REVIEW ON
3D FOOD PRINTING: A NEW ERA OF FOOD PREPARATION

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Abstract

3D Food Printing is an innovative step in food preparation that promises to revolutionize food formulation and manufacturing processes. Preparing foods with sensory attributes from various ingredients and additives has always been a requirement. Three-dimensional (3D) Food Printing combines 3D printing and digital gastronomy to revolutionize food manufacturing by allowing for customized shape, color, flavor, texture, and even nutrition. Binder-jetting, selective laser sintering, inkjet printing, and extrusion-based printing comprise a 3D Food Printing technique. Food materials such as chocolate and dough are used to create designed shapes layer by layer. The purpose of this research is to analyze and summaries published articles and papers on 3D Food Printing and its impact on food processing, as well as to provide critical insight into the future direction of its development.

Keywords 3D Printing, customized food printing, food safety, food printing technologies.

1. Introduction

Three-dimensional (3D) printing is a method of creating objects by employing computer-aided design software and hardware that responds to the software's instructions. It is also known as "additive manufacturing" or "rapid prototyping" in the technical world (Lupton, 2018). Rapid prototyping, the process of modelling, assembling, and production using computer aided design (CAD), was invented by Kodama from Japan in the late 1980s (3D Printing Industry, 2014). 3D Food Printing is a rapidly growing industry these days. There has been a boom of papers about 3D printed food applications in the last five years alone (Figure 1). (Zhang et al., 2021). The primary advantage of 3D printing is the ability to customise the shapes, textures, and nutritional profile (Derossi et al., 2018). Researchers have utilised this technique to print cell grown meat and meat analogues (Godoi et al., 2016), which employs many of the same concepts employed in the biomedical area to print organs and tissues. 3D printing has also been used to make a variety of solid or semi-solid items, such as cookies, cakes, burgers, apples, and chocolates (Lipton et al., 2015; Yang et al., 2018). With improved 3D food technology, it may eventually be feasible to generate more appealing meals for folks who go to isolated locations for extended periods of time. Scientists making geological and environmental contributions, for example, may require 3D printed food when investigating in remote locations. Furthermore, NASA expects that 3D printing can be used to aid feed people on longer-duration space journeys (Terfansky et al., 2013). Furthermore, the combination of food and software has given rise to a slew of novel ideas, such as the concept of digital pantries. Online recipes prepared from a restricted number of semi-liquefied components are stored in digital pantries; these recipes can then be duplicated by others with the click of a button

(Lin, 2015). Websites like www.thingiverse.com enable 3D printing hobbyists to share computer data (Lupton, 2018).

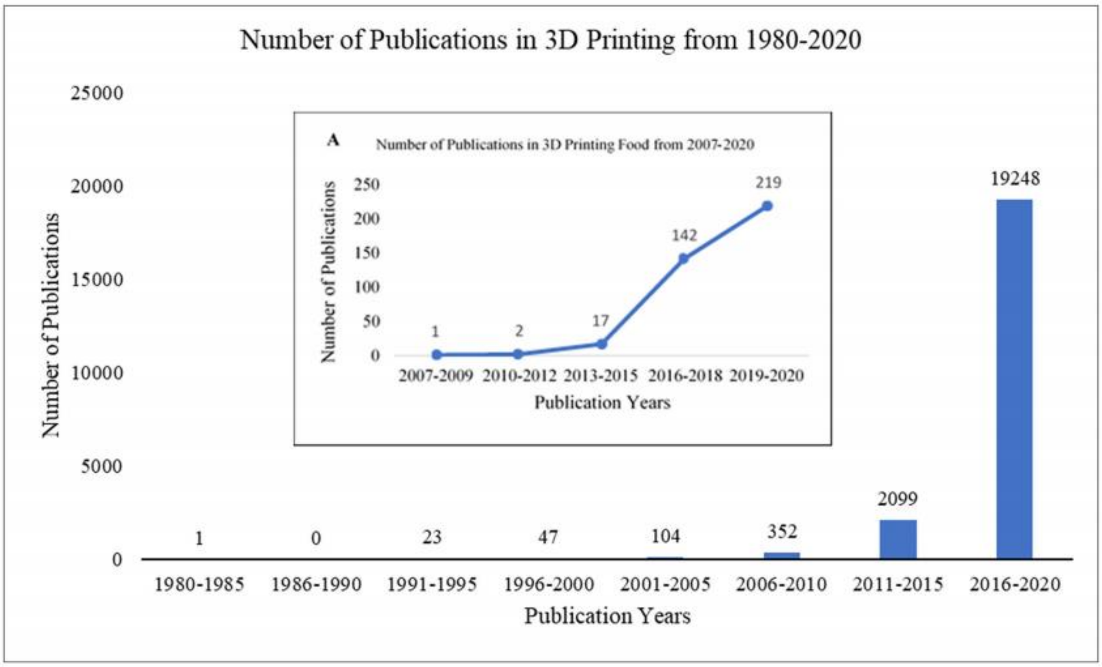

Figure 1: Number of Scientific Publications reported by Web of Science Clarivate Analytics containing the term 3D Printing in the title, keywords, and abstracts from the years 1980-2020. The insert A shows the number of 3D Printing Food Publications with the terms "3D printing, food" in the title, keywords, and abstracts. Both searches applied filters for articles and reviews. Adapted from (Zhang et al., 2021).

2. The Concept of 3D Food Printing

3D printing is a digital technique that involves layer-by-layer building by binding together materials such as polymers, powders, ceramics, metals, and organic metals such as tissue cells or meals (Nachal et al., 2019). It varies from robotic-based food manufacturing in that only human efforts may be decreased by automating numerous manual procedures in the latter, whereas printing meals allows users to design and create foods with customizable shapes, colour, flavour, and nutritional demands. Food 3D printing follows a well-defined sequential process (Figure2). This starts with creating a 3D CAD model of the desired geometry; either the model is generated or a geometry is scanned to obtain the most information about its surface features. It is then split into distinct layers using appropriate slicing software. Machine codes are generated for each sliced layer throughout this operation. Following that, the created G-codes and M-codes are sent to the printer in order to print the desired recipe. G-codes are a numerical control language that is generated by CAD software to guide motors in terms of printing region, printing speed, and printing axis. M-codes are supplementary directives that aid machine operation. Food systems, as complicated matrices, necessitate the use of adaptive slicing software for printing. This is related to issues in developing G-codes since they need a large amount of memory space and are difficult to process due to the complexity required in processing large amounts of data (STL files). This has an impact on the quality of the manufactured food as well as the process time requirements (Brown et al., 2014). There is a variety of software available for scanning, model development, and printing applications; the choice is based on the user's knowledge and the features necessary.

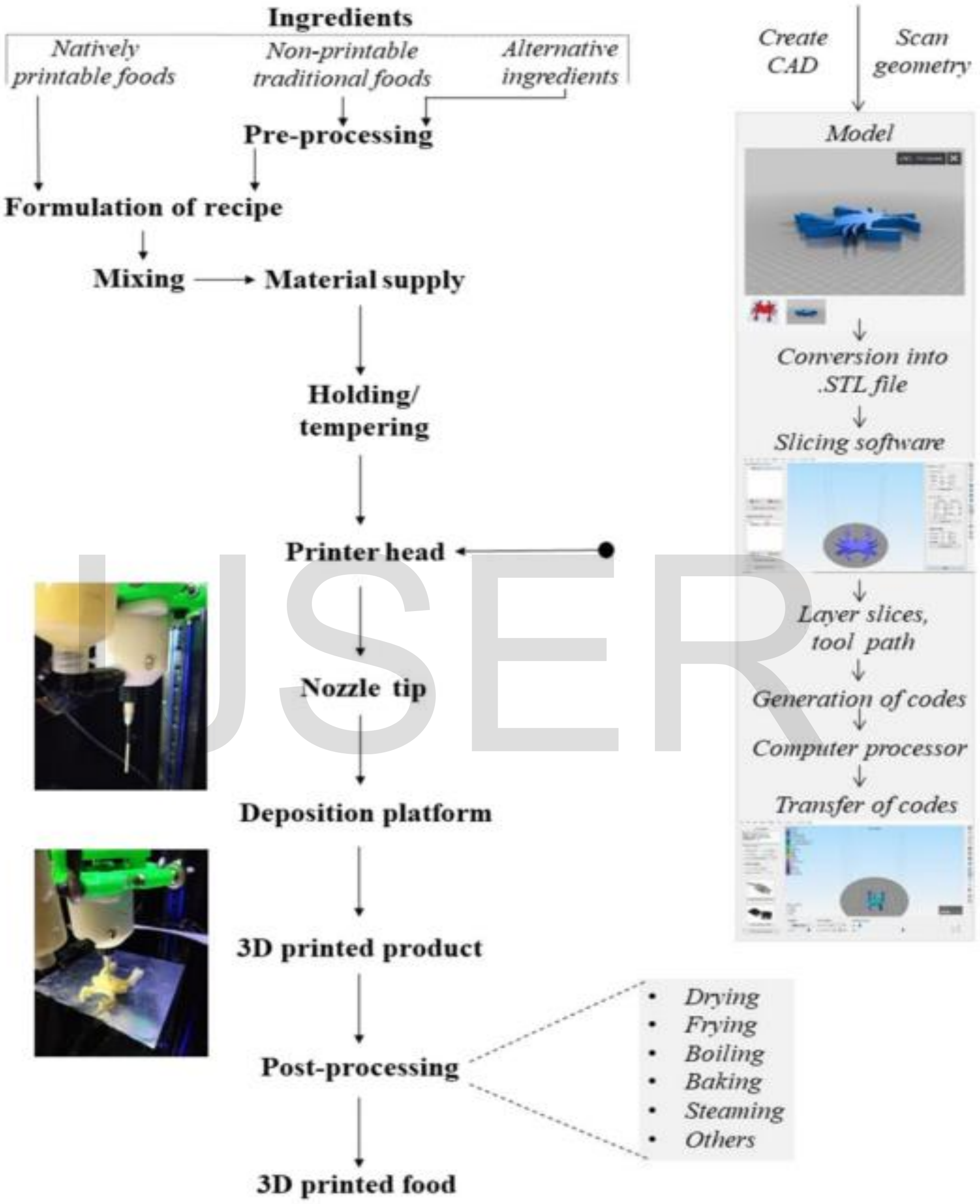

Figure 2: Schematic flow diagram of a typical extrusion based food 3D printing process. Adapted from (Nachal et al., 2019).

3. Food Printing and Platform Design

A Food Printing platform is made up of three axes (i.e., a Cartesian coordinate system), dispensing/sintering devices, and a user interface. Such platforms can manipulate food manufacturing in real time thanks to a computer-controlled material feeding mechanism. In the literature, both commercial and self-developed platforms have been used for Food Printing projects (Sun et al., 2015).

3.1. Universal Platforms

Researchers have changed open-source commercial printing platforms for Food Printing purposes in order to simplify and shorten the development process (Sun et al., 2015). One of these was the Fab@Home system.

3.2. Self-Developed Platform

Self-developed platforms are typically constructed to meet unique criteria in order to facilitate fabrication-related research (Torrone 2007; Hao et al., 2010). To optimise a fabrication process, researchers can construct such platforms flexibly based on dispensing mechanism, material property, and print head. Further development of these platforms will necessitate machine and material advances (Sun et al., 2015).

Food printers can be classified according to the type of platform:

Food printers built on universal platforms, which may be adapted from current open source 3D printing platforms. The Fab@Home Model 1, which was developed by certain Cornell University researchers and is ideal for printing foods via extrusion of liquid materials (Malone et al., 2007), is one example.

Food printers based on self-developed platforms, which allow for greater flexibility in the fabrication process; User control interface design, in which users have complete control over shape, ingredients, and materials (Sun et al., 2015).

Design modelling can now be done in three ways, thanks to the rapid development of information technologies: by creating online virtual customised foods and inviting customers to share their models; by configuring online visual products for self-service and online order; and by providing food co-creation sites dedicated to the production of gifts consisting of unique food products. As a result, culinary designs made by chefs and gastronomy experts can be replicated anywhere by downloading the original data files and utilising a 3D printer (Baiano, 2020).

4. 3D Food Printing Technologies

4.1. Binder Jetting

Binder Jetting (Figure3) involves depositing a binder selectively into the powder bed, cementing these areas together to make a solid part one layer at a time. Metals, sand, and ceramics in granular form are common materials utilised in Binder Jetting.

To begin, a recoating blade applies a thin layer of powder to the build platform. Then, an inkjet carriage travels over the bed, dropping droplets of a binding agent that binds the powder particles together. The coloured ink is also deposited during this phase in full-color Binder Jetting. When the layer is finished, the build platform descends and the blade re-coats the surface. The technique is then repeated until the entire section is finished.

After printing, the part is encased in powder and allowed to cure and strengthen. The part is then taken from the powder bin, and the unbound, surplus powder is cleaned using compressed air (Introduction to Binder Jetting 3D Printing).

The downsides include obtaining foods with a rough appearance and the need to dehydrate the finished items or further prepare the structure to improve its strength. Binder jetting printing can be used on powdered materials such as chocolate, starch, sugar, protein, and artificial meals (Pitayachaval et al., 2018).

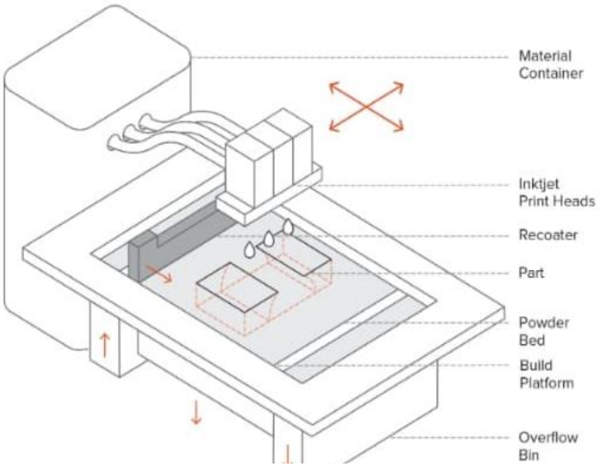

Figure 3: Schematic diagram of Binder Jetting. Adapted from https://www.hubs.com/knowledge-base/introduction-binder-jetting-3d-printing/#work.

4.2. Selective Laser Sintering/ Hot Air Sintering

Laser Sintering with Preference (Figure4) 3D printing is an additive manufacturing (AM) process that sinters microscopic particles of polymer powder into a solid structure based on a 3D model using a high power laser.

Inside the build chamber, the powder is disseminated in a thin layer on top of a platform. The platform warms the powder to a temperature slightly lower than the melting point of the raw material. The laser heats the powder to just below or right at the melting point of the material as it scans a cross-section of the 3D model. This mechanically fuses the particles together to form a single solid component.

The platform is then lowered into the build chamber by one layer, typically between 50 and 200 microns, and the procedure is repeated for each layer until the pieces are complete.

To provide optimal mechanical qualities and avoid wrapping in sections, the build chamber must be slightly cooled down inside the print enclosure and then outside the printer after printing. The completed parts must be extracted from the build chamber, separated, and cleaned of superfluous powder (Guide to SLS 3D Printing).

For direct metal laser sintering, the SLS machine (Figure5) may employ a single-component powder (Mellor et al., 2014). The laser only melts the outside surface of the particles in single-component powder SLS machines, which is known as surface melting (Mantihal et al., 2020). To build a three-dimensional object, the procedure will fuse the solid non melted cores to each other and to the prior layer (Periard et al., 2007).

A low velocity stream of hot air is directed to a powder media (e.g., sugar) in HAS (Figure5) to generate a two-dimensional image (Oskay et al., 2006). Following the formation of this image, the powder bed is slightly lowered and a thin coating of powder is put on top, covering the first layer.

The fresh layer is selectively fused using the same procedure (hot air). This process is repeated according to the design from the 3D model until the 3D thing is fully produced (Godoi et al., 2016). The hot air beam is channelled on top of the powder bed in the

HAS process, where the X and Y axes of the beam travel in opposite directions. The sintering powder forms the product, while the un-sintered powder remains and can be reused. SLS has been successfully used to create complex 3D structures utilising sugar or sugar-rich powders such as NesQuik powders (Gray, 2010). However, this method is only applicable to powder-based materials (Lai et al., 2007).

4.3. Inkjet Printing

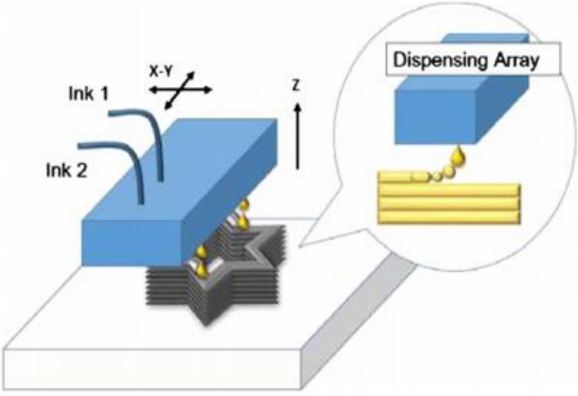

Figure 4: Inkjet Printing. Adapted from (J. Sun et al., 2015).

A stream of droplets is dispensed from a thermal or piezoelectric head in inkjet printing (Figure6) to materialise surface fillings or embellishments on products such as cookies, cakes, and pizza (Kruth et al., 2007).

There are two types of inkjet printing processes used: continuous and drop-on-demand printing. Ink is continually ejected through a piezoelectric crystal that vibrates at a consistent frequency in the first approach. The inclusion of conductive substances allows the ink to flow. Ink is ejected from a head due to the pressure produced by a valve in drop on demand printing. Drop-on-demand printing is more time-consuming than continuous printing, but it produces superior resolution and precision (Liu et al., 2017). This technology can be used on materials with low viscosity, such as chocolate, liquid dough, icing, meat paste, jams, and gels (Godoi et al., 2016). The following disadvantages must be mentioned: inkjet printing is only suited for surface filling or decorating and is not ideal for fabricating complicated food structures; the support materials cannot be recycled (Baiano, 2020).

4.4. Extrusion Method

Extrusion-based printing is often referred to as fused deposition modelling (FDM). Scott Crump devised it in 1988 and defined it as an automatic, non-laser-based method for quick manufacturing of items using non-toxic materials. It was developed to make plastic products but has now evolved into one of the most important 3D Food Printing technologies (Wales et al., 1991).

Extrusion technology is typically used on molten materials with a temperature control or semi-solid viscous system (Chokshi et al., 2004).

Figure 7 depicts the process of extruding food substrates. Heat is delivered to a material (through a heating block or syringe depending on the type of substance) and the right temperature is maintained to manage its viscosity and allow it to flow readily through the nozzle in hot melt extrusion (HME) (Tadmor et al., 1970).

Extrusion-based printing can be accomplished using one of three extrusion mechanisms: screw-based, air pressure-based, or syringe-based extrusion (Liu et al., 2017).

A screw that moves the food material ensures continuous nozzle feeding in screw-based extrusion. As a result, this mechanism is unsuited for high viscosity and mechanical strength food ingredients. Because the material is driven to the nozzle by air pressure in air pressure-based extrusion, it can only be used with liquids or materials with low viscosity. The nozzle feeding is sporadic (Sun et al., 2018). A displacement plunger applies force to the material in syringe-based extrusion. This mechanism is excellent for printing food products with high viscosity and mechanical strength, however it only ensures discontinuous nozzle feeding (Baiano, 2020).

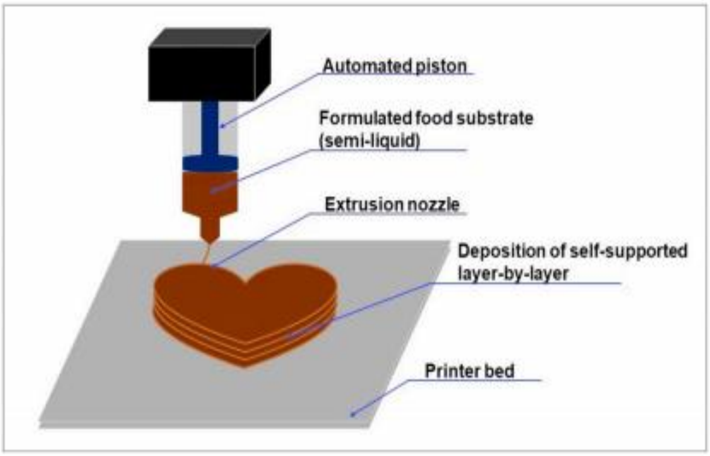

Figure 5: Schematic diagram of 3D fused extrusion process. Adapted from (S. Mathilal et al., 2020).

5. Food Inks

Food has a complex structure that influences its flowability and printability. Rheological properties, gelling, melting, and glass transition temperatures are all important factors in creating a visually appealing and stable 3D printed object (Zhang et al., 2018; Liu et al., 2017; Godoi et al., 2016). To be able to construct 3DP structures, it is necessary to fully understand the material's properties as well as the technologies that are relevant to it (Mantihal et al., 2020).

5.1. Sugar

Granulated or powdered sugar can be used in Selective Laser Sintering, Hot Air Sintering, and Binder Jetting in 3D Food Printing (Godoi et al., 2016). This is due to the fact that sugar can be melted or solubilized at the surface by heat or moisture, causing adjacent particles to fuse (Knecht, 1990). In addition, depending on its moisture content and purity, crystalline sucrose melts or decomposes at temperatures ranging from 160°C to 186°C. As a result, parameters such as compressibility and powder density are critical considerations because they influence powder flow ability in the vessel, which contributes to pattern construction when the heat source (either laser or hot air) is applied to the powder bed (Berretta et al., 2013).

Figure 8 depicts the printing of sugar powder with HAS (Images A and B) and binder jetting.

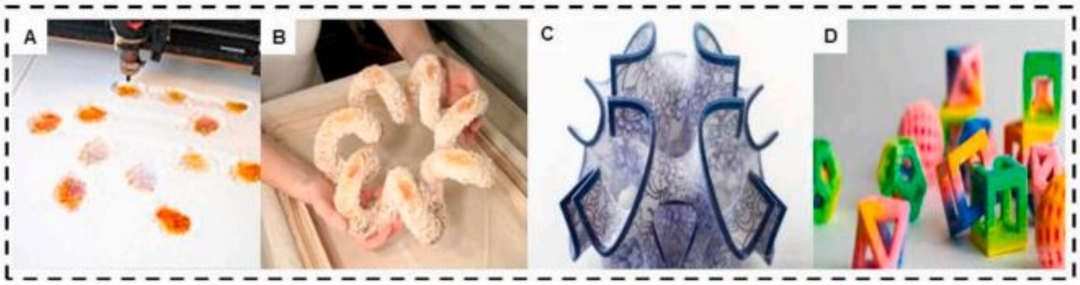

Figure 6: 3D construct made by selective hot air sintering and melting (SHASAM) (a) SHASAM process (b) toroidal coil sculpture made of granulated sugar (Oskay and Edman, 2006). These images were reproduced from the data available at http://candyfab.org/ (c) Complex sugar geometry with fine colour detail (d) colourful sugar candies. These images were reproduced from the data available at http://www.3dsystems.com/culinary/gallery.

5.2. Dough

When mixed with water, dough is a carbohydrate macronutrient derived from wheat flour that has viscoelastic properties. Viscoelasticity occurs when a gluten protein is water compatible, causing a swelling process when water interacts with the gluten protein. Dough can also retain gas, which slows the rate of gas diffusion in the dough mixture. Because gluten proteins have a large molecular size and a low charge density, they can interact with both hydrogen and hydrophobic bonds (Hoseney et al., 1990). Wheat flour dough has the ability to set during post-processing such as baking and frying due to its viscoelastic property. Dough may be a good candidate for 3DP because of this property.

Yang et al. (2018) investigated the effect of various ingredients on dough printability. They discovered that a sucrose content of 6.6 g/100 g in dough resulted in a more intact shape.

Figure 9 shows printed samples of dough with different sucrose compositions ranging from 3.3 g to 8.2 g of sucrose per 100 g of dough.

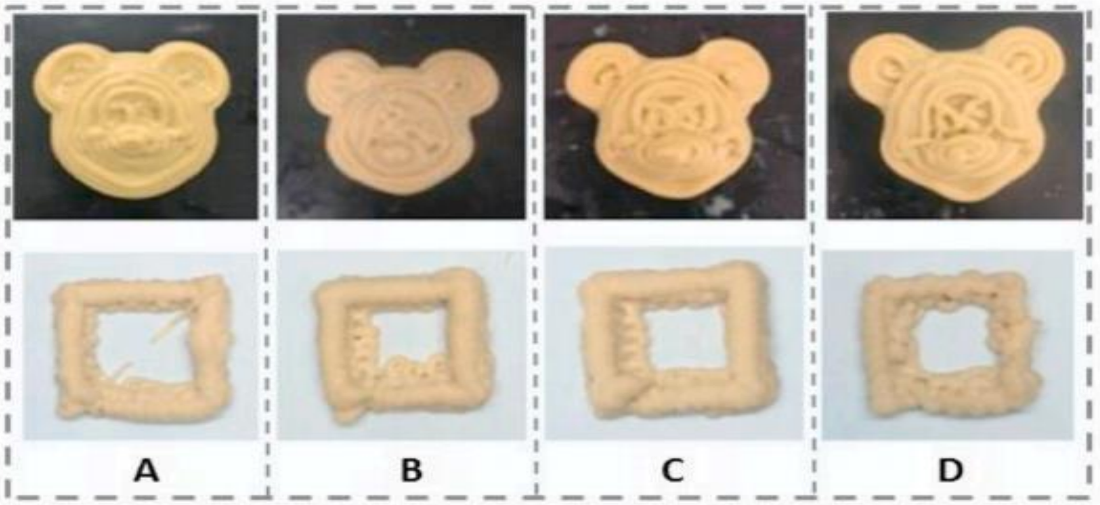

Figure 7: Representative images of dough printed using the Porimy 3D printer with various sucrose compositions (a) 3.3/100 g of formulation; (b) 5.0/100 g of formulation; (c) 6.6/100 g of formulation; (d) 8.2/100 g of formulation. Adapted from (Yang et al., 2018).

5.3. Chocolate

Finding an appropriate material that melts at the pre-selected temperature and rapidly solidifies upon adhering to the previous layer is critical in 3D printing, according to Hao et al., (2010) and Sood et al., (2010). These are characteristics of chocolate. Chocolate is a temperature sensitive material due to the presence of cocoa butter. Chocolate has a complex structure, and its flavour varies significantly even with minor temperature changes. Chocolate, for example, is semi-solid at room temperature but becomes viscous and has a low yield stress of about 10–20 Pa when heated to body temperature (37 °C) (Chen et al., 2006).

Other composites found in chocolate include soy lecithin, which acts as an emulsifying agent, improving the coating of hydrophilic sugar particles and hydrophobic fat molecules. This allows chocolate to flow and remain suspended during consumption.

To summarise, the tempering process in chocolate manufacturing consists of four stages: (1) complete melting, (2) cooling to the point of crystallisation, (3) crystallisation, and (4) melting out the unstable crystals. This is accomplished by keeping the temperature constant (32 °C) and adding seeds (properly tempered chocolate in the form of solid chocolate) to the mixture.

Figure 10 depicts intricately designed 2D printed chocolate objects (Mantihal et al., 2020).

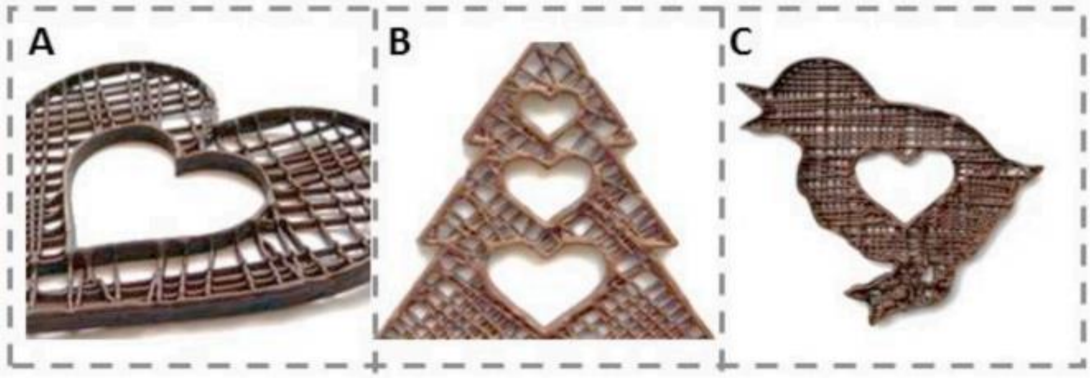

Figure 8: 2D printed chocolate with an intricate design produced by ChocEdge (a) Heart-in-heart shape (b) Hearts in Christmas tree (c) Heart in chicken. These images were reproduced from the data available at http://chocedge.com/gallery.html.

5.4. Dairy

The printing of dairy products has received less attention, possibly due to the fact that they range from cheese to milk components such as casein and whey protein, among others. This variety can be seen in the dairy-based inks that have been studied, which include pastes based on semi-skimmed (SSMP) or skimmed (SMP) milk powder (Lille et al., 2018) and milk protein, as shown in Figure 11 (Liu et al., 2018), as well as both processed (Le Tohic et al., 2018) and semi-hard model cheese (Kern et al., 2018).

A variety of dairy products or derivatives have also been used as ingredients in other food inks, including milk and butter in dough (Kim et al., 2019), dried nonfat milk in fruit snacks (Derossi et al., 2018), and sodium caseinate in gels (Schutyser et al., 2018). Lee et al. developed a method for performing direct ink writing (DIW) 3D Printing of milk products at room temperature in a recent study published in 2020. In the study, 3D printable milk inks were created without the addition of any rheological modifiers, and 3D structures were created using a DIW 3D printer via extrusion at room temperature.

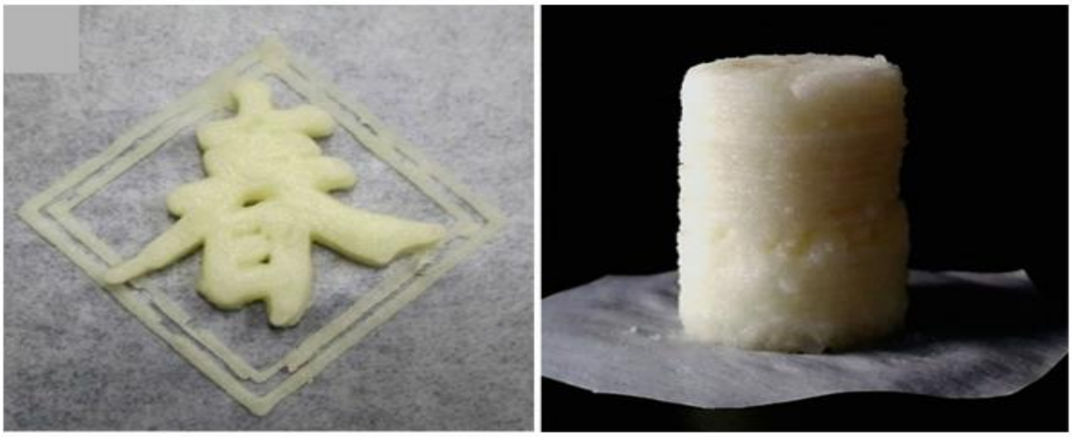

Figure 9: Milk protein pastes with incorporation of whey protein isolate. Adapted from (Liu et al., 2018).

They also demonstrated multi-material printing with milk inks (chocolate ink made by combining 20 w/w cocoa powder and chocolate syrup). This study provided an easy way to create other edible inks without the use of additives and to create a visually appealing meal without the use of temperature control.

In the case of cheese, calcium and pH levels were found to affect both the gel-sol transition temperature and the critical shear rate (above which flow instability and melt fracture are observed); this, in turn, determines the printing temperature and the parameter limits of the stable process area for hot-melt extrusion printing (Kern et al., 2018). Furthermore, the printing process's melting and shearing has been shown to influence the texture of processed cheese, with the printed sample being significantly softer than its original counterpart due to the disruption of fat globules (Le Tohic et al., 2018). These findings highlight the importance of better understanding the impact of dairy product properties and components on the printing process and vice versa. This will allow them to use their structure-forming capabilities in dairy-based food inks or as components in other inks, not only in 3D Food Printing but also in industries other than food, such as pharmaceuticals (Lee et al., 2020).

5.5. Hydrogel

Cohen et al. demonstrated one of the first printable and edible hydrogels in the literature when they tested combinations of two hydrocolloids (xanthan gum and gelatine) with flavour concentrates and discovered that they could simulate a wide range of textures, from weak to firm and smooth to granular (Cohen et al., 2009). Current research in 3D Food Printing of edible hydrogels aims to do one or more of the following: (a) explore new hydrogel inks, (b) determine the effect of different component types and/or concentrations, (c) optimise printing parameters, (d) develop printing technologies, and (e) establish theoretical models or simulations of the ink or printing process (Lee et al., 2020). As illustrated in Figure 12, new hydrogels include:

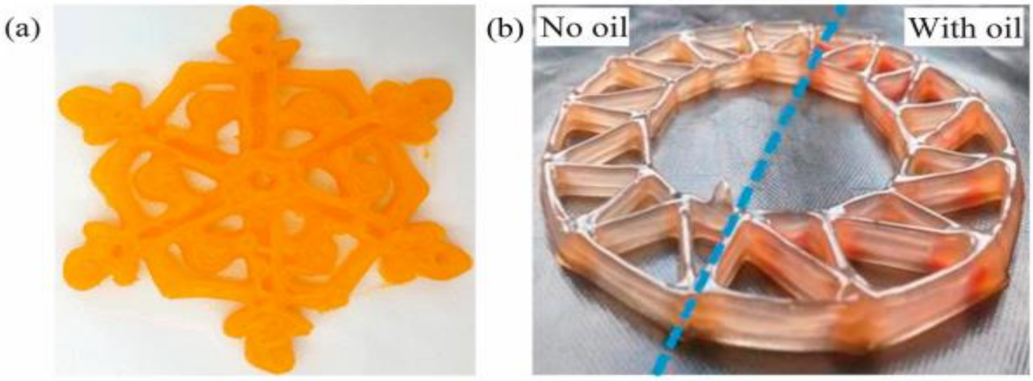

Figure 10: (a) Vitamin-D enriched orange concentrate with wheat starch and k-carrageenan; (b) Sodium caseinate with red-coloured olive oil droplets (right half) and without (left half). Adapted from (Azam et al., 2018) and (Schutyser et al., 2018) respectively.

- Low methoxylated pectin gel with sugar syrup and bovine serum albumin (Vancauwenberghe et al., 2017), and encapsulation of live plant cells (Vancauwenberghe et al., 2017);
- Sodium caseinate dispersion with sucrose, pectin, and potato starch (Schutyser et al., 2018);
- Fish surimi gel with sodium chloride (Wang et (Liu et al., 2019).

5.6. Alternative Food Ingredients

5.6.1 Plants: Fruits, Vegetables

While plant derivatives such as fruit juices or concentrates have been used to make hydrogels, this section focuses on inks that are derived from solid plant materials and thus take the form of slurries or pastes. In 3D Food Printing of Plant Inks, five steps have been identified: material selection, ingredient formulation, food ink preparation, printing conditions, and finally methods to extend the shelf life of the final structures (Ricci et al., 2019).

Mashed potato is a well-studied plant-based ink that can be made directly from raw potatoes (Liu, Zhang et al., 2018) or from gelatinized potato flakes or powder (Dankar et al., 2018; Liu, Bhandari et al., 2018).

Although mashed potato is extrudable on its own, the addition of additives (e.g., alginate, agar) (Dankar et al., 2018) or gums such as xanthan and k-carrageenan (Liu, Zhang et al., 2018) in concentrations as low as 1% has been shown to improve rheological properties and print outcomes such as texture, surface quality, and shape stability (Liu et al., 2019).

5.6.2. Meat

Surprisingly, meat in its various forms is by far the least well-researched of all the food ink categories identified here, with only one study focusing on it extensively through the development of a printer with a peristaltic pump to extrude slurries of fibrous meat and gelatine (Liu et al., 2018). Other reports on the subject were brief, usually as part of a study of several materials, such as turkey and scallop purees with transglutaminase (Lipton et al., 2010), blended canned tuna (Kouzani et al., 2017), and pastes of shrimp or ground chicken with other ingredients such as egg white and cooking wine (Hertafeld et al., 2019).

Alternatively, 3D Food Printing could be used to create meat-like products from other ingredients (Liu et al., 2019).

5.6.3 Others

In 2018, Liu et al. presented a study on the development of novel food formulations for 3D printing. This formulation is based on a complex mixture system consisting of egg white protein (EWP), gelatine, corn starch, and sucrose. According to the findings of the rheological and tribological studies, a 5.0 percent (w/w) EWP mixture could improve the hardness and springiness of gel samples. According to the findings, 3D printing based on the EWP complex system is a promising method for producing food objects with complex shapes.

K. Keerthana's (2020) research focuses on the development of fiber-enriched snacks made from mushrooms, an alternative food ingredient. For the first time, the printability of mushrooms is reported in this study. Their freeze-dried powder was discovered to be unprintable; however, the addition of wheat flour improves printability. The findings provide new insights into the use of sustainable alternative food sources for the preparation of healthy snacks, particularly when it comes to customization.

6. Additives and their Effects

Several additives have been mentioned in previous sections, ranging from common hydrocolloids like gums or starches to specific ones like sodium chloride in surimi gel (Wang et al., 2018). Their primary roles in food inks can be divided into two categories: those that improve printing outcomes and those that improve performance in other areas. The former is primarily concerned with texture modification in order to improve printability and quality (e.g., precision, surface smoothness), as well as stability in order to withstand post-processing when necessary. The latter type includes a broader range of benefits, such as improved health or nutrition, sustainability through the use of alternative food sources, and improved flavouring of food inks. For comparison purposes, when compared to traditional sources such as meat or fish, insects not only provide comparable high quality protein and nutrients, but also improve sustainability (e.g., more efficient feed-to-meat conversion rates, smaller land requirements, and reduced greenhouse gas production), though consumer acceptance remains a major barrier to its wider use (Food and Agriculture Organization of the United Nations 2019). 3D Food Printing could be used to create structures that look and taste appealing by incorporating insect protein into food inks, potentially encouraging otherwise resistant consumers to try these foods. However, additives for health or flavour may have an effect on the rheological or other properties of the ink, particularly when combined with other components or additives. This was demonstrated in a study by Kim et al., who investigated the effect of ions, sugars, or pH changes on ink viscosity using gels made with one of four hydrocolloids in combination with a food ingredient (salt, sucrose, or acetic acid), as these may be naturally present or added when seasoning food inks (Voon et al., 2019). Although xanthan and guar gum showed little change, indicating their resistance to such additions, locust bean gum and hydroxypropyl methylcellulose showed a general decrease in viscosity (Kim et al., 2018). Furthermore, as with chocolate, there may be maximum additive concentrations above which the ink is no longer printable (Hao et al., 2019).

7. Pre and Post Treatments

7.1 Pre-treatment of Food 3D Printing Materials

Materials with appropriate physical and chemical properties, such as particle size, fluidity, rheology, and mechanical properties, are critical for 3D printing. Initially, metals, ceramics, cells, tissues, and synthetic polymers were commonly used for 3D printing, which was done in organic solvents, crosslinking agents, and extreme conditions, and did not meet food safety standards. As a result, one of the major challenges in 3D printing food products is the selection of food-grade materials. Food materials should have adequate fluidity, viscosity, rapid recovery performance, and mechanical strength to easily flow out of the nozzle tip and be capable of self-supporting and maintaining shape after printing. As a result, pre-treatment of food ingredients to achieve these properties, such as proper fluidity, rapid recovery behaviour, and appropriate mechanical strength, is critical for successful printing. Food 3D printing materials are currently classified into three types: powder, gel system, and dough (He et al., 2019).

7.1.1 Preparation of Powder Materials

Powdered materials are widely used in the types of 3D printing discussed above, but each technique has different requirements for powder properties (Holland et al., 2018; Holland, Tuck et al., 2018; Liu et al., 2017). To meet the material requirements of various printing technologies, such as comminution and microencapsulation, it is frequently necessary to pre-treat the materials before printing (He et al., 2019).

7.1.1.1 Comminution

One of the most important goals of comminution is to produce powder with the desired particle size and flow ability. This is the most fundamental requirement for the material to flow out of the nozzle. Particles that are too large or too small have a negative impact on 3D printing. There are numerous methods for powder grinding, with ball mill treatment being one of the most common in food 3D printing. It crushes and mixes materials by using the impact of falling abrasive bodies (such as steel balls, goose hatching stones, and so on), the grinding action of the grinding body, and the inner wall of the ball mill (He et al., 2019).

7.1.1.2 Microencapsulation

Microencapsulation technology is a method of forming solid particles by encapsulating gases, solids, and liquids in a microcapsule (Fang et al., 2010). It is frequently used in the food industry to embed functional components such as polyphenols, enzymes, probiotics, functional oils, vitamins, minerals, and so on in capsules to protect against the effects of the environment (Borgogna et al., 2010; Nazzaro et al., 2012). Fused deposition manufacturing, inkjet printing, selective laser sintering, and binder jetting can only print a few powdered materials such as powdered sugar, chocolate powder, and some starches. The majority of the powders, however, are not directly used for food 3D printing. Before 3D printing, they must be mixed with appropriate solutions to form soft materials such as gel, mud, and dough (He et al., 2019).

7.1.2 Preparation of Gel

Depending on the dispersion medium, gels can be dry gels, hydrogels, aerogels, or organo-gels (Gulrez et al., 2011). Because many high molecular polymers in the food industry, such as polysaccharides, peptides, and proteins, are hydrophilic polymers, water is frequently used as a dispersion medium to form hydrogels ('gel') (He et al., 2019).

7.1.3 Dough

To successfully 3D print dough, it is generally required that the dough can be extruded smoothly and retain its structure and shape after 3D printing (Yang et al., 2018).

However, these two conditions can sometimes be contradictory: dough with low mechanical strength can be smoothly extruded, but shape stability is poor and easily collapses; dough with high mechanical strength cannot be extruded. As a result, the key to 3D printing success is to create dough with appropriate physicochemical properties. Because the cookie dough requires post-treatment (baking) after 3D printing, a traditional recipe may quickly deform during baking, affecting product quality (He et al., 2019).

7.2 Post-treatment of Food 3D Printing Materials

Following the completion of 3D printing, there may be some defects on the product's surface that necessitate post-processing operations to improve printing precision and shape stability. Post-processing techniques for 3D printed non-food products are relatively mature, and include support removal, model repair, polishing, surface painting, and coloration, among other things. However, the post-processing of 3D printed food products is entirely different, primarily consisting of drying, cooking, and cooling (He et al., 2019).

7.2.1 Drying

Freeze drying, oven drying, and vacuum microwave drying are the current drying methods used for post-processing 3D printed products.

Yang et al. (2018) created a juice gel for 3D printing by combining potato starch and concentrated mango juice in a ratio of 13.04:86.96. The printed product was vacuum microwave dried at 150 W for 4 minutes, and the shape stability was very well maintained, with up to 99.8 percent precision of the sample shape. Furthermore, the sensory quality of the product was satisfactory. According to the findings, vacuum microwave drying may be a promising method for preserving the shape stability (Figure13) and sensory quality of 3D printed food products. This method could be used to treat other 3D printed gel materials after they have been printed.

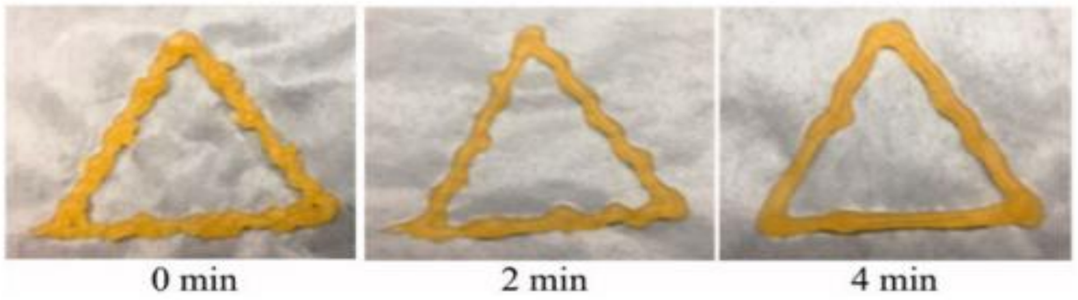

Figure 11: Representative photos of 3 D printed mango juice gel samples with MVD post-treatment 20 min after printing. Adapted from (Yang, Zhang, and Liu 2018).

Bianca C. Manigila et al. (2020) used dry heating technology (DHT) to process wheat starch for 2 and 4 hours at 130°C. For 4 hours, the ink based on starch DHT demonstrated the best printability and reproducibility. Another observation was that DHT increased the texture possibilities on the printed samples. These findings suggested that DHT is a viable process for improving the properties of wheat flour-based inks, making them suitable for 3D printing applications.

7.2.2 Rapid Cooling

Another method for effectively maintaining the structural stability of 3D printed products is rapid cooling.

Yang et al. (2018) quickly cooled the 3D printed dough samples in a low-temperature freezer (65° C) for 0, 5, and 10 minutes (Figure14). The findings revealed that without the frozen process, the baked dough collapsed prior to baking. However, after being fast frozen for 5-10 minutes, the baked dough had a very good shape and structure stability, particularly the sample that had been fast frozen for 10 minutes, which matched the structure of the initial design.

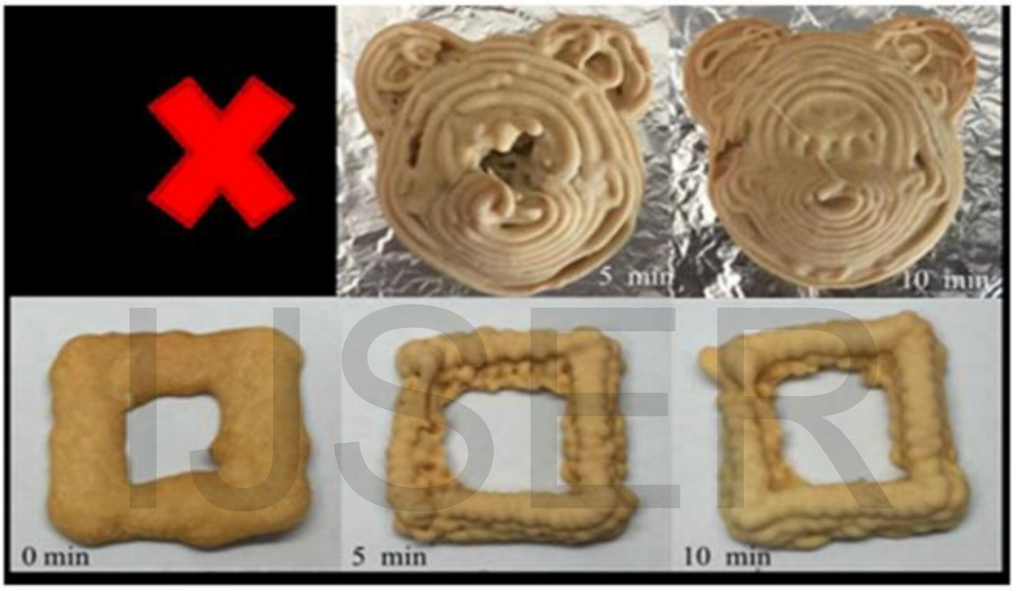

Figure 12: Effect of different fast cooling times on printed baking dough before baking. Adapted from (Yang, Zhang, Prakash, et al., 2018).

7.2.3 Cooking

7.2.3.1 Traditional Cooking

3D printing should be adaptable to traditional food processing techniques such as baking, steaming, frying, and other cooking methods in order to promote commercialization and consumer acceptance of 3D printed foods. The shape stability of printed products during cooking can be solved in two ways: formulation control and additives. In general, the formulation of 3D printed food is critical to shape stability during cooking (He et al., 2019). Severini et al., (2016) made the dough by combining 100 g wheat flour with 54 g distilled water and allowing it to rest for 30 minutes before 3D printing. After 15 minutes of baking at 200° C, the product shape accuracy was very close to the target structure (Figure15). However, the sample surface after baking was rough due to physical and chemical changes such as protein denaturation, dehydration, and starch gelatinization during baking. Furthermore, studies have shown that adding transglutaminase (0.5%) to the meat slurry allows the printed sample to retain shape stability (Lipton et al., 2010; Lipton et al., 2015). For example, when transglutaminase was added to scallop meat paste for 3D printing, the fried product retained the majority of its original shape with only minor deformation (Figure16) (Lipton et al., 2010; Lipton et al., 2015).

Figure 13: Shape of 3 D printed cereal-based samples before and after baking. Adapted from (Severini et al., 2016).

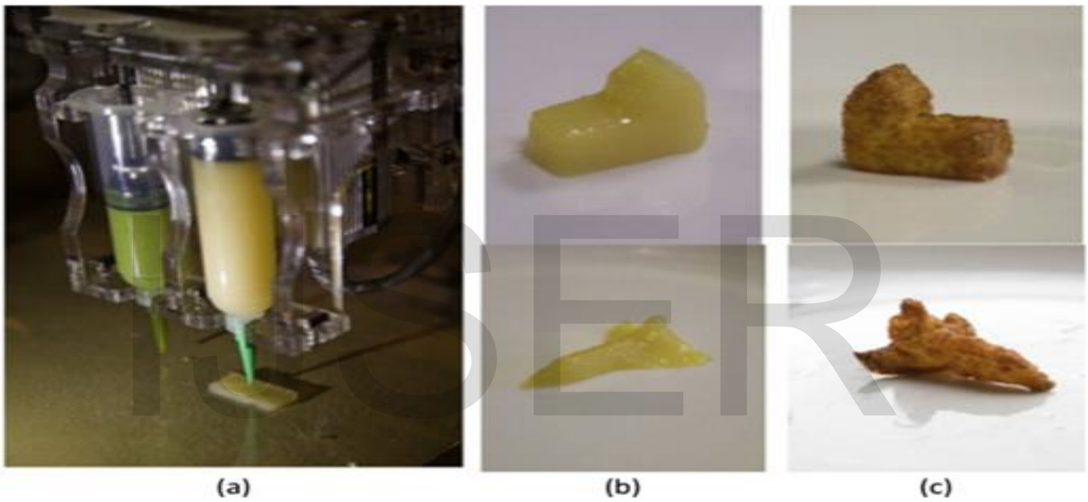

Figure 14: (a) 3 D printing of scallop meat; (b) and (c) are 3 D printed samples before and after frying, respectively. Adapted from (Lipton et al., 2015).

7.2.3.2 Modern Cooking Techniques

To achieve fresh taste and flavour, modern cooking techniques employ advanced technologies such as information technology and mechatronics (Fukuchi et al., 2012). Unlike traditional cooking methods (e.g., baking, heating, frying), which uniformly heat all raw materials, modern cooking techniques such as laser cooking can locally heat a portion of the raw materials in a short period of time, resulting in a different taste of food and eating experience (Fukuchi et al., 2012) Researchers have recently merged 3D printing with laser grilling to process food. Blutinger et al. (2018) printed the dough into cuboids with thicknesses of 3.0 mm, lengths of 30 mm, and widths of 30 mm. Two alternative heating processes were used to prepare the printed dough (baking and laser cooking). The results showed that the starch swelling and nutritional levels in the laser cooked and oven baked dough samples were fairly similar. By adjusting the laser cooking mode, one may regulate the texture of the finished cooked dish, making it more appealing to consumers. As a result, laser cooking is a promising post-processing approach for 3D-printed food products.

Furthermore, vacuum cooking (or "sous vide") is a contemporary cooking method. The meal is vacuum-packed in a heat-stable vacuum bag and heated for an extended period of time at a low temperature (Fukuchi et al., 2012; Lipton et al., 2015). In comparison to typical cooking methods, sous vide can inhibit the oxidation of specific chemicals to avoid off-flavors, prevent the volatilization of flavour and moisture during cooking, and improve food shelf life (Baldwin 2012).

8. Factors influencing 3D Food Printing

Food qualities, external experimental design, and parameters based on food elements are all factors that influence effective 3D Food Printing. Rheology, texture, ingredient concentration, and food ink composition are all important food attributes. 3D printing equipment, printing conditions, processing procedures, and print design are all examples of external impacts. Both food qualities and exterior components must be thoroughly considered and analysed for the most effective printing (Zhang et al., 2021).

8.1 Food Properties and Characterization

Food characteristics are a broad category that encompasses both food inks and their ingredients. Food content, composition, and structure all have an impact on critical components including rheology and texture. Printability is made up of rheology, texture, and their relative qualities. To begin, rheology can be employed as one approach to show printability and describe food ink input. As a result, texture is used to evaluate the 3D printing output and structural stability of the finished object (Zhang et al., 2021).

8.1.1 Rheology

Rheology may investigate the flow of a food system under controlled settings, allowing us to consider multiple components such as viscosity, shear stress, shear rate, loss modulus, storage modulus, and yield stress. Viscosity is a measurement of a material's capacity to resist force, which is a component of printability. Optimizing the material content or using additives can result in optimal viscosity. Food ink resists the force applied by the 3D printer when 3D printing, and optimal ink flow is essential to effectively produce an object. Furthermore, when 3D printing food, shear stress, shear rate, and yield stress must all be taken into account. The force that generates deformation is referred to as shear stress, and the rate at which deformation is produced is referred to as shear rate. Both principles have a direct impact on viscosity, which is critical in 3D printing. Viscosity falls when shear rate and shear stress increase due to increasing deformation imparted to the matrix, which rips down the resistance. Because of the reduced resistance, ink flows more easily through the extruder. Yield stress is the greatest amount of force that can be applied before irreversible deformation occurs. The interaction of shear rate, shear stress, and yield stress all contribute to the robustness and stability of a possible food ink. Shear modulus, another rheological component, is the ratio of shear stress to shear strain. Shear modulus greater than 2000 Pa is typically used to forecast the printability of a material (Kim et al., 2017).

8.1.2 Texture

Texture is a physical quality of food that relates to sensory and structural factors. Textural analysis is critical for understanding the structural stability of 3D food and identifying appropriate mouth feel and sensory features.

Hardness, resilience, cohesion, and springiness are also useful markers of structural integrity since they show the object's strength and ability to rebound from external stresses. The maximal force used prior to the food fracturing is defined as hardness, whilst springiness and resilience describe the rate and amount of recovery following deformation, respectively. Other factors, like as chewiness and adhesiveness, can provide information about the quality and mouth feel of 3D printed food (Zhang et al., 2021).

8.1.3 Composition

The food matrix's overall composition has a considerable impact on its printability. This involves both the macronutrient content and the use of additives. When compared to a heterogeneous system having many constituents, food products can be printed with varying levels of effectiveness when printed alone (Zhang et al., 2021).

8.1.4 Formula Optimization

Component ink ratios have a direct impact on parameters such as viscosity and texture, which must be tuned to produce flowable ink that sets after printing. Higher ingredient concentrations typically increase viscosity, which can either help or hinder the completed 3D printing process (Zhang et al., 2021).

8.1.5 Food Ink Structure

Food ink structure, in addition to content and formulation, can influence printability. Several methods, such as utilising gel-like emulsions and high internal phase emulsions, can be used to modify the structure of food ink (Liu, Meng et al., 2019; Li et al., 2020). Emulsions can be utilised to make semisolid, printable materials. Micro fluidization and Pickering emulsions were used to create gel-like emulsions (Zhang et al., 2021).

8.1.6 Printability

The capacity of a material to be successfully printed in a certain application is referred to as printability. Shear modulus, viscosity, hardness, and springiness are rheological and textural variables that can be used to forecast the material's printability (Zhang et al., 2021).

A comparative study (2019) demonstrates the printability of egg yolk (EY) and egg white (EW) with rice flour blend. Both EY and EW were discovered to be non-printable in their native forms. However, when EY and EW are combined with rice flour, they form a smooth paste with pseudoplastic properties, allowing the material to be printed (Arukiruthika et al., 2019).

8.2 Experimental and Processing Components

In addition to interior food components, experimental and processing components necessitate perfect design and execution, which necessitates fine-tuning printing process parameters and processing processes. Furthermore, for future reproducibility and success, experimental design and equipment require a better level of explanation.

In this section, we will look at how external effects and characteristics play a role in improving the 3D Food Printing process (Zhang et al., 2021).

8.2.1 Process and Mechanical Parameters

For successful 3D printing of food, process parameters such as temperature and mechanical parameters such as printing speed, layer height, nozzle height, and diameter must be optimised. Temperature is an important parameter since it influences rheological and textural qualities. Temperature, for example, frequently has an inverse connection with viscosity (Zhang et al., 2021).

For good results, 3D printing factors such as printing speed, layer height, nozzle height, and nozzle diameter must all be tuned. Printing speed is an important mechanical parameter that has a direct impact on structural stability. While faster printing rates can enhance efficiency, they have historically resulted in lower resolution prints and unstable structures due to imprecise extrusion, uneven layer creation, and the nozzle's inability to maintain the inputted speed (Hertfaeld et al., 2019; Severini, Derossi, et al., 2018; Derossi et al., 2018). Lower printing speed delays the printing process, resulting in structural instability since it is difficult for the layers to maintain themselves for a lengthy period of time.

Layer and nozzle height, in addition to printing speed, can have a considerable impact on the final structure of 3D printed food. When the layer height is excessively high, the structure has too few layers to support its own weight, resulting in low structural integrity. The distance between the nozzle and the printing surface is determined by nozzle height, which must be tuned for high resolution printing. Prints at lower nozzle heights may clump together, while prints at higher nozzle heights may spread too widely apart, resulting in lower accuracy. Similarly, when the nozzle diameter rises, the print becomes larger, resulting in lower printing precision and inappropriate weight distribution due to an imbalance in the shape's foundation (Zhang et al., 2021).

8.2.2 Processing Techniques

Pre and post processing processes such as cooling or heating by various means can have an impact on the success of food 3D printing. Cooking, baking, and freezing are examples of these procedures. Uncooked foods with low rigidity sag, increasing the distance between the nozzle and the extruded layer, resulting in uneven printing with poor structural integrity (Hertfaeld et al., 2019). Microwaving and freezing have been used as pre-processing methods.

IR heating has been employed as a post-processing step to increase the stiffness and structural stability of many culinary inks containing sesame paste, chicken paste, shrimp paste, and jujube jam.

There are several more approaches that have the potential to be used in 3D Food Printing. These methods include the use of dual extrusion as a pre-processing phase or the addition of extra ingredients after printing. Single extrusion feeds are commonly utilised in 3D food studies (Zhang et al., 2021).

8.2.3 Shapes

A shape in 3D printing is three-dimensional, which means it has a length, width, and height that together produce a volume. Maintaining the final 3D printed shape is critical for its identity and uniqueness. Changing the shape of food can have an effect on the 3D printing process by altering the final structural stability and printing time. Because printing speed is limited to maintain precision, shapes with infill and greater dimensions take longer to print. The shape can also have an impact on structural stability. Solid cylinders are a frequent test form that has been used in previous published work.

While irregular and non-uniform shapes add variety, they are also more likely to have poor structural stability due to uneven distribution than uniform shapes like cubes or cylinders. Shapes can be used to create one-of-a-kind things for printing, but they bring new issues due to uneven weight distribution (Zhang et al., 2021).

9. Nutritional and Functional Characteristics of 3D Printed Foods

9.1 Nutritional Characteristics

3D Food Printing can help with chewing and swallowing problems, often known as dysphagia. Dysphagia sufferers can only be served mashed meals, which are objectively unpleasant and sometimes nutritionally deficient. In reality, pureed and strained foods can be used as printable materials in 3D printing to recreate their original appearance or to generate new acceptable textures without diminishing their nutritional intake (Aguilera et al., 2016).

By varying nutrient concentrations, reducing or eliminating undesirable substances such as anti-nutritional factors, introducing healthy ingredients such as vitamins, fibres, and phytochemicals into tradition, and making the food shape and structure pleasant, 3D Food Printing can be used to produce customised meals for elderly people, athletes, pregnant women, and children (Roos et al., 2013).

3D Food Printing technology can also be used to alleviate the issue of food scarcity in impoverished countries. These outcomes can be obtained by creating novel food structures into which the essential nutrients can be put in the desired amounts, as well as by utilising unorthodox food sources.

Few studies have been conducted to study the effects of specific 3D printing techniques on the nutritional content of printed foods. It has been established, for example, that the use of hot air as a sintering source in selective sintering technology reduces the nutritious value of the finished product (Pityachaval et al., 2018).

9.2 Physicochemical Characterization

Understanding the physicochemical properties of 3D printed foods is critical for determining their safety and quality. More research is needed to assess the safety, quality, and viability of edible prototypes for commercial purposes before 3D Food Printing can expand its market reach. Additional traditional food science-based methodologies used to better characterise food that can be employed in 3D food systems to better understand their respective quality (and safety) are discussed further below (Zhang et al., 2021).

9.2.1 Moisture Content

Moisture content is the amount of water in a product and is typically expressed as a percentage or ratio. Water has an impact on various essential food qualities, including weight, viscosity, shelf life, texture, and microbiological safety (Isengard, 2001). Because moisture content has an impact on essential features of printability such as rheology and texture, its impact on printability should be researched further. The dry oven method is commonly used to determine moisture content in 3D food. Moisture content should be included as an experimental parameter in future 3D food research to increase rheological characteristics and printability (Zhang et al., 2021).

9.2.2 Water Activity

Water activity (aw) is the amount of water available for utilisation in chemical processes and microbiological activity (Sandulachi et al., 2012). Water activity can be measured using a variety of ways, including vapour pressure, osmotic pressure, freezing point depression, boiling point, dew point, and several other characteristics (Sandulachi et al., 2012; Syamaladevi et al., 2016). Water activity is another measure of shelf stability; a higher water activity (more than 0.85) indicates that microbial growth is more likely (Sandulachi et al., 2012).

Water activity assessment is critical for long-term shelf-life stability and microbiological safety if 3D printing food production is ramped up. 3D food must meet the same important water activity parameters as regular meals. Microbial safety issues can be considerably decreased by selecting and creating food inks and/or prints with lower water activity. However, decreased water activity poses its own set of issues. While reducing water activity can inhibit microbial growth, at a low aw (0.5), food becomes more prone to oxidation and rancidity, resulting in a decline in quality and shelf life (Barden, 2014). Reduced water activity can also lead to greater temperature resistance in a variety of microbial strains. Further heat treatment, which can result in quality and cosmetic difficulties, is one possible solution (Syamaladevi et al., 2016).

9.2.3 Colour

Because colour is the basis for consumers' initial evaluations of appearance and quality in food, colour measurement of 3D printed food is critical. There are few reports in the literature on the effect of 3D printing on colour.

In Dankar's (2018) work, for example, the colour parameters hue angle, brightness, and chroma were measured before to printing and after processing in a 3D printed potato puree application. The data revealed that the 3D printing method caused no change in colour, while additives such as agar and alginate caused declines in brightness values. All other data indicate that the 3D printing process may have an impact on the overall colour of food and, as a result, should be more widely evaluated as a tool to identify overall food quality, appeal, and as a preliminary indicator for comparison with traditional food products.

10. Microbiological Analysis

With recent technological developments in 3D Food Printing innovation and the potential for future commercialization, one significant difficulty that must be addressed is the development of a validated sanitation technique for microbial decontamination. Standard cleaning measures may not be successful due to the unique design of 3D printers. Microbial safety is one of the most important factors that is investigated and implemented in traditional food manufacturing. Foodborne infections caused by microorganisms such as bacteria, yeast, and mould can be caused by poor sanitation and storage techniques (Zhang et al., 2021).

Food contact surfaces must be cleaned to remove foreign contaminants such as soil before being sanitised to eliminate microbes. Surfactants and alkali products can be used as cleaning agents on food contact surfaces to dissolve food particles by denaturing proteins and lowering surface tension (Srey et al., 2013). Because of its ease of use, effectiveness, and low cost, sodium hypochlorite (bleach) is the most commonly used sanitizer for food contact surfaces (Meireles et al., 2016). Furthermore, various sanitation procedures like ultrasound, UV radiation, and chemicals like calcium lactate, electrolyzing oxidised water, and hydrogen peroxide could be used for 3D printing applications.

11. Safety of 3D Printed Foods

The safety of 3D printed food is not an easy task. It is related to the interface between 3D printer parts and food ingredients or food in production, and it may involve microbiological problems as well as the migration of leachable compounds.

Most food products must be heated prior to extrusion in order to form a flexible paste that can pass through the extrusion nozzle. Instead, the food structure must be chilled after printing to boost its mechanical strength. Heating and cooling procedures may increase the susceptibility of food to microbial development (Yang et al., 2017; Lipson et al., 2013).

Aside from the basic concept of food safety, special considerations must be considered when food is processed.

Aside from the basic concept of food safety, unique considerations must be considered when food is produced via 3D printing. As with conventional food equipment, the parts of a 3D printer that come into contact with foods must meet the following criteria: be safe under normal use conditions, durable, corrosion-resistant, non-absorbent, and easily cleanable; have easily cleanable surfaces; and have no breaks or sharp internal angles. Thus, the safety of printed food is dependent on the type of 3D printer used and the use of proper cleaning processes (Baiano et al., 2020).

12. Consumer’s Perceptions towards 3D Food Printing

Acceptability and pleasantness of 3D printed food are fascinating topics, and various research have been undertaken to identify the aspects that influence them.

Lupton and Turner (2016) conducted a qualitative study to evaluate consumer perceptions about 3D Food Printing. In March 2016, they conducted a four-day online focus group discussion with 30 Australians. Their research revealed a reluctance to accept 3D printed foods as safe and even edible due to unfamiliar elements such as: the processing of these foods using digital technology, which few people have directly experienced; the appearance of the 3D printed foods, which can be unusual or strange; and the ingredients used to fabricate these foods, which can include substances considered non-edible or unacceptable as foods in Western cultures (for example, insects, algae). Participants also voiced concerns about the healthiness of 3D printed foods due to their sugar, salt, fat, and preservative concentrations; the safety of the manufacturing settings; the presence of allergies; and the process's capacity to maintain nutrients. According to the authors, individuals would be more likely to like 3D printed foods if their appearance was acceptable and qualities such as quality, nutritional value, and freshness were assured and made transparent to consumers.

Brunner et al. (2018) conducted research on the establishment and evolution of consumer attitudes regarding 3D Food Printing and the associated food conceptions. The study included 260 German-speaking Swiss people who had little prior experience about 3D-printed food. The researchers discovered that providing individuals with specific information did not help them overcome their aversion to 3D printed foods.

Manstand and McSweeney evaluated consumer sentiments toward 3D printed foods in compared to conventional food goods (2019). To begin, they held two focus groups to determine what consumers believe about 3D Food Printing. The responses from the focus groups were then used to produce an online survey with 329 participants, all of whom were residents of Atlantic Canada. As a result of the survey, three consumer clusters were identified: the markedly interested cluster (140 participants), which consisted of people who wanted to learn more about 3D Food Printing and were convinced that this technology could reduce food costs while increasing benefits; the moderately interested cluster (98 participants), which consisted of people who were excited to try 3D printed foods; and the not interested cluster (91 participants), which consisted of people who were convinced that 3D printed foods were unacceptable and not safe.

13. Commercial and Economic Issues of 3D Food Printing

3D printing has been dubbed the "third industrial revolution" technology because it has the potential to drastically transform business models, alter the global economic order, relocate the location of fabrication, and affect supply networks (Garrett et al., 2014). In 2019, the total value of the 3D printing market was 6422.5 million USD, and it is predicted to reach 44520 million USD by the end of 2026. The predicted compound annual growth rate (CAGR) for 2021–2026 is 31.4 percent. 3D printing is a versatile technology that can be used by both small businesses and large corporations. In reality, the first can easily and quickly react to demand, whereas the second may streamline their supply chain by producing 3D printed spare parts and final goods in-house. 3D printing is also a relatively inexpensive technology because it does not necessitate significant infrastructure investment. Traditional manufacturing techniques, on the other hand, would be prohibitively expensive for underdeveloped countries due to the physical infrastructure and human resource needs. 3D printing is a promising technology for industrialised countries as well, because it provides opportunity for individual freelancers and small manufacturers (Fuldauer, 2020).

Applications of 3D printing to food may be economically disruptive as well as an opportunity for the development of company innovation strategies, according to strategic foresight. Indeed, it has the ability to alter production dynamics such as labour and material supply, consumer demand, supply chains, pricing competition, and government policy (Charlebois et al., 2018). 3D Food Printing has the potential to have a significant impact on the global economy, bridging the gap between small and large-scale firms and altering the food industry in a variety of ways. As an example, on-demand food production will make inventory management easier and less expensive, as well as enable for resource management optimization. In addition, food innovation and culinary inventiveness will grow (Flatworld Solutions, 2020). 3D Food Printing will alter the supply chain in the same way that additive manufacturing applications in other industries have.

Only a few studies have looked at the economic, social, and environmental ramifications of 3D Food Printing adoption. To address this gap, Dabbene et al. (2018) used the system thinking methodology to create an economic model capable of evaluating the effects of the introduction of additive manufacturing technology in the food market on small-batch production firms such as restaurants, bakeries, and confectionery, which appear to be the most promising companies for the adoption of this technology. The model was divided into three sections: suppliers of food capsules holding raw ingredients, new talents, and printer manufacturers. According to the model, as 3D printing technology becomes more widely used, the need for food capsules rises. As a result, manufacturing volumes grow, and, thanks to economies of scale enabled by the use of innovative processes or machinery, production costs and selling prices of food capsules reduce. At this stage, the supply chain shifts: suppliers of traditional raw materials will now serve both small-batch production enterprises (though their demand declines) and food capsule manufacturers (and their demand increases). The usage of 3D printers necessitates abilities such as computer-aided design and knowledge of food properties, which small-batch production enterprises lack.

Within the Magic Candy Factory experiment, the German company Katjes makes 3D printed candy (Lupton et al., 2017). La MIAM Factory is a Belgian company that specialises in 3D printing chocolate, either by developing 3D models or by using those supplied by customers (Stevenson, 2020).

14. 3D Printing and Food Packaging

3D printing has the potential to be a disruptive alternative to the more than 90% of plastics produced from virgin fossil feed supplies. According to a World Economic Forum research, "95 percent of the material value of plastic packaging (80–120 billion USD) is lost annually, with 32 percent of plastic packaging escaping from collection systems generating major expenditures and heavily contributing to greenhouse gas emissions" (The New Plastics Economy, 2016). 3D printing could be a viable way to make food packaging from recycled plastics (after operations such as cleaning, drying, shredding, and extruding), but it would necessitate strategic planning and processing systems that are different from the ones currently in use. In terms of energy effect, 3D printing has the ability to lower input costs and energy requirements while also shifting labour dynamics toward computerised manufacturing chains (Gebler et al., 2014).

3D printing is currently transforming food package design prototyping. Prototyping with earlier technologies can take months, whereas prototyping with 3D printing technology can be completed in weeks. Users can design and create their own unique packages using 3D printing. Because of its intrinsic characteristics, 3D printing may be used to design and manufacture unique shapes of food containers such as bottles, trays, and cups. 3D printing, for example, can be used to generate three-dimensional effects on package surfaces.

Another intriguing challenge is the use of 3D printing to create biodegradable packaging from agro-food waste. As an example, Nida et al., (2020) recently released a study on the optimization of printing settings for rice husk fractions of varying sizes. They discovered that adding guar gum helped to convert non-printable rice husk into a printable state, resulting in a 3D printed food box.

15. Current Legal Framework

3D-printed foods, like all other types of foods, may include allergies, be contaminated, and cause food poisoning if poorly produced or kept. Such issues are already governed by mandatory national, federal, and international standards.

Another intriguing legal problem involving 3D-printed meals is their labelling. 3D-printed foods may be classified as imitation foods and should be labelled differently than the foods from which they are inspired. Alternatively, if the cost of producing conventional meals exceeds the cost of 3D printing, and the conventional and printed foods are indistinguishable, the sale of 3D printed foods without specific labelling would be food fraud (Tran et al., 2016).

In the European Union, 3D printed foods could be deemed 'novel foods,' i.e. food that had not been consumed to a significant extent by humans prior to 15 May 1997, when the first Novel Food Regulation entered into force. The novel foods are governed by the new Novel Food Regulation 2283/2015. (Regulation 2283, 2001). The phrase "novel Food" simply refers to foods that are or have been historically consumed outside of the European Union, as well as foods made using new technology and manufacturing procedures. According to this Regulation, 'new foods' must be: safe for consumers; correctly labelled so that customers are not misled; and, if intended to replace existing meals, they must not differ in such a way that intake of the 'novel food' would be nutritionally unfavourable for the consumer.

The Food and Drug Regulations in Canada define "novel foods" as substances that do not have a history of safe use and have been manufactured, processed, preserved, or packed using a procedure that has not previously been applied to such foods. Because 3D printing is novel and has no track record of safety, it should be subjected to pre-market approval by Health Canada before being advertised or sold. Approval timeframes might range from 6 months to 2 years.

Food Printing methods, on the other hand, are based on the utilisation of food components to assemble food products. In a possible future scenario, 3D Food Printing could be used to generate new foods from chemical (non-food) molecules in order to address famines or food scarcity. In such a case, more particular regulation will be required, in addition to epidemiological studies on the short- and long-term impacts of such foods on the human body.

Furthermore, regardless of the application domains (foods, everyday objects, medical devices), the spread of 3D printing has resulted in an increase in unlawful product production, resulting in violations of intellectual property rights, patent law, and copyright law (Baiano, 2020).

16. Future Perspective of 3D Food Printing

3D Food Printing is a new field that has had limited success in food applications so far. 3D Food Printing costs are becoming competitive for smaller productions such as customised foods and personalised meals. This technology will enable the production of foods that are developed and manufactured to satisfy individual needs by controlling the amount of printing material or the nutritious content (Sun et al., 2018). In fact, 3D printed foods will meet the following requirements: meal composition tailored to individual diets; the utilisation of novel components; and sensory and functional food modification (Severini et al., 2018). When food printers are combined with nutrition models, users will be able to regulate their diet and precisely calculate calories by selecting component amount and type as well as the associated production parameters via an interface (Sun et al., 2018).

Long-duration space missions are another prospective area of expansion. NASA (National Aeronautics and Space Administration) is investigating the feasibility of producing 3D printed food systems in order to increase the duration of life support systems during space missions. These systems should be able to deliver foods with the following characteristics: safety, acceptability, diversity, nutritional stability, long shelf life, minimal use of spacecraft resources and crew time, and waste minimization (3D Printed Food System for Long Duration Space Missions). Similarly, 3D printed foods may be useful for feeding airline passengers and military personnel (Lupton, 2020). In the case of soldiers involved in combat operations, real-time sensors will be able to monitor their physiological status, transfer their biometric data to 3D food printers stationed near the battlefields, and transport the printed food to the warriors.

Another intriguing aspect of 3D Food Printing is the use of 3D food printers in the kitchens of fine dining establishments. Food Ink, a pop-up restaurant specialising in 3D printed food, debuted in 2016 with the promise of offering gourmet cuisine from "pixels to printer to plate." Food Ink uses the Flow multi-material 3D printer to create its dishes (3D Printing and the Future of Supply Chains, 2016). Another business imagined a restaurant where the entire service (tables, cutlery, and food) would be 3D printed. Other restaurants throughout the world are incorporating 3D printed dishes into their menus. Some components of molecular gastronomy, such as the use of sodium alginate to generate liquid jellification, can be applied in digital production methods based on extrusion. The end result is a new science known as 'digital gastronomy.'

Despite extensive research in the 3D Food Printing field, there are still many challenges to the technology's adoption and application. Food printing, for example, is an underdeveloped area in Europe due to a shortage of highly specialised personnel, equipment manufacturers, and sufficient raw materials (3D Printing and the Future of Supply Chains, 2016). Furthermore, there are other problems that mass food customization via 3D printing must encounter and overcome. They are as follows: a better understanding of the chemical, physical, and biological properties of the material to print; the development of more performing food inks; an understanding of the relationships between the properties of the feedstock materials and those of the printed food; the development of new feeding mechanisms (for example, a cooling device) capable of shortening the time required to create the rigid structure capable of supporting the overlying layers; and, last but not least, For all of these reasons, 3D printing technology cannot replace traditional food production, but it might be viewed as an intriguing alternative to make customised foods for prototypes or limited productions (Le-Bail et al., 2020).

17. Conclusion

3D Food Printing is a novel and promising agro-food technology with the ability to alter the design, nutrition, and content of foods. Many unique and sophisticated items have been printed, including butterflies, Mickey Mouse, apples, and pyramids. There are numerous qualities that necessitate further information regarding 3D Food Printing. As a result, this review evaluates the previous scope of study while also identifying areas for development in 3D Food Printing. Again, it is vital to regain consumer trust by explaining the nature of these items and providing information about their safety via more explanatory labelling systems.

Finally, some organisations have begun to investigate the potential of 4D printing, which involves integrating additional materials within the layers of 3D printed items that change shape or colour when activated by an external stimuli such as water, acid solutions, or temperature.

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