD) software to save a design model as standard-stereo-lithography (STL) file, while the rapid prototyping use native CAD, Blender or Google SketchUp files (Berman, 2012). The first 3D printing technology developed at MIT was the powder deposition method (Sachs, Cima, Williams, Brancazio, & Cornie, 1992) (Cambridge, MA). This method is based on the deposition of a thin layer of a specific powder formula followed by the deposition of a suitable binding agent. The latter was essential to create links within the consequential powder elements. The quality of 3D printed objects is greatly affected by several variables, including the deposition method itself, binding criteria, liquid formulation, printing options (i.e. Drops-on-demand, DoD, or continuous-jet, CJ) as well as post-printing treatments (Utela, Storti, Anderson, & Ganter, 2008; Bose, Vahabzadeh, & Bandyopadhyay, 2013).

More recently, several 3D printing technologies have been developed. These include laser sintering (SLS), fused deposition model (FDM), robotic assisted deposition, direct ink writing, laser-assisted bioprinting (LAB) and micro-extrusion (Bose et al., 2013; Murphy & Atala, 2014). To date, the most interesting researches and technical application of 3D printing focus on materials science such as polymers, metals, production of pharmaceutical dosage forms (Gburek, Vorndran, Muller, & Barralet, 2007) and scaffolds for tissues generation (Sobral, Caridade, Sousa, Amno, & Reis, 2011; Bose et al., 2013; Murphy & Atala, 2014). Goyanes, Buanz, Basit, and Gaisford (2014) investigated the application of FDM technique to obtain drug-loaded tablets. The authors explored the effects of different 3D structures on the kinetic of chemical compounds release. The results proved that 3D printing could be an effective method to manage personalized-dose medicines. Studying the application of 3D printing for tissue generation, Sobral et al. (2011) produced several 3D scaffold architectures able to improve the cell seeding efficiency and cell distribution. Other interesting results in the field of biomaterials fabrication, animal tissues as well as edible polymers are available in literature (Mironov et al., 2009; Tessmar, Bradl, & Gopferich, 2009).

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In food applications, 3D printing technology may provide opportunity to develop foods at low environmental cost and better quality (Yang, Zhang, & Bhandari, 2015) or to fabricate food structures with complex geometries and tailored nutritional contents (Godoi, Bhesh, & Bhandari, 2016). Moreover, apart the type of technology, several variables significantly affects the performance of 3D printed structures. For instance, in the case of fused deposition material, the printer setting should be optimized in terms of extrusion temperature (°C), extrusion speed (mm), traveling speed (mm/s), layer height (mm), fill density (%), nozzle size (mm), shell thickness (mm), etc. Goyanes et al. (2014) studied the effect of different infill percentages (from 0% to 100%) on the quality of drug-loaded tablets proving that the infill level has a significant effect on the dissolution kinetic. This was probably due to the changes in the extrusion pattern during printing. Given these promising results, the interest in the application of 3D printing technology in food science is increasing (Wegrzyn, Golding, & Archer, 2012). Among the above discussed technologies, laser-sintering, fused deposition material and extrusion deposition have been used in some cases in order to obtain 3D printed food structures. Sugar-based powders are the best materials to obtain complex shape structures through laser sintering technology (The-CandyFab-Project, 2008). A like-FDM technique was used in order to produce 3D chocolate objects (Causer, 2009; Hao et al., 2010). The Netherlands Organization for Applied Scientific Research (TNO, 2015) proposed a 3D printer based on the deposition of pastes obtained by mixing several food ingredients. Lipton, Arnold, and Nigl (2010) obtained a cake shape by using a twin head extrusion and post-cooking. However, all the above examples were focused on the production of commercial 3D food printer systems according to the consumer interests. On the other hand, in order to improve the knowledge of this technology when applied in food science, very few experiments have been performed in detail. Hao et al. (2010) found a linear relationship between extrusion speed and both bead diameter and mass of printed chocolate. Gracia-Julia, Hurtado-Pnol, Leung, and Capellas (2015) studied the behavior of three food materials such as beef burger preparations, cheese cracker dough and pizza dough during 3D printing. The results showed that beef preparation and pizza dough were only printable by using a 4 mm nozzle while the cheese crackers were extruded with nozzles between 1.5 and 4 mm. Also, beef preparation was better printed by increasing the amount of salt and pepper probably due to the solubilisation of myofibrillar proteins, which decrease the force required for the extrusion. Vancauwenberghe et al. (2015) studied different formulation of bio-inks based on pectin with the aim to obtain 3D printed edible objects. In a first step, a bio-ink formulated with pectin, sugar syrup, bovine serum and $CaCl_2$ was printed. Then a post-processing consisting in the incubation of the object in a $CaCl_2$ solution was performed to solidify the structure. Aregawi et al. (2015a) printed cookies by using the selective laser sintering technique (SLS). Other interesting examples were reported from Wegrzyn et al. (2012), Aregawi et al. (2015b), Vallons, Diaz, van Bommel, and Noort (2015), Klomp et al. (2015) and Diaz, van Bommel, Noort, and Vallons (2015).

From the above papers limited information on the effects of the printer variables such as travel speed, print speed, infill levels, layer eight, etc., on the printing performances of the food are available. Given these considerations, the main aim of this paper was to study the printability of a wheat-based food product as affected by some printing variables. More specifically, the printing performances of the dough as well as the characteristics of the cooked samples were studied by analyzing the changes in dimension, shape, microstructure and texture properties.

2. Material and methods

2.1. Dough preparation

Commercial wheat flour 0 type (according to the Italian Food Regulation, 2001) was purchased locally and used for this study. Farinograph test was performed according to the standard AACC Method 54-21 (AACC, 2000) (Brabender, Duisburg, Germany) to determine the optimal mixing time and water absorption capacity of the flour to reach 500 BU. The farinograph analysis showed a development time of 4 min and a stability of 10 min, which is typical of strong flours. For experiments, the dough was prepared by mixing 100 g of wheat flour with 54 g of distilled water (according to farinograph absorption) in a planetary kneader (model cooking chef, Kenwood Ltd. UK). Ingredients were initially mixed for 1 min at low speed (60 rpm), the bowl was then scraped down, and mixed again for 3 min at the same speed. The dough was then covered with plastic wrap and left to rest for 30 min before use.

2.2. Experimental design

A Box-Behnken design of two variables, infill level (%) and layer height (mm), and three levels of variation were used for experiments (Box, Hunter, & Hunter, 1978). More specifically, the infill level refers to the solid fraction in the inner part of the designed structure and can be interpreted as the print quality. A full factorial design of $3^{(k-p)}$ experiments was performed, where *k* is the number of independent variables and *p* is a parameter which refers to the interaction effects that are confounded with any other. In our case a total number of experiments $N = 3^{(2-0)} = 9$ were performed (Box et al., 1978). Table 1 shows the Box-Behnken design with the coded values for each independent variables and each experimental condition used during experiments. In this case, the response surface methodology was not used to model or optimize but to investigate the effect of the two independent variables on the main properties of 3D printed objects. The experimental conditions of Table 1 were repeated in triplicate for a total of 27 printing tests. The other printing variables were set as follows: extrusion at room temperature, print speed (30 mm/s), travel speed (50 mm/s), number of shells of 1 and nozzle size of 0.6 mm. The three-dimensional structure used for food printing was designed by using the browser based 3D design Tinkercad (Autodesk, Inc.). A simple structure consisting in a cylinder with a diameter of 17 mm and a height of 25 mm was chosen for printing the snack. From Tinkercad, a stereolithography interface format file, .stl, was obtained and used as basis for changes infill and layer height in accordance with Table 1. CURA 15.04.2 (Ultimaker B.V., The Netherlands) software was used to modify the setting of .stl file obtaining the 9 different 3D structures of Box-Behnken.

2.3. Production of snacks by 3D printing

After resting, the dough was loaded into a tight piston chamber on which 4 bars pressure were continuously applied to convey the dough to the micro extruder for printing. A 3D Printer mod. Delta 2040 (Wasp project, Italy) equipped with the Clay extruder kit 2.00 (Wasproject, Italy) was employed for 3D printing experiments. The objects were printed on a stainless steel screen (2 mm mesh) and immediately frozen at −18 °C until being cooked and analyzed. Samples

Table 1
The arrangement of Box-Behnken design.

Experiments	Codes		Variables	
	Layer height	Infill	Layer height (mm)	Infill (%)
1	0	+1	0.4	20
2	+1	0	0.5	15
3	−1	−1	0.3	10
4	−1	0	0.3	15
5	+1	+1	0.5	20
6	0	−1	0.4	10
7	+1	−1	0.5	10
8	−1	+1	0.3	20
9	0	0	0.4	15