3D FOOD PRINTING WITH IMPROVED FUNCTIONAL PROPERTIES: A REVIEW

FONKSİYONEL ÖZELLİKLERİ İYİLEŞTİRİLMİŞ 3B GIDA BASIMI: BİR DERLEME

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ABSTRACT

In food industry, 3D printing gives the opportunity to fabricate 3D food structures using layer-by-layer deposition of the food material that may not be possible using conventional food production techniques. 3D food printing technology has been used to develop foods with different shapes or textures. Also, different food materials can be printed in different layers for creating functional foods with a complete nutritional balance. The novel and appealing textures with 3D printing are launched for elderly people having swallowing difficulties (dysphagia) or children and athletes who have different energy and nutrition requirements. Moreover, 3D food printing technology has a great potential to reduce food waste by making use of discarded food parts such as meat scraps, and damaged fruits and vegetables. However, there are some obstacles regarding the building of a 3D structure, as well as retaining the designed geometry in the post-deposition period. The composition and properties of food materials and processing parameters are effective on the characteristics of the final 3D printed foods. This review focuses on the recent developments on 3D food printing process according to different food categories, and pre or post processing parameters.

Keywords: 3D food printing. Rheology. Thermal properties.

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ÖZET

Gıda endüstrisinde 3B baskı, gıda maddesinin katman katman birikimini kullanarak geleneksel gıda üretim teknikleri ile mümkün olamayabilecek 3B gıda yapıları üretme fırsatı verir. 3B gıda baskı teknolojisi farklı şekil ve dokulara sahip gıdalar geliştirmek için kullanılmaktadır. Ayrıca, farklı gıda maddeleri farklı katmanlarda basılabilerek tam bir beslenme dengesi oluşturmak için fonksiyonel gıdalar üretilebilmektedir. 3B gıda basımı ile yutma güçlüğü çeken (disfaji hastası) yaşlılar veya farklı enerji ve beslenme gereksinimleri olan çocuklar ve sporcular için yeni ve ilgi çekici dokuya sahip gıdalar üretilebilmektedir. Ayrıca, 3B gıda baskı teknolojisi, et artıkları, hasar görmüş meyve ve sebzeler gibi atığa ayrılan gıda parçalarını kullanımıyla gıda atıklarını azaltmak için büyük bir potansiyele sahiptir. Bununla birlikte, 3B yapının inşasında ve baskı sonrası dönemde tasarlanan geometrik şeklin korunmasında bazı güçlükler vardır. Gıda maddelerinin bileşimi, özellikleri ve işleme parametreleri nihai 3B baskı yapılan gıdaların özellikleri üzerinde etkilidir. Bu derleme, 3B gıda baskı sürecindeki son gelişmelere farklı gıda kategorilerine göre ve işleme öncesi veya sonrası parametrelerine odaklanmaktadır.

Anahtar kelimeler: 3B gıda basımı. Reoloji. Isıl özellikler.

1. INTRODUCTION

3D printing of food materials is important for customized food manufacturing by nutrition, texture and taste modifications. From nutritional point of view, macro and micro nutrients are selected depending on the consumer taste or meeting the requirements of people having specific needs or alternative protein sources, such as edible insects that are utilized for functional food development [1, 2, 3]. Besides with 3D printers, some ingredients such as salt, sugar and fat may be positioned on specific locations between layers that are influencing the mouthfeel perception at first bite [4]. Therefore, healthier food production is possible with the reduction of these ingredients.

The novel and appealing textures with 3D printing are launched for elderly people having swallowing difficulties (dysphagia) or children and athletes who have different energy and nutrition requirements [5, 6]. This technology allows producing food with right consistency and soft texture with improved nutritional quality as well as visually acceptable products [4]. Especially, providing the required mouthfeel and texture is utmost priority for dysphagia patients. International dysphagia diet standardization initiative (IDDSI) had implemented a framework for creating a standard terminology for assessing the texture and thickness (consistency) of foods and drinks that are used for the people with dysphagia of all ages [7]. In this framework, the drinks are classified into 5 categories (0-4) by level: 0 having thin and level: 4 having extremely thick consistency, while the texture modified solid foods are classified into 6 categories (3-7) by level: 3 having liquidized texture and level:7 having easy to chew or regular texture (Figure 1).

**Figure 1.** Complete framework classification of foods and drinks [7].

The inauguration of 3D food printers was for developing artisan chocolate and confectionery with attractive structures [5, 8]. However, there are some obstacles regarding the building of 3D structure as well as retaining the designed geometry in the post-deposition period. Not only the composition and properties of food materials to be printed, but also the processing parameters of 3D printers are effective on the final 3D printed foods.

Depending on the driving mechanisms, 3D food printing techniques can be summarized under three categories; inkjet printing, extrusion printing and heat source printing [9]. The most popular 3D printing technique for food production is the extrusion-based techniques with its convenience and controllable processing parameters [10]. Each and every 3D printing technique might not be suitable for food production and it has to be chosen with care depending on the properties of food. "Foodini" 3D printer launched by

Natural Machines startup company with the idea of freshly printed healthy meals and the printed food samples are shown in Figure 2 and 3 [11].

Figure 2. The "Foodini" 3D food printer. Picture provided by Natural Machines with permission [11].
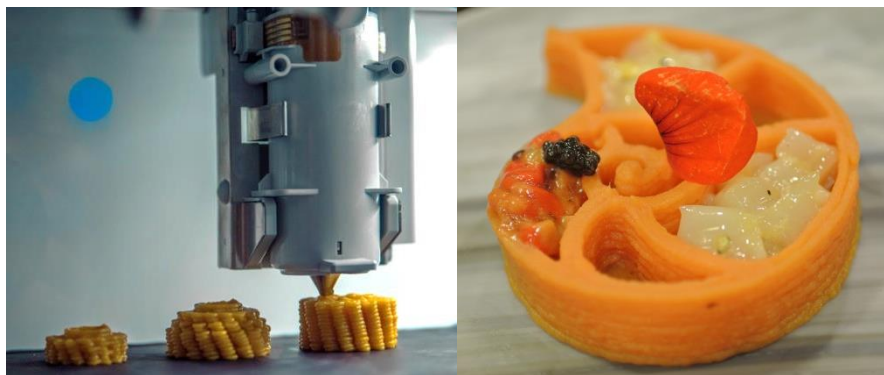
(a)   (b)

Figure 3. (a) Corn-based snack printing close-up (b) 3D-printed nautilus dish designed and printed by Natural Machines. Pictures provided by Natural Machines with permission [11].

This review focuses on the recent developments on 3D food printing process according to different food categories. Viscosity, thermal properties, post processing treatments and limitation related with 3D food printing are also discussed.

2.   EVALUATION OF THE PRINTABILITY OF VARIOUS FOOD APPLICATIONS
In food industry, 3D food printing (3DFP), also known as additive manufacturing (AM) or food layered manufacturing (FLM), gives the opportunity to fabricate a 3D food structure using layer-by-layer deposition of the food material that may not be possible using conventional food production techniques [12]. In the area of food science, 3D printing technology has been used to develop different shapes, textures, flavors, colors, etc. [2]. The printability of food materials depends on the flowing structure of a food ink (or food puree) and extrusion through a nozzle, followed by keeping the shape after being printed. The benefits and limitations of utilizing 3D printing technologies in food applications are summarized in Figure 4.
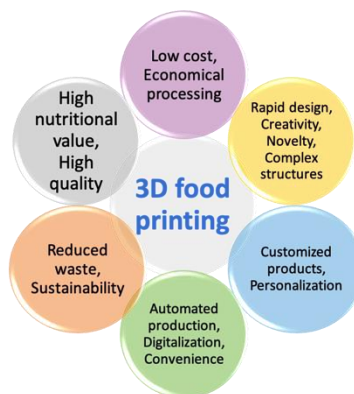
Figure 4. Benefits of using 3D food printing technology

The 3D printing process can be performed at room temperature, which can ensure the stability of heat labile nutrients from degradation [13]. Moreover, when heat or light labile ingredients, such as bioactive compounds and oils, are incorporated within the layers of printed foods, they will be protected against environmental effects and will be able to provide better nutritional value [4]. Also, the sensory quality of food product can benefit from that, since rancid oil taste is an undesirable sensory characteristic in food products that can be inhibited by 3DFP. Additive manufacturing actually uses food parts that would normally be discarded as waste, such as, meat scraps, fish or sea food byproducts, damaged fruits and vegetables etc. [4, 14].

Parameters such as; flow rate, printing speed, and nozzle diameter may affect the overall visual appearance and microstructure of the 3D printed food samples [15, 16, 17, 18]. 3D printing of a food materials includes the following steps; (i) selection of the type of food material (ii) defining the formulation with ratios of each ingredient (iii) preparation of the paste (iv) defining the 3D printing conditions (v) prolonging the shelf-life of the 3D printed food by heat treatment or other methods [19].
The most recent studies on the 3D food printing applications are presented in the following sections.

2.1. Cereal-based Foods
Cereal-based foods are staples in many countries around the world as a part of their daily diet. The homogeneous viscosity of dough gives it an advantage for easy 3D printing [19]. Cookies [20], pizza [8], and pasta [21] are some of the cereal-based food products that are produced using the 3D printing technology. Moreover, fortification of cereal-based products using additive manufacturing has been a point of interest by many researchers. For example, dough formulations containing different ratios of wheat flour, water and additives (calcium caseinate) were fortified with probiotics [22]. The researchers found that the shape of the 3D printed dough was preserved during baking, and depending on shape and baking temperature, probiotics survival was high enough for some trials to describe them as probiotic food. Researches focusing on fortification with insects are discussed later under Section (1.1.5).

Additives such as gums and stabilizers are mostly added into dough formulations in order to increase printability properties. Pulatsu et al. [23] investigated the printability and post processing capacity of cookie dough formed using different types of flours (tapioca, wheat, rice) and fats (butter, shortening) with different levels of sugar and milk, without using any additives. The researchers yielded the best printable cookie dough that also kept its shape during post-process baking using the least amount of sugar and milk, with tapioca flour and butter. Liu et al. [24] investigated the effects of water content and rice type (waxy, japonica and indica) on the quality of 3D printed rice dough. Waxy rice that is rich in amylopectin, resulted in the best shape, with high precision, but when the printed food was steamed in the post-processing stage, the shape was deformed and it had swollen. The in vitro starch digestibility of the steamed samples was found to be reaching the highest extend for waxy rice samples followed by japonica and indica rice samples.

Interestingly, these results had a positive correlation with the amylopectin content of the rice types. This phenomenon can be attributed to the higher surface area related with higher amylopectin content, or with the structure of amylopectin [25]. It is important to note that the digestibility of starch decreased in 3D printed rice dough samples, compared to the traditional rice dough samples that are steamed. This result is in contrast with the findings of Alonso et al. [26], where the researchers stated that printing increased the in vitro digestibility of starch. This increase might arise from the fact that the surface area increases with printing. All in all, formulation materials have an impact on the quality outcome of the 3D printed food, which may impact post-processing properties and its desirability by the consumer.

2.2. Fruit and Vegetable-based Foods
Fruits and vegetables are rich in vitamins, minerals and dietary fiber which help to maintain a balanced diet and keep good health [27, 28]. Consumption of fruits and vegetables daily at a recommended dose can help prevent several diseases such as cardiovascular diseases (CVD), obesity, diabetes and some cancer types [28]. United States Department of Agriculture (USDA) and World Health Organization (WHO) recommend consuming 1 to 2 cups of fruits and 1 to 3 cups of vegetables daily [25, 26; 27]. Fruits and vegetables contain 70 to 90% water [29], which affects their viscosity and printability. Fruits and vegetables are among the most difficult food materials to be 3D printed due to their low viscosity, high fiber content and wide range of biological variance [19]. In order to overcome the low viscosity problem, high viscosity fruits such as banana and avocado can be incorporated within the formulation to reduce phase separation [19]. Otherwise, a thickener or a gelling agent, such as starch, pectin or gelatin can be added to the formulations to improve the printability properties of fruit and vegetable mixtures. For instance, a banana-based fruit snack using pectin [13], a pea-based vegetable snack using avocado [30], orange leather using wheat starch [31] and lemon juice gel using potato starch [16] have been successfully 3D printed. Moreover, Azam et al. [31] precooked the orange concentrate together with the wheat starch, which yielded improved gel strength.

Many fruits are susceptible to enzymatic browning. In order to overcome this issue during the period of 3D printing, citric acid (lemon juice) or other organic acids (malic acid etc.) can be incorporated within the formulations [19]. For example, Derossi et al. [13] used lemon juice and ascorbic acid in order to inhibit the browning of banana in their formulation.

2.3. Chocolate-based Foods
Chocolate was one of the first food products that were fit for 3D printing due to its natural melting and freezing properties. Chocolate melts during heat extrusion printing and solidifies after it is printed very rapidly [19]. The ink has to hold its structure while being printed (self-supporting property), and this highly depends on the rheological properties, such as viscosity, and thermal properties, like melting point [32]. Additives, such as starch, can be incorporated within the formulations to improve rheological characteristics like it is used for fruit and vegetable-based 3D printed foods. For instance, use of magnesium stearate salt - a generally recognized as safe (GRAS) food additive- enhances the flow properties of chocolate ink [32].

Complex structures (such as a bunny or a hexagon shape) could be successfully 3D printed using hot-melt extrusion with chocolate [32, 33]. Cold- extrusion printing of chocolate has been attempted by Karyappa and Hashimoto [34] using chocolate syrup and paste mixed with cocoa powder for improving rheological properties, which was compared with cake icing. The fabrication of 3D models consisting of chocolate-based inks without temperature control was successfully made [34]. When rheological properties were improved by using cocoa powder, direct ink writing was successfully applied with chocolate-based ink and the whole process was named chocolate-based ink 3D printing (Ci3DP) [34].

Chocolate 3D-printing is also applicable for masking the taste, texture and appearance of drugs especially used for children [35]. The pediatric friendly chewable oral drugs used for pain relief and fever reduction were 3D printed with chocolate inks and the technology successfully produced cost effective dosage forms having a rapid and high dissolution in the gastrointestinal tract.

2.4. Hydrocolloid-based Foods

3D printing is limited by the printability of the food material. Chocolate, for instance, is a food material that can be printed by its natural state depending on its crystallization and melting behavior. Proteins have the advantage of forming gel-like structures which are suitable for 3D printing. Egg yolk, for example, can be used for 3D printing purposes due to its heat-induced gelling properties [36]. However, egg yolk couldn't be 3D printed giving rigid shapes without heat treatment, so Xu et al. [36] studied different heat treatment parameters. Egg yolk heated at 76°C for 8 minutes gave the best result with a rigid and stable shape, suggesting that the protein denaturation was at an appropriate level, providing a desirable viscosity level for 3D printing [36]. Above this temperature, egg yolk became too hard for successful printing. The authors suggested that egg yolk can be employed as a binder for different food formulations in future studies. Egg white protein is also commonly used in food products due to its functional properties such as heat-set gelation, foaming and emulsification [37]. Therefore, Liu et al. [37] investigated the potential of using egg white protein as an additive to improve the 3D melt extrusion printing purposes of food formulations consisting of gelatin, corn starch, and sucrose. As expected, the egg white protein ensured the food mixture to tolerate its own weight during 3D printing by changing its textural properties and forming a stronger gel [37].

Liu et al. [38] studied the properties of milk protein gel formed using sodium caseinate as a potential reference for 3D printing gel-like structures. The protein content of the gel affected the printability. Lower protein contents (350 g/L) yielded to unprintable gel structures and higher protein contents (500 g/L) yielded to lower printing quality, whereas medium protein contents (400-450 g/L) gave the best results for printability and shape retention properties [38]. All in all, proteins can indeed be used as an additive in 3D food printing technology to improve textural properties of complex food structures.

Zhou et al. [39] evaluated the effect of Maillard reaction products (MRP) on dough made from pea protein and potato starch. Melting temperature and glass transition temperature (T_g) plays a crucial role in printing properties of food materials. However, the researchers did not find a significant difference in T_g values when they incorporated different MRP ratios (2 to 10 g) to the dough. The best printing result was achieved when 6 g of MRP was added into the mixture [39]. Chuanxing et al. [40] evaluated the effect of pea protein addition to potato-based meals on 3D printing properties. For this purpose, potato starch and pea protein at different concentrations (0-8%) were hydrated and gelatinized at 67 °C [40]. Similar results in means of T_g was found that addition of pea protein did not significantly change the T_g of the potato starch material [40]. The best printing result was achieved with 1% pea protein added to the potato-based mixture. Therefore, printability of potato starch can be improved with the addition of proteins into the formulation.

Liu et al. [18] examined the printing characteristics of gelled potato starch with different starch concentrations (10 to 30%) using different printing parameters such as temperature, nozzle speed, nozzle diameter and nozzle height. At 10% potato starch concentration, the gel network was too weak for printing. At higher concentrations such as 15 and 20 % the gel network was strong enough to successfully complete 3D printing. However, at concentrations higher than 25% the gel became too dense and clogged the nozzle and the printing process failed [18]. Low printing temperatures (60°C) yielded to whiter color and low printability due to partial gelatinization and uneven gel network. Increasing the temperatures up to 70°C yielded to even gel network and better printability properties. However, temperatures above 75 °C resulted in lower printability [18].

Chen et al. [41] 3D printed letters using soy protein isolate with sodium caseinate and varying concentrations of gelatin. Soy protein gel alone and soy protein-sodium caseinate gel could be printed without clogging the nozzle, but their low viscosity yielded to deformed 3D printed letters [41]. The 3D printed letters looked better when gelatin was added into the printing mixture. As the gelatin concentration increased, the melting temperatures decreased and the printing properties got better [41]. Complex structures could be 3D printed at high gelatin concentrations (6-10%).

Huang et al. [42] developed different brown rice gel formulations using various hydrocolloids such as; guar gum, xanthan gum, agar and sodium carboxymethyl cellulose. Brown rice gel did not maintain its shape and easily broke when 3D printed due to its low viscosity. The viscosity of brown rice improved when hydrocolloids were added, except for xanthan gum added alone, which yielded to a lower viscosity. When xanthan gum and guar gum were added together, the rice gel had the best hardness and printability results, as well as the best textural properties without any fractures [42]. Wang et al. [17] investigated the printability of fish surimi gel and found that adding NaCl into the formulations improves the flow characteristics and post-processing shape retention. The researchers examined the printing characteristics of fish surimi gel with different NaCl concentrations (0 to 1.5 g/ 100 g) using different printing parameters such as nozzle moving speed, nozzle diameter, nozzle height and extrusion rate. Water holding capacity and the strength of fish surimi gels improved with increasing NaCl concentrations [17]. Therefore, addition of salt into animal protein based gel formulations can improve their printability properties.

2.5. Insect-based Foods

Edible insects are rich in protein and micro nutrients, such as iron, copper, sodium, potassium, zinc and selenium [43]. Due to their high nutritional content, insects are regarded as the future food by many food scientists. However, the insects are generally associated with dirt and therefore, many people are disgusted by the idea of consumption of insects. One way to overcome this bias can be hiding the insect within the food and masking its presence, which means consumer will not see the insect itself. Hence, researchers around the world experiments combining entomophagy (insect eating) with the 3D printing technology. For instance, a project called 'Insect Au Gratin' handled by the London South Bank University produced insect flour by using ingredients such as butter, cream cheese, spices and chocolate [44]. Within the scope of this project, insect dough of different shapes was formed. In addition, Severini et al. [15], successfully fortified wheat flour with insect (mealworm) powder and created snacks using 3D printing technology. These studies show that the combination of insects with other ingredients and processing them using additive manufacturing into various attractive shapes might change consumers' preferences.

2.6. Customized Food Applications

One of the major benefits of 3D food printing is the wide range of products that can be created. Customized products for certain ages (i.e. children or elderly) or for people with specific diseases, such as swallowing and chewing difficulties (dysphagia) can be produced using this technology. Moreover, athletes needs diets rich in particular elements, such as high-protein intake, and food specific for athletes can be produced by 3D printing technology. Derossi et al. [13] successfully produced a fruit-based printed snack for children (ages 3 to 10) that targets to increase daily vitamin D, calcium and iron intake. Such products can surely make the normally unappealing fruit and vegetable dishes fun for kids when they are printed in colorful shapes of animals, flowers etc.

Low calorie, low sugar and low salt foods can be printed by incorporating these ingredients between the layers, rather than mixing them together [4]. This will burst the taste of such ingredients at the first bite and therefore, can be used in lower amounts than regular for giving the same taste. Dysphagia is a disease that affects the swallowing abilities. The foods designed for people with swallowing difficulties are limited. The sufferers of this disease may get bored from eating the same foods over and over again. Kouzani et al. [45] used the 3DFP technology to print food in an appealing shape (fish) for dysphagia patients using pureed tuna fish, pumpkin and beetroot. Dick et al. [46] incorporated hydrocolloids (guar gum and xanthan gum) into pork paste to create 3D printed food for people suffering from dysphagia. Moreover, creative art works can be 3D printed. For instance, Zhao et al. [47] successfully 3D printed personalized portraits using strawberry jam.

3. EFFECTS OF FOOD PROPERTIES ON 3D PRINTING

3.1. Effect of Rheological Properties

Foods having a wide range of viscosity are available for 3D- printable food formulations, such as low viscosity sauces, jams or mixtures are used as food inks that are deposited on pizza or cookies [5, 10, 48]. Besides, high viscosity bread or cookie dough, meat pastes and fish purees are printed by different 3D-printing methods [6, 10, 45, 49]. Starches, gums, pectins, other hydrocolloids, gelatin, enzymes or fats may be utilized for achieving the desired flowable viscosity and retaining the post processing geometry [5, 6, 10, 48, 50].

Shear-thinning behavior helps to create self-supporting structures, like observed in the study of 3D-printing with soy protein isolate-gelatin and soy protein isolate-sodium alginate mixtures [41]. Gelatin at low temperatures had created a 3D-network with hydrated soy protein isolate and the water was stabilized in this structure, thus the mixture was converted into an elastic gel. Similarly, banana-based 3D-printed fruit snacks that had a shear-thinning behavior were also able to retain their designed shape [13]. Besides higher elastic modulus (G′) values compared to viscous modulus (G″) values are associated with the higher shape strength.

Viscoelastic properties of cookie dough were also evaluated for characterization of 3D-printed structure stability after baking [23, 51]. In the study of Kim et al. [51], wheat flour-based cookie dough had higher G′ than G″, therefore the dough formulations with or without hydrocolloids had solid like viscoelastic behavior. However, the type of hydrocolloid had different effects on shear modulus values, at the same level of addition; the dough with methylcellulose had significantly lower shear modulus values than the dough with xanthan gum. On the contrary, the extrudability of xanthan gum added into cookie dough formulations, especially over 0.5% level had high extrudability values indicating the difficulty of 3D-printing [51]. Rheological behavior of vegetable inks prepared from broccoli, spinach and carrot powders were also evaluated with respect to the type of added hydrocolloids. Incorporation of xanthan gum, guar gum, locust bean gum and hydroxypropyl methylcellulose (HPMC) resulted in different printability values [52]. Shear modulus values were compared for assessing the printability and deformation of vegetable powder-based inks, and at the lowest vegetable powder levels (10%), HPMC added formulations had the lowest shear modulus values, whereas at the highest powder level (30%), xanthan gum added mixture had the lowest shear modulus. In contrast to these shear modulus values, the resolution of 3D-printed structure from xanthan gum added formulations were better than the HPMC added formulation for both of the 10% and 30% vegetable powder levels [52].

The effects of flour and other ingredients on rheological behavior of cookie dough were evaluated in the study of Pulatsu et al. [23]. The yield stress values of dough formulations varied between 7.6-285.1 Pa, whereas the dough with tapioca flour had the lowest yield stress when the formulation included the highest levels of milk (65 g milk/ 100 g tapioca flour). However, depending on the creep recovery tests, the dough from tapioca flour with reduced sugar level (37.5 g/100 g tapioca flour) and low milk content (32.5 g/100 g tapioca flour) had the lowest deformation and the highest recovery values which made this formulation superior for 3D printing [23].

In addition to the viscosity modification, hydrocolloids alone were tested as reference material for 3D-pring as food-inks. In the study of Kim et al. [53], agar, gelatin, gellan gum, guar gum, HPMC, locust bean gum, methylcellulose (MC) and xanthan gum solutions with various concentrations (8-10-12%) were 3D-printed as reference materials. The gel strength was evaluated with texture profile analysis (fracturability, hardness and stiffness) and rheological tests were performed. The hardness of the printed gels increased with increasing amounts of hydrocolloids, but the highest stiffness was observed for gellan gum followed by gelatin. Besides, the viscosity changes of these gels were monitored in order to evaluate the storage stability, and as a result; the viscosity of guar gum and locust bean gum gels gradually decreased, therefore these hydrocolloids were excluded from the reference materials list of 3D-printable inks [53].

The complex food formulations can also be 3D-printed by manipulating the viscosity of the mixture. In the study of Liu et al. [54], complex food formulations were prepared from egg white protein, gelatin, corn starch and sucrose at different levels in order to evaluate the effect of viscosity on 3D printability. At fixed extrusion conditions, the optimum formulation that had self-supporting structure following the deposition stage was the mixture having a viscosity (1.374 Pa.s) located in the middle range of all tested formulations [54]. These complex mixtures had shear-thinning behavior and like other food systems, the printable formulations had elastic behavior with higher elastic modulus than the viscous modulus values.

In addition to the printability evaluation with rheological measurements, the mechanical strength of the printed objects is assessed with texture analysis before and after processing. Especially structural strength of fried or dried snacks is important for the product quality. Feng et al. [55] had studied the effects of infill path on the texture of yam powder and potato processing by-products based 3D-printed air fried snacks. They had tested three infill levels (20-50-80%) by six different printing structures in parallel, cross and complex forms, and the higher levels of infill path resulted in higher breaking force. The overall trend in breaking force was similar independent of the level of potato by-products or the pattern, although the bending height did not follow the same trend. For example; bending height of only yam including rectilinear pattern had increased from 4 mm to 5.2 mm when the infill level was increased from 20% to 50%, but the bending height again decayed to 4.3 mm. In contrast, the bending height of complex structures, such as triangular and honeycomb pattern steadily increased with respect to the increasing infill levels [55]. The cylindrical shape pattern with same infill level was selected for 3D printing of wheat flour-based snacks with different edible insect substitution levels and the hardness of these snacks were compared according to insect level and baking temperature [15]. The hardness gradually increased from 35 N (0% insect) to 52 N for 20% insect enrichment, though the hardness did not increase linearly with respect to baking temperature elevation. The lowest hardness was observed for the intermediate temperatures, whereas the highest hardness had belonged to the highest baking temperature.

3.2. Effect of Thermal Properties

Thermal stability of printing materials is determined prior to the 3D-printing applications, since the materials have different behaviors during cooling or heating applied through processing or post-processing stages of printing. Especially gelation of gelatin or crystallization of chocolate-based inks during cooling and melting of cheese, melting of gelatin, recrystallization of cellulose or pasting of starch induced by heating, further effects the mechanical behavior of printed geometry [32, 33, 41, 50, 54, 56, 57, 58, 59]. Heating and cooling applications during printing promotes the flowability of the feeding through the nozzles and helps to reach the desired viscosity levels. For example, the 3D printers are heated above the crystallization temperature of chocolate generally between 31-48°C before printing of chocolate-based inks [32, 33, 35, 50, 60].

The processing conditions and printing parameters of 3D-printed food samples that are subjected to heating and/or cooling applications are summarized in Table 1. Depending on the applied heat treatment, the feeding material might have variations in differential scanning calorimetry (DSC) profiles due to the components or additives used for flowability improvement. Such as pure soy protein isolate solution or soy protein isolate+ sodium alginate mixtures had no significant peak between 0-120 °C, although the incorporation of gelation to these solutions at different levels resulted in an observable peak around 29°C which was associated with the melting of gelatin [41]. Similarly, Liu et al. [59] observed in their study that the DSC profiles of rice pastes varied with the addition of sodium alginate into the pastes. The glass transition temperature shifted to little higher temperatures for waxy and japonica rice pastes, while the glass transition temperature of indica rice paste shifted to a little lower values with the addition of sodium alginate. Besides, the endothermic peak area that was associated with melting of starch crystals was different for each rice paste depending on the type of rice flour and the peak area deviated from pure starch pastes with respect to the addition of sodium alginate [59].

Table 1. 3D-printing of food samples

Feed	Printing parameters*	Heating/cooling before printing	Cooling after printing	Printed shape	Reference
Dark chocolate, chocolate-corn syrup mix., drug loaded chocolate-corn syrup mix.	D: 2 mm, E: 5 mm/s, ID: 100%	Yes/45°C	No	Bone, cartoon characters, star	[35]
Cellulose powder-xanthan gum-ethanol-Tween 20	WD: 100 μm	Yes/30°C	No	2D square layers	[56]
Cheese	D: 1.5 mm, E: 4-12 ml/min	Yes/75°C	Yes/4°C	Cylinder	[57]
Dark chocolate	D: 1.37 mm, P: 300-700 mm/min	Yes/31-36°C	Yes/ 19.9-23.7°C	Heart, bunny	[33]
Dark chocolate	D: 0.61 mm, P: 21 mm/s	Yes/ 48°C	Yes/4°C	University logo	[60]
Dark chocolate, magnesium stearate	D: 0.8 mm, P: 70 mm/s	Yes/32°C	Yes/ 15-22°C	Hexagon	[32]
Egg albumen powder, gelatin, corn starch, sucrose	D: 1 mm, E: 0.004 cm^3/s, H:3 mm, P: 70 mm/s	Yes/ 40°C	No	Snowflake, star	[54]
Mango juice, potato starch	D: 1 mm, H: 1 mm, P: 25 mm/s	Yes/ 30°C	No	Triangle frame	[61]
Pavlova meringue	D: 0.61 mm, P: 40.2 mm/s	Yes/ 10°C	No	Australia map	[60]
Soy protein isolate, gelatin and sodium alginate mixture	D: 1.55 mm, H: 0.6 mm, ID: 100%, P: 10 mm/s	Yes/ 35°C	Yes/4°C	Anchor, cartoon character, cylinder, logo, pear, rabbit	[41]

D: nozzle diameter, E: extrusion speed, F: flow rate, H: height, ID: infill density, P: printing speed, WD: well depth

4. POST-PROCESSING

A cooking technique such as baking, steaming, frying or extrusion cooking is often necessary after 3D printing food materials [2, 8]. Also, the food needs to be dried for extending storage period. However, depending of the complexity of 3D printed food texture, non-uniform heat distribution inside the product may occur and maintaining the desired shape of printed food may then be challenging [1, 6, 8]. It is therefore important to keep the shape of the 3D printed food material intact during the cooking and drying processes.

The structure and storage stability of 3D printed food is ensured by proper packaging and storage conditions depending on the type of 3D printed food. For instance, Severini et al. [30] employed both air and modified atmosphere packaging for evaluating the microbial load of fruit and vegetable based samples in polypropylene trays.

5. LIMITATIONS

First of all, one serious problem to be faced with 3D food printing may result from equipment pieces that are cleaned insufficiently [30, 62]. Food safety is a great concern in food processing and unfortunately, there hasn't been many studies related to the food safety aspect of 3D food printing. Then consumers start categorizing materials as edible and non-edible at early ages. The geography they live in, their cultures and traditions, their families and religions play an important role on defining what is edible and what is not. Therefore, any innovative and new material or technology raises a question in many consumers' mind

(neophobia). On the other hand, some people may be looking for excitement and novelty in what they consume (neophilia) [14]. To find out the consumer reactions, a 30-panelist discussion group was formed in Australia, University of Canberra and they were given images of 3D printed sweets, chocolates, pasta, carrots, a meal with vegetables and chicken, a snack made from ground insects and a pizza [14]. The quality, freshness and price for value were among the most important factors for the participants when they are making food choices. Environmental sustainability was not an aspect they would consider when buying food, except for one participant. All in all, because of the freshness being among the top priorities for food selection for the majority of the participants, the idea of consuming discarded or leftover foods, such as damaged fruits and vegetable, was not appealing [14]. This led some participants to suggest that such foods are suited for the poor and ill. Some participants had concerns about the bacterial load of 3D printed foods. The authors believe that the use of 'printing' term might be a factor in raising concerns because the tradition printing (including 3D printing) uses a lot of chemicals, such as color inks and plastics [14]. Therefore, people who are not familiar with 3D food printing concept might be scared and biased at the moment they hear 3D food printing, as printing is associated only with non-edible things beforehand. This suggests that using similar terms such as "additive manufacturing" or in case the term "additive" seems scary for consumers, "food layered manufacturing" might overcome these biases. This study suggests that the consumers have to be educated on what 3D food printing is and the benefits before anything.

In addition, researchers found that using different infill patterns affect the infill densities and size of the printed food [63]. In cookie samples, lower infill densities required fewer ingredients and hence bigger sizes, whereas the cookies with the largest infill had the smallest size. All the cookies included the same amount of ingredients and hence the same amount of calories. However, the bigger the cookies, the more time was required for the panel participants to chew and the more satiety that they perceived [63]. Therefore, playing with the 3D printing shape and patterns can help tackle obesity. Lin et al. [63] developed a phone app where the consumer can choose their satiety level and play with the infill properties and size of the printed food. Last but not least, even though labeled to be among the "future food", the possibility of finding a 3D printer in every kitchen depends on one thing: "*They need to become cheaper, faster, and easier to use*" [62]. Scaling up 3D food printing is another issue that is limited to printing speed [4].

6. CONCLUSIONS

3D printing technology is initially developed for artisan chocolate and confectionery production for its attractive appearance. Today this technology is evolving through the manufacturing of special foods with customized nutritional and textural properties that are meeting the requirements of children, athletes or patients with swallowing problems. However, the 3D printers in the current stage is far from the state-of-the-art, as it lacks of transferring the knowledge between the food properties and handling into 3D sustainable and reproducible structure modelling.

3D printing technology has a great potential for recovery of waste or underutilized fruit, vegetable, meat or seafood parts by incorporating these parts into the feeding formulation as a puree or paste. Also different food materials can be printed in different layers for creating a complete nutritional balance as a functional food. The essential food ingredients such as vitamins, other antioxidant compounds or dietary fiber may be incorporated into the printing formulation, although these ingredients are susceptible to degradation by presence of oxygen and light. Therefore, these nutrients should be preserved during storage by proper packaging and storage conditions. In spite of having much potential in further development, the food safety and sustainability issues related with 3D printing technology have not yet been fully studied. Besides, the standards and limitations related with the 3D printed functionalized foods are not yet established.

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