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3D Food Printing: an experimental approach

Marisa Matos Pimenta da Silva

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FACULDADE DE FARMÁCIA

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3D Food Printing: an experimental approach

Dissertação do 2º Ciclo de Estudos Conducente ao Grau de Mestre em Controlo de Qualidade

Trabalho realizado sob a orientação dos Prof. Doutores Beatriz Oliveira e Rui Lapa.

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Abstract

Eating is an essential action for people to have energy, but also is a way to make people happier. Throughout the years of human evolution, the eating habits passed from eating raw food, to cooking it, to mixing ingredients and is now a true form of art. With the technological advances, several devices emerged. One of the most recent, are 3D printers. Following the increasing application of 3D printing to various processes, the idea of combining this technology with food arouse and this approach of cooking can be a problem solver. This new concept can bring several advantages and it can change life as people know it. It can become a more sustainable way to eat, with the ability to use unconventional ingredients like insects, algae, plants, or unwanted meat trims. Furthermore, by producing on demand, the food by-products sector can be optimized. The valorized by-products can be useful in the control of some diseases: cardiovascular diseases by better controlling the meals and adding supplements to the food mix; to fight obesity, via some printing parameters, that can control the amount of calories without altering its aspect, and also by altering the components present in the mix. This technology also revolutionizes the confectionary sector, as it can be used to intricately decorate cakes and pastries, in a much easier way than by traditional means. Years after the appearance of 3D food printing, a group of MIT researchers comes up with 4D printing, with time as the fourth dimension, where the 3D printed piece changes its shape or color in function of time due to external or internal factors, like pH or temperature. Obviously, there is still a lot to explore in either fields, with the issues of human health safety and regulations as the most urgent matters, but also the way the public perceives printed food.

A conventional 3D printer was adapted to print with dough and to have a pre-cooking system. A mix of flour and water was tested, assessing the viscosity and the best ratio to print with, which was found to be 50/50. A piece made of this dough was successfully printed, optimizing the printing parameters, ready to take to the oven.

Keywords: 3D food printing; food printability; 4D food printing; modified 3D printer.

Resumo

Comer é uma ação essencial na vida das pessoas para obterem a energia necessária, mas também é uma forma de lhes trazer felicidade. Durante os vários anos de evolução humana, os hábitos de alimentação passaram por comer alimentos crus, para cozinhar e misturar diferentes ingredientes e agora é uma forma de arte. Com os avanços tecnológicos, cada vez mais equipamentos têm surgido, onde se incluem as impressoras 3D. Este conceito tem tentado ser uma solução para muitos problemas. Com as diferentes aplicações da impressão 3D a vários processos, surgiu a ideia de combinar esta tecnologia com alimentos. Este conceito pode vir a ser uma maneira mais sustentável de alimentação, com a possibilidade de usar ingredientes não convencionais, como insetos ou cortes de carne que normalmente não são usados. Reduz o desperdício do setor alimentar, produzindo apenas de acordo com a necessidade. Também pode auxiliar no controlo de algumas doenças, por exemplo, doenças cardiovasculares, controlando melhor as refeições e adicionando suplementos à dieta, além de poder ser uma forma de controlar o fator nutricional; combater a obesidade por meio de alguns parâmetros de impressão que podem controlar a quantidade de calorias do alimento impresso sem alterar o seu aspeto, ou alterando os componentes presentes na mistura que será usada para a impressão. Esta tecnologia também irá revolucionar o setor de confeitaria, pois pode ser usada para decorar intricadamente bolos e doces, de uma maneira muito mais fácil do que pelos meios tradicionais. Anos após o surgimento da impressão 3D de alimentos, um grupo de pesquisa do MIT começou a trabalhar com impressão em 4D, sendo o tempo a quarta dimensão, onde a peça impressa a 3D muda de forma ou cor em função do tempo e devido a fatores externos ou internos, como o pH ou a temperatura. Obviamente, ainda há muito a explorar em ambos os campos, com as questões de segurança alimentar e regulamentação como os assuntos mais urgentes, mas também a maneira como o público vê os alimentos impressos.

Uma impressora 3D convencional foi adaptada para imprimir com massa para bolacha e ter um sistema de pré-cozimento. Uma mistura de farinha e água foi testada, avaliando a viscosidade e a melhor proporção para usar na impressão, que se verificou ser 50/50. Uma peça foi impressa com sucesso, otimizando os parâmetros de impressão, e pronta para levar ao forno.

Palavras-chave: impressão 3D de alimentos; impressão de alimentos; impressão 4D de alimentos; impressora 3D modificada.

Table of contents

Figures

Tables

Abbreviations list

3D – Three-dimensional

4D – Four-dimensional

ABS - Acrylonitrile butadiene styrene

CAD – Computer-aided design

FD – Filament diameter

FDM – Fused deposition modelling

LH – Layer height

MIT – Massachusetts Institute of Technology

PLA – Polylactic acid

PS – Printing speed

STL - Standard Triangle Language or Standard Tessellation Language

TNO – Netherlands Organization for Applied Science Research

1. Introduction

1.1. Food sector development

Eating is a complex action to fulfil our need for energy and nutrients, that is part of human behavior since the beginning of times. Over the years, cooking started to become a business and an art form rather than just being the way to food consumption. The food industry is a huge producing sector worldwide but the demand for food products continues to grow, due to the growing of the human population. As world population is increasing, it becomes more difficult to have food for everyone and it brings up different environmental issues, such as overconsumption and large amounts of waste. Also, the lack of different options of viable meals are bringing up health issues due to nutritional imbalanced profiles, mostly due to pricing caused by the difficulties the industry faces to present cheap and quick meals rather than healthy and nutritious.

Innovative ways of cooking are always being sought and new ideas keep emerging, therefore, a new application of the 3D printing technology is being explored to be used in the food sector. For instance, Hershey already developed a 3D chocolate printer in association with 3D Systems (1), and Barilla also experimented with this technology in association with researchers from TNO (2).

1.2. Three-dimensional food printing

3D printing is a way of manufacturing that creates a 3D object with deposition of consecutive layers on top of each other (3). Charles Hull is usually credited for creating the first working 3D printer in 1984, that was commercialized by 3D Systems in 1989 (4). Since the first steps with this technology, many different applications were studied over the years, and in 2006, researchers at Cornell University introduced the first 3D printing system compatible with various materials, which they described as a "*versatile, low-cost, open and "hackable" printer*" in the Creative Machines website, capable of printing with food like chocolate, dough and cheese, the Fab@Home Model 1 (5,6).

This technology basically consists of a cartesian coordinate system of three axes, X-Y-Z with a support that allows a printing nozzle to move along all three, with dispensing or sintering devices, designated E-axis, and a software (Figure 1).

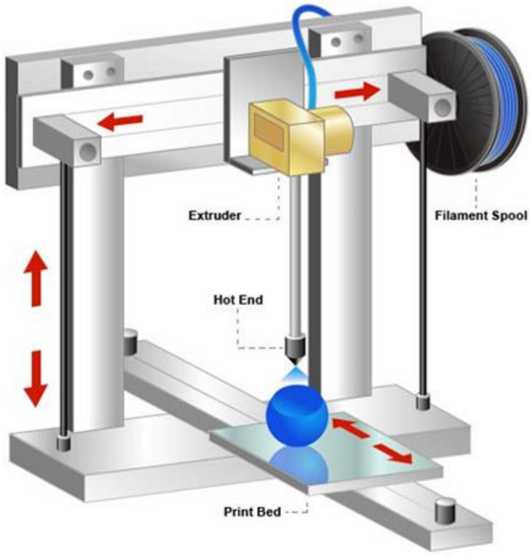


Figure 1 - Scheme of a 3D printer. Retrieved from https://circuitdigest.com/article/beginners-guide-for-getting-started-with-3d-printing

With a computer-controlled system, fabrication can be manipulated in real time. The device uses cartridges filled with flexible edible matter, such as food pastes, purees, powders, doughs, liquids and gels made from substances like sugar, chocolate, cheese, flour, fruit, vegetables and animal proteins, allowing for a variety of meals to be prepared (7). To take advantage of a printer in its entirety, with the goal of making new and personalized dishes to the taste of the user, four functions were proposed as essential: metering, mixing, dispensing and cooking (8) as these are the basic steps to produce a dish, either traditionally or using 3D printing. Although, with the available 3D printers the dispensing function is the only one operational on the device, because there is not a way to automatize all the process yet. Consequently, the metering and mixing still has to be done in the traditional way, as well as the cooking.

1.3. Advantages

In the last few years, this merger between 3D printing and the food sector has demonstrated an exponential growth and a possibility for a new niche market. It offers the ability to introduce alternative ingredients such like plant-based meat (9), algae or insects (10), and shape them into desirable dishes and tastes. Despite being nutritionally rich and sustainable ingredients, they are frequently seen as undesirable to eat by the general public. 3D food printing makes possible to turn these food ingredients into pleasing options by means of creating an appellative meal without the perception of those ingredients, making this technology a tool to produce well accepted and sustainable dishes. Also, it is known that the food sector produces a lot of by-products that goes to waste which can be reduced by adopting this technology. Food pieces that are considered waste because they are unappealing to the consumer but have high nutritional value can be used to fabricate 3D food which has the power to turn it more appealing to the consumer. Besides that, the production process itself using this technology produces less waste than any other option of food production by using fewer raw materials and less energy (11).

Aiming to make food more appealing, the pastry and personalized food items industries can benefit a lot from 3D food printing. The appearance of the food is almost as important as the taste, which presents an opportunity for cake designing and pastries that can be distinguishable. Weddings and themed parties usually have personalized cakes and other goods made to order, which can be much easier to make by the specialized companies if using 3D printing technology. These food pieces made by design normally takes hours of hard work by the part of artisans to do, and could be much more fast and simple to do with a printer for the decorating, as well as diminish the errors caused by the human factor and be much more repeatable. However, the big events are not the only to benefit from this cooking approach, we can also use it in everyday situations, for instance, to demonstrate a gesture of affection. The availability of 3D printer would facilitate the delivery of written messages on food that until now required some expertise to make or a placed order to some bakery. Wei et al. (12) studied the impact of this type of messages on different people, and concluded that most participants believed that messages received written in food instead of the traditional ways, like a text message or a letter, also provided a sensation of affection and care. One participant even said, *"I usually forgot the content I sent or received from SMS, but I can remember clearly the words on food, and also who sent it to me*". Therefore, one important role of the technology here described would be to facilitate communication and bonding, providing an easier way of delivering care and affection.

Another role of major importance is the way that 3D printing can help people with some health problems, like dysphagia or obesity. Dysphagia is characterized as a difficulty in swallowing, that obligates the person who suffers from it to eat soft meals like purees and similar types of foods. These types of meals are unattractive to the consumer and are often without much flavor and both of these problems can be solved by 3D printing food. There are a lot of flavors and supplements that can be added to the printing purees and mixes that can resemble meals like for example meat. This solves the flavor and aspect problems. Regarding obesity, there are studies that will be discussed further, to use this technology to control the caloric content in printed meals and still be satiating, by for example altering the infill percentage of the printed piece. It is also possible to alter the nutritional profile of printed meals, by reducing unhealthy components, and adding some healthy ingredients (13). Of course, there are also the supplements that can be added to the printing mix for people with special nutritional needs, like athletes or even someone with a cardiovascular disease or high cholesterol levels. This mixes with supplements could facilitate the intake and reduce the ingestion of numerous supplemented pills along the day.

The 3D printing technology has the ability to change how people prepare their meals. In the future when it is fully developed, it can provide a way to have a ready to eat meal with fresh and variable ingredients with only a few steps required. For instance, the device uses cartridges or syringes filled with flexible edible matter, such as food pastes, purees, powders, doughs, liquids and gels made from substances like sugar, chocolate, cheese, flour, fruit, vegetables and animal proteins, allowing for a variety of meals to be prepared (7). In addition to the preparation of the printing mix, the final product still needs to be cooked or baked if the ingredients used were raw.

The use of this technology to manufacture food raises a question of major importance that is being a little overlooked. If this is going to be the way to eat of tomorrow, then health and safety issues are going to come up during the printing process, but also during the food preservation stage, mainly in terms of microbiological safety. The whole process needs to be examined and regulated to prevent risks to human health. Despite this being such an important point, there is no scientific papers dedicated entirely to it on the literature. Only one study was found in which the printed samples were subjected to microbiological analysis (14).

In order for this technology to work and be used at its greatest potential, consumers need to be educated about the subject and learn about the benefits as well as the negative aspects. It is believed that it has much more advantages than disadvantages as presented in this work. There is an urgent need for marketing and consumer's attitudes assessment, as the number of this two are very low at this point, but the studies performed until now show a rather negative opinion from the public and little knowledge about the technology itself (15–17). However, they also reveal that it is possible to educate consumers and change this perceived negativity that they misplace.

1.4. Four-dimensional printing

More recently, 4D printing has made an appearance, initiated by a research group in MIT (18); it adds to the 3D spatial coordinates a fourth dimension, time, allowing for the transformation of the 3D printed structure to change its shape or properties over time. This suggests that the printed objects are no longer static, but can be active and transform independently (18). However, to achieve the transformation of the structure, stimuli are required, that can include alterations in "*temperature, ambient air humidity, external electric or magnetic field, or other external stimuli such as pH variation, light impact*", according to

Le-Bail et al. (19). One application of this technique can be the production of 'smart foods' that present, for instance, color changes based on the evolution of decomposition stage of the printed material.

1.5. Aims

Three-dimensional food printing is an emergent technology with many promising applications, with the number of papers about every aspect of it growing every day. Thus, the main goal of this work is to deeply approach the main aspects of this theme and gather as many information as possible, in order to present a global view and to provide some guidelines for future work on this subject.

Using the information gathered, the aim is to perform some experimental work to take a conventional 3D printer that uses plastic to print and adapt it to print with food. The final goal was to produce a cookie using this technology.

2. Three-dimensional printing technology

2.1. The process

The printing process begins with a virtual 3D model that must be designed by the user in a computer-aided design software (CAD). The objective of this software is allowing for the creation of a 3D model object using vectors that give the coordinates for placing every layer and every corner to be printed. Various CAD software can be found online and for free with basic functions, like TinkerCAD (AutoDesk) or Blender (Blender Foundation). There are also others available as an application for the computer which have more complex functions, like AutoCAD (AutoDesk). The 3D object is converted to a file that a printer-control computer software is able to open. Such software, like Cura (Ultimaker) or MatterControl (MatterHackers), usually has a slicing feature which translates the 3D model into individual layers, that are translated into machine codes, called G-codes or geometrical codes, that commands the printer where and when to move or stop and at what speed, what temperature to apply as well as other parameters. These codes are uploaded into the printer and initiate the actual printing process (Figure 2) (20).

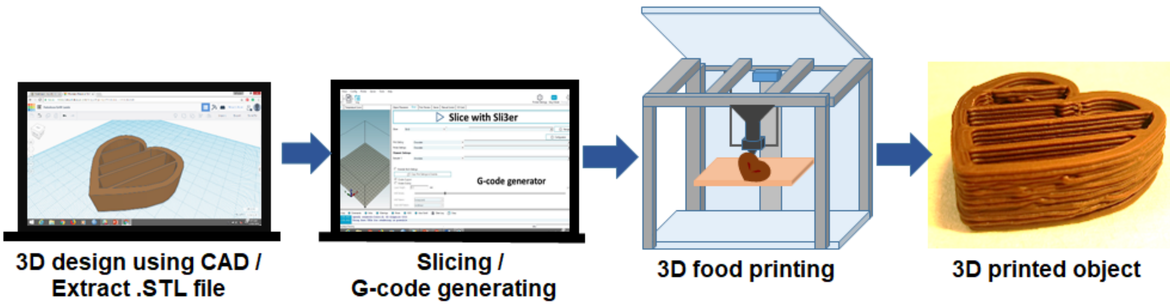


Figure 2 - Schematic representation of steps from CAD design to final 3D printed object. Adapted from (21).

The printer-control software, also called user interface can hold the three functions: tools to design shapes and structures (CAD); the conversion of this design into a digital 3D model; and the slicing and subsequent G-code generating, programming the dispensing pathway. The choice of the software should consider the purposes of the fabrication as well as the working environments, whether they be household, factory, or laboratory. Table 1 presents some examples, commercialized and open access.

Table 1 - List of some of the most used slicing software. Adapted from https://all3dp.com/1/best-3d-slicer-software-3d-printer/

Software	Type of user	Cost	Operating system
Cura	Beginners/Advanced	Free	Windows, Mac, Linux
MatterControl	Beginners/Advanced	Free	Windows, Mac, Linux
OctoPrint	Intermediate/Advanced	Free	Raspberry Pi, Windows, Mac, Linux
Simplify3D	Beginners/Advanced	$150	Windows, Mac
Slic3r	Advanced/Professional	Free	Windows, Mac, Linux
SliceCrafter	Advanced	Free	Browser

The user interface also allows to control printing variables like nozzle height and filament diameter, as well as printing speed and quantity of material dispensed. The printing parameters and the rheological properties of the food materials as well as the finishing of the printed object are highly correlated. Consequently, it can be concluded that every time the food formula changes in properties, new optimization tests should be performed, aiming to find the best results. There are many studies published that experimented with several parameters. Table 2 summarizes some 3D printing parameters.

Table 2 - Information of some of the most important parameters in 3D food printing. Adapted from (22).

Name	Definition	Measurement unit
Printing speed	Rate of printing movements	mm/s
Infill speed	Rate of printing during filling	mm/s
Layer height	Height of the layer of deposited material	mm
Nozzle size	Diameter of the nozzle	mm
Filament diameter	Diameter of the filament used for printing	mm
Infill	Level of filling the void phase of the object	%
Printing temperature	Temperature of the printhead	°C
Bed temperature	Temperature of the printer's bed	°C

Printing speed is one of the most important parameters. It controls not only the speed of the X-Y-Z axes, but also the rate of the extruder, controlling the amount of extruded material per unit of time. Setting the proper printing speed enables to find an equilibrium between the speed of the movements and the quantity of material extruded, avoiding over or under-deposition. Mantihal et al. (23) tested extruded chocolate at 32°C and used a printing speed of 70 mm/s, not obtaining good results at higher or lower values. Yang et al. (24) studied the effect of nozzle speeds from 15 to 35 mm/s on the quality of a printed structure obtained with 15 g of potato starch per 100 g of lemon juice gel, concluding that the highest the speed used, the lower the quality of the structure due to the breaking of the filaments. Wang et al. (25), obtained similar conclusions printing with fish surimi gel added NaCl (1.5 g NaCl/100 g of mixture) using nozzle moving speed from 20 to 32 mm/s. The authors stated that a speed too high led to the breaking of the filaments, while a speed too low created instability in the structure during the deposition of the material.

Layer height can be defined as the distance between the nozzle tip and the top of the last layer of deposited material, and it has a very important role in the visual aspect of the printed object. The lower the layer height, the greater the number of layers deposited and the smoother the surface of the printed structure. However, the layer height seems to be highly correlated to nozzle size, which is the diameter of the tip used in the deposition. Liu et al. (26) printed samples of mashed potatoes with different viscosities, using a nozzle diameter of 2 mm and a layer height of 3 mm. Although the authors reported several defects on their samples, such as poor resolution and lack of accuracy, this might be a result of the non-optimization of the printing speed in relation to the changes in viscosity. Similarly, Yang et al. (24) studied the effect of some printing variables on the quality of lemon juice gel cylinders, concluding that the nozzle height considerably affects the quality of the printed food. Nevertheless, in the visual results shown in their paper (Figure 3), the structural details improve when using a lower nozzle size, suggesting a lower layer height. The nozzle size is also related to the filament diameter, since the second is dependent on the first. The filament diameter regulates the extrusion rate of the material deposited.

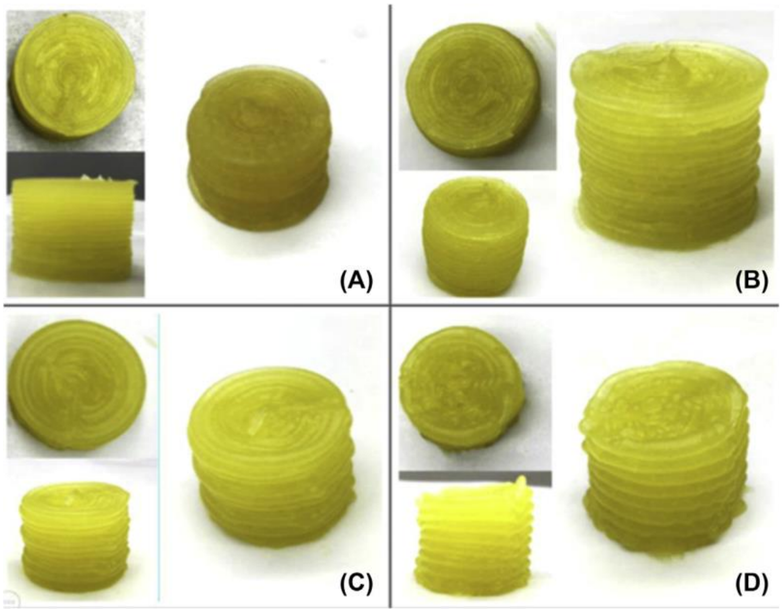


Figure 3 – 3D lemon juice gel cylinders printed with different nozzle diameters (A= 0.5 mm, B= 1.0 mm, C= 1.5 mm, D= 2.0 mm). From (24).

Infill, also designated fill density, defines how much inner volume to fill. For instance, an infill of 60% indicates that 60% of the internal part of the object must be filled. The infill percentage may help to support the object, as a higher infill can prevent it from collapsing on itself, or it could be used to achieve specific textures like crunchiness or hardness, for products like chocolate or biscuits. Mantihal et al. (23) used chocolate to print a hexagonal shape, with parallel, cross-sectional and no internal support (Figure 4). Results showed that printing the samples using cross-sectional support conferred higher structural stability and hardness, pointing out that the infill percentage can be used to customize the textural properties of the final product.

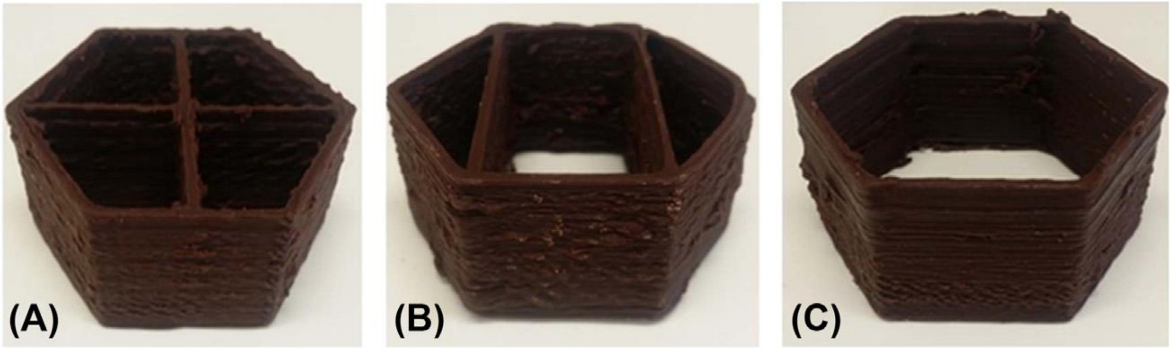


Figure 4 - Samples of 3D printed chocolate. (A) sample with cross-sectional support; (B) sample with parallel support; (C) sample with no support. From (23).

Kim et al. (27) experimented with several food products, and printed samples shaped like spider web, maple leaf, pentagonal prism, and spiral shape with 0% infill. Severini et al. (28) printed a pyramid shape with 25% infill using a linear infill pattern, which allowed the samples to bear their own weight without considerable defects. Yang et al. (24) used lemon juice gel to print cylinders with 100% infill. Severini et al. (29) analyzed the impact of the infill percentage on the quality of 3D printed cereal-based snacks shaped like a cylinder. Results showed that the breaking strength was decreasing as the percentage of infill decreased, suggesting that this parameter may be effective in controlling the textural properties.

2.2. Printing devices

Printing platforms to work with food can be acquired on the market or can be self-developed. There are many devices available that work with food, like Natural Machine's Foodini or ByFlow's Focus, that are constructed based on specific needs and ideas. They work solely with food but are designed according to dispensing mechanism, property of materials and printhead, in order to optimize the production process, printing with a low range of food materials. However, there are more offers on the market that work with conventional materials like PLA or ABS, that are available to be purchased and can be adapted to print with food. One of the most common modifications is to change the original printhead and replace it for a specific-designed dispensing unit capable of extruding edible materials (30). However, more often than not, the printers' software needs to be adapted to the new extruder, which is complex and requires a high knowledge about the whole process and firmware.

3. 3D printing techniques

As mentioned before, food printing process creates food pieces in a layer-by-layer manner. In order to achieve this, several techniques exist that work in different ways and are capable of producing food products with different materials. There are basically four printing techniques that can be used: selective sintering; binder jetting; inkjet printing; and extrusion technique. However, the extrusion-based printing, also known as fused deposition modelling (FDM) or hot-melt extrusion, is the most frequently used. Nonetheless, below is a resume of the four techniques.

3.1. Selective sintering technique

This technique is applied to construct 3D sugar structures, as it requires a powder that can be sintered, like sugar. First a coat of powder is spread, then a fusion source such as hot air or laser moves along X and Y axis to bind powder particles together, by heating to temperatures lower than the melting point of the materials, to diminish thermal distortion and facilitate the formation of a solid layer as well as fusion to the previous ones (Figure 5 a and b). The process is repeated for each layer until the full 3D object is completed. For instance, TNO's Food Jetting Print used laser to fuse sugars and Nesquik powders (31). The fused material formed the object while the loose powder continued in place as a structure support and could be reused for the next item.

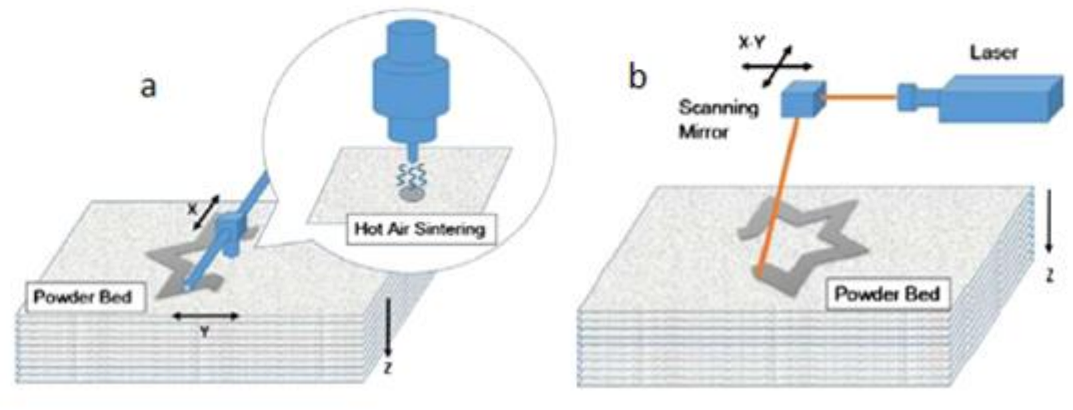


Figure 5 - A schematic representation of selective sintering technology through (a) hot air and (b) laser. From (20).

3.2. Binder jetting technique

The binder jetting works a little like selective sintering: a powder layer is firstly deposited on a platform, then a liquid binder sprays that layer before the next one is deposited, in order to bind the two consecutive powder layers together and so on (Figure 6) (32). In 2013, Sugar Lab (33) adopted 3D Systems' Color Jet Printing technology to print on a sugar bed, using different flavor binders, to fabricate intricate sculptural cakes for weddings and other special events, with no violation of any food safety requirements.

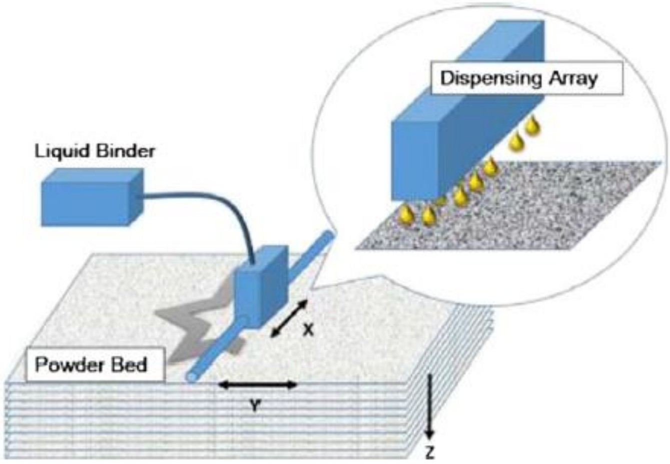


Figure 6 - A schematic representation of binder jetting. From (20).

3.3. Inkjet printing technique

This technique uses a syringe-like printhead to dispense a stream of droplets in a drop-on-demand way, which fall due to gravity and dry through the evaporation of solvents, mainly to decorate cookies, cakes, or pastry, although it does not form a completely 3 dimensional image but a 2.5 (Figure 7) (30). De Grood Innovations' FoodJet Printer used this technique to deposit drops onto pizza bases, biscuits, and cupcakes (34).

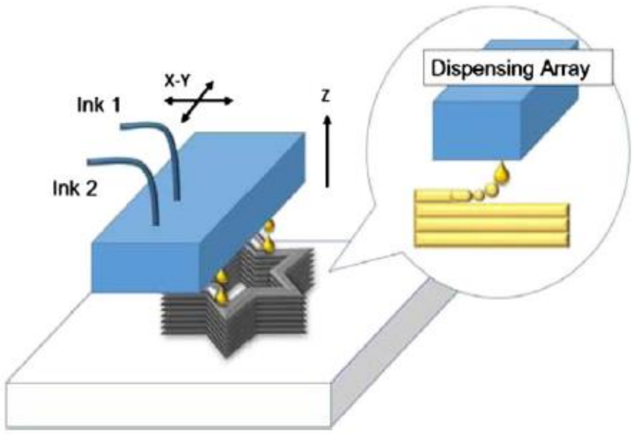


Figure 7 - A schematic representation of the inkjet printing technique. From (20).

3.4. Extrusion-based technique

Some naturally printable materials like cheese, frosting, and hummus can be easily extruded using this technique (35,36), but is more often used to make personalized 3D objects out of chocolate (37,38). Extrusion-based technique or more commonly referred to as fused deposition modeling, was described for the first time in 1991 (Figure 8). A melted semisolid edible polymer is extruded from a mobile FDM printhead and deposited onto a substrate, each layer hardens almost instantly after extrusion and merges with the previous one. Researchers from MIT applied hot-melt chocolate as a dispensing liquid, using compressed air to push the molten chocolate out of chambers, and developed a functional prototype "digital chocolatier" (8). This extrusion-based technique can accomplish complex food items, difficult to make by traditional ways, using a single material and with high repeatability (36). The extrusion technique is the only one able to print with the majority of fresh ingredients as long as they are a paste or semi-solid, depositing the food material onto a platform in the desired shape (39). This fact makes this technique the most favorable to be used when working with food printing.

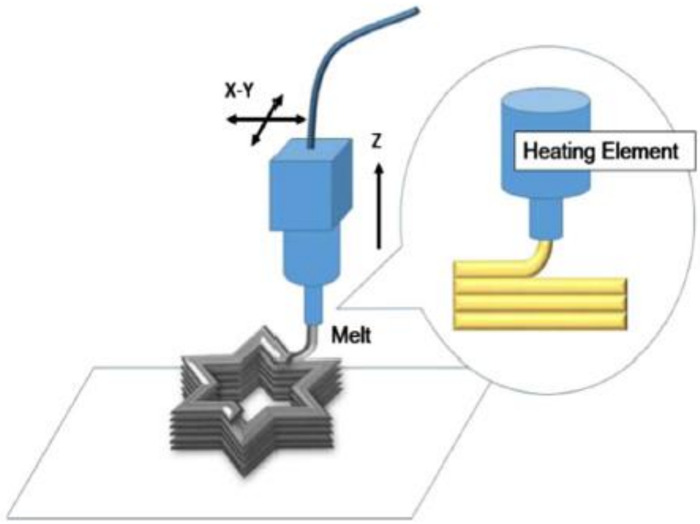


Figure 8 - A schematic representation of extrusion technology. (20).

Extrusion can be accomplished using a syringe-like nozzle, a rotary screw or air pressure driven extrusion (13). Syringe-based extrusion works with a stepper motor that drives the piston down gradually pushing the material out of the nozzle, making this more suitable for printing with food materials with high viscosity (13) (Figure 9 a). The extrusion rate can be easily controlled by adjusting the speed of the motor. However, if the viscosity of the food materials is too high, the motor will require more power to extrude it. The syringe-based extrusion has been extensively used in food printing processes and reported in many published studies (13,40–42). With a rotary screw, a rotating auger controlled by a programmed motor is used to deposit food material from the nozzle (39) (Figure 9 b). The screw-based extrusion has been reported not capable of achieving good printing precision when working with food materials that present high viscosity and mechanical strength (39). However, it has been successfully applied to print with food materials like, for example, *Nostoc sphaeroides* biomass (43), mashed potatoes (26), fish surimi (25) and dough (44). The air pressure driven extrusion works similarly to the syringe-based extrusion, the food materials in the cartridge are driven by the air pressure generated by a pneumatic pump (Figure 9 c).

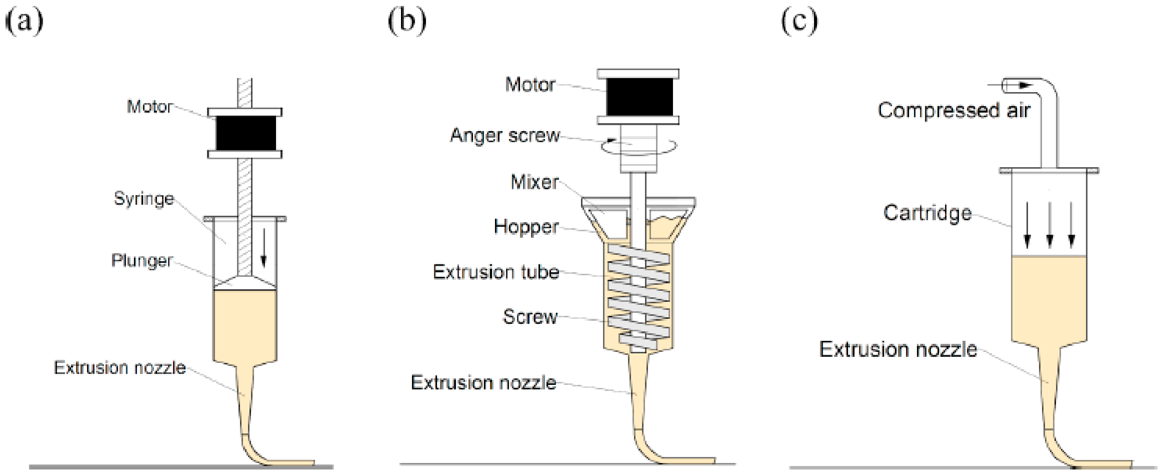


Figure 9 - Schematic representation of extrusion mechanisms. (a) syringe-based extrusion; (b) screw-based extrusion; (c) air pressure driven extrusion. From (45).

4. Food printing materials

There are a lot of food materials that can be used with printing. However, a suitable material should present gel-like attributes and a degree of viscosity that allows the material to be smoothly extruded but also has sufficient mechanical strength to maintain its 3D structure after extrusion (26). It also should possess shear-thinning behavior that allows easy extrusion at high-shear rate (10,46). It is why rheological studies are one of the most important to make this technology work; if the material is highly viscous the nozzle can clog; if it is too fluid it cannot hold its 3D shape. The food materials available to be used with 3D printing can be divided into three groups: natively printing materials, non-printable traditional materials, and alternative materials.

4.1. Natively printable materials

These materials are referred to as natively printable because of their capability for easy extrusion from a syringe-like printhead, with no need for the addition of flow enhancers. Some of these materials can be hydrogels, cake frosting, cheese, hummus, chocolate, purees, and dough (35). Some of the mentioned foods are mechanically strong enough to retain their structural form after deposition, and do not need further processing, but materials like dough are likely to lose their 3D shape after deposition and require baking afterwards. Thus, many studies are being performed to alter traditional recipes so that softer food materials can achieve appropriate viscosity. As these are the easiest food materials to print with, they are the most used in experiments to study the 3D technology. The most commonly used material is chocolate that provides confectioners the opportunity to produce intricate chocolate pieces. There are printers available on the market that work solely with chocolate, such as the Choc Creator.

4.2. Non-printable traditional materials

These type of materials are traditional food products like rice, meat, fruit and vegetables, that are not printable on its own, hence, to alter its rheology and to enable their capability of extrusion, additives like xanthan gum, agar-agar, gelatin and transglutaminase, have been used as additives (47). A well optimized food formulation using this type of materials can be an excellent delivery channel for macro and micronutrients. For instance, Anukiruthika et al. (41) experimented 3D printing with egg yolk and egg white, sources of nutrients and many functional properties, with rice flour blends and obtained satisfactory results.

4.3. Alternative materials

Alternative materials are those emerging as novel sources of functional constituents, extracted from unconventional fonts, such as algae, fungi, seaweed, lupine, and insects as a way to obtain mainly an increased amount of protein and fiber (Figure 10) (20). In the "*Insects Au Gratin*" project, created with the intent to insert insects in food products and trying to diminish the aversion of the general public to practice entomophagy, insect powders were mixed with icing and soft cheese to create food products (48). Furthermore, products that are now considered waste from the agricultural and food processing can be turned into biologically active metabolites, enzymes, and food flavor composites that can be used as additives to the material mixes used in food printing to enrich the paste (49,50), giving birth to a sustainable, eco-friendly and healthier way to eat, resourcing to 3D printing of food. The goal of using these unconventional materials is to solve the concerns around the food supply due to the increasing human demographic explosion (51).

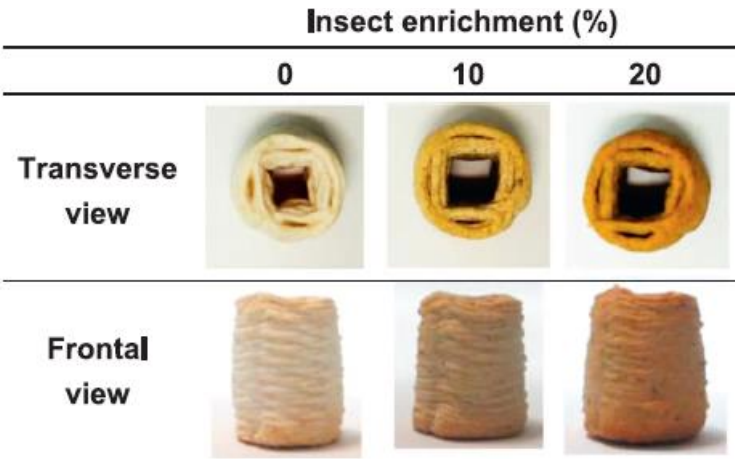


Figure 10 - 3D printed samples enriched with insects and baked. From (52).

4.4. Hydrocolloid additives

As referred in the non-traditional printable ingredients section, there is a need for additives that alter the rheology of some food materials to make them more printable. Hydrocolloids are valuable food additives that are able to interact and bind with water and can serve as a gelling agent, thickener, or stabilizer. The most commonly used include xanthan gum, starch, and gelatin.

Xanthan gum is obtained by aerobic fermentation of sucrose or glucose by *Xanthomona campestris* (53). At low concentrations it forms a solution with high viscosity, thus it can significantly increase the viscosity of food materials. Although being more expensive than starch, it is a common choice for a thickener thanks to its great thickening ability at low concentrations and to its stability at a wide range of temperature, pH, and salt concentrations. A solution of this hydrocolloid is very pseudo-plastic and gel-like at rest for concentrations above 1% by weight (54).

Starch consists of two gluco-homopolysaccharides, amylose and amylopectin. The amylose and amylopectin content percentage is dependent on the plant source (55). Due to its granule structure, native starch cannot be dissolved in cold water. The dispersion needs to be heated above the native starch gelatinization temperature (~90 °C) in order to form a solution. Its molecules contain several hydroxyl groups that have the ability to interact with water through hydrogen bonding, leading to an increase in viscosity. On the other hand, amylose may aggregate to form a gel, which is possible to alter the foods texture during storage, however this process can be reversed by heating or shearing the gel. It is possible to alter the properties of starch physically, chemically, or enzymatically (55) (Table 3).

Gelatin is a significantly pure protein food component, obtained by the thermal degradation of collagen, the most common protein and structural mainstay in the animal kingdom (56). The most common sources include demineralized cattle bone and bovine and pig skin. It is used as a food additive for gelling, thickening, and stabilizing. This water-soluble polymer origins thermally reversible gels with water, and the gel-melting temperature is below 35°C, conferring gelatin products distinctive organoleptic properties and flavor release (57).

Table 3 - Treatments that can alter the properties of starch and its consequences. Adapted from (58).

Treatment	Properties
Acid hydrolysis	Reduced molecular weight Reduced viscosity Increased retrogradation
Oxidation	Low viscosity High clarity Low temperature stability
Crosslinking	Higher stability of granules towards swelling, high temperature, high shear, and acidic conditions
Esterification	Lower gelatinization temperature Lower tendency to form gels Higher clarity
Etherification	Higher clarity Higher viscosity Reduced syneresis and freeze-thaw stability

5. Advantages

The 3D printing technology offers a more sustainable way to eat in times where the demand for food is growing and there is an urgent need to diminish waste (59). This can be done in several ways. The first one consists of including unconventional fonts of protein that are not usually utilized on food, the most obvious are insects but others can be used. Of course, these fonts of protein can be powdered and utilized in conventional ways to cook as well, but can only be added to milkshakes or cakes, and with this technology is possible to produce a complete plated meal using these powders. An important example is the mentioned above, "*Insects Au Gratin*" project, where powdered insects, like mealworms and crickets, were mixed with icing, chocolate and cream cheese to create food products, intending to help diminish the dislike for eating insects of the general population (48). Severini et al. (52) also printed a snack made of wheat flour dough enriched by ground larvae of Yellow mealworms and baked after printing (Figure 14), obtaining a significant increase on amino acid quantity and protein digestibility when compared to the sample with no insect enrichment. Enriching the food pastes with protein isolates is another option to prepare meals with alternative protein fonts, like whey protein or soy protein, as Chen et al. (60) showed when tested the printability of soy protein isolate mixtures with sodium alginate and gelatin. Liu et al. (42) studied the effect of whey protein isolate on the printing performance of milk protein concentrate. Liu et al. (61) also experimented with milk protein composite gel and tested the material behavior during and after printing and tested its rheology (Figure 11).

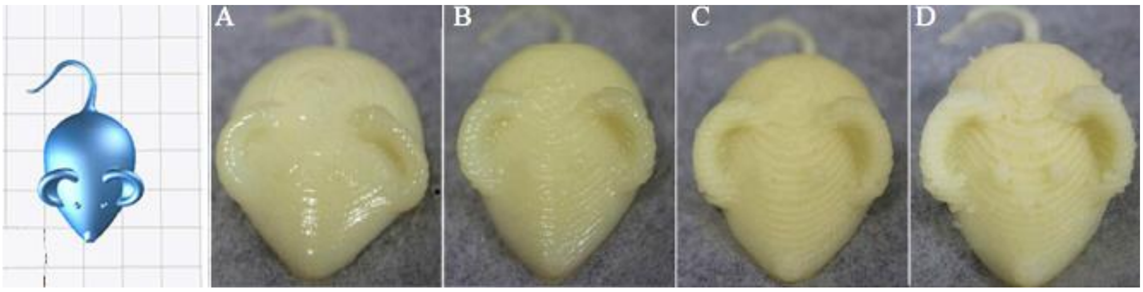


Figure 11 - Printed objects prepared with milk protein composite gels with different total protein contents (a: 350 g/L; b: 400 g/L; c: 450 g/L; d: 500 g/L). From (61)*.*

Instead of substituting the font of the protein there is a way of substituting the meat that is obtained by killing animals, once cattle raising produces many waste and pollution. This can be achieved using a bioprinter and stem cells (62). Stem cells are unspecialized cells that can differentiate into specialized cells when stimulated the right way (63). For example, stem cells can produce muscle cells and meat is made of muscle. The fabrication of printed meat initiates by doing a biopsy on the animal in order to obtain the required stem cells that will multiply in the lab. The cell mixture is deposited on a surface specially made, using a 3D printer, with multiple layers, that will later fuse and form the muscle (62). A company from New Jersey is trying to obtain raw meat tissue by printing these cultured stem cells. An inkjet printer deposits the cells into an agarose gel support structure to allow the cells to fuse (64). Hereafter, the agarose structure is removed, and the tissue suffers low frequency stimulation in a bioreactor to maturate meat fibers (65). Also, a medical scientist, Giuseppe Scionti, working at the University of Catalunya discovered, by accident, a way to "bio-hack" plant-based proteins so that they can have a meaty texture. For the prototypes, he used a mix of rice and pea proteins, that tasted and felt like a traditional fibrous steak, although it looked more like a strawberry-flavored gummy sweet (66).

Last but not least, as previously said it is known that the food industry produces a lot of waste. The 3D printing technology is a way to produce food in a way of demand, meaning that food is only produced if it is needed, and this could be a way to reduce the amount of discarded food. Also, according to Conroy et al. (67) only 7.2% in weight of a cattle carcass accounts for cuts that are considered high value. To this note, Meat and Livestock Australia proposed the creation of a "meat ink" using secondary cuts, trims, and by-products (68). They collaborated with ByFlow to produce canapés and meals using the meat (69).

The extrusion-based 3D food printing constructs food pieces layer by layer, allowing it to produce decorative features with any design possible and a staircase effect on oblique and curved surfaces. There is a Dutch based company that promise to develop "*next generation candies, sweets and decorative decorations for the pastry industry*" (70), and have produced a 3D printed lemon merengue tart as an example of the food pieces that can be developed (Figure 12).

Figure 12 – Tart with 3D printed sugar merengue crown. Retrieved from https://3dchefblog.wordpress.com/2015/07/06/3d-printed-lemon-meringue-tart/

Barilla was developing a project with TNO to create a 3D pasta printer, and even launched a 3D modeling competition that invited participants to submit designs for 3D printable pasta shapes, with the same ingredients as regular pasta. The pasta designed using 3D printing has extreme freshness, offering an additional advantage. One of the contestants designed a dynamic 3D model of pasta that would bloom into a shape of a rose when put into boiling water (71). This competition proved that pasta could take any desired shape and can be a fun twist to our meals. Severini et al. (14) printed a blend of fruit and vegetables and conducted a sensorial evaluation afterwards, using an untrained panel of 20 people. Overall, all the tested sensory attributes showed higher scores for 3D printed samples. The greatest significant difference was observed for the overall appearance, which definitely supports the hypothesis that 3D printing technology may be able to positively affect the visual aspect of foods. This could encourage consumers to choose more healthy foods, particularly when for children, for whom it was proven that visual appearance is a factor of utmost importance for their food choice (72). On the other hand, for the remaining sensorial attributes evaluated the 3D printed samples did not show statistically differences from the conventional food formula, indicating that the 3D printing did not degrade the color, taste, or odor of the food sample.

A different approach is taste design. A United Kingdom company created a 3D printer that can print jelly-like liquid capsules that are filled with intense flavor into unexpected textures and shapes. For example, at a food conference they printed a jelly that looked like a raspberry but tasted like a strawberry. The capsules are made out of sodium rich gel and contain only natural ingredients, in this case fruit juice, which can be shaped to mimic existing fruits and foods or combine the shape with an unexpected flavor to create surprising and new tastes (73).

Several publications are seen as promising to attenuate some health concerns using 3D food printing (74–76). This technology has the ability to allow the manufacturer to alter the food piece in whatever way is wanted, either on ingredient composition or in the manufacturing process itself. For instance, there are at least three ways to improve food: enrichment, by adding a component which brings benefits to our health, like fatty acids or fibers, despite any amount already being present on the meal or not; substitution, by replacing a substance present for another with healthier properties; elimination, by removing an unhealthy substance or at least diminishing its concentration. For example, it is possible to remove a certain percentage of fat from a cookie dough and replacing it for another component, according to Severini and Derossi (77), thus reducing the caloric intake and unhealthy properties. Another example is a cereal-based food structure with probiotics, living microorganisms that provides health benefits when consumed in adequate amounts, printed by Zhang et al. (40).

Lipton et al. (51) announced the design of a program, which took a person's health information such as height, weight, and age to determine the base metabolic rate. A record of all activity and caloric consumption was kept in a calendar and an activities' metabolic equivalent of task was stored in a table. Calories burned at the end of the day were calculated and 10% of the day's caloric expenditure was then produced in the form of a 3D printed cookie, using two cookie doughs alternating from layer to layer, one sugar free and other full sugar, to control the caloric content, on Fab@Home Model 3 System. The cookie was then presented to the individual as a way to ingest 10 percent of the daily energy spent and being an effective way to control the calories ingested. With the increasing obesity and continuous search for ways of fighting this tendency, here lies a possible solution. Another possibility is to control the printing settings and adjust the infill percentage to control the number of calories, without having to eat a smaller meal. Lin et al. (76) developed the FoodFab project, a system that enables users to control their food intake by modifying the food's internal structure using two different 3D printing parameters: infill pattern and infill density or percentage. They performed two experiments with a total of 30 participants, where they studied the effect of these variables on the participants' chewing time which is known to influence perceived satiety. The results showed that infill pattern and density can indeed modify chewing time, and thus control the feeling of satiety.

Dysphagia is a swallowing difficulty that affects a considerable percentage of the population, mainly the elderly and that prevents people suffering from it to enjoy eating. The European Union funded the Personalized Food for the Nutrition of Elderly Consumers (PERFORMANCE) project, aiming to apply food printing to produce customized soft foods with personalized nutritional contents for elderly with swallowing or chewing difficulties (78). Scientists on the project have successfully imitated foods, such as peas and gnocchi. A survey done by the PERFORMANCE concerning 3D printing food in nursing homes have shown that 54% of inquiries thought the food texture was good, 79% felt that the printed food was equivalent to the one prepared traditionally and 43% preferred the printed food when dysphagia occurred (79). Also, researchers from Deakin University in Australia created a process to print tuna fish meals for people with dysphagia, using a mix of purred tuna, pumpkin, and beetroot (74). Dick et al. (80) also experimented with pork paste added xanthan gum and guar gum to produce meals that could be categorized as "*potential transitional foods within the International Dysphagia Diet Standardization Initiative Framework*".

However, dysphagia is not the only condition that can benefit from this technology. A group of students from Brac University in Bangladesh (75) created a software that takes in the age, gender, height, weight, and disease information from hospital patients' charts, and uses these variables to run the first algorithm to calculate personalized protein, fat and carbohydrate counts. A second algorithm calculates the exact amount of ingredients required to prepare their meals per day, based on the diseases of the patients. The final objective of the software is to print out a list of the daily ingredient count and display a selected 3D model that can be printed. They aim to come up with nutrition specific solutions for people suffering from diseases such as cardiovascular disease, hypertension, diabetes, Kwashiorkor, and chronic kidney disease, and use 3D printing technology to improve patients' quality of life.

The last advantage presented a way to make life easier for people with diseases, but this technology can also facilitate life for healthy people as well. Most individuals eat lunch at work or school and equipping the facilities with 3D food printers, eventually when they also have the cooking feature, would make so much easier for this people to prepare meals because they would not have to cook them at home and carry containers around or eat reheated food. This could be a major tool for the workplace or for schools, but also for the household as the printer lays down the meal without needing great attention. Several studies are available in the literature experimenting with printing conventional meals. For instance, Lipton et al. (47) printed scallop and turkey meat purees using transglutaminase as additive, one was deep fried and the other cooked *sous-vide* and found that both structures held their form while printing and after cooking. A group of chefs even consumed the printed meats to analyze if it had the proper taste and texture and both materials passed examination (47). Likewise, Liu et al. (81) successfully printed chicken, pork and fish in a slurry form with the addition of gelatin. Liu et al. (26), assessed the printability and rheological properties of mashed potatoes added potato starch. The study showed that objects printed with 2% starch were the most adequate to 3D printing, displaying excellent extrudability and printability. Severini et al. (14) used a blend of fruit and vegetables to print a pyramid shape. Likewise, Derossi et al. (82) used fruit to produce a fruit-based snack for children, that could provide 5–10% of energy, calcium, iron and vitamin D of 3–10 years old children. The most interesting study was published by Hertafeld et al. (83) who tested a way to print food with simultaneous cooking using infrared and successfully printed a pyramid of sesame paste with chicken and shrimp paste developing a way to print a ready to eat meal (Figure 13).

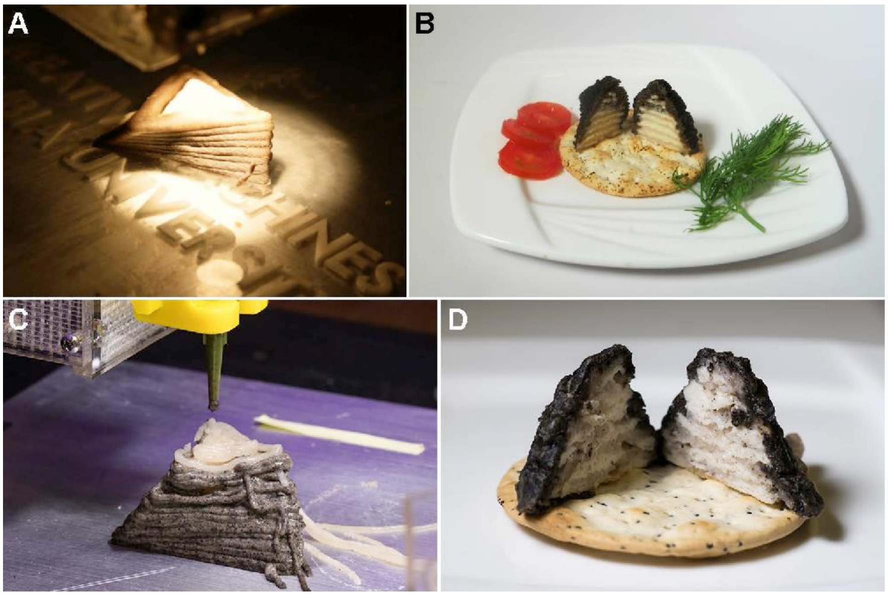


Figure 13 – Samples of multi-material food printing. (A) Infrared spot cooking sesame paste and chicken paste. (B) Cooked sample of printed black sesame with alternating chicken and shrimp paste. (C) Sample of sesame, chicken and shrimp paste printed without in situ cooking. (D) Handmade sample of sesame and chicken paste cooked for 10 min at 177 °C. Adapted from (83).

There are several standards that foods need to follow, to not represent any risks for human health, for instance the ones regulated in the Commission Regulation (CE) No 2073/2005 on microbiological criteria for foodstuffs. 3D printed foods need to follow these standards as well in order to be commercialized. However, almost no studies are found in which the safety of the printed samples is assessed. Severini et al. (28) printed a blend of fruit and vegetables and monitored the changes in microbiological parameters for 8 days at 5°C under modified and non-modified atmosphere. Initial microbial concentrations started high, with psychrophilic, mesophilic bacteria and yeast counts between 4 and 5 log CFU/g, on day 0. The authors explained that initial microbial count could have been increased by the printer itself, via its pistons and extruders, as all the ingredients were accurately washed before printing, aiming to reduce the initial microbial contamination. Microbial concentration remained stable until day 6, on both food preservation conditions, and presented a decrease of almost 2 log CFU/g at 8 days. For both preservation conditions, mesophilic bacteria and yeasts did not show significant differences during the storage time.

The idea and opinion of consumers towards this technology and 3D printed food itself is of utmost importance for its development and success. Nevertheless, little studies are found assessing consumers acceptability. Lupton and Turner conducted a study in 2016, leading to three published papers, regarding acceptability of 3D printed foods of several types (15,16,84). The study was conducted online with a group of 30 people aleatory chosen in an online survey company's website, using a questionnaire with several groups of questions. One of the first group of questions aimed to assess the knowledge of the user about 3D food printing, revealing that most of the participants was unaware of such technology being possible to use in the food sector, and even disbelief that it could be functional (84). In another section of the questionnaire, the participants were presented with seven photographs of different 3D printed food that included: "*(1) a collection of brightly-colored sugar confections in geometric shapes; (2) a "bunch" of carrots made from carrot puree; (3) a grayish-white-colored geometric-shaped snack made from ground insects; (4) a white dinner plate displaying a meal of food made from gelled chicken puree (shaped like a drumstick) and gelled vegetable purees and sauce (of the type served in nursing homes); (5) a printed pizza base topped with tomato sauce and cheese; (6) a box of rose-shaped pasta bearing the name of a well-known Italian pasta brand, with some of the (uncooked) pasta displayed next to the box; and (7) several rose-shaped chocolates*" (15). In general, responses were very ambiguous, table 4 presents some responses of the consumers.

Table 4 – Responses, presented as %, to the question "Would you eat this food yourself or serve it to family members or guests?" (n=30). Retrieved from (15).

Type of 3D printed food	Would eat it myself	Would not eat it	Do not know	Would serve it to others	Would not serve it to others	Do not know
Sugar confections	35	47	18	39	46	15
Carrots	52	30	18	36	36	28
Insect snack	14	76	9	14	76	9
Chicken and vegetable meal	43	47	10	35	46	19
Pizza	69	21	10	62	24	14
Pasta	66	21	13	69	17	14
Chocolates	59	17	24	57	18	25

The chicken and vegetable meal as well as the carrots were considered healthy and natural ingredients, but how they were made raised questions about the processing and safety. The printed pizza and pasta as well as the chocolate had positive responses because people were already used to them being molded using mechanical parts and the appearance was very similar to the conventional products. The sugar confections although already being a highly processed product like chocolate, was perceived as unnatural and unhealthy due to the intricacy and bright colors. The insects as expected were the product that received the most negative responses, perhaps given the Western culture's antipathy towards entomophagy, in this case the reactions were mostly due to the grounded insects rather than to the way the product was manufactured.

They raised the question about 3D printed cultured meat, and numerous concerns were expressed about it being "*unnatural*," "*too processed*," "*not real*," "*not fresh*," "*not safe*," and about the "*chemicals*," "*hormones*," "*risks*" and "*additives*". Only a small number of participants presented a positive response (16). In 2019, Manstan and McSweeney conducted a similar study, with an online survey with 329 participants, where they were presented 8 pictures of mashed potatoes, meatballs, pizza, and cookies, 4 of them of the conventional products and the other 4 of 3D printed. Then they were asked if they would buy or eat the product and if they thought it was healthy or highly processed. The results showed that participants were more likely to buy the 3D printed meatballs instead of the conventional ones but showed no difference in their willingness to eat the printed or the conventional. Furthermore, the subjects did believe the presented printed foods to be healthier than the conventional products, excepting the mashed potatoes. It was also indicated that conventional foods were more processed than the printed products (17). Brunner et al. (85) also performed a questionnaire study in 2018, written and sent to participants with a total of 260 questionnaires answered and analyzed. The aim was to assess the initial opinion people had about 3D food printing and the change of attitude after some informative paragraphs about the subject. The participants' previous knowledge was revealed to be relatively low and the initial attitude towards 3D printed food, although not being unanimous, it was rather negative. This analysis showed that the more the consumers, including the ones with food neophobia, became nutrition conscious, convenience oriented and agreed with the presented benefits, the more their responses changed towards accepting the 3D printed food concept (85).

6. Four-dimensional printing

Pei (86) defines 4D printing as “*the process of building a physical object using appropriate additive manufacturing technology, laying down successive layers of stimuli-responsive composite or multi-material with varying properties. After being built, the object reacts to stimuli from the natural environment or through human intervention, resulting in a physical or chemical change of state through time*.” Considering this definition, if a 3D printed object changes its color after printing due to an environmental change as a function of time, this can be considered as 4D printing. He et al. (87) studied the effect of potato flake content and pH values (adding citric acid or sodium bicarbonate), in mashed purple sweet potatoes after 4D printing, to evaluate the color change of the printed food objects due to pH alterations and concluded that its color would gradually alter as a response of pH values over time (Figure 14). Ghazal et al. (88) printed 4D food products with anthocyanin-potato starch gel and lemon juice gel, that changed its color when sprayed with solutions that had different pH, but also as a response to an internal pH stimulus from the lemon juice gel. A group from MIT (89) used a 3D printer to experiment with gelatin and celullose to create an object that would change shape. They created pasta that would change its conformation when boiled; a transparent edible film that would wrap fish caviar when immersed in water; gelatin strips that would maintain its length if cooked at low temperature (~25°C), and if cooked at higher temperature (~40°C) the linkage between segments would be dissolved shortening and twisting the segments.

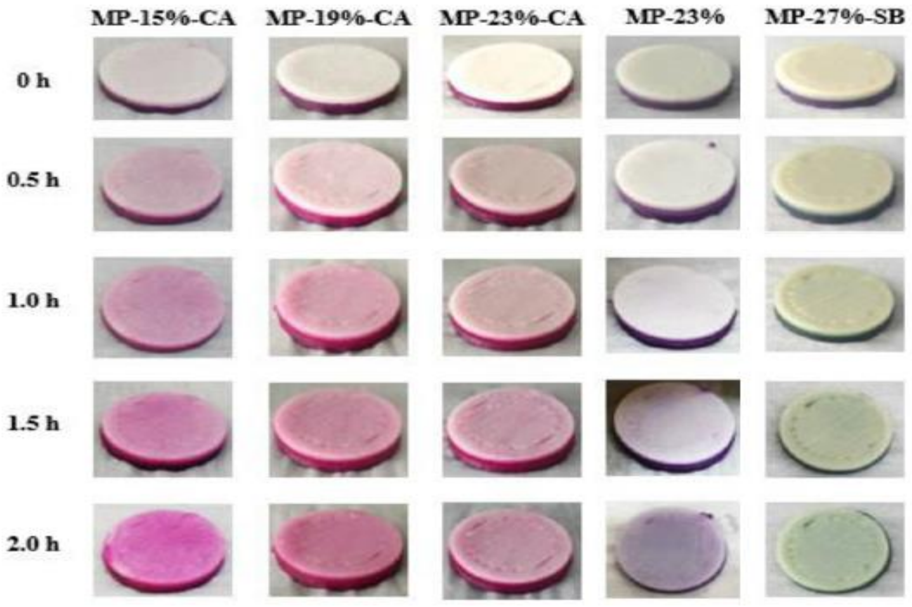


Figure 14 - Color changes over time of printed mashed potatoes with different content percentages, from 0 hours after printing until 2 hours later. MP % is the quantity of potato flakes, CA is addition of citric acid and SB is addition of sodium bicarbonate. Adapted from (87)*.*

7. Printing devices

Ever since this innovative technology hit the market with little commercial offer, the number of companies offering new 3D printing equipment and different related projects started to grow year by year, and it is expected to become a mainstream food production branch in the future. A summary of some available 3D food printers is presented in table 5.

Table 5 - Summary of devices available on the market.

Printers	Printing material	Developed by	References
Choc Creator V2.0 Plus	Chocolate	Choc Edge	ChocEdge (90)
Focus	Thick pastes	byFlow	Askew (91)
Foodini	Pastes	Natural Machines	Askew (92)
Chef 3D	Pizza	BeeHex	Garfield (93)
Deco-pod	Pastes for cake decoration	BeeHex	BeeHex (94)
PancakeBot	Pancake batter	Particular inventor in association with StoreBound	Lansard (95)
Mycusini	Chocolate	Print2Taste	Boissonneault (96)
Procusini	Pasta, chocolate, marzipan, cassis, fondant	Print2Taste	All3dp (97)
ChefJet Pro	Pastes	3D Systems	3D Systems (98)
Brill 3D Culinary Studio	Powders	3D Systems	3D Systems (99)
Createbot	Pastes	Createbot	Carolo (100)

The high demand for this type of technology is transforming research projects in business companies. A good example of that happened in the University of Exeter in the United Kingdom, with a project that aimed to create a 3D printer that could produce chocolate objects. The result was the Choc ALM prototype, and in 2012 the Choc Creator V1 became “the world's first commercially available 3D chocolate printer”. The Choc Creator V1 immediately caught the attention of the public and media and has been followed by Choc Creator V2 and V2.0 Plus (90).

Furthermore, a Dutch company presented their first 3D food printer, “Focus”, in 2016. In 2019, the company launches “byFlow Studio”, an online platform, where they give access to recipes and designs, where customers can also upload their own, and all of this is sent to the printer via wi-fi. With the purchase of the Focus, they offer a 3-year license of byFlow studio. This platform is an alternative to the software mentioned in the subsection *The Process*, to create the 3D designs and upload them into the printer. Additionally, they aim to develop 3D printing technology which can read data from a “DNA Passport”, which contains information on what vitamins and nutrients each person needs and transform that into a meal (91).

In 2017, a company based in Spain, was in the middle of a project to develop a printer designed exclusively to work with food, with stainless steel capsules which can be filled with the desired ingredients. This system allows the consumers to prepare a wide range of products, differently from most available printers which work with a limited range of ingredients (92). In fact, they currently have “Foodini” on the market.

There is also a lot of talking about 3D printed food to be manufactured and eaten in space, so NASA and a Texan company have been working together to develop a 3D printer to print food in long-duration space missions (101). Actually, a NASA spin-off, created in 2017, created a 3D pizza printer called Chef 3D, which could print a 12-inch pizza with dough, sauce, and cheese in one minute. The Chef 3D is now off the market, but they also debuted earlier this year a 3D printer for cake decoration, the Deco-pod (93,94). PancakeBot is a 3D printing system that prints pancakes, designed by an inventor from Norway, Miguel Valenzuela. It uses a special batter dispensing system, that allows to dispense the liquid pancake batter onto the griddle, controlling where it is dispensed by using a combination of compressed air and a vacuum system. The griddle is heated allowing the batter to be turned into edible pancakes (95).

A German startup has recently launched a low-cost chocolate 3D printer. It is called ‘mycusini’ and it can print a wide range of 2D and 3D chocolate constructs. The company expected to start shipping by February 2020. However, this was not the first printer created by Print2Taste. They launched the Procusini 3D system, in 2015, which was directed at professional hospitality and food industries (96). Also, in 2019 the Procusini 4.0 became available, with five specially formulated food cartridges: pasta, chocolate, cassis, marzipan, and fondant, some of them in different colors. Along with the purchase of Procusini, the user gains total access to their online platform, the Procusini Club, which provides ready-to-print templates, as well as video tutorials and tips for getting the most out of the printer (97).

A company from South Carolina, reaches the market with interesting ideas. First it was the culinary lab, a culinary innovation center in Los Angeles where chefs, mixologists and culinary innovators could go to experiment with the ChefJet Pro, a 3D printer of their creation (98). By the second half of 2020 they expect to have a new 3D printing system available, the Brill 3D Culinary Studio, in association with Brill Inc., a leader in bakery ingredients and products (99).

Createbot is a multi-material food printer created by a company from China. Among the various paste-type foodstuffs it can print with cookie batter, bean paste, mashed potatoes, chocolate, and even sesame paste. To be able to work with all these different materials, the Createbot’s extrusion head adjusts its temperature according to the material. In terms of connectivity, this printer can be controlled from several devices such as mobiles, tablets, and computers (100).

Another market approach was followed by a food tech startup, that instead of building a printer, they have an online platform, where customers can go to choose a design, whatever they want, that is uploaded to the servers and 3D printed into a popsicle, that is then delivered to the buyer (102).

8. Experimental Chapter

Considering all the information gathered, experimental work was performed aiming to adapt a conventional 3D printer to be used with cookie dough with a system of pre-cooking. Aiming to successfully 3D print and cook a cookie that could be nutritionally and sensorially compared to a traditional one.

8.1. Materials and Methods

Since the strategy used for the development of the device was based on a replacement of the thermoplastic components used on a conventional 3D printer, some assumptions were used: possibility of using current materials, namely syringes, motors, and heating elements.

In this sense, we opted for the use of polypropylene syringes with eccentric luer slip or luer slip nozzle, volumes of 10 and 20 mL and rubber stopper.

The extruder tip adaptable to the nozzle of the syringe was constructed using a Teflon tube and fixed using Kapton tape (polyamide). The characteristics of the extrusion tip result from the need to obtain filament with well-defined dimensions and simultaneously withstand temperatures up to 300°C.

The mechanical device developed to move the syringe system was designed to minimize its volume and weight (Figure 15).

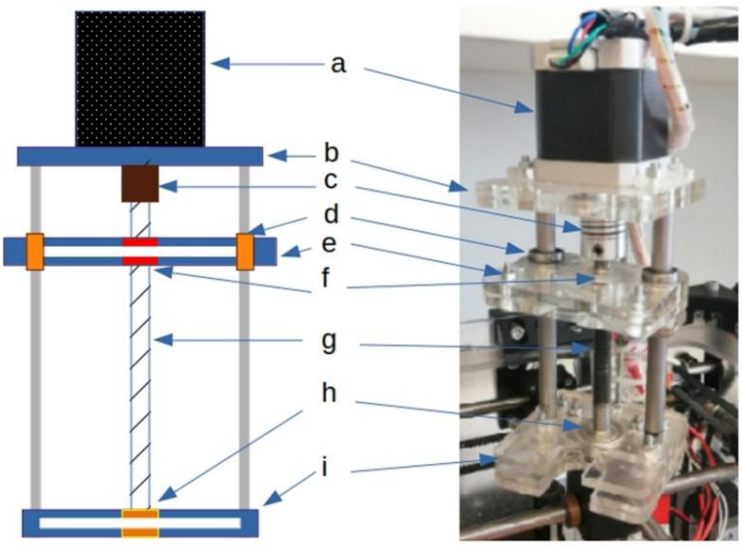


Figure 15 – The extruder developed: a) motor (Nema 17 motor, 1.8º, 47.1 N / cm); b) engine support; c) homokinetic joint; d) linear bearings (LM8LUUM); e) mobile cart with fixation of the syringe stem; f) traction nut; g) endless screw (d = 8 mm); h) bearing (608ZZ); I) base and fixation of the syringe handle.

The support, carriage and base parts were designed using CorelDraw x6 and cut using a numerical control machine and LASER beam from Universal Laser Systems.

Given the need to pre-cook the dough to be tested, the temperature control of the conventional extruder was adapted to a hot air injection device over the deposited material. For this purpose, a device was constructed (Figure 16) and attached to the assembly of the extruder.

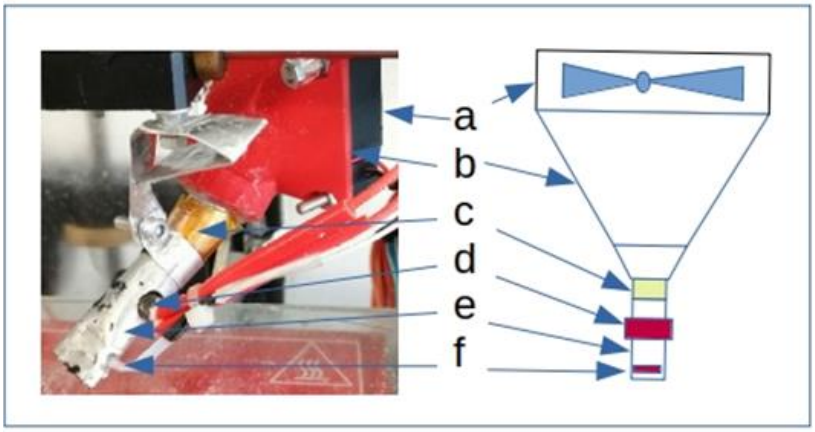


Figure 16 - Hot air injection device diagram: a) thermocouple (PT100); b) aluminum metal tube; c) heating resistance; d) thermal insulator (polyamide); e) adapter (styrene); f) fan (12V, 4 cm in diameter).

The body of the adapter was made by 3D printing, using ABS (acrylonitrile-butadiene-styrene) with an Ender 3 printer. The coupling to the extruder device was made using an aluminum metallic tape.

The main body of the 3D printer was a Vertex 3D printer from Velleman (Velleman nv, Belgium). The operating characteristics of this printer suggested it was appropriate to the type of modifications that were intended to be introduced, namely due to the type of movement of the extruder that has two degrees of freedom; the third degree of freedom, corresponding to the "z" axis, is the only one that can affect the position of the piece to be printed.

- Control Board

The microcontroller used (AVR ATmega2560) (Figure 17) has the necessary interconnections to the different control elements, having only been necessary to modify some power elements and connections. It also has the possibility of power control of resistive elements and A / D converters used for temperature sensors. The digital sensors, namely the position of the axes, are also foreseen since the adaptation was not complex.

The power supply had a power of 500 W, enough to all the devices used.

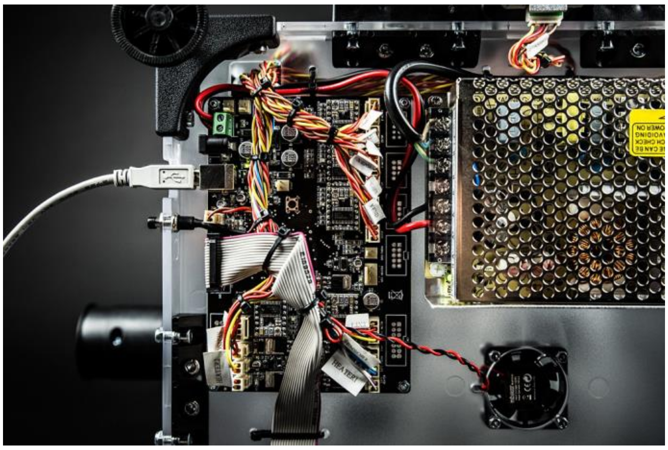
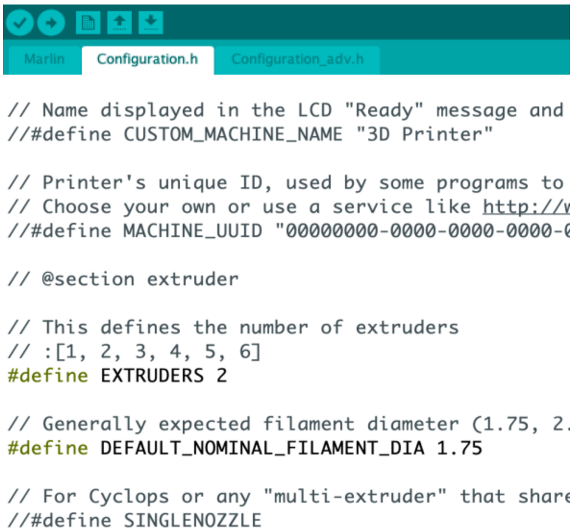


Figure 17 - Image of the used microcontroller.

- Firmware

The firmware used was modified from the original version, accordingly to the modifications introduced and the characteristics of the printer's microcontroller. All the modifications were made using Marlin Arduino version 1.0.6 using C/C++ (Figure 18). The control board selected was an Arduino MEGA 2560 or MEGA ADK.




```
// Name displayed in the LCD "Ready" message and
//#define CUSTOM_MACHINE_NAME "3D Printer"

// Printer's unique ID, used by some programs to
// Choose your own or use a service like http://v
//#define MACHINE_UUID "00000000-0000-0000-0000-0

// @section extruder

// This defines the number of extruders
// :[1, 2, 3, 4, 5, 6]
#define EXTRUDERS 2

// Generally expected filament diameter (1.75, 2.
#define DEFAULT_NOMINAL_FILAMENT_DIA 1.75

// For Cyclops or any "multi-extruder" that share
//#define SINGLENOZZLE
```

Figure 18 - Image of the configuration file using Marlin.

Due to the modifications introduced in the initial model, the firmware was modified in order to meet the handling needs of the new extruder. Thus, once different stepper motor controllers (A4988) were used, the numerical control characteristics were modified.

All the variables were adapted and stored as a configuration file for example, heated bed, location of limit switches, stepper motor rotation to linear motion, build volume, direction, filament extrusion and speed.

- Software

In the creation of the 3D models to be printed, Tinkercad (Autodesk) was used, which allows to obtain models in STL format (Standard Triangle Language or Standard Tessellation Language) which were transferred to the printing software.

After testing different 3D printing programs MatterControl (MatterHackers) was chosen due to characteristics as ease of use and being user friendly.

- Tested materials

To perform the printing tests, a mixture of water and non-fermented type 55 flour was used. The optimal ratio between the two constituents was assessed using a viscosimeter (AMETEK Brookfield, USA), with 40%, 50% and 53% of tested flour.

8.2. Results and discussion

The study began by evaluating the rheological properties of the dough to be used.

Regarding the testing of the dough the mixture showed a pseudoplastic behavior and 50/50 to be the best ratio regarding viscosity, considering the results obtained with the viscosimeter (Figure 20) and a visual test in a preliminary printing test. After optimization of the printing for this dough and for the production of a traditional cookie produced on a 3D printer, the composition of the dough needs to be more complex, as the traditional ingredients such as eggs and sugar has to be added. Then more tests need to be performed to assess rheological properties and printability.

The changes in the printer hardware and software were tested during the printing with this dough, analyzing the steps of the motors, the deposition of the dough, the temperature in the pre-cooking mechanism and the quality of the printed pieces, in order to adjust some features that were not working correctly. After several custom modifications of the mentioned features the printer worked properly

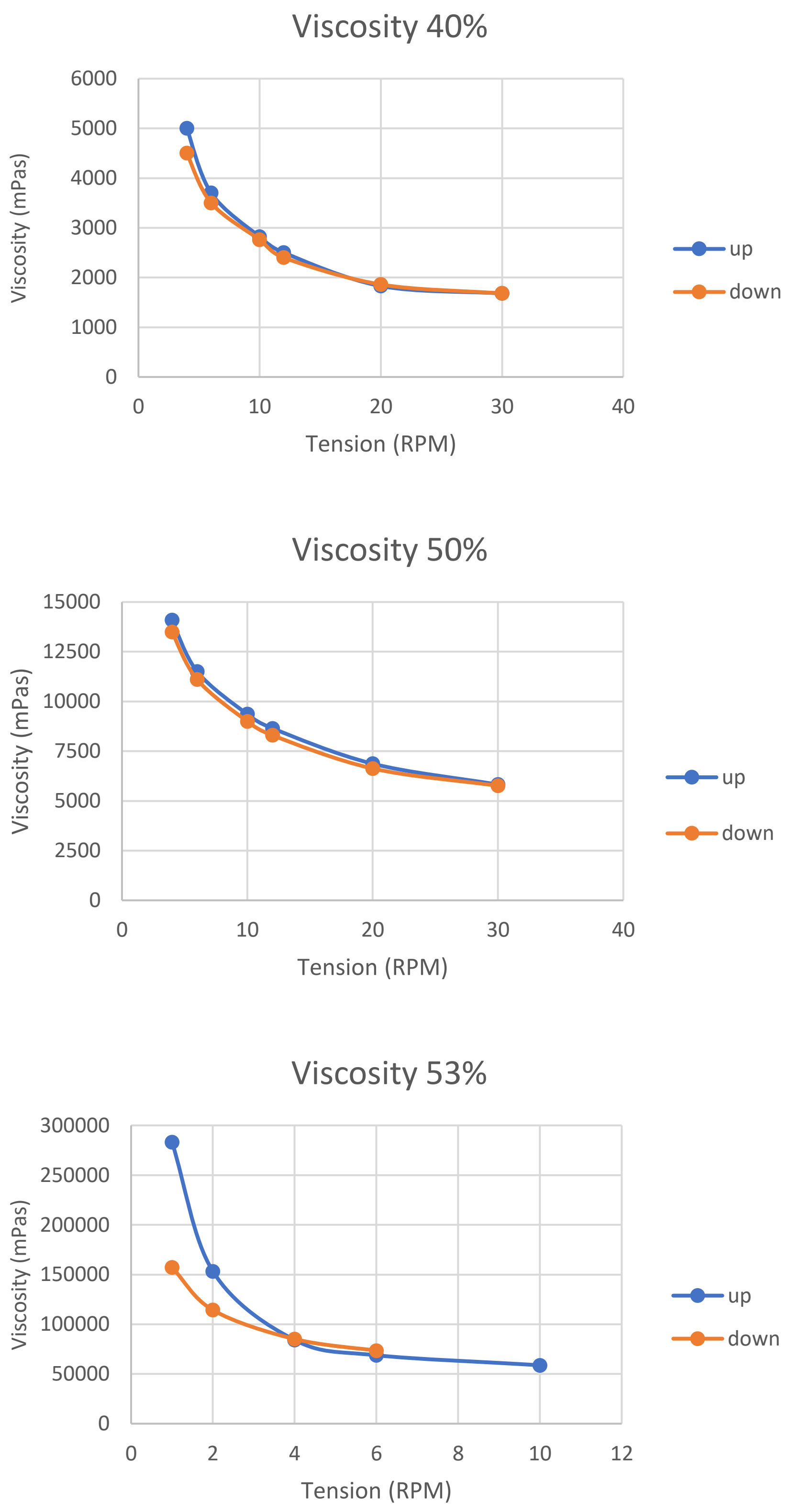


Figure 19 - Graphics representing the viscosity vs tension, for a ratio of 40/60, 50/50, 47/53, water and flour, respectively.

The printing tests were performed using a square shape with no middle section (Figure 20), in order to assess the capability of this process to shape outer and inner corners. Results showed that for these particular conditions, the parameters to achieve best printability were a filament diameter of 2,5 mm, a layer height of 1 mm and a printing speed of 5 mm/s, that allowed for the pre-cooking of the dough without affecting the quality of the printing.

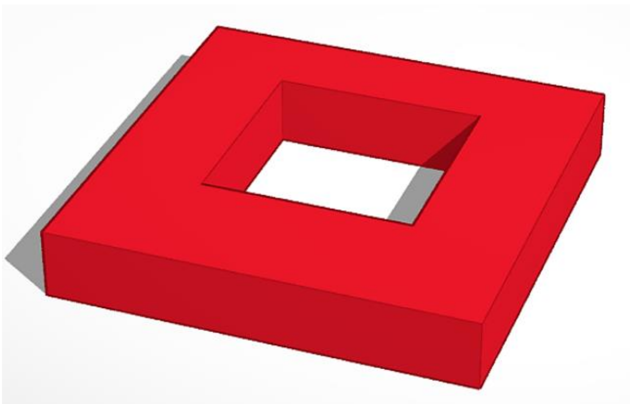


Figure 20 - 3D model used to perform the printing tests.

Figure 21 represents 3D printed samples, that did not hold well their form. The corners were rounded therefore the square shape was not well represented. The samples also presented a little dragging.

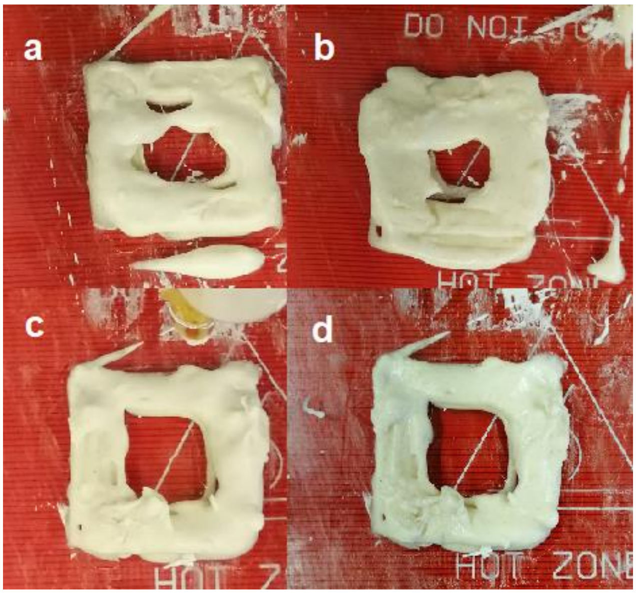


Figure 21 - 3D printed samples. a: filament diameter (FD) 2 mm, layer height (LH) 0,6 mm, printing speed (PS) 6 mm/s; b: FD 2 mm, LH 0,7 mm, PS 6 mm/s; c: FD 2,5 mm, LH 0,7 mm, PS 6 mm/s; d: FD 2,5 mm, LH 0,8 mm, PS 6 mm/s.

Samples represented in figure 22 presented too much deposition, causing the shape to lose its form. In figure 22c, the filament diameter was augmented leading to a less amount of material being deposited, and the layer height was diminished, improving the shape of the sample by preventing misshaping caused by excess of deposited material.

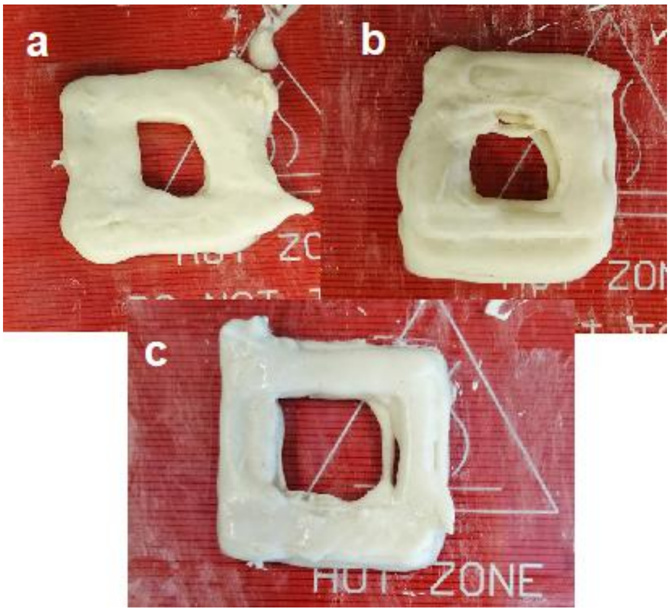


Figure 22 - 3D printed samples. a: FD 2 mm, LH 1 mm, PS 4 mm/s; b: FD 2,25 mm, LH 1,2 mm, PS 5 mm/s; c: FD 2,5 mm, LH 1,1 mm, PS 5 mm/s.

In opposition to the last samples, figure 23 presents 3D printed samples with low amount of material deposited, which was corrected by diminishing the filament diameter, allowing for more deposition of material, and increasing the layer height. Figure 23c shows improved results.

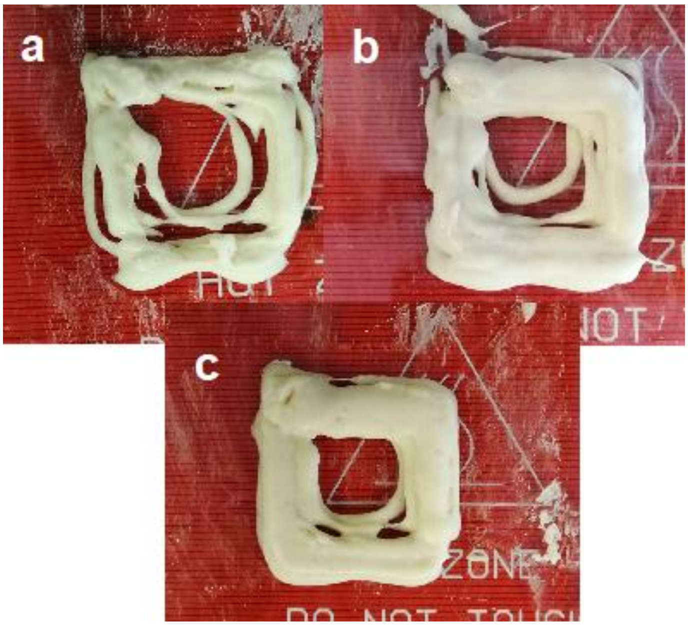


Figure 23 - 3D printed samples. a: FD 3 mm, LH 1 mm, PS 6 mm/s; b: FD 2 mm, LH 1,2 mm, PS 5 mm/s; c: FD 2,5 mm, LH 1,2 mm, PS 5 mm/s.

Results presented in figure 24 were the best obtained, with the corners of the squares well designed, with sufficient material deposited not allowing for empty spaces in the shape, but not so much that it would cause dragging and misshape. Figure 24c was the best due to presenting the better shape, more linear. However, there was a line of material deposited misplaced in the outer perimeter.

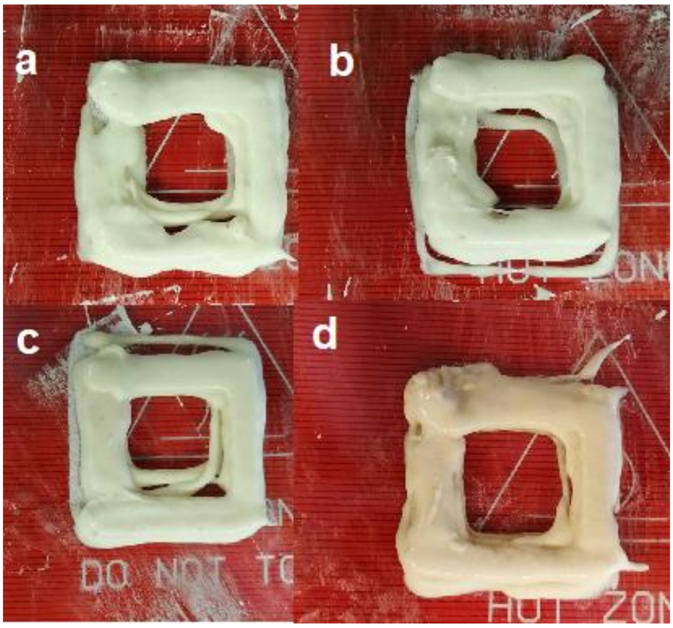


Figure 24 - 3D printed samples. a: FD 2,5 mm, LH 0,9 mm, PS 6 mm/s; b: FD 2,5 mm, LH 1 mm, PS 6 mm/s; c: FD 2,5 mm, LH 1 mm, PS 5 mm/s; d: FD 2,5 mm, LH 1 mm, PS 4 mm/s.

9. Conclusion

In the past 10 years 3D food printing technology has been growing and evolving, being a promising technology to customize nutrition and personalizing food, and to revolutionize the confectionary industry. As well as a way to solve some problems in people´s lives, like dysphagia or overweight, or some of the world´s major issues like overconsumption of non-sustainable ingredients and mass production, or at least these are possibilities already being explored. Despite, it needs further studies to assess the safety of manufacturing food using a 3D printer and its real ability to be used in nutrition and diseases control, as the number of studies on this subject is low. The same goes to using the technology with readily available, cheap, and less valuable or less consumed ingredients, to minimize the sustainability problems of feeding an ever-growing human population. It would be of great importance to further explore this possibility to not over explore the Earth’s natural resources.

To take fully advantage of 3D food printing, all the printing variables need to be understood, from the G-code, to how the CAD and slicing software works, to the printing parameters. By knowing how the device works and how the software commands translate into real moves it can be better understood how a printed piece is made, and what parameters can be altered to perfect the final product. As people commonly say, “we also eat with our eyes”, and this technology is a way to produce intricate and delicate designs, appealing to the eye, that would be very difficult to do by traditional methods, but knowledge is required to achieve them. Using 3D printers to decorate pastry is starting to be common, as it is possible to make complex designs that can make everyone flabbergast and are very hard to do manually or take too much time. The visual impact is very important, as we more often appreciate better a plate or dessert beautifully decorated than just a huddle of food, even if they taste the same.

Understanding the rheology of the food pastes is another very important point, as it is crucial for the printer to work and for the final product to be finished. Knowing the rheological behavior of the material utilized facilitates the extrusion and printing. Obviously, a low viscosity material is easier to extrude but it flattens after extrusion, and this can be overcome by using food additives. Nevertheless, it is necessary to study the effect of the additives in food ingredients and how they interact with each other, to fully benefit from their use. It also is necessary to assess if the use of such additive does not bring any risks to human health and regulate their use in the production of 3D printed food.

Alongside with rheology, choosing the printing method is also key, because some methods work better with powders and others with purees. Hence, if the aim is to construct a sugar sculpture, methods like selective sintering or binder jetting may be appropriate. To decorate cakes and other sweet goods, inkjet printing or the extrusion method work better. If the objective is to print a meal using purees or pastes, the only method to do so is by extrusion.

Chocolate has been one of the most commonly used material in food printing so far, mainly because of its capacity for melt extrusion and popularity among the public; the idea of making sweet treats using this technology seems more and more appealing. Doughs and mashed potatoes are also popular materials because of their ability to be molded, although doughs need further cooking after extrusion. Nevertheless, the number of papers assessing the ability to use this technology to print traditional meals like meat and vegetables is increasing, but much work still needs to be done before this is a viable way to food consumption.

In a time where 3D food printing is still not fully controlled, 4D food printing appears. It can bring benefits like flat packaging for pasta for example, or it can add even more fun and convenience to our meals, with shape shifting during cooking and self-chopped or self-wrapping sheets. It is important to keep innovating but it is also important to master a technique before moving on to the other.

In spite of all the benefits listed, some people are still not convinced that using 3D printing technology to eat is such a great thing. The concept of fearing the unknown is still very much present in this area, as people are reticent about the idea of consume food that comes out of a printer because printing is still very carved as paper and ink on the average person's mind. But it is time to start opening up to include 3D food printing in our food habits. As this technology enters our society, marketing campaigns are necessary, or else this will not achieve the greatness it is destined to have. Printing some sweets and offering to the public in a supermarket before commercializing for example, it would be a great way to introduce 3d printed foods to people and prove to them that they are tasty as well as beautifully designed, and this is a step as important as overcoming the technological problems in this area.

Despite the positive results obtained in this preliminary work, optimizing the printing process and achieve a consumable food product using 3D printing still has a long way to go, and further studies are necessary with a dough with the same ingredients used in the production of traditional cookies.

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