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Applicability of protein and fiber-rich food materials in extrusion-based 3D printing

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In this study, the applicability of extrusion-based 3D printing technology for food pastes made of protein, starch and fiber-rich materials was assessed, as a starting point in the development of healthy, customized snack products. The printability of starch-, cellulose nanofiber-, milk powder-, oat- and faba bean protein-based materials and their mixtures was evaluated by examining the ease and uniformity of extrusion as well as the precision and stability of the printed pattern. The best printing precision and shape stability was obtained with a semi-skimmed milk powder-based paste. Rheological measurements revealed that the shape stability after printing was linked with the yield stress of the paste. Post-processing by oven drying was most successful at high initial solids contents (<50%) of the printed samples. Extrusion-based 3D printing is a promising tool for producing healthy, structured foods, but further research is needed for optimising the mechanical properties of the printed materials.

1. Introduction

Digitalization is a rising way of increasing efficiency both in the supply and manufacturing chain. 3D printing technology is an example of digitalization of food manufacturing industry. It is forecasted that 3D printing will be the next disruptive and transformative food technology in the coming decade (Karlgraad, 2011). 3D printing is based on additive manufacturing (AM) that is a layer-by-layer manufacturing process, which takes advantage of phase transitions or chemical reactions to fuse material layers together based on 3D model data (Wegrzyn et al., 2012). The term 3D printing is defined as fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology, however, it is often used synonymously with additive manufacturing (SFS-ISO/ASTM 52900:2016; Wohlers, 2014). In this paper the term 3D printing is used to refer to both additive manufacturing and 3D printing technologies.

The existing 3D printing technologies are classified into seven process categories, which are powder bed fusion, directed energy deposition, material jetting, binder jetting, material extrusion, vat polymerization and sheet lamination. Each of them have several sub-technologies which all have some similarities but also several differences related to e.g. form of feedstock, form of energy used in system, multi-material handling capability and restrictions in design. (SFS-ISO/ASTM 52900:2016).

The 3D printing technology has generally been used in non-food sectors such as motor vehicles, aerospace and medical applications. New 3D printing technologies introduce flexibility and novel design into industrial mass production and enable the manufacturing of complex shapes, unique solutions and new kinds of combinations of materials and components. Growth in the 3D printing industry has accelerated over the past 5 years as an increasing number of organizations adopt 3D printed products and services. The increased production speeds decrease the costs of the manufactured parts which will make the 3D printing technologies relevant for use also in vehicles, machines as well as in other industry areas. The trend is that 3D printing is increasingly used for producing parts or components for final products rather than only for prototyping. The selection of 3D printable materials includes plastics, metals, ceramic, concrete, wood and other bio-based materials (Wohlers, 2014).

Applying 3D printing in food manufacturing has recently accelerated. The earliest application of 3D printing in food manufacturing focused on printing of a “cake mix” by paste extrusion of a mixture that consists of starch, sugar, corn syrup, yeast and a cake frosting (Yang et al., 2001). Later on granular bed

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sintering technology which utilizes a laser beam or a binding agent to melt or fuse granular materials has been adapted to form sucrose based 3D objects by melting and fusing sugar granules with selective hot air melting technology (Sun et al., 2015) which later on extended to commercially available 3D printers that enables formation of neat and complex 3D structures based on sugar (http://www.3dsystems.com/culinary/gallery). Besides sintering, ink jet printing of sugar by using alcohol as a binder can be applied to produce 3D candies (Park, 2013). Cornell University, Department of Mechanical and Aerospace Engineering faculty and students, has made the first multi-material 3D printer available to public. The printer was first based on a single head extrusion system which has been later on extended up to eight extrusion heads enabling printing of diverse materials from epoxy to silicone to chocolate and cheese. Later on in collaboration with Cadbury and Dr. Liang Hao from University of Exeter and his students worked further on the concept of chocolate printing. The group has focused on the technological issues of chocolate tempering, deposition precision, and process control, which led to the development of world's first chocolate printer introducing co-creation concept to the consumers (Causer, 2009). Filled chocolate was later on printed by hot melt extrusion type 3D printing head (Zoran and Coelho, 2011).

The biggest challenges in 3D food printing are ingredient mix rheology, structure accuracy and shape-stability, compatibility with traditional food processing technologies (e.g. baking and drying) and printing speed. For example, traditional cookie recipes have been shown to be compatible with 3D printing but due to the presence of high amount of fats they don't retain their shape and structure after post-processing (e.g. baking) (Lipton et al., 2010). Thus, to enable 3D printing of cookie recipes the ingredients and their proportions need to be modified. For example, shape stability after printing reduced by increasing the amount of butter in butter-egg yolk-sugar mixture whereas increasing the egg yolk concentration increased width/length stability but decreased height stability (Lipton et al., 2010). Pizza recipe is another traditional food product, which needed recipe adaptation to enable the manufacture of 3D printed pizza. The pizza dough required extra water addition whereas addition of thickeners to the tomato sauce needed to enable their printability by a paste extrusion based 3D printer (Lipton et al., 2015). Prior to extrusion the cheese was melted by heating at 150 °C cooled down on the sauce surface. The use of 3D printer instead of a mold enabled the manufacture of custom shaped pizza in a shorter time (30 min vs 24 h including fermentation) (Lipton et al., 2015). In addition, there are technological challenges to tackle, for instance printing of batters is strongly dependent on oscillations in the flow during its pumping process, which has an impact in the final quality of the printing outcome (Millen, 2012). 3D printing technology has also been utilized in developing various hydrocolloid based structures. Cohen et al. (2009) printed various combinations of xanthan gum and gelatin to create a “mouthfeel matrix” where the material was rated along two orthogonal axes: 1) weak to firm, and 2) smooth to granular in comparison to other common food materials. The study showed that the 3D printed structures made of the two hydrocolloids in various percentages can cover a mouthfeel range from liquids to solid vegetables. Pure xanthan and gelatin followed weak to firm axis (e.g. 0.5% gelatin → milk like texture, 4% gelatin → mushroom like texture) as a factor of hydrocolloid concentration however when the two hydrocolloids were combined they started to possess granularity (e.g. 1% gelatin & 4% xanthan → risotto like texture, 1% gelatin & 8% xanthan → tomato like texture). The intensity of granular structure increased with increasing xanthan:gelatin ratio (Cohen et al., 2009).

Despite the recent studies and steps of progress, the majority of the technologies for 3D food printing are still under research and development phase. . The major benefits we foresee for 3D printing of food materials are flexibility, configurability and high material use efficiency. The flexibility coming from 3D printing technology will enable the use of alternative food ingredients which the industry will face in future to create improved products with respect to nutritional content, health benefits and shelf-life.

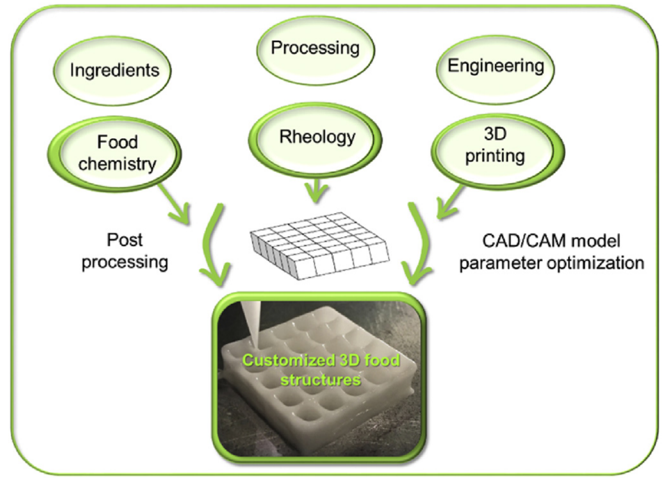

Fig. 1. Schematic illustration of multi-disciplinary workflow related to the use of 3D printing technology in food manufacturing.

The aim of this study was to utilize 3D printing technology in design of healthy novel structures, which are high in fibre, protein and low in fat or sugar. For that purpose various protein, starch and fiber-rich food ingredients and their mixtures were selected for this study based on their potential as nutrients and functional ingredients in 3D printed foods. . The development of 3D printed customized structures requires cross disciplinary interaction between food chemistry (e.g. to define the state/phase transitions of ingredient mixes), processing (e.g. to optimize the rheological properties of the ingredient mixes during and post-printing) and engineering (e.g. 3D printing technologies to create customized healthy food structures) (Fig. 1). Shape and design elements have been the major focus within the scarce number of studies done around 3D food printing. However, our lab aims at utilizing this “next disruptive food technology” in design of healthy novel structures.

2. Materials and methods

2.1. Materials

The raw materials used in the pastes prepared for 3D printing were starch, milk powder, cellulose nanofiber, rye bran, oat protein concentrate and faba bean protein concentrate. The starch was a cold water swelling modified food starch derived from waxy maize starch (Ultra-Sperse® M, Ingredion). Two types of instant milk powders from Valio Ltd. with a difference in fat content were used in the pastes. The skimmed milk powder (SMP) consisted of 35% protein, 53% carbohydrates (all lactose) and 0.6% fat (manufacturer's data). The semi-skimmed milk powder (SSMP) was lactose-free and consisted of 37% protein, 38% carbohydrates and 15% fat (manufacturer's data).

Cellulose nanofiber (CNF) was prepared from once dried bleached birch Kraft pulp from Finland. The dry matter composition of the pulp was 73% cellulose, 26% hemicellulose and 1% lignin. The pulp suspension (2% dry matter) was pre-refined by passing it once through an ultra-fine friction grinder (Masuko Supermasscolloider