Strengthening Global Food Science and Technology for Humanity

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3D Food Printing: Opportunities, principles, limitations, and new ways in food production

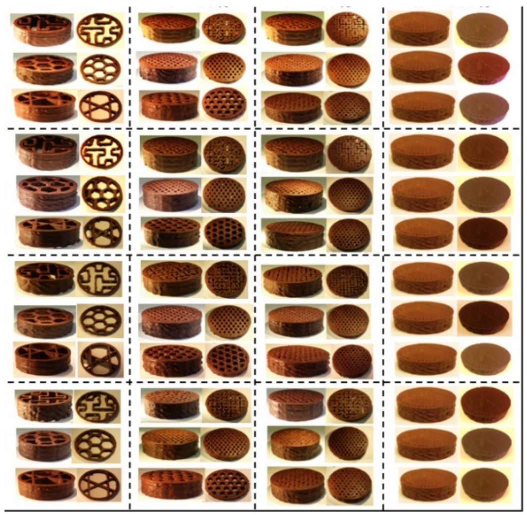
Abstract

The idea of printing food products based on digital 3D models is indisputably innovative, intriguing and provides many opportunities to completely renew how food is produced. Indeed, 3D food printing has ambitions of nutritionally and sensory personalized food manufacturing, on-demand food production, food waste reduction and innovative sensory perception. While the first experiments were focused only on chocolates, later, a large diversity of food, such as fruits, meat, fish, vegetables, potato, cereals, and dairy products, were used as edible inks. In all cases, it has been possible to replicate the digital models with enough accuracy although many challenges still limit the application at the industrial level or for home use. This contribution analyzes and discusses the scientific information on the ambitions, the basic principles and the main processing variables, the most important applications, and the reasons limiting the use on the market. Finally, future perspectives such as 4D food and programmable texture have been analyzed.

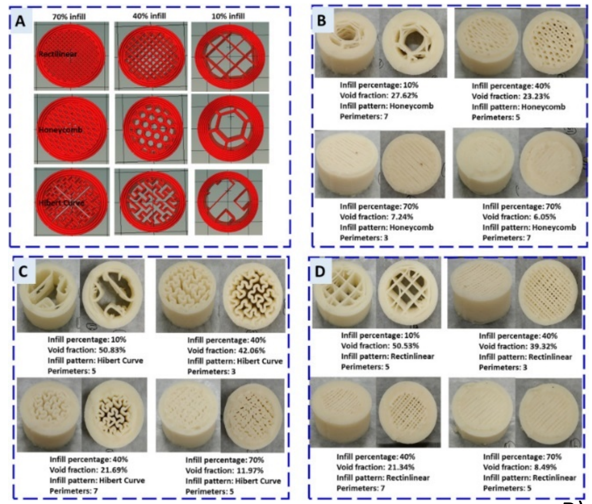
Main themes and new opportunities

Additive manufacturing (AM) technology, popularly known as 3D Printing (3DP), has widely shown its capacity of accelerating the process of industrial innovation and creation of goods based on end-users' needs. This has made feasible the concept of customizable products hence the food sector intuitively has considered the 3DP as a source of renewing how food might be produced. Primarily, though, 3D Food Printing is the only technique capable to translate digital images into tangible food products and this opens the way for innovative and intricated shapes and dimensions maximizing food's eye appeal, helping in differentiating or identifying food products, and improving the overall enjoyment of food consumption. Indeed, the usage of 3D CAD software to design innovative structures and the 3D printing process that adds dozens of degrees of freedom to the common food fabrication, allow the creation of structures never thought before. Earlier Cohen et al. (2009) stated that '*after solving the main issues of slow printing and price, the remaining question is what the ways in which 3DFP will completely modify the food sector, while no doubts on whether 3DFP may affect food manufacturing and consumption*'. Examples of unprecedented structures may be found in many scientific papers, press releases, and web site of companies (Hao et al., 2019; Kim et al., 2021b; BluRapsody, 2021; ChocEdge, 2021). For instance, Bluraphsody (2021) a startup of the Barilla Group produces innovative shapes and letters of pasta '*making your dinner and your events even more exclusive*' not only for their visual aspect but also for maximized seasoning's perception. Periodically, scientific documents and press publish pictures of innovative food shapes obtained by 3D Food Printing (Figure 1).

Figure 1 – Examples of 3D printed food with innovative shape, dimension and internal structure. A) 3D printed chocolate (from Manthial et al., 2019); b) 3D printed mashed potato (from Liu et al., 2018a); C) and D) 3D printed shape of pasta (BluRaphosdy, 2021).



A)



B)

3D: Op

C)

D)

However, the novelty of 3DFP is well beyond the creation of food with upgraded and more fascinating visual aspects, with many additional benefits on the food chain, nutritional/healthy and sensory properties, satiety, consumer's behavior and sustainability. Therefore, for instance, when the printing of customized goods is reworded as **personalized 3D printed food**, the production of foods with desired sensorial and nutritional properties offers many solutions to contribute to the better health status of consumers by reducing the risks of chronic diseases. Indeed, desired sensory properties might facilitate the adoption of a more complete daily diet by inclusion of foods rich in bioactive compounds which may otherwise be discarded because of being unappealing (i.e. some fruit or vegetables commonly discarded by children). Derossi et al. (2018a) designed and printed innovative fruit-based snacks for children of 3-10 years old providing 5-10% of the daily intake of energy, calcium, iron and vitamin D. Severini et al. (2018a) printed a pyramid-shaped snack consisting of a blend of fruits (pears, kiwi fruit, avocado) and vegetables (broccoli and raab leaves) to confer a physical structure to the common smoothies widely appreciated for their taste and the significant nutritional and functional properties. More recently, Tomasevic et al. (2021)

thoroughly reviewed and discussed many examples of using 3D printing as a tool for innovative fruit-based functional foods. Interestingly, the possibility of printing ink-gels enriched with live plant cells that, for their unique properties, offer many perspectives for novel texture, taste, colour and nutrient content (Uribe-Wandurraga et al., 2020). In addition, 3D Food Printing may directly contribute to the manufacturing of nutritionally personalized foods from different angles. First, the principle of dispensing/depositing small amounts of food material per unit of time offers the opportunity of dosing each ingredient with high accuracy in order to modulate the content of macro- and micronutrients according to the needs of each individual or small group of consumers. Similarly, mg or mg of specific elements, such as minerals, could be precisely added to each 3D printed structure by dispensing/dosing aqueous solution of such minerals to a printable food formula. In addition, 3D food printing being centrally based on the use of digital data, could use medical and nutritional data to delineate specific requirement of consumers such as the computation of energy, macro- and micronutrients and then to design the food formulation employed for process building of the final product. Interestingly, this opportunity could help to reinforce the immune systems of vulnerable or hospitalized people with wide benefits on the society (Derossi et al, 2021). Examples of the creation of 3D printed food with enriched nutritional properties have recently been published (Liu et al., 2017; Zhang et al., 2018; Liu et al. 2020; Yoha et al., 2021). Liu et al. (2020) realized some 3D printed mashed potatoes enriched with probiotic strain *Bifidobacterium animalis subsp*. Lactis BB-12 with beneficial effects on the gut and immune function. Yoha et al. (2021) studied the synergistic effects of the encapsulation of *Lactiplantibacillus plantarum* (NCIM 2083) and 3D food printing to provide new insight on the design of personalized 3D printed probiotic foods helping to modulate the immune systems by the inhibition of pathogenic colonies. Zhang et al. (2018) adopted 3D printing to create innovative cereal-based structures containing probiotic bacteria (*Lactobacillus plantarum* WCFS1) highlighting a viable count in the 'honeycomb' edible structure exceeding 10^6 CFU/g. Another interesting possibility is the design of proper 3D structures – also by an approach of programmable voids generation - addressing novel texture properties that when optimized for specific consumer's group can help to reduce relevant problems such as swallowing and mastication issues that often limit the intake of important nutrients by the elderly (Kouzani et al., 2017; Vancauwenberghe et al., 2019; Derossi et al., 2021a; Pant et al. 2021).

Furthermore, the relationship between the texture of food and satiety and satiation perception must be recognized. By proper control of the 3D printing variables, it is possible to prepare food products within a wide range of texture properties – from very fragile to hard material – with more or less mastication work and jaw movements inducing a fast satiety perception (Bolhuis and Forde, 2020; Lin et al., 2020). Such approach would be of great relevance to tackle the growing pandemic crisis of obesity (Derossi et al., 2021). Finally, though, 3DP supports the decentralization of food manufacturing and the consumer-centric system of production allowing the manufacture of products close to the final customer (Gao et al., 2015; Chan et al., 2018). By reducing the tight dependence on the supply chain, it would be possible to increase the overall sustainability of the food system with a significant reduction in energy consumption and gas emission generated by transportation, and the amount of food waste or food loss at industrial or home level (Derossi et al. 2021a). Some interesting scientific discussion on the potential use and benefits of 3D food printing have recently appeared (Gholamipour-Shirazi et al., 2020; Derossi et al., 2021a; Wilms et al., 2021; Le-Bail et al., 2020; Tomasevic et al., 2021).

Basic principles and relevant variables

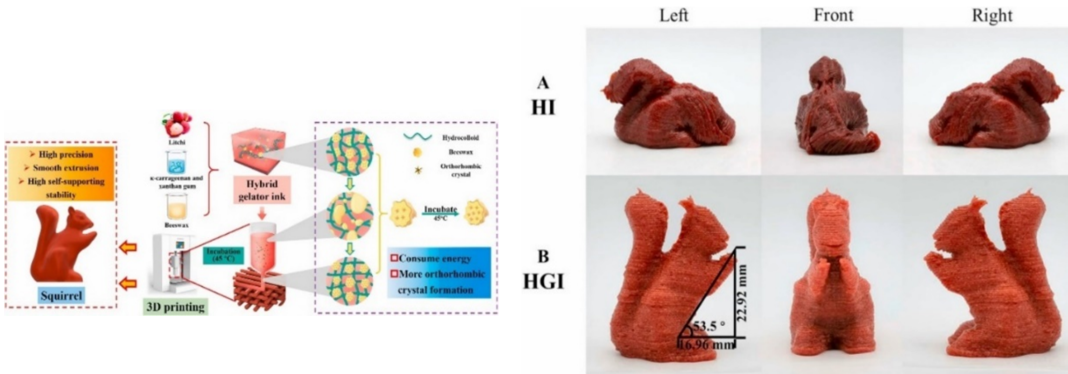
The 3D food printing is a complex process of converting a digital model into a physical product through the layer-by-layer deposition of food material controlled by the movements of the 3D printer in the X ,Y, Z plane which, in turn, are described in the G-Code. More precisely, we have to consider a fourth axis, the E-axis, that defines the movement of the stepper motor per unit of time. 3D Food Printing is a very popular term, but many other 'printing' technologies exist under the broad group of Additive Manufacturing (AM).

Some of these are Selective Laser Sintering (SLS), Fused deposition modelling (FDM), Binder jetting, Inkjet printing, and extrusion-based system, among others (Dankar et al., 2018). However, the extrusion of edible pastes by using screw-based or syringe-based systems has been used for 95% of the scientific documents and practical applications (Severini et al., 2018; Godoi et al., 2018) while the SLS has been limited for creating sugar-based 3D structures (Candyfab, 2020). Therefore, in this contribution only the printing by extrusion will be discussed and analyzed.

At first, the 3D digital models may be created by using a large series of Computer-Aided Design (CAD software) for beginners of professional users (TinkerCad, 2021; Rinho, 2021; Grassopher, 2021). Such models are then converted into a Standard Tessellation Language (.STL), the .STL file employed for the slicing step in which all printing variables are defined and a G-code, consisting of all the commands for the printing movements and material deposition, is generated (Nijdam et al., 2021a).

Considering here that the first purpose of 3DFP is the building of an accurate replica of the digital model, two main branches of activities must be performed and optimized. The first is the creation of a printable food formula and second is the setting of printing variables to get the highest fidelity of printing.
The assessment of the rheological properties such as shear-thinning behavior, yield stress, viscosity and recovery behavior are essential to evaluated the potential printability of the food formulas (Feng et al., 2019; Dick et al., 2021). Food matrix with high viscosity at rest commonly show an excellent structural stability after deposition due to the capacity to maintain the weight of the overlaying layers but, contrarily, they can be hard to deposit through the nozzle or can clog the nozzle. The yield stress is of great importance being an accurate index of the stress required for the flow of the ink that means the minimum force required to initiate the material deposition (Liu et al, 2019; Liu et al., 2021). Once the flow is initiated, a shear thinning behavior, indicating the viscosity reduction as a function of shear increase, is widely desired to assure a homogenous and continuum deposition of the food filament. Furthermore, a recovery stage characterized by the fast rheological changes of the food matrix during the transition between the extrusion and deposition and, finally, the capability to keep the stacked filaments are others important properties that define a good printability of the food material (Dick et al., 2020, Zhu et al., 2019). To improve printability/extrudability of food material several publications have been dedicated to the understanding and optimization of the rheological properties of the food formulas aiming to make them easily printable and stable over time (Wilms et al., 2021). While some authors have modulated the food ingredients to improve the printability/extrudability (Severini et al., 2018; Pulatsu et al., 2020; Jagadiswaran et al., 2021) many others have studied the use of structuring/gelling agents - i.e. starches, milk-gels, carrageenan, xanthan gum, and agar - and their blends to studying effects on the rheological properties and their relation with printability and printing fidelity (Maniglia et al., 2020; Dick et al., 2020; Paolillo et al., 2021; Montoya et al. 2021; Vancauwenberghe et al., 2018; Uribe-Alvarez et al., 2021). More recently, Tian et al. (2021) prepared a printable food material that compared the use of beeswax, κ-carrageenan and xanthan gum to improve the printing quality of the 3D printed food (Figure 2). Results clearly show the effectiveness of the food formula with beeswax (hybrid gelator ink, HGI) while when using only κ-carrageenan and xanthan gum (hydrogelator, HI) several defects were observed.

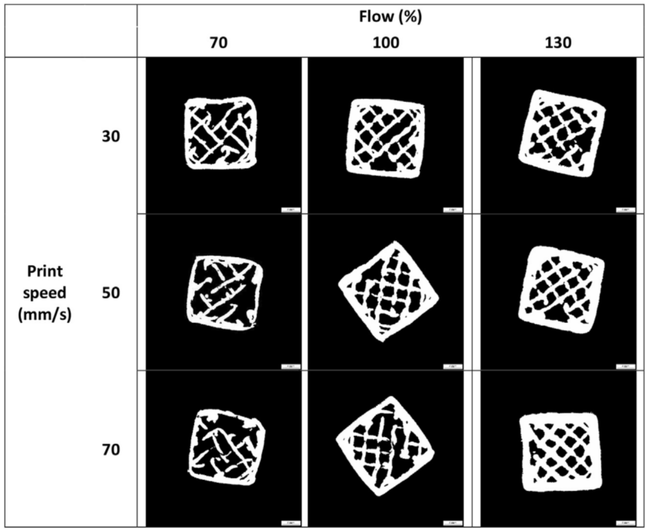
Figure 2 – Effect of different kinds of gelling agents on the quality of the printed food structure (from Tian et al., 2021). A) workflow employed during the experiment; B) Pictures of 3D printed squirrel without using beeswax (HI) and with beeswax (HGI).



However, the definition of food formulas that fit appropriate rheological behaviour for an easy deposition and robust structural stability is a hard work especially without any general rules/information. Therefore, some authors have focused their efforts on innovative methods to evaluate the printability of food formulas. Fahmy et al. (2020) developed a camera-based system for the in-line assessment of extrudability of some cereal-based inks. Diversely, other researchers proposed a useful map of the relationship between rheological properties and printability of food material to furnish a useful guideline for a more practical realization of high-printable formulations (Zhu et al., 2019). Furthermore, Ma et al. (2021) aimed to develop a predictive model for extrudability of food materials by analyzing the images of single filaments of 131 combinations of edible materials.

Let us now assume a high capability to design and develop a food formula easy to print deposit and keep the 3D structure after printing. Then, the other challenge/question that we have to tackle/responding is: *will the setting of printing variables be suited to get a high printing quality?* Indisputably, although the food matrix is highly printable the performance of the printing process will depend on whether printing variables are properly defined (Derossi et al., 2018b). Therefore, for instance, the imbalance between the printing speed (mm/s) and the rate of material deposition (mm^3/s), creates several troubles to the quality of the 3D structure. Unfortunately, this imbalance occur many times as affected by a complex interrelation between engineering features, rheological properties of food material and the software of the printer. For instance, studying the effects of some printing variables on the quality of a fruit-based snack by acquiring the X-ray cross-sectional images of the printed samples, the structural defects occurring when print speed and the extrusion rate/flow were not in equilibrium were clearly shown (Derossi et al., 2018a) (Figure 3). For high printing speed (70 mm/s) and a minimum flow (70%), the amount of material was not enough for a homogenous filament. On the contrary, when the flow is high (130%) and the printing is slow (70 mm/s) the external shell and of any filament are too thick due to the excess of material deposition.

Figure 3 – Representative X-ray cross-sectional images of 3D printed fruit-based snacks as a function of print speed and flow (from Derossi et al., 2018a).



Importantly, many other variables have to be accurately defined to obtain high-quality printing such as printing speed (Derossi, et al 2020a; Yang et al., 2018), extrusion rate (Vancauwenberghe et al., 2017), nozzle size (Yang et al., 2018), layer height (Yang et al., 2018; Zhu et al., 2019), infill density (Severini et al., 2018b), distance and speed retraction, printing path (Derossi et al., 2018b), and travel speed (Derossi, et al., 2020a). Here, though, it is sufficient to examine the effects of three of them, layer height, nozzle size and infill density, which have been subjected to detailed experiments.

The layer height is the distance between two overlaying layers. The most important thing to consider here is that while the theory on AM technology says that the best layer height (LH) is equal to the nozzle diameter and a critical layer height could be computed as reported in many publications (Yang et al., 2018; et al., 2018; Hao et al., 2019), in the real applications and to improve the adhesion between the layers, LH is generally used at 80% of the nozzle diameter although in some cases values of 50% provided the conditions for best printing (Jagadiswaran et al., 2020). This situation allows depositing a food filament with a like-rectangular shape greatly improving the adhesion and structural stability rather than what happens when printing a theoretical cylinder (Ma et al., 2021).

When LH is too low, the tip of the nozzle may move and deposit the edible material inside the previous layer with, of course causes several problems resulting in shape discrepancies. Contrarily, for too high LH, the material is irregularly deposited creating many defects of the final 3D printed structure (Wang et al., 2018). However, the setting of a unique layer height can be insufficient for a high-quality printing. In some experiments, we have shown that the distance between the nozzle tip and the previous layer could increase as many layers are deposited (Derossi et al., 2020a) due to the relaxing/collapse of the first layers under the growing weight of the structure.

The nozzle size literally is the diameter of the nozzle through which the food formula is extruded/deposited. Overall, the smaller the nozzle size, the higher is the resolution of the 3D printed structure with many possibilities of building more complex and fine structures. However, the majority of the scientific documents employed nozzle sizes of 0.6 to 2 mm (Yang et al., 2018; Mantihal et al., 2019a; Park et al., 2020; Fahmy et al., 2021; Cui et al., 2022). Yang et al. (2018) clearly showed the different fineness of the 3D printing when using nozzle size from 0.5 to 2.0 mm (Figure 4a); similar results were obtained by Huag et al. (2019), but it is worth to note that by reducing the nozzle diameter, the overall printing time significantly increases thus reducing the low productivity rate (Figure 4b).

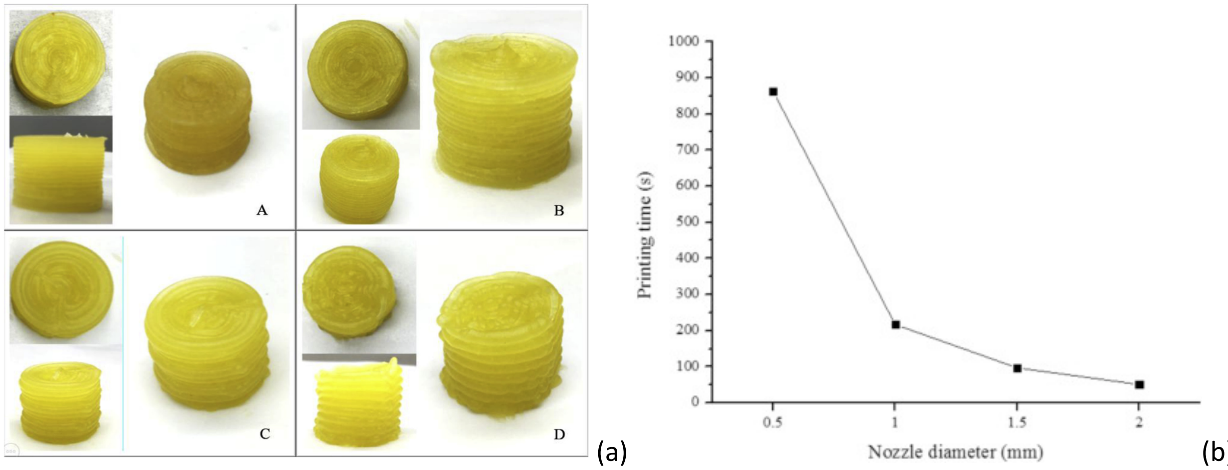


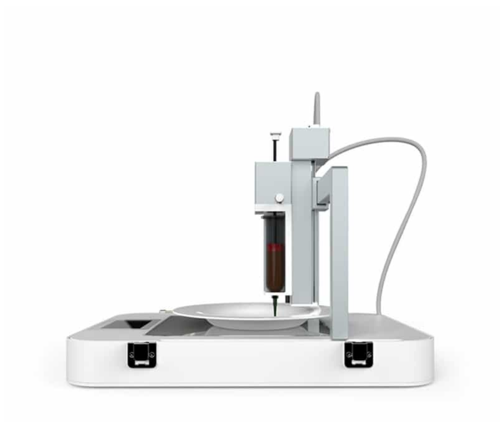
Figure 4 – Effects of nozzle sizes on the visual aspect (a) and printing time (b) of 3D printed lemon gel (from Yang et al., 2018). For figure 4a the 3D printed samples have been obtained by using a nozzle size of 0.5 mm, 1.0, 1.5 and 2.0 mm respectively for A, B, C and D.

Of course, by increasing the nozzle diameter a higher amount of food material per unit of time is deposited and many others interrelated variables, mainly printing speed and the layer height, have to be newly modulated to maintain a high printing fidelity (Khalil and Sun, 2007; Yang et al., 2018).

Finally, it is important to condense the available literature on the importance of the infill level and the infill path. The first variable defines the volume fraction of the 3D sample filled during the printing process. More precisely, the infill level (also called infill density) is computed on the inner part of 3D digital model so that, when printing a cylinder with a diameter of 17 mm, infill levels of 10, 15 and 20% correspond to a final solid fraction of 74.8, 76.2 and 77.6%, respectively (Severini et al., 2018). The infill path specifies the geometrical pathway of the printer during the deposition of the infill which, in general, may be chosen among some default geometries included/allowed by the slicing software. The infill level improves the structural stability of the 3D printed food because the 'filling' sustains the external shell but, when the infill is greater than 50-60% the printing movements could become very complex with increased risks for structural defects. Furthermore, the quality of the 3D printed structure as well as on the texture properties are tightly connected with the infill path. An exhaustive example is the study by Liu et al. (2018a) who mixed three different infill levels (10, 40 and 70%) and three infill paths (honeycomb, rectilinear, Hilbert curve) (Figure 1b). Clearly, the 'hilbert curve' creates two different geometries when using different infill levels affecting the final quality of the 3D printed products. For any of the paths shown in Figure 1b, several defects may be observed for samples printed at 10% of infill with significant oozing indicating the extra-deposition of the mashed potato. This is because the mashed potato continues to flow through the nozzle tip during the travel moments (also called non-printing movements). Finally, it is important to recall that while the increase of the hardness is seemingly obvious and linearly correlated with the infill level of the food structure (Feng et al., 2020; Huang et al., 2019), not simply is the contribution of the infill path (Manthial et al., 2019a; Liu et al., 2018a). Therefore, for instance Manthial et al., (2019a) who printed chocolate structures with different infill paths, clearly showed that the cross path induces the higher resistance to break the samples. On the contrary, Liu et al. (2018) did not observe any difference in the hardness of 3D printed samples by changing the infill path. Meanwhile, Huang et al. (2019) found significant changes when the nozzle size was modified, probably due to the change in the number of layers deposited when reducing the diameter of the nozzle.

Main food materials utilized in 3D Printing

Here, it is very useful to stress the applications of 3D printing highlighting and discussing the most and least utilized printing systems and edible materials. Although the first document on 3D food printing is a patent of 3D cake production (United States patent, No. US62800784 B1, 2000) there aren't evidences on its application till 2007 when during the 18th Solid Freeform Fabrication Symposium (SFF), Periard et al. (2007) used the Fab@Home system in experiments for the creation of edible 3D objects with cake frosting, chocolates, processed cheese and peanut butter. Since then, TNO, Stratatys, many universities, and others public or private entities have focused on 3D Food Printing. Although several technologies have been experimented to get 3D printed food, such as jetter binding, laser sintering, etc., the extrusion technologies definitely are the most used. Also, the extrusion systems to deposit food materials may use cartesian, polar, delta and Scara configuration which refer to how the head and/or the bed of the printing system move within the X-Y-Z space allowing the printer to deposit food material under the control of the CAD models (Godoi et al., 2018). As example, Figures 5a and 5b show two commercial 3D printers that are widely used while Figure 5c reports the technologies used to extrude food materials through the nozzle.



A)

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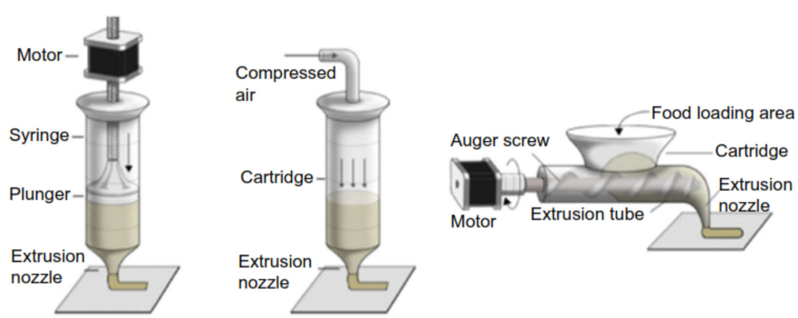
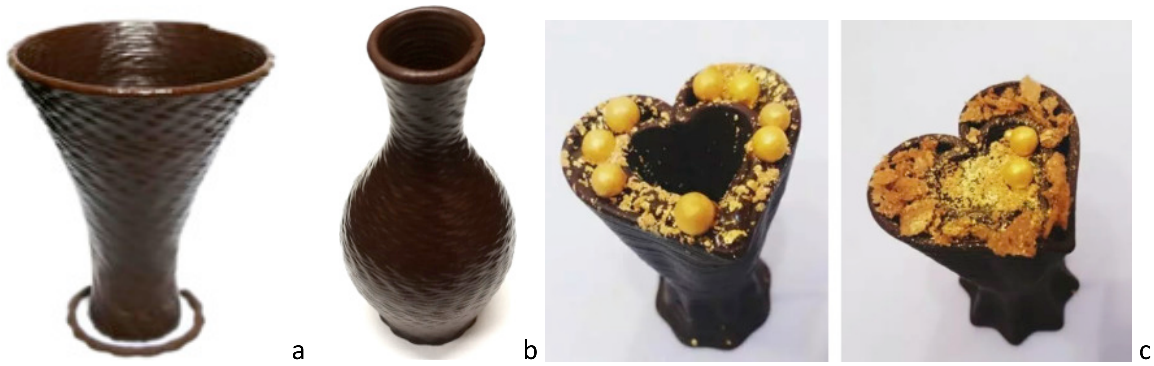


C)

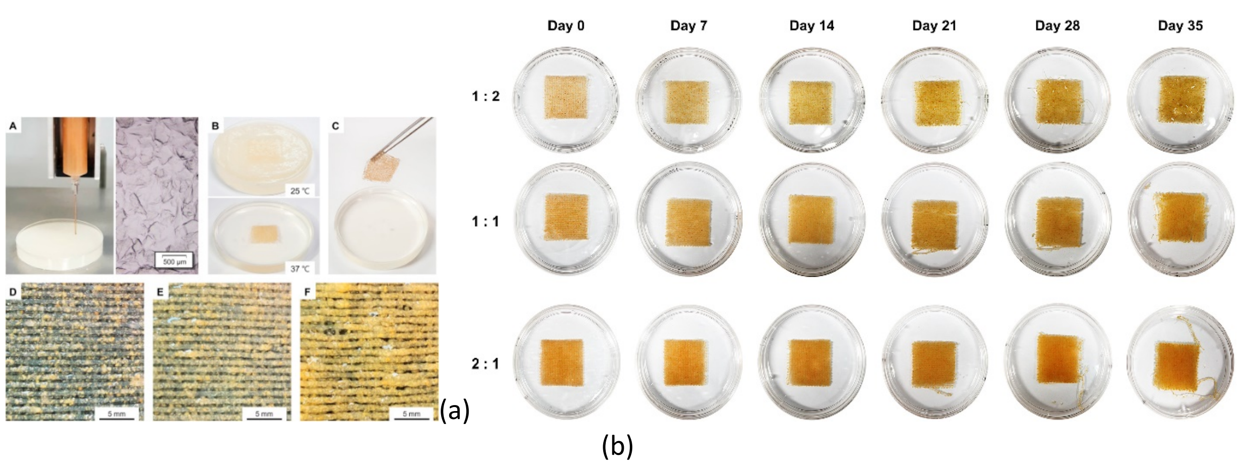
Figure 5 – Examples of 3D printers used for food application. A) byflow (From byflow, 2021) ; B) FoodBoot (From 3dfoodbot, 2021), C) common extrusion mechanisms (syringe based, air-compressed and screw-based) (Sun et al., 2018).

Perhaps, the first edible material used for 3D printing experiments has been chocolates due to the controlable melting and solidification (crystallization) temperatures. In this regard, the Figure 6 shows some representative images of 3D printed chocolates. However, many others food matrix may be prepared as pastes, cereal-doughs, ink-gels from hydrocolloids, and powders directly introduced in the food matrix (Lee et al., 2019; Jagadiswaran et al., 2021)

Figure 6 – Representative examples of 3D printing of chocolate. A), b) and c) from Hao et al., 2019

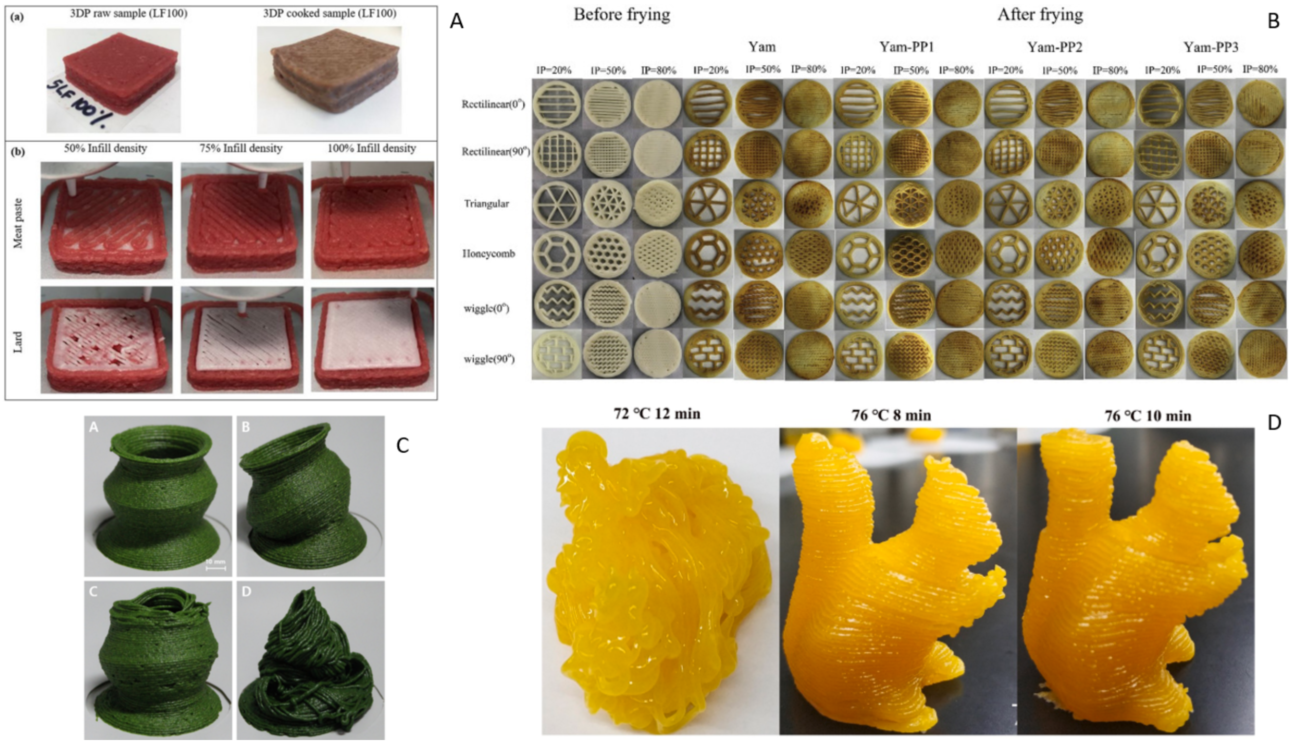


Later, many other materials have been used to print innovative food, such as potato (Liu, et al., 2018a; Feng, et al., 2020), chocolate (Mantihal, et al., 2019b), fruit and vegetables (Severini, et al., 2018a; Tomasevic et al., 2021; Guenard-Lampron et al.,2021; Liu et al., 2018b), cereal dough (Pulatsu, et al., 2020; Severini et al., 2016; Severini et al., 2018b; Derossi, et al., 2020), meat (Dick et al., 2019b; Kim et al., 2021a), eggs (Xu et al., 2020), surimi (Wang et al., 2018), yoghurt, cheese and others and dairy products (Le Thoic et al. 2018; Riantiningtyas et al., 2021; Uribe-Alvarez et al., 2020), starches and other hydrocolloids (Montoya et al., 2021; Liu et al., 2021; Wen et al., 2021) as well as complex food formula such as wheat starch and egg white powder (Fahmy et al., 2021), starch and lemon juice (Yang et al., 2018), alive cell plant introduced to bio-inks (Vancauwenberghe et al., 2019) cereal-based enriched with probiotics (Zhang et al., 2018), probiotic encapsulated in fructooligosaccharide, whey protein and maltodextrin (Yoha et al., 2021), novel source of nutrient mainly insect powder (Severini et al., 2018b), waste food from grape pomace and broken wheat (Jagadiswaran et al., 2021), and potato by-products (Feng et al., 2020). However, considering space limitations, only some selected examples are shown and discussed here. Considering fruit and vegetables, for instance, a blend of carrots, pears, kiwi fruits, broccoli raab leaves and avocado without gelling agents, was successfully printed in a pyramid shape. Also, very interesting is the approach of Park et al (2020) who printed a hydrogel consisting of carrot callus with 4% alginate in which the implanted cells significantly grow during incubation for a 35-day opening for an innovative food product with unprecedented nutritional content and texture properties (Figure 7).
Figure 7 – Printing process of callus embedded in alginate network (a) and changing over incubation period of 35 days for different carrot cell dispersion (b) (from Park et al. 2020)



For cereal-based food, we have worked on the effect of printing variables and different food formulas on the fidelity of printing of some simple structures such as cubes, cylinders (Derossi et al., 2018a; Derossi et al., 2020a), while other researchers have focused on the printing of cereal doughs enriched with probiotics (Zhang et al., 2018), waste and by-products (Jagadiswaran et al., 2021), and/ or the post-processing capacity of cookie dough (Pulatsu et al., 2020). Finally, Figure 8 shows examples of printing meat products, yam, egg yolk and spinach powder (Dick et al., 2019a; Xu et al.,2020).

Figure 8 – Examples of 3D food printing. A) printing complex meat with layers of meat and lard (Dick et al., 2019b); B) 3D structure of yaw for different infill path before and after frying (Feng et al., 2020); C) 3D printed structure of spinach powder at different granulometries (from Lee et al., 2019); D) 3D printed egg yolk after different eating to get a printable paste (adapted from Xu et al. 2020).

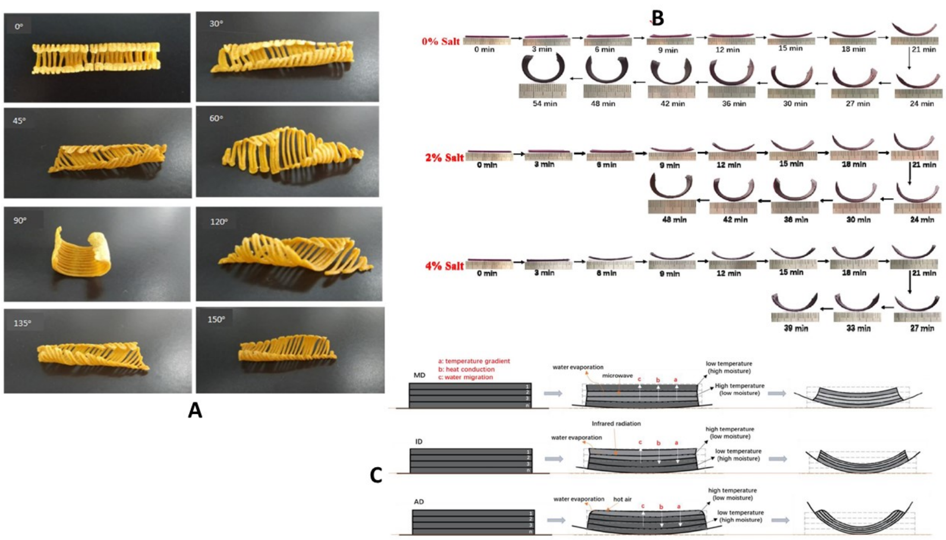


Looking to the future and 4D Food Printing and programmable food structure

While what generally count in 3D food printing is the creation of a complex shape, a more fascinating look, and novel functionalities, one might find it hard to imagine what would be the application of 4D printing in the food sector. However, looking to the future, new intriguing opportunities are growing on the periphery of 3D food printing. Essentially, 4DFP occurs when 3D printed edible structures undergo physical and/or chemical changes as a function of time, thus allowing dynamic modification of sensory and nutritional property of the food products. To do this a proper and accurate use of an external source of stimuli (i.e. light, temperature, pH, pressure, etc.) and material stimuli (i.e. gels, puree, cereal dough, etc.) activates, in a controlled manner, the changes of colour, shape, and flavour, among others, is necessary. Perhaps, the first example of 4DFP was performed at Massachusetts Institute of Technology (MIT) where the researchers realized the controlled change of the shape of pasta (3DPrinting, 2021) https://3dprinting.com/food/mit-produces-4d-shapeshifting-printed-pasta/). The shape change of 3D printed food during time could expand the application and the potential success of this technology due to the great implications on the visual aspect, texture, capability to entrap sauces and seasonings. In addition, some foods with flat shape could be produced and transported, thus minimizing the volume occupied with positive effects on the sustainability of the food chain. For instance, during contact with water, flat pieces of pasta could assume a 3D desired shape.

Shape change has been obtained by using the dehydration process to activate and drive different shape changes of 3D printed multi-materials depending on their mechanical properties. Chen et al. (2021a) printed layers of a pumpkin puree at different moisture content by using as 'bed printer' a paper sheet. Due to the differences in moisture content and mechanical behaviour of the pumpkin puree and the paper during dehydration, it was possible to trigger an increase of the bending angle as a function of drying time. The authors stated that the consumers could modulate the cooking time to meet their personal desires of the final shape while the company could offer innovative and personalized sensory experiences to the customers. Similarly, by using dehydration as an external stimulus for shape changes, He et al. (2020) and Liu et al. (2021) compared the capacity to get shape changes by using different drying techniques, i.e. microwave (MD), infrared (ID), and air-drying (AR) and, also, they evaluated the use of several printable food materials analyzing their capacity of changing the shape during dehydration process. Figure 9 shows some examples of shape changes of 3D printed food.

Figure 9 – 4D food printing. Examples of shape change over time activating by heating process. A) From Chen et al. (2020a); B) from Teng et al. (2021); C) from Liu et al (2021)



Furthermore, the colour change over time initiated by different stimuli is another interesting application of 4D food printing. He et al. (2020) utilized the capacity of anthocyanins from purple sweet potatoes to change colour when exposed to different pH values. By preparing a 3D printed structure of sweet potato alternatively deposited with layers at different pH between 2.5 and 7.8, the authors promoted a dynamic change of colour controlled by the rate of diffusion of the anthocyanins through the layers at different pH. A different approach was used by Chen et al. (2021b) who activated the colour change of curcumin powder, from yellow to pink, by exposing the samples to alkaline conditions released by microwave heating at 280 W for 1-3 min. The same approach was utilized by Guo et al. (2021) to induce colour and aroma change in a buckwheat dough.

The last option that needs to be mentioned is the activation of the aroma and nutritional change of 3D printed food over time. On this, few interesting experiments have assessed modalities for the activation of chemical reactions responsible for taste and aroma change. Phuhongsung et al.(2020a) by using a 3D printed dough containing soy protein isolate (SPI), k-carrageenan (CAR) and vanilla flavour, stimulated chemical reaction by microwave heating for 20, 40 and 60 minutes and observed a significant aroma change over time. In addition, for nutritional changes, a first example was reported by Teng et al. (2021) in which seeds of edible plants were placed in a 3D printed edible nutrient matrix observing the seeds germinating and the plant growth as a function of time with modification of sensory and nutritional content. More recently, Park et al. (2020) deposited an edible material consisting of carrot tissues embedded in an alginate ink-gel. The authors observed cell growth when incubating the 3D printed structure at 37°C making possible the nutritional changes over time. This result adds further considerations and hypotheses by taking into account the respiration of seeds or vegetable cells, 3D printing could be used to generate structures with programmable porosity and interconnected channels aiming to control the rate of oxygen transfer as well as the diffusion of nutrients through the solid matrix with effects on the rate of cells growth.

Apart from 4D food, it is worth mentioning the importance of the aforementioned effect of 3D printing variables on the texture properties, and the scientific evidence regarding the strict relationships between food structure and nutrient bioavailability (Yang et al., 2018), sensory perception, eating rate, satiation and satiety (Bolhuis and Forde, 2020; Lin et al., 2020) as well as some physical properties (i.e. heating and cooling rate). Lin et al. (2020) by modulating the infill level and infill path highlighted the possibility to affect chewing time, mandibular work and, finally, the perceived satiety that was higher for sample printed by using honeycomb, Hilbert curve and rectilinear paths, respectively.

Given these discoveries, a reverse engineering approach could be used by 3D food printing. The so-called programmable void generation other than the shape and dimension of 3D printed food could be used to generate or maximize benefits on the above properties. Therefore, one could speculate that by reducing the nozzle diameter, so that thin filament would be deposited, the surface contact with digestive enzymes could increase with advantages on the digestive phenomenon.

However, the prediction of mechanical properties, as well as mastication work of 3D printed food, has been subjected to only a few experiments and further research activities are needed. Vancauwenberghe et al. (2018) designed CAD models based on hexagonal honeycomb structures with structural diversities obtained by changing the number of cell size, a number of cells and pore size and porosity fraction. Later, by employing the finite element model (FEM) approach, the authors were capable to estimate the relative Young's modulus of 3D printed samples with excellent agreement with the analytical model. The same approach was used by Derossi et al. (2021) who studied the capability to get a 3D food structure with a programmable texture. In addition, they analyzed the post-printing process of cooking printed cereal-based snack and the creation of structural damages. However, by using a generalized form of the Gibson and Ashby equation, the authors proved the capability of estimating the maximum force to break the 3D printed samples as a function of their relative density.

Current limits, safety risks, sustainability and legal framework of the 3D printing of food.

The main obstacles that limit the application of 3D food printing at the industrial level or home are discussed here. With regard to the main technical issues the following obstacles can be outlined (Derossi et al., 2020): 1. Slow printing; 2. The extreme variability of the rheological properties of the food formula; 3. The need for new and optimized computer-3D printer interfaces for printing variables optimization; and 4. The lack of understating of the post-processing. The first three points are strictly interconnected and as previously reported, it is not feasible to accelerate the process whether the printing movements and the extrusion rate are imbalanced. The published scientific documents rarely report an average printing speed greater than 70 mm/s that is in antithesis with common values of 300 mm/s or more that characterize the non-food materials (Derossi et al., 2021b). Another important limit is the wide variability of the rheological properties of the food formulas, significantly affected by any change of the ingredients and their mass fraction as well as the effect of temperature during printing (Zhu et al., 2019; Nijdam et al., 2021a; Nijdam et al., 2021b; Tian et al., 2021). However, researchers have studied and defined the 'best printing conditions' for unique food formulas under observation such as for fruit and vegetables

(Chen et al., 2021a; Derossi et al., 2018a), cheese (Ross et al., 2021; Bareen et al., 2021), meat (Dick et al., 2021); cereal-based products (Derossi et al., 2020), chocolate (Rando and Ramaioli, 2021), fish (Kim et al., 2021a), and eggs (Anukirthika et al., 2019). Unfortunately, generalization or broad rules for 3D printing conditions have not been published although some authors have tried to fill the gap with new information (Ma et al., 2021). Given the above, the future applications of 3D printing in the food sector urge engineering solutions, sensors, interfaces and software capable of better managing and adapting the process to the properties of food materials (Nijdam et al., 2021a).

Another important and undervalued aspect related to the post-processing and the shelf life of 3D printed food products. Experiments dedicated to the use of printable food materials that need cooking process (i.e. cereal dough) agree on the difficulty to keep the shape and dimension of the 3D printed raw materials. During cooking or dehydration processing, physical and chemical modifications occur creating new voids, fractures, shrinkage, collapse and bending. For instance, when using cereal-based food materials, the high temperature used for cooking in the oven, 160 and 200°C, reduces the viscosity of the batter in the first minutes of the heating causing the lack of the desired shape due to the inability of the bottom layers to keep the weight of the overlying layers. On this point, while some researchers have worked on the composition of the food formula to gain high structural stability during baking (Pulatsu et al., 2020; Tian et al., 2020), others have used infrared lamp heating to get layer-by-layer cooking (Hertafeld et al., 2019) or printing directly on hot surfaces inducing starch gelatinization and protein denaturation of the wheat flours thereby conferring high rigidity on the initial layers.

Apart from the technical obstacles, the strong need of detailed experiments dedicated to the safety risk of 3D printed food should be noted. Unexpectedly such experiments have been completely undervalued although 3D printed food and 4D food could be considered as 'novel foods' which are regulated by the new Novel Food Regulation 2283/2015 reporting that they '*must be: safe for consumers; properly labelled, in order not to mislead consumers; and, if they are intended to replace other foods, they must not differ in a way that the consumption of the 'novel food' would be nutritionally disadvantageous for the consumers*' (Baiano, 2020). Whether the microbiological and nutritional quality of the food formula, before the printing process, could be guaranteed by using several common processing (i.e., thermal and non-thermal processes), the involvement of food industries capable to produce such safe, stable and printable food formula is essential to make the implementation of 3DFP on the market possible.

Furthermore, the effect of the printing *per se* on the microbiological safety due to the contact with mechanical parts as well as the need of the aforementioned post-printing process urges of detailed experiments. Considering that to improve the flowability of the food formula, a slight heating (30-40°C) is often utilized, the microbial growth could rise significantly with augmented safety risks (Yang et al., 2015). Moreover, for the application of 4D food printing, the external stimuli that trigger the changes over time could raise the safety risks. For instance, in the experiments performed by Ghazal et al. (2021) in which the colour changes were activated by increased pH values, the modified environmental conditions could favour microbial growth. Moreover, the shape change activated by heating (He et al., 2020; Liu et al. 2021) should also consider the potential degradation of the nutritional content of 4D food. Therefore, when external stimuli are used to activate the dynamic change of food properties, any potential drawbacks, mainly in terms of food safety, should be carefully considered. Nevertheless, there is a lack of relevant information on the safety of 3D printed. The search performed on the SCOPUS databank with the keywords [*3D Food Printing AND (shelf life OR safety or microbiol*)*] we retrieved only 7 documents of which only Severini et al. (2018) performed storage experiments of fruit and vegetable-based 3D printed food by analysing the effect on microbial growth under refrigerated conditions.

The 3D Food Printing and sustainability of the food chain is strictly connected. Firstly, the opportunities of the on-demand food manufacturing at the industrial level or for home use directly would reduce the amount of food waste. When used at the industrial or retail level, the consumers could select individual ingredients or food formulations, shapes and dimensions, as well as textures, among others, thus maximizing the overall acceptability and reducing the risk of rejection. When used at home, however, people could purchase the ingredients online and, after home delivery, those ingredients could be used to print any desired food product, either stand-alone or through the use of digital food models and online recipes. However, in both cases, the most important advantage is the opportunity to print exclusively the amount of food that people want to eat, thus significantly reducing the risk of wasting food products.

Conclusion

The 3D Food Printing allows conferring physical shape to a digital design through a layer-by-layer deposition process that counts dozens of degrees of freedom more than traditional manufacturing. One could simply say and imagine that 3DP is only useful for eye-appeal food, but 3DFP is more than that, counting on many benefits such as the creation of sensorially and nutritionally personalized food products, decentralization of food manufacturing, reduction of food waste, and business innovation. Among these, though, the idea of design and producing food products for people uniqueness contributing to a better healthy and active life and for improved sustainability of the food sector, is of great relevance for tackling this challenging period. The last 10 years has witnessed dissemination of many scientific publications; the earlier ones being essentially based on the understanding of the effects of most important printing variables on the quality of printed structures, while this was later focused on the creation of printable food formula. Though a young research field, the current literature has widely proven the feasibility of using 3D printing in the food sector. Indeed, many complex shapes have been successfully produced, some of which are not attainable with other common techniques, with accurate replicas of the digital models. In addition, some international companies already print a limited number of food pieces, mainly pasta, chocolate and candy, offering innovative solutions, sensory perceptions and increasing their market competitiveness. In this regard, we can find several experiments performed with a large diversity of foods such as fruit and vegetables, fish, meat, cereal, by-products, ink-gels, and eggs, among others. Furthermore, 3DFP is a very active field of research with many other innovations that are growing such as the creation of programmable textures aiming to control satiety and satiation, to mitigate swallowing problems, to enrich the food with doses of nutrients that fit the people uniqueness. Furthermore, looking to the future, 4D food Printing adds the change over time of taste, colour, shape, and nutritional content to 3D printed food, unleashing other branches of this technology. Considering the advantage of creating flat food, i.e., dried pasta, that acquire the desired 3D shape during cooking in water is an example. Indisputably, the reduction of the volume occupied during transportation would improve sustainability. Given the above, 3D food printing is still facing some problems that reduce its impact on a large application on the market. One of the most important is the printability of complex food materials that, according to current knowledge, is something unique/individual while generalized rules for the printability optimization would be of great importance. Indeed, a good and homogeneous printability is not easy to gather due to the enormous number of combinations among different food ingredients and, in addition, due to their natural variability. Second, computer-software-printer interfaces were created and optimized for plastic, metal, and ceramic, but they cannot be adequately adapted to the food materials. Therefore, new engineering solutions are required to customize the printing movements to the physical properties of food material making its use faster and easier, also for home application.

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