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Review

Three-Dimensional Printing Applications in Food Industry

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Abstract: Three-dimensional (3D) printing has gained increasing attention for its unique ability to create geometrically complex designs, which not only can be used for mass manufacturing but also has environmental and economic benefits. Additionally, as far as the food industry is concerned, this emerging technology has the potential to personalize products in terms of shape and/or nutritional requirements creating a wide range of food items with specially made shapes, colors, textures, tastes, and even nutrition using suitable raw materials/food components. In the future, 3D food printing could make complex food models with special interior design. This review gives attention to intelligent food packaging. Point-of-use machinery for manufacturing smart packaging, with a 3D printing approach, enables the use of multifunctional smart components and is self-identifying and highly sensitive, while using biocompatible non-toxic materials is cheaper than traditional manufacturing methods. This would create smart food packaging and in turn prevent customers from purchasing unsuitable food and thus reduce food waste. Future studies can make the process more compatible and efficient with a wide variety of materials that could be used to improve the 3D printing process.

Keywords: 3D printing; food technology; food packaging; ecofriendly

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1. Introduction

Three-dimensional (3D) printing or additive manufacturing is a technology that has been studied in the scientific community and applied in many fields for almost forty years, but in the last ten years, there has been a huge interest and increase in popularity [1]. All manufacturing processes rely on the innate tendency or inspiration of some people observing a natural process (or object) to create a production process (or product) that would function in the same way. This trend has been fueled by the extraordinary capabilities of 3D printing and has sparked a new era of innovation thanks to its accessibility, customization, efficiency, and affordability. The digital revolution has created a data-rich environment facilitating the ability to transform digital data into innovative physical products through the use of new technologies such as 3D printing [2].

Three-dimensional printing has gained increasing attention for its distinctive ability to create geometrically complex designs, which can be applied for mass manufacturing while having environmental and economic benefits. This technology enables transformations in material composition and structure through a printed object. Depth-changing patterns, porous films, thin films, regular gratings, fine-diameter lines, and dots can be formed with multiple heterogeneity or continuity in functionally planar patterns. Various parameters can be adjusted such as surface roughness, shape optimizations, bubble thickness, and novel topology. Throughout the variety of 3D printing, a few fabrication mechanisms provide discrete control between layers (for example, vat polymerization and powder bed fusion) or within a layer (for example, ink writing and material extrusion), and few platforms can enable point-by-point material variants (for example, binder jetting and material jetting) [3].

Three-dimensional printing technology in food industries offers new possibilities to make food more nutritious, more accessible, or more appealing. This emerging technology makes it easier than ever to create personalized meals based on one's caloric intake and specific nutritional needs. Three-dimensional printing can be used to create food products by controlling nutrition contents applicable to each individual or specific consumer group, including young and elderly people, pregnant women, and athletes. Via 3D food printing, a new opportunity is offered for people with exact nutritional benefits, for example, patients or the elderly who have problems swallowing or eating [4].

As food additives are necessary to improve the printability of food, their use has expanded significantly [5]. The knowledge of the effects of food additives on food texture and shape can improve the design and production of personalized meals by reducing reliance on trial-and-error design processes for designing novel food products [4]. Food-grade additives could be used to enhance the proper thickness of a liquid, i.e., a natural substance, and printability. Hydrocolloids such as sugars, starches, proteins, and carbohydrates could be used to enhance printability [6].

A disruptive alternative, 3D printing could account for over ninety percent of plastics made from pure scraps of life-form raw materials. By reusing plastics (after operations such as extruding, shredding, drying, and cleaning), 3D printing could be used advantageously to make excellent food packaging. The only limitation is the necessity for new tactical processing and planning systems different from the existing ones. It has the potential to change working conditions and reduce energy input in digitized production chains in terms of energy impact [7].

Synthetic plastics are convenient and versatile materials. They can be utilized to make a variety of helpful products, but the excessive use of plastic damages the environment irreparably. As a result, great efforts have been made toward the advancement of more environmentally friendly and biodegradable materials. Starch seems like a suitable alternative to synthetic polymers among the various alternatives. This is due to the following characteristics: good film-forming properties, high biocompatibility, complete biodegradability, low cost, and abundant supply. However, to improve the practical use of starch-based materials, there are some technical difficulties that need to be overcome [8].

Three-dimensional printing has been also involved in packaging fields. There are many forms of innovative packaging, such as unique shapes and die-cuts, sensory packages, and smart packages that have been constructed with this method [9]. The feasibility and efficiency of coaxial 3D printing were used to build smart food-packaging systems to monitor the environmental conditions and quality of packaged food in real time to meet the ever-increasing consumer demand for safe food [10]. The use of 3D printing is also an interesting challenge for the creation of biodegradable packaging starting from agro-food waste in terms of the best printing conditions, such as tiny pieces of rice husk of various dimensions. The addition of guar gum was useful in changing the non-printable rice husk into a printable type, resulting in a 3D-printed box for food use [11].

2. Advantages and Disadvantages of 3D Printing

A 3D printer generally works identically to a standard inkjet printer; however, instead of printing layers of ink onto paper, it uses materials to make a three-dimensional object. This method is completely innovative and has the potential to significantly replace traditional manufacturing methods due to many distinct advantages which are summarized in the following points [12,13]:

- Three-dimensional printers leave a smaller environmental footprint than conventional manufacturing systems. Relatively limited waste is produced due to the high recyclability of the raw materials and the fact that no mechanical processing is required. The raw materials can be reused over the course of several production runs.
- Three-dimensional printing can adapt physical morphologies accurately (for example, the orientation of constitute building blocks).

- The use and selective deposition of a wide range of multifunctional materials (polymers, ceramics, composites, food powders) during printing a product can be purposely designed.
- The restrictions that traditional manufacturing normally imposes do not exist in 3D printing. It enables complex dimensions and geometries in a wide range of quantities (for example, undercuts, substructures, and topologies).
- Three-dimensional printing offers greater design flexibility and improved manufacturing adaptability (for example, foams, lattices, and cells). The only barrier is the minimum project size that can be accurately printed.
- The procedure of copying the original is easier and faster (for example, fewer requirements are needed for mold, die, or component tools). Three-dimensional structures are reproducible and impossible to make by hand alone.
- With conventional methods, parts are constructed in several steps while 3D printing manufactures parts in a single step, significantly amplifying the efficiency from design to production.
- The ability to verify a design by printing a production-ready prototype before financing expensive construction equipment (e.g., molds, accessories, and tooling) minimizes risk and financial loss during the prototyping process.
- Most 3D printers do not require highly skilled staff making labor costs much lower than traditional manufacturing. The machine works in a fully automated way to produce the part according to the file uploaded by a single operator.

As with any other process, there are also limitations and disadvantages of 3D printing technology that should be mentioned [14,15]:

- The rheological and mechanical properties of most raw materials must be modified through the addition of flow enhancers to obtain an extrudable paste-like material.
- Another drawback of 3D printing is the composite material itself. The different chemical properties and storage requirements (temperature and humidity) of each component and how they are affected by the presence of the remaining components must be considered in combination when designing and piloting the 3D printing method.
- Some raw materials may be easy to extrude but cannot withstand a 3D structure, as is the case with vegetables which have a high water content.
- A lot of 3D products do not have the ability to withstand post-processing operations without losing the 3D intricate design due to cooking loss/shrinkage.
- Conventional techniques are still much faster than 3D printing. For example, a normal production line can produce up to nine thousand kilos of pasta per hour, while the printer can currently produce about four kilos per day [16].
- Three-dimensional printers currently have small print chambers which restrict the size of products that can be printed.
- Another potential problem with 3D printing is directly related to the type of machine or process used. If a printer has lower tolerance, the final product may differ from the original design. This can be fixed in post-processing but will have a negative impact on production time and cost.
- The shelf life of 3D-printed food products is limited to a few hours, while the corresponding products of traditional methods can be consumed even after 9–12 months.

3. Evolution of 3D Printing

In recent years, 3D printing has attracted global interest as an emerging process of manufacturing complex and innovative 3D objects that find application in various fields such as healthcare, biomedical and mechanical engineering, aerospace, architecture, education, consumer goods industry, textile industry, and food industry. New methods and advancements are regularly created to overcome the obstacles that arise when applying it to each field. To build a physical model, 3D printing technology has been used directly from 3D modeling without any mold assistance. This technology more than twice has been used to manufacture an intricate and complex part that was required in each industry.

More and more, the unprecedented properties and outstanding advantages of 3D printing have attracted the interest of food researchers at the laboratory and industrial levels worldwide. When we talk about 3D printing in the food industry, we are referring to the process of creating food using 3D printing technology. This technology makes use of food ingredients that are relatively viscous to confirm that, after extrusion, the material will retain the desired shape and appearance. In the future, 3D food printing could make complex food models with special interior design. The technique includes selective laser spraying and sintering (liquid binding) as well as extrusion-based printing. Food materials such as chocolate, gelatin, and sugar are used to create layer-based patterns [5,17]. Every food is a different intricate system consisting of several components. These components interact with each other during processing and form the microstructures that determine the characteristics of food such as shape, color, texture, taste, and stability [6].

Three-dimensional printing is defined as a technical operation in which the final product of a precise geometric shape is formed layer by layer by depositing material such as plastic, resins, graphite, carbon fiber, ceramics, paper, or food on a platform. It applies the same specification and layout as that of the three-dimensional computer-aided design (CAD) model or scanned model of the product. Before the printing process, the model is saved as an STL (Stereolithography) file, which is then converted into a geometric code, popularly known as a G-code. This is a programming language that the printer "understands", and it controls actions such as where the print head goes, what the temperature of the extruder will be, when to pause, how fast the print head moves, and more. The G-code controls the movement of the printer head which is responsible for the release of material in the 3D printer. The movement takes place in three axes, X, Y, and Z—left to right, front to back, and up and down, respectively—as the object is being printed depending on the information embedded in the G-code. This pattern information is separated layer by layer and finally assembled during printing according to a defined 3D pattern [7].

Three-dimensional printing has no resemblance to other manufacturing processes. A major technical advantage of 3D printing is the ability to switch from conventional printing to new production technologies. This technique ensures the fast design and cost-effective on-demand production of prototypes and molds that can be used to manufacture strong yet lightweight parts with complex geometry. It is an automated production process carried out in one step using a single piece of equipment, needing no additional accessories and requiring little or no human supervision. Only the materials needed for the part itself are needed, and the 3D printer has the ability itself to create multi-component systems with minimal waste [8].

The method of 3D printing is a relatively recent discovery. Its birth was placed in the early 1980s, but it became more widely known at the beginning of the following decade. Professor Hideo Kodama from Japan is considered the first to develop a rapid prototyping method, and Charles (Chuck) Hull of 3D Systems from California is the one who invented the stereolithography equipment. Kodama of the Municipal Industrial Research Institute in Nagoya, Japan, at the end of the 1980s developed the earliest 3D printing manufacturing when he invented two additive methods for fabricating 3D models. Kodama's early work in laser-cured-resin rapid prototyping was completed in 1981. His invention was expanded upon over the next three decades, with the introduction of stereolithography in 1984. Chuck Hull invented the first 3D printer in 1987, which used the stereolithography process. Its use was based on a method of creating solid objects by layering materials using a computer-generated design. This was followed by expansions such as selective laser sintering (SLS) and fused deposition modeling (FDM). Both methods had their first approved patents filed in 1988. The cost of 3D printers built over the next decade was quite high and began to drop dramatically when the patents expired in 2009. This allowed many more users to experience the new achievement of technology [11].

The rapid prototyping (RP) technology grew into additive manufacturing (AM). AM is a more advanced type and can create complex 3D objects layer by layer, either using plastic polymer filaments and metal or, in the recent past, edible materials such as chocolate and sugar. Specialized food 3D printers are designed specifically for the food industry, and 3D printing is beginning to be applied to food production. Apart from RP, according to [18], there are some broadly used technologies in AM such as selective laser sintering (SLS), fused deposition modeling (FDM), and stereolithography (SL). In addition, there are several research studies and plans in 3D food printing in a large number of areas, according to [4]. These studies range from the advancement of conceptual and inspirational thoughts to the in-depth understanding of material goods.

The most advanced 3D food printer allows the customer to choose one of the preloaded recipes on board and also allows the user to remotely design their food on their computers, phones, or certain IOT gadgets [19]. A plan to achieve 3D food printing is constructed from inkjet-printing food materials and expulsion-based printing, such as gelatin and sugar used with chocolate [20]. Being founded with regard to the rheological calculations of their stiffness gives a large enhancement to the dimensional soundness of 3D food objects [21]. Issues such as the mechanical properties of 3D printing and computational micro-design should be addressed. The above will help us enhance the quality of food printing [22]. Three-dimensional printing, while advantageous, will have to overcome some obstacles, the first of which is speed. It requires ingredients to cool first, and it uses different patterns from what food printers often print. Furthermore, customers need time to get used to the concept of food printers and not confuse it with synthetic food.

Tan et al. evaluated fourteen different food printing systems (Figure 1) based on their advantages (i.e., easy cartridge refilling, continuous operation, self-cleaning, temperature control, layer correction) and limitations in use (i.e., low capacity, small printing area, time-consuming, no heating ability) [23].

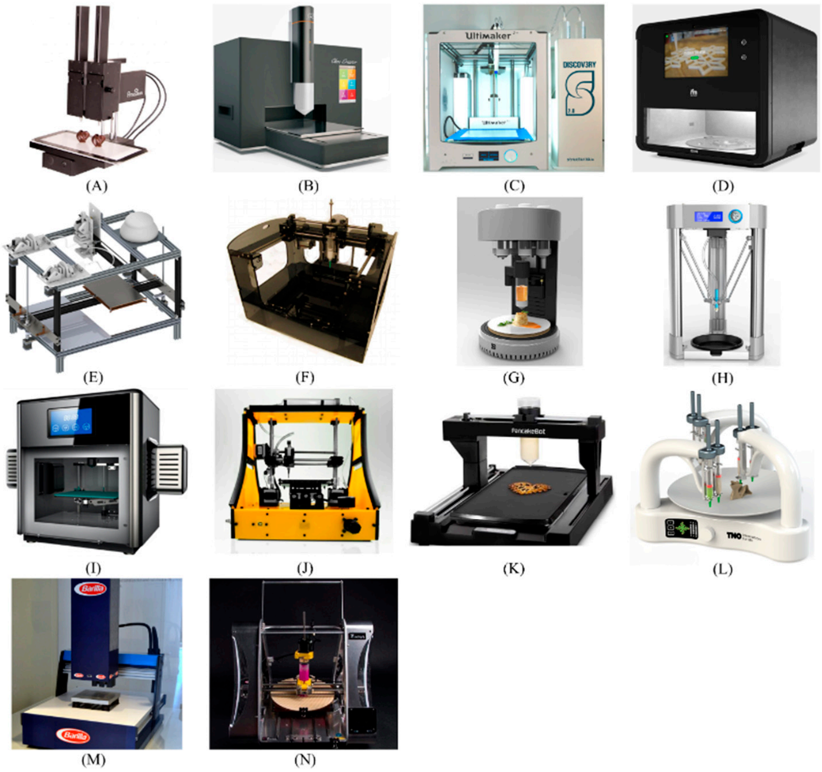

Figure 1. Various pictures of 3D food printing systems. (**A**) Procusini 3.0 Dual, (**B**) Choc Creator V2.0 Plus, (**C**) Discov3ry 2.0 paste extruder paired with the Ultimaker 2+, (**D**) Foodini, (**E**) F3D, (**F**) Fab@Home, (**G**) Sanna, (**H**) Model F5, (**I**) QiaoKe chocolate printer, (**J**) BeeHex printer, (**K**) PancakeBot 2.0, (**L**) The 3D everything concept printer, (**M**) Barilla 3D pasta printer, (**N**) Zmorph 2.0 VX multitool 3D printer. Picture taken from an article by Tan et al. [23].

The authors summarized the characteristics of the ideal food printer in terms of operational efficiency, operational speed, food safety, and functionality and concluded that printer development should be designed with a specific application in mind.

4. Three-Dimensional Printing Processes

Three-dimensional printing processes have been generally categorized into seven groups by ISO/ASTM 52900 additive manufacturing (general principles) terminology. All forms of 3D printing fall into one of the following process types based on the various related technologies that have been studied in each group: (**a**) *binder jetting* (powder bed and inkjet heat, plaster-based 3D printing), (**b**) *direct energy deposition* (laser metal deposition), (**c**) *material extrusion* (fused deposition modeling), (**d**) *material jetting* (multijet modeling), (**e**) *powder bed fusion* (electron beam melting, selective laser sintering, selective heat sintering), (**f**) *sheet lamination* (laminate object manufacturing, ultrasonic consolidation), and (**g**) *vat polymerization* (stereolithography, digital light processing) [24]. This classification was only applicable to non-food prints. An extensive study of recent publications in the field of 3D printing shows that 3DP techniques applied to food production can be classified into four main groups [20]: (1) selective laser sintering (SLS); (2) hot air sintering (HAS); (3) liquid binding; and (4) the extrusion method. The last one is the method that most research groups/labs around the world use [7]. The main methods used in 3D food printing will be discussed next.

4.1. Selective Laser Sintering (SLS)

Selective laser sintering (SLS) is an additive manufacturing process that belongs to the powder bed fusion group. This method can be applied to create multiple layers of the food matrix where each layer contains different food material components. It uses a laser as the power and heat source to sinter powdered material. A presentation of this technology is depicted in Figure 2.

Firstly, a layer of powder is deposited on a build platform and leveled by a roller or blade. Secondly, powder particles are locally fused by a laser which is directed automatically at points predetermined by a 3D model. The next step after the first layer reaches a certain thickness is to lower the platform to start depositing the second layer and so on until all layers are deposited and the final 3D object is created [25]. Examples of 3D printing constructs based on SLS technology are shown in Figure 3. The successful printing of a product is affected and dependent on raw material properties such as the particle size and shape, density, coarseness, porosity, and texture of the powder. Furthermore, the arrangement of the particles and their behavior in relation to temperature greatly affect the flowability of the powder. SLS has advantages over other techniques for processing complex macroscopic designs because the unsintered powder provides the necessary support in designs that include vacancies and protrusions while supplementary support structures must be printed in extrusion printing, the most used method for the 3D printing of food [26].

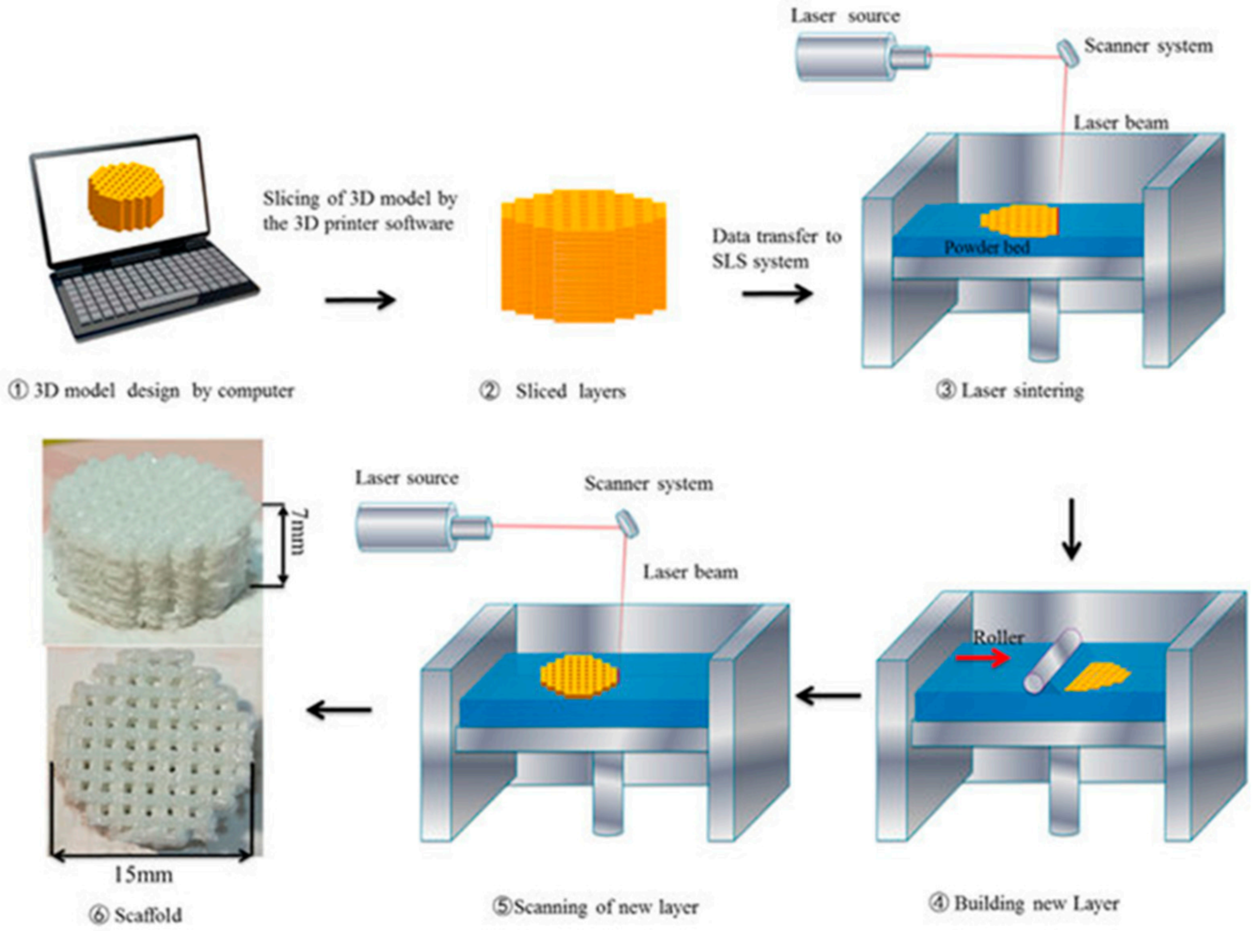

Figure 2. Simplified schematic presentation of the SLS process. Picture taken from an article by Qin et al. [27].

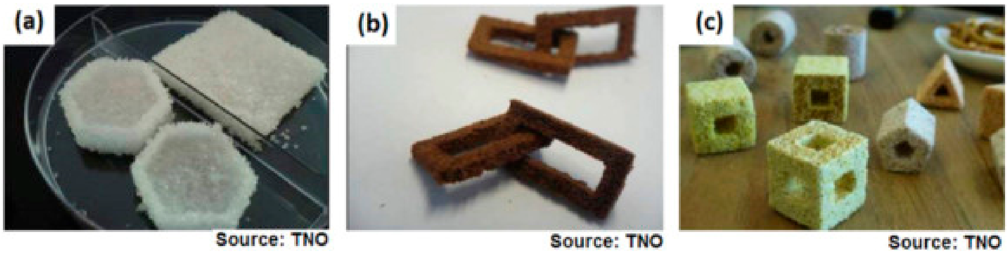

Figure 3. Examples of 3D printing technique based on SLS technology: (**a**) sugar, (**b**) Nesquik, and (**c**) curry cube, paprika pyramid, cinnamon cylinder, and pepernoot pentagon constructs. Picture taken from an article by Godoi et al. [25].

4.2. Hot Air Sintering (HAS)

In this technique, the raw material is mixed under the influence of a low speed and regulated flow of hot air passing through a narrow beam, thus creating the first two-dimensional (2D) form of a homogeneous powder. At first, the powder bed is slightly lowered, a thin flat layer of particles is spread to the top of the bed, and the fused powder is selectively fused in the new layer. The newly printed 2D object is actually merged with any overlapping connected regions in the first layer. By repeating this procedure, a 3D object is progressively formed. When the construction of the 3D structure is completed, the bed returns to its original position, the molded product is separated, and the unused raw material (powder) is not discarded but retained to be used in the next manufacturing cycle [25].

This method has the advantage that printing is completed in less time compared to other methods because the hot air is applied directly to the powder material without requiring any movement of the printer bed. The same applies to the SLS method too. These two methods require no post-curing and use confined auxiliary means. On the other hand, the HAS method cannot be used for printing fresh food ingredients since it is only limited to powder materials [20]. Moreover, in this method, the final step of post-processing may be necessary to remove the remaining quantity of food powder and to improve the surface roughness and mechanical properties (strength and ductility) of raw material [28].

4.3. Liquid Binding

During this method, the printer head ejects a liquid binder (ink) which is precisely deposited onto a thin layer of powder following a cut 2D profile created by a 3D computer model. The binder joins adjacent particles, thus creating a three-dimensional structure. Cohesion is due to different mechanisms such as sintering, chemical reaction, and the formation of liquid bridges [24]. The liquid (such as flavor liquids and colors) is vital in this method as it binds certain areas of a given layer of the powdered material (such as sugar) [18]. A diagram of this technique is depicted in Figure 4. As shown in the figure, there are two chambers: one is filled with construction material powder which is fed into the second chamber by a leveling roller, and the second chamber is used to implement the 3D model. The 3D model is made by gluing the building material into powder using the liquid binder. The powder is poured on top of the building platform which has been lowered to a depth equal to the height of the first layer to be created. The liquid adhesive binder is supplied through an inkjet print head at a controlled rate while the head moves along the horizontal plane. After the first layer is spread, the platform is lowered again to a depth equal to the height of the second layer, and more powder is rolled out from the first chamber. All successive layers are built in a similar way.

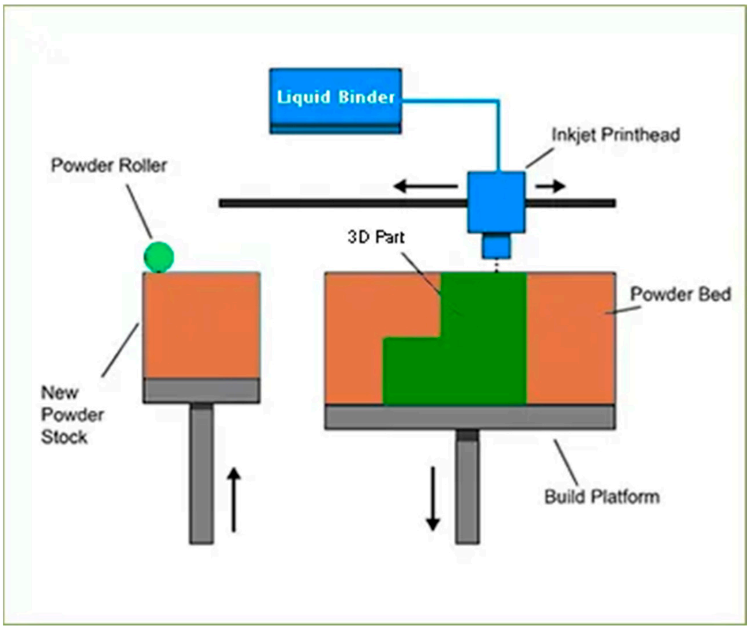

Figure 4. Simplified schematic presentation of the liquid binding process. Picture taken from an article by Nikhil [29].

The advantages of binder jet 3D printing compared to other 3D printing technologies are mainly the ability to create products with high solid content, manufacturing with flexible material compositions, and easy color printing on different parts. The greatest progress of this technology is the short printing time to produce a 3D object [30]. The disadvantage of this technique is the poor smoothness of the printed food, which requires post-treatment operations such as high-temperature curing. The food, which is usually fabricated food, is made of sugar and starch powders [31].

The feasibility of binder jet 3D printing, instead of the most commonly used extrusion-based method, to create protein-rich foods using calcium caseinate (CaCas) powder was investigated by Zhu et al. [30]. They successfully printed foods using powder mixtures of CaCas, starch, and medium-chain triglyceride (MCT) powder. The addition of native starch to calcium caseinate enhanced printability during powder bed printing. Printed foods with different texture properties were obtained by changing the ingredients, binder composition, and post-treatment by heating. By changing the deposited binder amount and CaCas content in the dry powder mixtures, food textures obtained ranged from crumbly to springy. According to the authors, this technology provides new opportunities for the preparation of personalized protein-rich healthy snacks, such as protein bars having a springy wine-gum-like texture.

4.4. Extrusion Method

Extrusion-based food printing is the most popular method used in food printing due to its simplicity and the fact that extrusion is commonly used in conventional food processes [32]. This technique can be further classified into room-temperature extrusion, fused deposition manufacturing, and gel-forming extrusion, according to different printing material states [31]. In extrusion-based 3D printing, the ability of the material to be squeezed out of the nozzle in a continuous manner (called extrudability) and the stability of the printed shape are the two main concerns [33]. Extrudability refers to the initiation of flow and the formation of a stable filament during printing, while stability relates to shape fidelity and shape reservation over time after printing.

The process has been outlined to follow the steps below [34]. The first step involves designing a virtual 3D model. This model is translated into individual layer patterns and ultimately generates machine codes for printing (second step). The third step involves selecting a food recipe, and during the fourth step, the actual printing starts. The extruded material is dispensed either by moving the nozzle over an automatic platform or by moving the platform under the nozzle to form a layer. This platform can be heated for extra adhesion. Once the first layer is completed, the extruder and the platform are parted away, and the second layer can then be directly deposited onto the growing object. One layer is deposited on top of a previous layer until the object's fabrication is complete (fifth step). Finally, the food after deposition can undergo cooking (baking, frying, or drying). A schematic presentation of the extrusion process is illustrated in Figure 5. The final step, or post-processing, may be needed to maintain the shape of the product, assure microbiological safety, extend shelf life, or make it aesthetically acceptable to consumers [35].

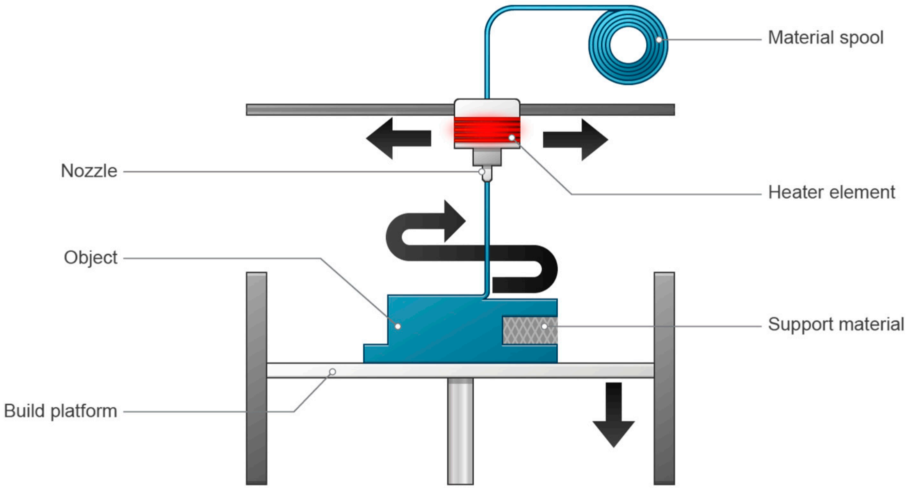

Figure 5. Simplified schematic presentation of extrusion-based printing. Picture available online [36].

A big challenge to 3D-printed food is to maintain the shape stability during cooking. There are two main ways to solve this problem: formulation control and additives. For example, it has been shown that the addition of transglutaminase to the scallop meat paste allowed the printed sample to remain stable, and the fried product retained most of the original shape (Figure 6), with very thin areas of deformation [31].

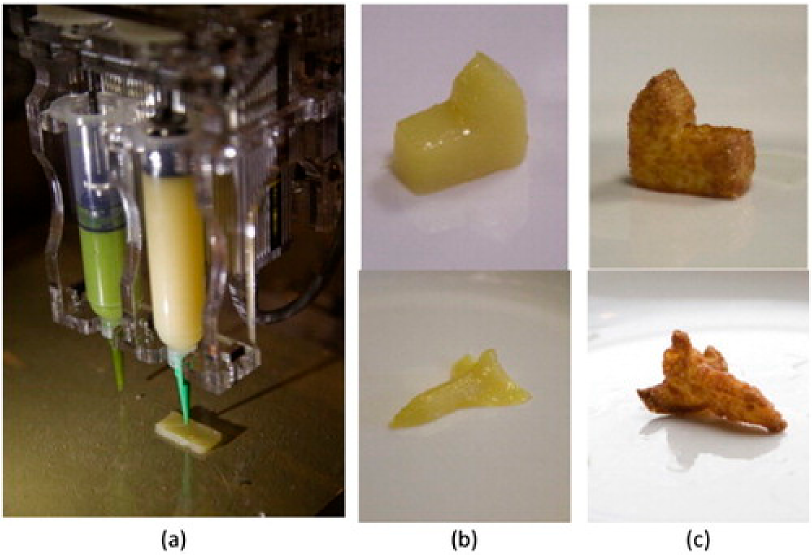

Figure 6. (**a**) Three-dimensional printing of scallop meat; (**b**) 3D-printed samples before frying; and (**c**) 3D-printed samples after frying. Picture taken from an article by He et al. [31].

Another study showed that the viscosity and mechanical properties of lemon juice gel differ with the addition of various types of starches (potato starch, sweet potato starch, wheat starch, and corn starch). As shown in Figure 7, 15% potato starch provided a smooth surface, fewer defects, and no compressed deformation on the printed object while less or more of this starch resulted in low and high viscosity, respectively, and thus the final shape was not successful [37].

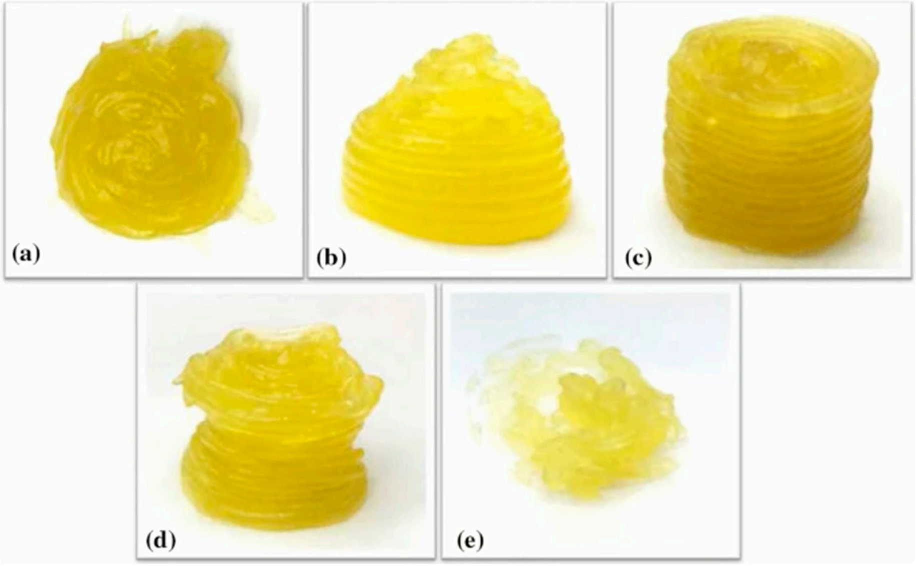

Figure 7. Various structural designs of 3D-printed lemon juice gel product at varying potato starch percentages: (**a**) 10%, (**b**) 12.5%, (**c**) 15%, (**d**) 17.5%, (**e**) 20%. Picture taken from an article by Waghmare et al. [37].

Kim et al. investigated the printability of vegetable (broccoli, spinach, and carrot) inks produced using various hydrocolloids (xanthan gum, guar gum, locust bean gum, and hydroxypropyl methylcellulose) with different powder contents (10% and 30%). When the powder content was increased to 30%, the hydrocolloid with the lowest water hydration capacity, hydroxypropyl methylcellulose, showed the greatest differences in rheology and printability when different vegetable sources were used [5]. The results are shown in Figure 8.

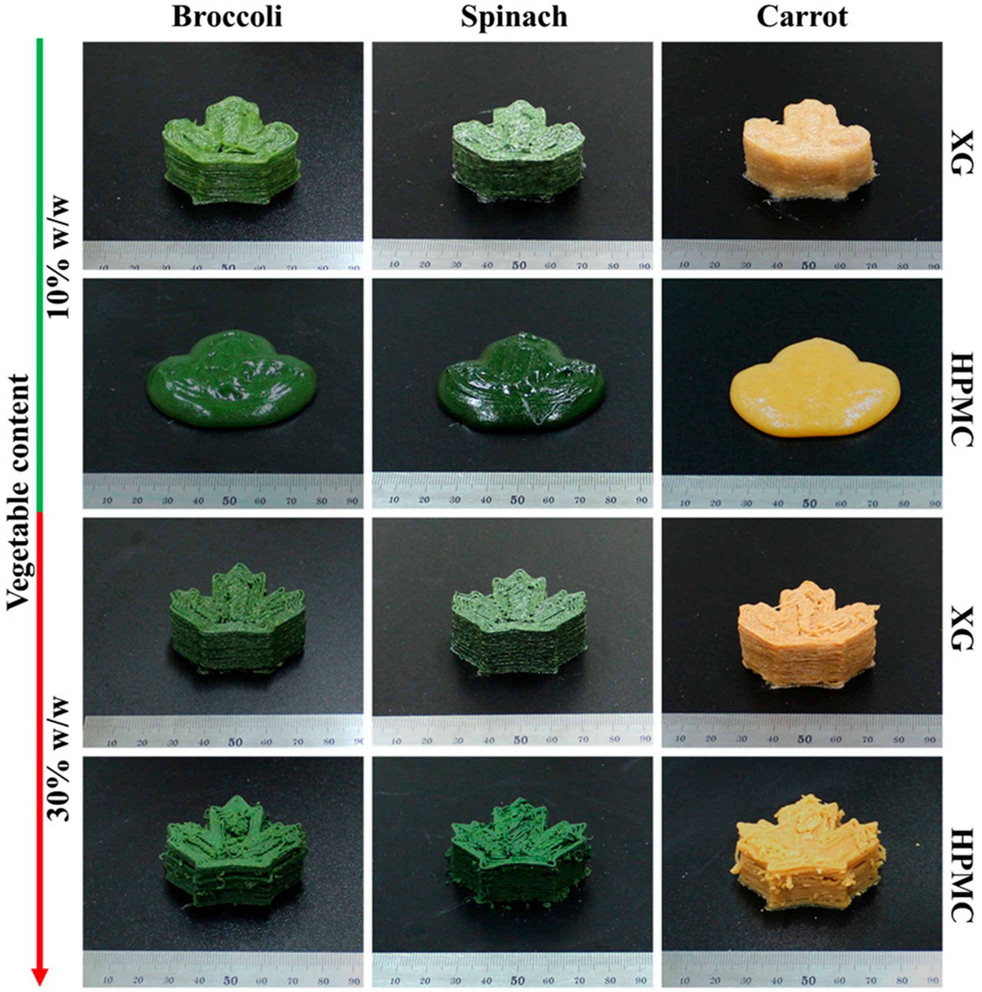

Figure 8. Image of xanthan gum and hydroxypropyl methyl cellulose products containing 10% and 30% vegetable powder. Picture taken from an article by He et al. [31].

Many edibles and flowable materials can be employed in extrusion-based printing such as potato starch, gelatin, pectin, xanthan and gellan gum, sodium alginate, and methylcellulose. Among printed food that has been reported are cheese [38], mashed potatoes [39], cookie dough, protein gel, surimi, tomato paste, chocolate [32], snacks formulated by wheat flour enriched with edible insects as a novel source of proteins [40], and cereal-based food structures containing probiotics [41]. To create "printable" recipes, we need to consider key parameters such as pH, temperature, nozzle diameter, viscosity distance between the nozzle and the printing bed, layer height, the speed of the x, y, and z axes, pressure, and low speed [7]. These parameters can be optimized depending on the desired texture and how accurate the printed object is, in other words, how well it matches the size and shape of the original design [38]. Many researchers mentioned that the viscosity of food also affects the quality of 3D-printed food products. It is valuable to consider the rheological properties of the materials because appropriate viscoelastic properties are crucial to allow them to be extruded through the nozzle [35].

Liu et al. prepared whey protein isolate (WPI) and milk protein concentrate (MPC) powders at different ratios in paste using an extrusion-based 3D printing system [42]. It was reported that as the WPI content increased, the printing quality of the protein pastes improved, and the printed objects became complete and without imperfections. The protein paste with a ratio of MPC and WPI at 5:2 presented the best printing performance, i.e., the extrusion was successful, and the paste retained its space structure and showed a better match to the designed 3D models.

A nutritionally customized fruit-based snack designed for children was also obtained by means of this technology [43]. The printed snacks matched the features of the designed structure to a large extent. This report proved that it is possible to obtain new foods with the desired shape and dimension. Moreover, printed food can be improved to perfectly fit the designed structure, considering that food materials have complex structures with vast differences in physicochemical properties both before and after the printing process.

The relationship between the rheological properties and printability of three types of starch (potato, rice, and corn starch) for hot-extrusion 3D printing (HE-3DP) was systematically investigated [44]. The authors indicated that concentrated starches present shear thinning and strain responsiveness, which were printable as HE-3DP materials. The results obtained from this work could provide, according to the authors, useful information for the selection of starch-based food materials and the optimization of 3D printing parameters for developing next-generation individualized food.

Fruits and vegetables have been successfully used to fabricate 3D food products using hot melt extrusion. Three-dimensionally printed objects from a mixture of orange concentrate (OC), wheat starch (WS), and gums are shown in Figure 9. One of the results of this study was that the gums (guar, k-carrageenan) enhance the apparent viscosity and storage coefficient of the mixture, while gum arabic causes the opposite effect [37].

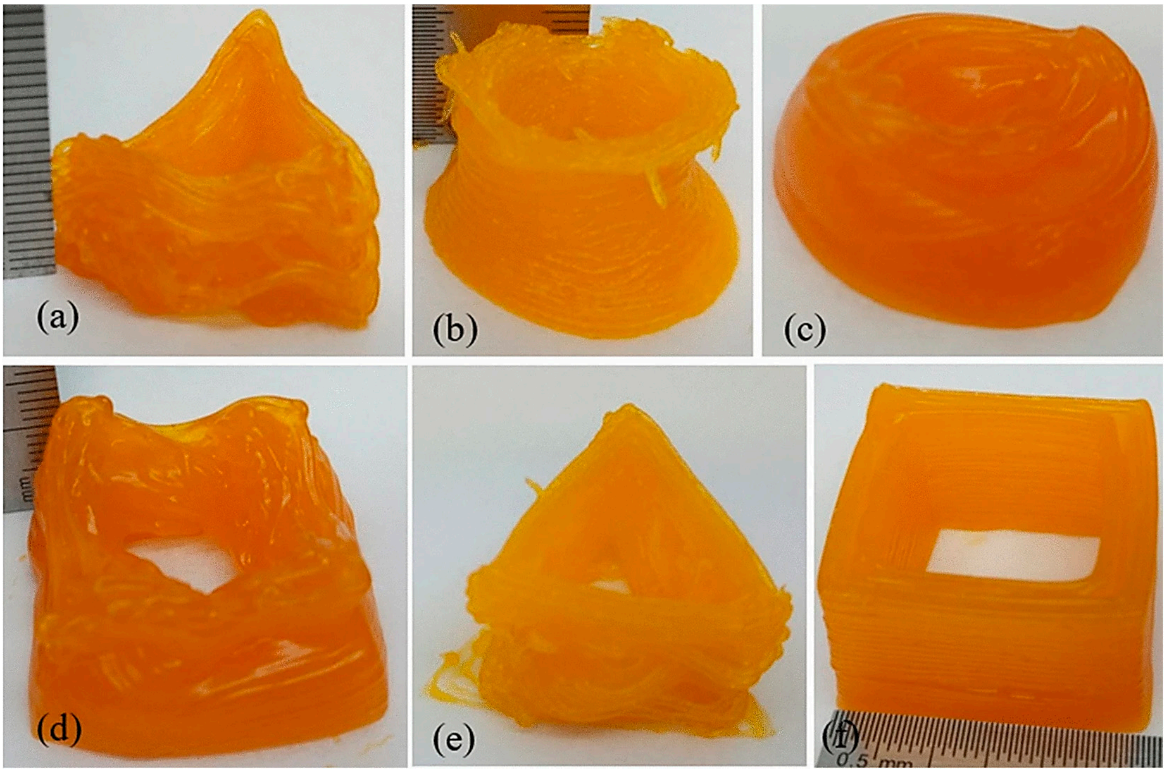

Figure 9. Three-dimensionally printed samples of OC-WS and OC-WS-gum blends. (**a**) Hollow triangle, (**b**) cylinder, (**c**) hollow cylinder, (**d**) hollow square, (**e**) hollow triangle, and (**f**) hollow square. Picture taken from an article by Waghmare et al. [37].

5. Intelligent Food Packaging

Food packaging protects food from tampering or contamination from physical, chemical, and biological sources to extend shelf life and provide the consumer with good-quality food. Packaging also presents branding and nutritional information and promotes marketing [45]. With traditional food packaging, potential food adulteration or fraud may not be detected. Smart food packaging, however, provides real-time communication about the condition of food and ensures that consumers receive higher-quality food products. An intelligent packaging system indicates and monitors parameters (i.e., freshness, temperature, pH, gas) related to the physicochemical condition of the product during transport and storage. Additionally, this technology prevents food loss to a large extent, and therefore it reduces food waste. However, current intelligent food-packaging products are not affordable in the food industry, as the conventional technologies used today increase the cost of the product, and consumers do not seem willing to bear it. An additional drawback is the availability and use of safe food-friendly materials to produce smart packaging components such as sensors that monitor and record the parameters the consumer is informed about. So, the global scientific community has been looking for alternatives in recent years.

Three-dimensional printing has been used to create sensors that can monitor food quality, ensure package integrity, and verify food authenticity [46]. Various advantages have been reported, such as simplicity, versatility, low cost, high accuracy, high strength, the wide adaptation of materials, simple maintenance, and colorful printing. This is a viable technology for making smart components that can be integrated into conventional food packaging to create intelligent ones. A 3D printing approach to intelligent food packaging has been recently reported by Tracey et al. [8]. They described additive manufacturing based on two aspects: stereolithography and as a cost-effective solution for the fabrication of smart packaging systems. The comparison of conventional technologies with additive manufacturing showed that the latter excels in terms of high resolution, complex geometry, simultaneous multi-material printing, and suitability for large- and small-scale manufacturing while the disadvantages are that the extrusion-based 3D printing technique was time-consuming and stereolithography was rather expensive. However, it should be noted that the initial cost of printers for stereolithography can be relatively high as 3D printing is still a new technology, but already in the last decade, the prices of printers have shown a significant decrease due to the development of newer models of printers [47].

The three-dimensional printing approach to point-of-use machines and the fabrication of intelligent packaging allow multifunctional smart components, self-indicating, and the development of high sensitivity, utilizing biocompatible non-toxic substances which are cheaper than traditional fabrication techniques. This would make intelligent food packaging more widespread and, subsequently, prevent customers from purchasing inadequate food items and lessen food waste [8].

Both intelligent and active packaging systems comprise smart packaging. The aim is to give the consumer more accurate information concerning the prevention of food spoilage and the product, using antioxidant and antimicrobial agents [48].

Food freshness indicators (FFIs) are a cost-effective intelligent packaging approach that uses as-it-happens detection. It observes the spoilage/freshness conditions of food, also informing the customers of the food status. Suitable FFIs should make the difference between typical spoiled food, medium fresh, and fresh visible to the naked eye. Few enhanced parameters such as polymers and halochromic colorants are utilized in the FFIs. In addition, the technique of preparation can directly influence the performance of that food. However, the creation of FFIs has well-established conventions; the application of novel methods for preparing FFIs and the utilization of natural coloring materials from different sources in the development of FFIs have grown because of the increasing research in this field [49].

Developing biodegradable packaging from renewable resources is important to solve the environmental problems caused by using synthetic plastics. Due to their safety and abundant resources, food packaging based on polysaccharides, anthocyanin, and essential oils has attracted much attention and will be discussed next.

Polysaccharide films used as smart food packaging ensure biodegradability, safety, and renewability. Although many works have been published on food packaging using alginate, chitosan, and other polysaccharides, there are few studies on polysaccharide film printing. This aspect is under research probably due to many requirements for edible ink and the lack of a suitable printing method [50]. An edible screen-printing ink with chitosan solution that can be used in the food package printing industry has been described [51]. According to the researchers, it not only has the excellent properties of traditional ink such as fineness, viscosity, initial dryness, tinting strength, and adhesion to the substrate, but it is edible as well.

Caro et al. developed new active packaging films based on chitosan and chitosan/quinoa protein with chitosan-tripolyphosphate-thymol nanoparticles via thermal inkjet printing [52]. It was concluded that these films improved the water vapor barrier, acted as a good platform for the delivery of active compounds, and increased antimicrobial activity against relevant microorganisms such as *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa.* This technology could enable the development of new packaging materials to extend the shelf life of fresh fruits.

Chitosan–starch films with natural extracts were developed by Lozano-Navarro et al. [53]. They showed that films with fruit and vegetable extracts (beetroot, cranberry, and blueberry) exhibited the best antimicrobial activity against various bacteria and fungi in comparison with the original chitosan–starch film. It was also found that the chitosan coatings composed of starch or gelatin and their mixture with thymol and geraniol prolonged shelf life during storage and protected strawberries against fungal decay [54].

Anthocyanins are natural water-soluble pigments that are gaining more and more attention due to their excellent properties such as potential health-promoting properties, biocompatibility, and different colors at varying pH. In smart food-packaging systems, they have a very high probability of being considered as a suitable pH indicator. These innovative films have been illustrated to enhance the relative excellence of food items made and the food safety. They could be used as a fast, accurate, and reliable tool monitoring the progress of freshness and/or spoilage. Anthocyanins have countless potential advantages as a powerful tool to fulfill one of the goals of smart packaging which is observing food freshness. [55].

Much research is being conducted, in addition to anthocyanins, into the various types of applications of essential oils in food packaging. For example, shikonin extracted from *Lithospermum Erythrorhizon* root has been utilized as a dye added to the cellulose membrane in order to create a color-rendering film [56]. However, no actionable relevance has been established in this research. Therefore, whether it can be applied to food packaging is currently uncertain. The preservation effect of essential oils can only be achieved by the careful study of different food points, although there are many studies that have placed them in packaging substances and used essential oils as an additive that preserves food. In this way, some analyses have been conducted on using essential oils and natural anthocyanin dyes in food packaging as well. Essential oils can increase the shelf life of foods as antimicrobial antioxidants. The pH value of the environment determines the color of anthocyanin, which is the first food preservation reaction in observing the effectiveness of the essential oil. However, in this study, the dual indicator membrane has great application prospects [57].

In [57], chitosan, mulberry anthocyanin, and lemongrass essential oils were used as an interlayer using a 3D printer. Further, cassava starch was used as a protective layer to form indicator films. The antioxidant and antibacterial properties of indicator films containing lemongrass were noteworthy, and furthermore, the release rate of essential oils increased with a rise in pH.

Meat and meat products are prone to microbial contamination and the oxidation of their lipids and proteins. To ensure food safety and maintain quality, many intelligent packaging systems have been tested [58]. Among the most used devices in this type of packaging are gas indicators. These are small devices that can be printed on packaging films and respond to changes in the internal gas composition, thus stipulating a scheme for monitoring the quality and safety of food products.

6. Recent Applications of 3D Food Printing

In the last decade, 3D food printing has attracted the interest of researchers worldwide, which is reflected in the published research papers. Figure 10 compares the number of publications returned by a search containing the keywords "3D printing" or "three-dimensional printing" and those for "3D food printing" or "three-dimensional food printing", from 2010 to 2023 (by the end of January), in the Google Scholar database. There is a continued increase in publications related to 3D printing in general, except for the years 2021 and 2022 possibly due to the impact of COVID-19 on global scientific development in all areas not directly related to the pandemic. However, when it comes to publications related to 3D food printing, which account for an average of 31% of citations, the increase is continuous. Figures for the first month of 2023 show that an extremely high number of publications is expected by the end of the year.

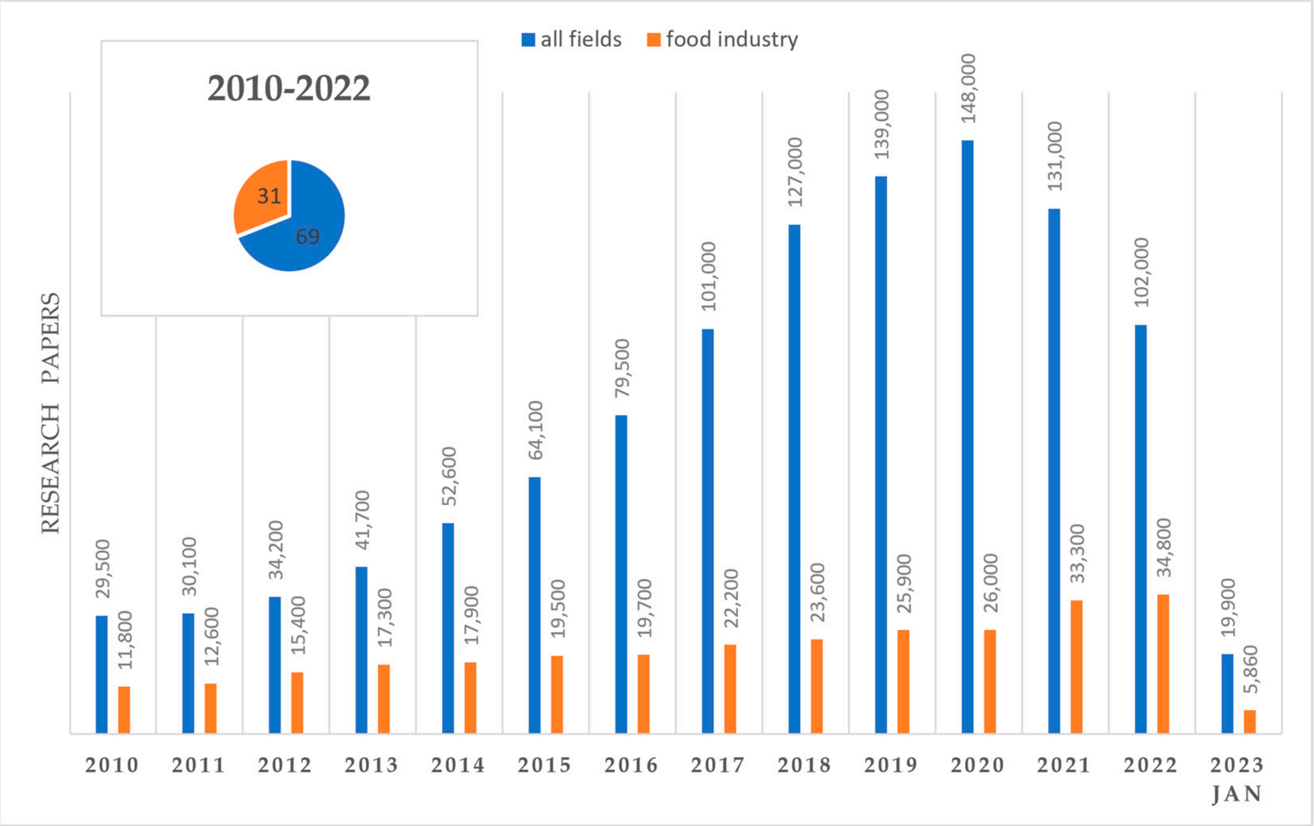

Figure 10. Number of publications from 2010 to 2023 (until the end of January) on 3D printing in all fields and in the food industry. The inset shows the average % distribution for the period 2010–2022.

Some characteristic recent examples of the application of the studied technology in food preparation are described below while Table 1 shows some basic food products obtained with 3D technology from the beginning of the application of the method until today.

Table 1. Types of food products obtained with 3D technology.

Food Product	Description	Ref.
fruit	Fruit-based snack; provides 5–10% of energy, Ca, Fe, and vitamin D for 3–10-year-old children.	[43]
vegetables	Smoothie of selected fruit (kiwi, pears, avocado) and vegetables (carrots, broccoli); more appreciated appearance than the non-printed smoothie.	[59]
cheese	Processed cheese; 3D printing substantially affects its structural properties (texture, rheology, microstructure).	[60]
pasta	Various printed pasta shapes (e.g., rose-shaped).	[61]
meat	Multi-constituent composite meat products using beef paste and lard; suitable for sous-vide post-processing.	[62]
bread dough	Different composition of water, sucrose, butter, flour, and egg contents; formulation invented specifically for 3D food fabrication.	[63]
chocolate	Samples of hexagonal shape, with parallel, cross-sectional, and no internal support.	[64]
	Three-dimensional prints (heart shape and logo) with suitable quality by varying the deposition parameters.	[65]
cereal foods	Cookies; innovative food texture, modulation of taste perception, and sensory sensations.	[66]
ready-to-eat meals	A pyramid of sesame paste with chicken and shrimp paste with simultaneous infrared cooking.	[67]
	Multi-material constructs of turkey meat, scallop, and celery.	[68]
potato	Printed mashed potatoes with different concentrations of potato starch.	[28]

Three-dimensional printing undoubtedly offers both flexibility in design and many improvisational possibilities. An innovative way of utilizing this flexibility to generate customized ready-to-eat sweetmeats with varied textures was presented by Bareen [69]. A finite element analysis simulation and the characterization of the rheological properties of the printed material were used to improve the predictability of the complicated 3D printing process. The authors proposed heat acid coagulated milk (HACM) semi-solids, a traditional East and Southeast Asian milk product, which is widely used in the preparation of various conventional sweetmeats and polyol composites (HACMP) to be used to print light food products. The printability of these creations was evaluated by studying the influence of the intricate structure on rheological properties, microstructure, and printing performance. Results indicated that both nozzle diameter (*d*) and infill density alter the weight and void fraction of the printed fabrication to a significant extent. In contrast, the above parameters do not seem to be affected by the layer design. Changing the layer orientation pattern resulted in noticeable differences in the hole volume, hardness, and stickiness of the printed structure. Furthermore, what appeared to significantly affect the rheological characteristics, length, consistency, and void fraction of the printed structures was the increased polyol concentration. Modeling and simulating deformation and internal stresses inside the structure in 3D-printed geometries described in this study may have applications in 3D food printing.

Another recent study described a method to facilitate the rational design and fabrication of plant-based edible inks which are used for the development of personalized foods with unique properties. The aim was to improve the gelling properties of peanut protein and achieve 3D printing by combining it with two natural polysaccharides, carrageenan (Car) and gellan (Gel) gum, to prepare cold-set composite hydrogels (Figure 11) [70]. The addition of these polysaccharides improved both the mechanical strength and toughness of hydrogel. The printed objects can be recycled due to the thermo-reversible cold-set properties of the two polysaccharides used, which may help reduce waste and production costs. The color response of the printed object to pH was realized by incorporating natural pigment (anthocyanin-rich purple sweet potato flour) into the composite hydrogels. These pH-sensitive materials may be useful in 4D food printing applications in cases where the ink is not stable but changes after printing.

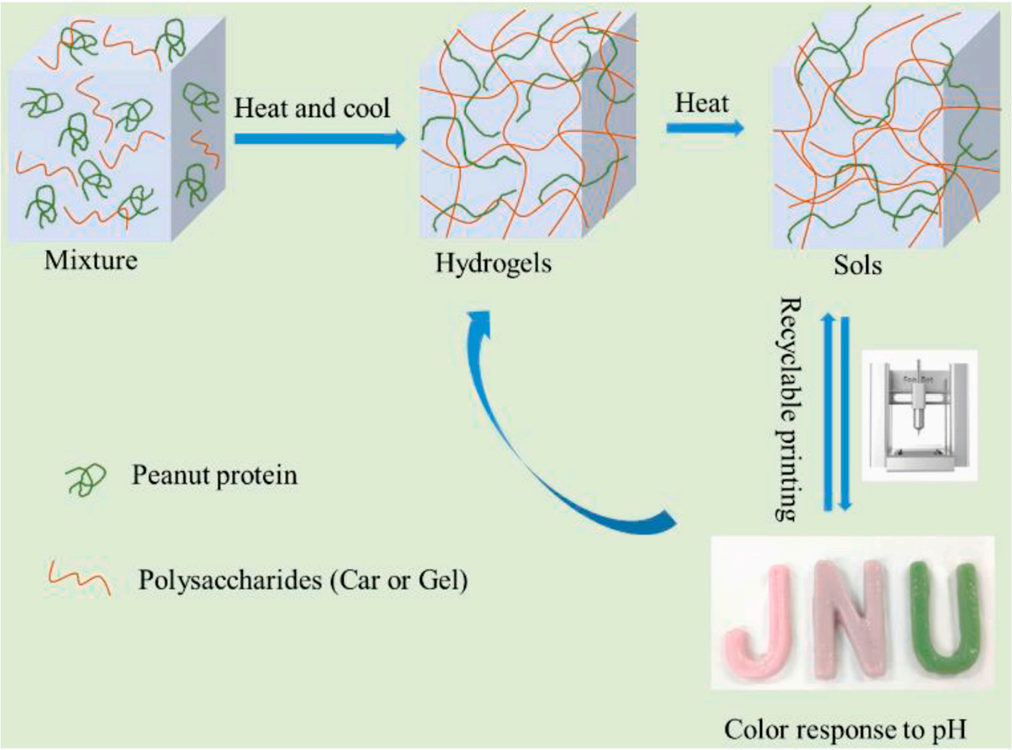

Figure 11. Schematic diagram of peanut protein-polysaccharide semi-interpenetrating network hydrogel fabrication and 3D printing. Picture taken from an article by et Lin et al. [70].

Qiu et al. produced stable high-internal-phase Pickering emulsion (HIPPE) gels with enhanced performance, which could be used as 3D printing inks for future food creations and nutrition delivery systems [71]. Particularly, they successfully fabricated zein-glycyrrhizic acid composite nanoparticles, which were then used as a stabilizer to prepare HIPPEs containing 75% oil, which were resistant to creaming and had gel-like properties. Satisfactory levels of stability and the optional rheological properties required for 3D printing were achieved by adding magnesium chloride. This increased strength was mainly attributed to electrostatic screening and salt bridge formation by the polyvalent magnesium cations, which enhanced the interactions between the particle-coated oil droplets and the particle network in the aqueous phase. The high-internal-phase Pickering emulsions developed in this study may facilitate their widespread use in food manufacturing where semi-solid state printing inks with rheological properties that do not hinder but facilitate the process are required.

Qiu successfully developed a novel 3D-printed dysphagia diet containing apples and roses with the addition of xanthan gum (XG) and basil seed gum (BSG) and tested it for printability [72]. Both gums were chosen for their unique properties. XG is one of the most extensively investigated texture agents used in the development of dysphagia foods because it can improve the texture, consistency, appearance, and taste of many foods, while BSG can act as a stabilizing, emulsifying, foaming, and thickening agent, and in addition, it can retain a large amount of water. Different blends and concentrations of the above-mentioned gums were incorporated to improve printability and to create chewing or swallowing behavior acceptable and desired by the consumer. The results showed that all gum-added inks improved the hardness, stickiness, stiffness, and self-supporting ability of the printed food except for the ink with only xanthan gum added. The combined addition of XG and BSG at a mixing ratio of 2:1 presented the best printing accuracy and led to steady structures with improved surface smoothness.

Another study described an innovative technique based on 3DP technology to fabricate porous spherical beads from corn starches that are different in amylose content [73].

The beads had a porous internal structure while the technique eliminated the use of surfactants, organic solvents, and additional extraction steps. The authors investigated the effect of amylose content on the 3D printability and structural properties of starch gels which were prepared using two different drying methods (freeze-drying and supercritical carbon dioxide (SC-CO_2)). By varying the rheological properties of the starch-based inks, three-dimensional beads with large differences in shape and dimensions were obtained. Higher gel strength, lower shrinkage, and lower density were achieved for the product with the highest amylose content. Corn starch with a high amylose content resulted in beads with the smallest 3D-printed size, which was estimated to be ~980 μm. The use of high-amylose starch combined with the SC-CO_2 drying method resulted in final printed products with excellent properties such as high surface area, ultra-low density, and high porosity. The difference in specific surface area values between pellets dried by the SC-CO_2 method and lyophilized ones reaches 175 m^2/g.

Another research group created good-quality 3D-printed chocolates by replacing high-fat cocoa butter with gum arabic emulsions. The products had low fat content and desirable melt-in-the-mouth behavior [74]. Optimal 3D printing ability was found to have a cocoa butter: icing sugar: cocoa powder ratio of 2:1:2.5. Cocoa butter was replaced by water-in-cocoa butter emulsions at different concentrations (25%, 50%, and 75%) which were formed from different water/oil ratios (2:8, 3:7, 4:6). The reduced-fat chocolate formulations possessed the desired polymorphic V form of cocoa butter and rheological properties that facilitated the printing process. The snap quality of the chocolate increased after the incorporation of high emulsion content. Even reduced-fat chocolate that replaced up to 75% cocoa butter with 2:8 water/oil emulsions or 50% cocoa butter with 3:7 water/oil emulsions gave 3D chocolates with good print quality.

Without a doubt, most of the above-described applications are the product of research at the laboratory level and have not been implemented on an industrial scale. Presently, 3D food printing is mostly used in decorating and fabricating food products such as chocolate, cookies, and cakes; however, the actual printing of the food is done in a few areas only and by few companies. Some characteristic examples are presented in Table 2 [75,76] along with the company name and the applied method of 3D printing.

Table 2. Commercially available food products obtained with 3D technology.

Food Product	Company Name/*Process*
Smoked Salmon Fillet	Austrian Revo Foods/*Extrusion*
Fruit-Flavored Droplets	Dovetailed Design Studio's/the world's first liquid-based 3D printer
Pasta (unique shapes)	Italian Barilla in collaboration with the Dutch company TNO/*Fused Deposition Modeling*
Chocolate and Cocoa Products (unique shapes and exclusive flavors)	Mona Lisa 3D Studio/ *Extrusion*
Pizza, Burgers, and Cookies	Printer Foodini/ *Extrusion*
Edible Sweet Decorations	Printer ChefJet/ *Extrusion*
Meals (proteins, carbs, other nutrients), Pizza	NASA funded Systems and Materials Research Corporation (SMRC)/*Extrusion*
Pizza	BeeHex Pizza Printer/*Method*
Chocolate	Mondelēz & 3P Innovation/Cadbury Dairy Milk 3D printer/*Melt-extrusion*
Chocolate (various shapes, sizes, and geometries)	Hershey Company in collaboration with D Systems/CocoJet, chocolate 3D printer/*Extrusion*
Products of Sugar	CandyFab/*Selective Hot Air Sintering and Melting (SHASAM)*
Vegan Meat (burgers, kababs, and sausages)	Redefine Meat/*Extrusion*

7. Conclusions

Although 3D printing has mainly focused on the production of plastic products, it has been a revolutionary method in food production as well. The main innovation with 3D food printing is that it can be done in a highly controlled manner, offering endless possibilities in terms of texture and taste that can be exploited when developing food products that are both appealing and of high quality.

The quality of 3D food printing is operation-based rather than operator-based as in traditional food processing, so processing parameters must be optimized to achieve high-end printability. These parameters include pH, temperature, nozzle diameter, viscosity distance between the nozzle and the printing bed, and layer height. Optimization of the above parameters should be performed keeping in mind a targeted application.

As a result, 3D food printing is a dynamic technology that has the potential to simplify food manufacturing processes and establish high material use efficiency in terms of minimizing waste, portion control, and the production of well-structured, nutritious, and tasty food products. Food ingredients such as carbohydrates, fats, fiber, functional components, proteins, sugar, and hydrogels such as alginate and gelatin can be used in the right manner for making healthy and tasty food. A variety of 3D printers can be used to print food by improving the capabilities of each printing method (extrusion, sintering, melting, etc.) depending on the material, eliminating existing limitations and incorporating new capabilities.

8. Future Recommendations

The biggest challenge in 3D food printing is its application on an industrial scale. Currently, most studies focus on developing printable materials or adjusting printing parameters to improve printing accuracy and product stability. However, limited studies refer to the development of a new technology or the modification of an existing one that will give access to large-scale production systems. This is still a work in progress and requires a lot of research and time to successfully integrate 3D printing into commercial applications.

Any study related to the possibility of using 3D printing in the food industry should take into account in advance the modified or new food value chains, products, and services that will emerge in the coming years. Such an innovative preparation technique should not follow developments but precede them.

Traditional food preparation techniques seem unable to be completely replaced by the new method on an industrial scale. In addition to the other limitations, we also need to move beyond shape printing to food texture printing, which has slowly begun to appear in the scientific community. The future of 3D printing is 4D printing that will produce food products whose shape and size will change according to environmental conditions. Four-dimensional food printing has not acquired yet great focus from the industrial and academic fields compared to other fields of 4D printing. The use of smart materials that exhibit self-assembly, versatility, and self-healing properties and can change the shape and design of printed food according to their environment must be extensively studied.

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