



3d Food Printing Technology: An Overview

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Abstract

3D food printing has emerged as a transformative technology in the food industry, offering innovative solutions for personalized nutrition, culinary creativity, and improved food textures. By utilizing edible materials as "inks," this technology enables the precise creation of intricate and customized food products with precise control over shape, texture, and flavour. While challenges remain in terms of viscosity control, stability, and taste maintenance, 3D food printing holds immense potential for revolutionizing the way we produce and consume food. This technology can address food scarcity, cater to specific dietary needs, and reduce food waste, making it a valuable tool for promoting healthier and more sustainable food solutions. Through 3D food printing, personalized nutrition becomes a reality. Individuals can enjoy meals tailored to their specific health data, allergies, or fitness goals, ensuring precise control over macronutrients and micronutrients. This is especially beneficial for healthcare patients, athletes, and the elderly, who require specialized dietary needs.

Sustainability is another key advantage of 3D food printing. By minimizing food waste through precise portioning and utilizing alternative protein sources like edible insects and plant-based ingredients, this technology contributes to a more environmentally friendly approach to food production. Additionally, 3D food printing can repurpose food by-products, reducing the overall ecological footprint. Beyond personalized nutrition and sustainability, 3D food printing offers exciting possibilities for culinary creativity. Chefs can experiment with unique textures, flavours, and designs, elevating the dining experience to new heights. From intricate chocolate sculptures to precisely layered pastries, 3D food printing opens up a world of artistic expression. While challenges such as material limitations and consumer perception persist, the potential benefits of 3D food printing are significant. As the technology continues to evolve, it has the power to revolutionize the food industry, promoting healthier, more sustainable, and personalized food solutions for consumers worldwide.

Keywords: 3D food printing, personalized nutrition, food texture, edible materials, viscosity control.

Introduction:

3D printing of food materials has emerged as a transformative technology in the food industry, enabling the production of customized food products that cater to diverse dietary needs, preferences, and health conditions. This process allows for precise modification of nutrition, texture, and taste, making it a highly versatile tool for personalized food manufacturing. From a nutritional standpoint, 3D printing offers the flexibility to select and adjust macro and micronutrients based on consumer preferences or the dietary requirements of individuals with specific health conditions, such as athletes, children, or the elderly.

The technology was first introduced in the confectionery industry, where it was used to create intricate and attractive structures of artisan chocolates and candies. However, over time, the application of 3D food printing has expanded to more complex food products. One of the main challenges associated with 3D food printing is ensuring the stability of the printed structure, both during and after the printing process. The food materials

used in the printing process, their properties (such as viscosity and thermal behaviour), as well as the processing parameters of the printer, all play crucial roles in determining the final quality of the printed food.

There are three main categories of 3D food printing techniques: inkjet printing, extrusion printing, and heat source printing. Among these, extrusion-based techniques are the most commonly used due to their convenience, controllability, and adaptability to various food materials. However, it is important to carefully select the appropriate printing technique based on the specific properties of the food being printed, as not all methods are suitable for every type of food material.

A noteworthy advancement in this subject has been Natural Machines' creation of the "Foodini" 3D printer. The Foodini printer focuses on creating freshly printed meals with enhanced nutritional profiles. It allows for precise placement of ingredients such as salt, sugar, and fat between layers of food, which can significantly impact the mouthfeel and taste perception. This feature also supports the production of healthier foods by reducing the amount of unhealthy ingredients like salt and sugar while still maintaining the desired flavour and texture.



Fig 1: 3D Printer Foodini: how it works.

One of the most promising applications of 3D food printing is in healthcare, specifically for individuals with dysphagia, a condition that makes swallowing difficult. For these individuals, the texture and consistency of food are of utmost importance. 3D printing technology has made it possible to produce soft, easy-to-swallow foods with improved nutritional quality and visually appealing designs. The International Dysphagia Diet Standardization Initiative (IDDSI) has established a standardized framework for assessing the texture and consistency of food and drinks for people with dysphagia. This framework classifies drinks into five levels based on thickness (ranging from thin to extremely thick) and solid foods into six levels based on texture (from liquidized to chewable).

In addition to its healthcare applications, 3D printing technology has the potential to create novel and appealing food textures for a broader range of consumers, including children, athletes, and individuals seeking alternative protein sources. For example, edible insects, which are considered a sustainable and nutritious protein source, can be incorporated into 3D-printed foods in a way that is more palatable and visually appealing.

Furthermore, employing 3D food printing makes it feasible to create elaborate food patterns that would be unfeasible to do with conventional cooking techniques. This opens up new possibilities for culinary creativity, enabling chefs and food manufacturers to experiment with unique shapes, patterns, and textures. The ability to customize food in this way also has significant implications for the food service industry, where restaurants and food manufacturers can offer personalized meal experiences tailored to individual tastes and dietary preferences.

Despite its many advantages, 3D food printing still faces several challenges, particularly related to the properties of food materials, the viscosity of the printing inks, and the post-processing treatments required to maintain the desired shape and texture of the printed foods. Thermal properties are also a concern, as food materials may undergo changes in consistency during heating or cooling processes. Addressing these limitations will be crucial for advancing the technology and expanding its applications in various sectors.

The 3D food printing represents a groundbreaking innovation in the food industry, offering unprecedented opportunities for personalized nutrition, creative culinary experiences, and improved food textures for individuals with specific dietary needs. While there are still technical challenges to overcome, the potential for 3D food printing to revolutionize the way we produce and consume food is immense. As the technology

continues to evolve, it is likely to play an increasingly important role in promoting healthier, more sustainable, and more customized food solutions for consumers around the world.



Fig 2: 3D Food Printing



Fig 3: 3D Printed Burger

Edible material:

In 3D food printing, a wide range of edible materials can be used as "inks" to create various food products. These materials must have specific properties, such as appropriate viscosity and consistency, to be processed by the printer and retain their shape post-printing. Below are common edible materials used in 3D food printing:

Doughs and Pastes: Bread dough often used to create baked products like customized bread and pastry shapes. Pizza dough can be shaped and layered precisely for pizza production. Pasta dough is suitable for creating unique pasta shapes with high precision. Pastry dough is used for confectionery or baked goods like croissants and tarts.

Chocolates: Melted chocolate is popular material for creating intricate and artistic chocolate designs, especially in the confectionery industry. Chocolate's malleable properties make it ideal for printing complex structures.

Sugars and Sweets: Sugar syrups is often used for creating candy or edible decorations due to their moldable nature when heated and cooled. Marzipan is a malleable almond paste that can be shaped and printed into detailed forms for confectionery purposes.

Fruit and Vegetable Purees: Fruit purees are used for printing snacks, desserts, and healthy foods with customized shapes and designs. Popular choices include banana, strawberry, and apple purees. Vegetable purees like carrot, spinach, and pumpkin purees are often used for creating customized nutritious foods, especially for individuals with specific dietary requirements.

Protein-Rich Materials: Meat pastes where ground meat or meat pastes can be extruded to create processed meat products with unique shapes or textures. Fish and seafood pastes are similarly, fish can be ground and printed for customized meals, particularly in fine dining or specialized cuisine. Alternative proteins (insect

flour, plant-based proteins) in which edible insects, such as cricket flour, or plant-based proteins like soy and pea protein, can be used in printed foods, offering sustainable and high-protein alternatives.

Edible Gels and Hydrogels: Agar-agar is a gelatinous substance derived from seaweed, commonly used for creating jellies or food structures that require a gel-like texture. Gelatin is used for desserts or confectionery, providing a flexible, moldable structure that is both nutritious and flavorful. Pectin is a naturally occurring substance in fruits used to create jams and jellies, often employed in 3D printing for texture control.

Dairy-Based Materials: Cheese pastes and soft cheeses or cheese pastes, like ricotta or cream cheese, are used to create layers in savory dishes or decorative food items. Yogurt and cream both are employed in layered food creations, such as parfaits or custom-designed desserts, due to their consistency and flavor adaptability.

Flours and Starches: Corn starch is mixed with water to create printable dough for producing gluten-free food items. Wheat flour mixtures are used in dough formulations to print breads, cakes, and other bakery products. Potato starch is common in savory dishes and snacks to provide structure and crunch in the printed food.

Fats and Oils: Butter and margarine is used for creating layers in pastries or adding flavor to food designs. Cocoa butter is used in chocolate-based printing or to create fat-rich, smooth-textured foods.

Condiments and Sauces: Tomato sauce is used for layering in pizzas or adding flavor to various food prints. Mayonnaise or mustard is applied in specific designs or food products where customization of taste and aesthetics is required.

Edible Powders: Spices (cinnamon, nutmeg) are used as powders in 3D printing to add flavor and visual appeal. Dehydrated vegetable and fruit powders are added to enhance flavor, color, or nutritional content of printed food.

Edible Insects: Insect powders (e.g., cricket flour) are a sustainable protein source used in 3D printing to create high-protein snacks and alternative food products.

Alternative Ingredients for Special Diets: Gluten-free ingredients are such as rice flour or almond flour, are used to create gluten-free 3D printed foods for individuals with celiac disease or gluten intolerance. Low-fat or low-sugar ingredients can be incorporated into the print material to cater to health-conscious consumers or people with dietary restrictions.

Egg-Based Materials: Egg white is used for texture in savory dishes or for aerating printed foods. Egg yolk is employed to create rich textures in desserts and baked goods.

Other Miscellaneous Ingredients: Nutritional additives (vitamins, minerals) can be added to create fortified foods for specific nutritional requirements. Colorants (natural or food-safe dyes) are edible materials are used to give 3D-printed foods vibrant, appealing colors, especially in the confectionery industry.



Fig 4: Edible material used in 3D Printed Foods

Table 1: Various food materials utilized for extrusion-based 3D printing.

Nutrients	Food Materials
Carbohydrates	Lemon juice gel Mashed potato Pectin Fruit snack Fruit and vegetable blend Smoothie Dough varying Baking cookies Skim milk powder Hydrocolloids
Proteins	Turkey meat and scallop Fish surimi gel
Lipids	Bacon fat Chocolate Cheese

Challenges with Edible Materials in 3D Food Printing:

3D food printing is a revolutionary technology that offers unique opportunities for creating intricate and customized food products. However, the use of edible materials in this process comes with several challenges that need to be addressed for successful outcomes. Key among these challenges are viscosity control, stability and structure, and the maintenance of taste and texture.

Viscosity Control

One of the foremost challenges in 3D food printing is achieving the right viscosity of the material being extruded. Viscosity refers to a fluid's resistance to flow, and in the context of 3D printing, it is crucial for ensuring smooth extrusion through the printer's nozzle. If the material has too high a viscosity, it may not flow adequately, leading to clogs and inconsistencies in the printed structure. Conversely, if the viscosity is too low, the material may flow too freely, resulting in a loss of shape and detail during printing.

To achieve the desired viscosity, food technologists often employ various thickeners and stabilizers, such as starches, gums, or proteins, which can enhance the flow properties of the edible materials. The selection and combination of these additives must be carefully considered, as they can significantly influence the material's performance. Additionally, environmental factors such as temperature and humidity also play a vital role in viscosity, making it necessary to maintain consistent conditions throughout the printing process.

Stability and Structure

Once the food material is extruded, it must retain its shape and structure until it sets completely. This is a significant challenge, especially for materials that are prone to collapse or deformation due to their inherent properties. Factors such as the composition of the material, the speed of extrusion, and the ambient conditions can affect the stability of the printed structure.

For example, gelatinous materials may require careful control of cooling rates to prevent sagging, while more rigid structures may need additional support during the printing process to maintain their shape. Moreover, the choice of raw materials can significantly influence structural integrity. Ingredients with high moisture content may lead to instability as the water evaporates, while others may not provide sufficient binding properties to hold the structure together. Finding a balance between rigidity and flexibility in the printed materials is essential to ensure that the final product can withstand handling and transport without losing its shape.

Taste and Texture

The success of 3D-printed foods hinges not only on their visual appeal but also on their taste and texture. Achieving the desired mouthfeel is critical in creating an enjoyable eating experience. This involves maintaining the nutritional content and structural integrity of the printed food while ensuring that it meets consumers' expectations for flavor and texture.

Texture plays a crucial role in how food is perceived; it can enhance or detract from the overall eating experience. For instance, consumers may expect a certain level of crispiness in a cookie or tenderness in a meat product. This can be challenging to achieve with 3D printing, as the process may alter the texture of the

food during printing and post-processing stages. Techniques such as layering different materials or incorporating additional texturizing agents can help achieve the desired mouthfeel.

Furthermore, maintaining nutritional value while focusing on taste and texture is another layer of complexity in the formulation of 3D-printed foods. Many food manufacturers strive to create healthier alternatives without compromising flavor. This often requires innovative ingredient combinations and formulations that provide the same sensory experience as traditional foods while enhancing their nutritional profile.

Advantages and Disadvantages of 3D Printed Food:

There are many **advantages** of 3D printed food—from being quicker and easier than traditional food-preparation methods, to being a more-healthy option, to less food waste. The 3D-printed food offers advantages as follows:

1. Aids in Creating Elaborate and Imaginative Meal Designs

3D printing food allows chefs and food creators to unleash their creativity and introduce visually stunning and intricate designs that captivate diners. This improves the dining experience by offering unique and personalized presentations that would be difficult to achieve through traditional methods.

2. Waste Reduction Achieved by Using Ingredients Effectively

By utilizing precise amounts of ingredients, 3D printing minimizes food waste. This efficiency not only reduces costs for businesses but also contributes to environmental sustainability by conserving resources and minimizing landfill waste.

3. Improved Structure and Texture Consistency

Consistency in structure and texture is important, especially in commercial food production in which uniformity is key to customer satisfaction. 3D printing ensures that each food item meets the desired specifications consistently.

4. Possibility of Mitigating Food Scarcity

With the ability to utilize alternative ingredients such as plant-based proteins, 3D-printed food offers a promising solution to food scarcity. 3D printing has the potential to address global food shortages and reduce dependence on traditional farming practices.

5. Substitutes for Particular Dietary Requirements or Limitations

Customizable food options cater to individuals with specific dietary needs or restrictions, such as gluten-free or vegan diets. This inclusivity not only enhances accessibility to nutritious meals but also empowers individuals to make healthier choices that align with their dietary preferences or requirements.

6. Participation in Initiatives for Sustainability

3D printing food in-house contributes to broader sustainability initiatives by lowering food transportation requirements and the demand for resource-intensive components. 3D printing food aligns with the growing demand for environmentally conscious practices within the food industry.

7. Inventive Presentation of Food

The visual aspect of dining is as important as taste, especially in high-end dining experiences. 3D-printed food allows for innovative and captivating presentations that engage diners on a sensory level, elevating the overall dining experience and fostering appreciation for culinary artistry.



Fig 5: Future implementation and various applications for 3-D food printing.

Despite its many advantages, 3D printing food also has its **disadvantages**. The disadvantages of 3D-printed food are listed below:

1. Limited Speed and Scale of Production

The current speed and scale of 3D-printed food production may not meet the demands of all types of food-service environments, which may limit its practical application in high-volume settings.

2. High Initial Cost

Acquiring 3D food printers can need a significant upfront expenditure. For smaller businesses or individuals, this may be a barrier to adoption. Additionally, ongoing maintenance costs may further contribute to the overall expense.

3. Specialized Training Requirement

Operating 3D food printers effectively requires users to have specialized training and expertise. This could lead to challenges in finding personnel capable of managing the equipment and optimizing production processes.

4. Limited Material Options

While a variety of edible materials can be used in 3D printing, the range may still be limited compared to the materials and ingredients associated with traditional cooking methods. This limitation could restrict the diversity of dishes that can be created using this technology.

5. Regulatory and Safety Concerns

There are regulatory and safety concerns regarding the use of 3D-printed food, particularly as it relates to the sourcing and handling of ingredients. Additionally, hygiene and sanitation of the printing process may be called into question.

6. Perception and Acceptance

Despite its potential benefits, 3D-printed food may face challenges in gaining widespread consumer acceptance due to perceptions about food quality, authenticity, and the role of technology in food preparation. Overcoming these perceptions could require significant marketing and education efforts.

Additionally, cultural 3Dprinted food may have a negative impact on traditional culinary techniques and cultural food history, raising concerns about the loss of culinary diversity and authenticity.

3D Food Printing Technology

1. **Extrusion-Based Printing:** The primary method used in 3D food printing involves working with paste-like or dough-based materials such as chocolate, mashed vegetables, and proteins. This technique allows food to be extruded through a nozzle, building intricate shapes and designs layer by layer. Temperature control is crucial, especially for temperature-sensitive ingredients like chocolate, to ensure precision. Additionally, this method offers control over the texture of the food, enabling the production of various textures, from soft to crunchy, depending on the food material and the parameters set. It is widely applied in the creation of

pizzas, cakes, and other multi-layered or decorated dishes. Users can also make real-time adjustments to parameters such as speed, layer thickness, and ingredient flow to achieve more accurate prints.

2. **Inkjet Printing:** Liquid-based 3D food printing uses liquid food materials such as sauces, syrups, and food dyes to create intricate designs. The printer deposits fine droplets of liquid to build layers or add decorations with precise detailing. This method is particularly known for enhancing the appearance of cakes and pastries by adding patterns, colourings, and decorations. The technology ensures food safety by precisely placing the liquid without contamination. It is frequently used in cake decorating and high-end confectionery products, allowing for customizable designs, from personal messages to complex patterns. However, it is less versatile, being best suited for decorative and flavour-enhancing purposes rather than the production of solid foods.

3. **Binder Jetting:** Dry ingredient printing utilizes powdered food materials such as sugar, flour, or protein powders, with a liquid binder selectively applied to specific areas to hold the powders together. This method allows for the creation of custom structures that maintain their integrity, making it suitable for detailed shapes like candies or cookies. It is often used to produce crunchy, porous textures, commonly found in baked goods. Additionally, dry ingredient printing enables the creation of complex, multi-layered structures in a single print. Its applications range from sugar sculptures and baked goods to energy bars. However, scaling can be challenging due to the speed and complexity involved in printing larger, high-volume food items.

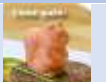
4. **Selective Laser Sintering (SLS):** Laser-based fusion in 3D food printing uses a laser to heat and fuse powdered food materials into solid structures. Although still in the experimental stages, this method, known as selective laser sintering (SLS), shows great potential for producing high-precision, intricate food designs due to the precision of laser technology. It is particularly suitable for temperature-sensitive materials like chocolate, which require careful control for melting and setting. This technique holds promise for high-end gourmet applications where artistic design is essential and may lead to innovative textures and flavours in desserts and snacks. However, the use of lasers in food production presents challenges related to food safety, requiring stringent safety standards and food-grade certifications.

5. **Fused Deposition Modeling (FDM):** Fused deposition modeling (FDM) in 3D food printing involves heating food materials until they melt, then depositing them in layers to form intricate designs. It works effectively with versatile materials like chocolate, cheese, and other ingredients that harden upon cooling. This method offers high precision in controlling the layering process, allowing for the creation of complex and detailed food structures. As the food cools and hardens in real-time, it makes the process efficient for certain types of products. FDM also supports multi-ingredient printing, enabling the production of layered, multi-flavoured foods. Often used in high-end restaurant kitchens for creating decorative elements, this technique requires precise temperature control to ensure optimal melting and cooling during the printing process.

6. **Robotic Arms and Multi-Ingredient Systems:** Advanced 3D food printers equipped with robotic arms offer increased precision and efficiency in the food printing process. These printers are capable of handling multiple ingredients, allowing them to switch between materials during printing to create complex, multi-layered dishes. They also enable high levels of customization, producing meals tailored to individual dietary needs, taste preferences, or nutritional requirements. The use of robotic arms speeds up the process, making it more efficient, especially for intricate designs. Additionally, these printers allow chefs to make real-time adjustments to ingredients, shapes, and layers, fostering creativity. Their versatility makes them suitable for use in restaurants, food labs, and industrial food production. However, these systems remain expensive and are primarily used in experimental or high-end applications.

Table 7. Various companies of 3D food printers in food industry

(All data and pictures were taken from each company's website).

Company	Model	Food Materials	Type	The Linked Website	Product Pictures
CandyFab	CandyFab-4000	Sugar	SLS	https://candyfab.org/	
3D Systems	ChefJet	Chocolate, sugar, starch, protein	Binder Jetting	https://uncrate.com/chefjet-3d-printer/	
Choc Edge	Choc Creator V2.0 Plus	Chocolate	FDM	https://www.3dsystems.com/	
3DCloud	QiaoKe	Chocolate	Extrusion	http://chocedge.com/	
Blue Rhapsody	Barilla-developed 3D pasta printer	Starch for pasta or letters	Extrusion	https://blurhapsody.com/	
Fouche Chocolates	Fouche Chocolate printer	Chocolate	Extrusion	https://www.fouche3dprinting.com/	
Nourished	Printrbot	Sugar, starch for vitamin	Extrusion	https://get-nourished.com/	
Natural machine	Foodini	Chocolate, cake	Extrusion	https://www.naturalmachines.com/	
Hershey	CocoJet 3D Printer	Hershey Chocolate	Extrusion	https://www.thehersheycompany.com/	
Katjes Magic Candy Factory	3D Gummy Candy Printer	Candy	Extrusion	http://magiccandyfactory.com/	
BeeHex	Chef 3D	Pizza	Extrusion	https://www.beehex.com/	
ByFlow	Focus 3D Food Printer	Chocolate	Extrusion	https://www.3dbyflo-w.com/	
Print3Taste	Procusini 3.0	Chocolate, jelly	Extrusion	https://www.procusin-i.com/	

WASP	Power WASP EVO	Chocolate	Extrusion	https://www.3dwasp.com/	
Zmorph	Zmorph VX	Chocolate, cake	Extrusion	https://zmorph3d.com/	
XYZ Printing	3D Food Printer	Cookie, cake	Extrusion	https://www.xyzprinting.com/	
Open Meals	Pixel 3D Food Printer	Sushi	Extrusion	https://www.openmeals.com/	



Fig 5: 3D Food Printing Additive Manufacturing Technology

Evaluation of the printability of various food applications:

3D food printing (3DFP), also known as additive manufacturing (AM) or food layered manufacturing (FLM), enables the creation of intricate 3D food structures through layer-by-layer deposition, offering possibilities beyond conventional food production. This technology allows for the development of various shapes, textures, flavors, and colors, with the printability of food materials depending on their flow properties and ability to maintain shape post-printing. One advantage of 3DFP is that it can be performed at room temperature, preserving heat-sensitive nutrients and improving food safety by protecting delicate ingredients from degradation.

In the cereal-based food sector, 3D printing is used to create products like cookies, pizza, and pasta, with researchers exploring fortification methods, such as adding probiotics to dough formulations. For fruit and vegetable-based foods, the high water content and low viscosity of these materials present challenges, but incorporating thickeners or high-viscosity fruits can improve printability. Chocolate is another popular material for 3DFP due to its melting and solidifying properties, allowing for creative designs and even applications in pediatric medicine to mask the taste of drugs.

Moreover, edible insects, rich in protein and nutrients, are being incorporated into food products through 3DFP to address consumer biases by disguising their presence. Customized food applications for specific dietary needs, such as for children or individuals with dysphagia, showcase the potential of 3D printing technology to create appealing and functional food products. Overall, 3DFP offers innovative solutions for enhancing food design, nutrition, and consumer experience while addressing food waste by utilizing byproducts.



Fig 6: Workflow and different final products of 3-D printed foods.

Influencing factors of 3D food printing technology:

Interior factors:

The choice of raw materials is a crucial internal factor influencing the success of 3D food printing (3DFP). During the 3D printing process, food materials can face challenges such as collapse or deformation due to their own weight, making the selection of suitable ingredients imperative for achieving desired results. The characteristics of the raw materials, including their consistency and physical properties, play a vital role in determining the overall effectiveness and outcome of the printing process. One of the key elements affecting the printing success is the gelatinization of starch. When starch is subjected to heat and moisture, it undergoes gelatinization, causing its molecules to swell and soften. In 3D food printing, this transformation is significant as it affects how the starch behaves under pressure. For instance, when gas pressure is applied during the extrusion process, the internal molecules of starch may initially contract, leading to reduced viscosity and potential inconsistencies in the final product. As the material is extruded through the nozzle, the expanded molecules can cause variations in flow and shape retention, ultimately impacting the quality of the printed food. Achieving the right balance in starch gelatinization is therefore essential for ensuring that the printed food maintains its intended shape and texture.

In addition to starch, oligosaccharides—a category of carbohydrates made up of 2 to 10 monosaccharide units—also significantly contribute to the printing process. These compounds exhibit low solubility and function effectively as edible fibers and thickening agents. When combined with proteins and fats, oligosaccharides can help achieve the ideal viscosity needed for successful printing. This combination allows for better texture and mouthfeel in the final product, enhancing both the sensory experience and the structural integrity of the printed food. Proteins, too, play a critical role in the 3D printing of food. Protein polymers carry electrical charges that can influence how the materials interact during the printing process. The charge on protein molecules can affect their solubility and, consequently, the viscosity of the mixture, which is essential for maintaining a consistent flow through the printing nozzle. Moreover, proteins contribute to the nutritional profile of the printed food, making them valuable ingredients in developing healthy and appealing products. However, care must be taken to control the printing environment, as factors such as temperature and humidity can affect the behavior of these protein-based materials. Fat content is another consideration in 3D food printing. Fat-soluble vitamins, for example, are prone to oxidation when exposed to air, which can degrade their nutritional quality. To ensure the stability of these vitamins, it is essential to minimize air exposure during the printing process. This can be achieved by implementing protective measures such as inert gas atmospheres or carefully controlling the printing environment to reduce the potential for oxidation.

Overall, the main ingredients used in 3D food printing significantly impact the process and the quality of the final product. The interplay between starch, oligosaccharides, proteins, and fats can determine the printability of the material, the structural integrity of the printed food, and the overall sensory characteristics. Therefore, selecting the right combination of raw materials and understanding their properties is essential for achieving successful results in 3D food printing. By carefully considering these factors, food technologists and chefs can innovate and create unique, high-quality food products that cater to diverse dietary preferences and needs.

As 3DFP technology continues to evolve, the emphasis on raw material selection will remain paramount in harnessing its full potential for culinary creativity and nutritional enhancement.

External factors:

Temperature plays a crucial role as an external factor that significantly influences the outcomes of 3D food printing. Different food materials require specific temperatures for optimal extrusion and molding to ensure a smooth printing process and maintain the quality of the final product. The heating of raw materials to the appropriate temperature is essential not only for facilitating smooth extrusion through the printing nozzle but also for achieving effective molding on the build platform.

Each type of food material has its own optimal temperature range. For instance, materials like chocolate and candy are generally printed at elevated temperatures. The high temperatures allow these materials to achieve the desired viscosity for proper extrusion, which is necessary for intricate designs and layering. However, excessively high temperatures can negatively impact the cooling and setting time of the materials, potentially altering the flavor and texture of the food. On the other hand, materials like meat and pasta are typically printed at or near room temperature. This difference underscores the importance of tailoring the printing process to the specific characteristics of each raw material to achieve the best results.

In addition to temperature, the method of extrusion also affects the appearance and overall quality of the printed products. There are several common extrusion methods, including pressure extrusion, screw extrusion, and syringe extrusion, each with its unique advantages and drawbacks. Pressure extrusion relies on applying pressure to push the raw materials through the nozzle. This method can be advantageous in minimizing contact between the raw material and the machinery, but it tends to be slower and is prone to producing bubbles within the extruded food, which can compromise the aesthetic quality and structural integrity of the print.

Screw extrusion involves using an electric screw to pull the raw material down the feeding mechanism. This method effectively reduces the formation of bubbles due to its design, which facilitates continuous movement of the material. However, screw extrusion does involve direct contact with the raw material, which could potentially lead to heat buildup or degradation of sensitive ingredients. Syringe extrusion, on the other hand, uses a syringe-like mechanism to generate pressure and extrude the food material. This method also involves contact with the raw materials, making it suitable for printing solid and semi-solid foods, but it may not provide the same level of consistency in pressure as screw extrusion.

Furthermore, the distance between the nozzle and the build platform significantly influences the molding effect of the printed food. If the nozzle is positioned too close to the platform, the extruded material may encounter excessive pressure, preventing the raw ingredients from forming properly and risking the possibility of clogging the nozzle with unformed material. This situation can lead to contamination and further operational challenges during the printing process. Conversely, if the nozzle is too far from the platform, the extruded food may lose its desired shape and structure before it has a chance to settle properly on the build platform. This scenario can result in disrupted layer structures, leading to an unsatisfactory final appearance.

In summary, both temperature and extrusion methods are pivotal factors in the 3D food printing process. Adjusting the temperature to suit the specific raw materials ensures that they are extruded smoothly and molded correctly, while the choice of extrusion method affects the appearance and integrity of the printed product. Additionally, maintaining the appropriate distance between the nozzle and the printed food is vital for achieving the desired structural quality and aesthetic finish. By understanding and optimizing these external factors, food technologists and chefs can improve the quality and appeal of 3D-printed foods, paving the way for innovative culinary creations that meet diverse consumer needs and preferences. As the technology continues to develop, the ability to fine-tune these parameters will remain essential for maximizing the potential of 3D food printing in both commercial and home kitchens.

Current Trends in 3D Food Printing

1. Personalized Nutrition:

- **Tailored Meals:** 3D printing allows for highly personalized nutrition, where foods can be designed based on individual health data like DNA, allergies, or fitness goals.
- **Nutrient Control:** Macronutrients (proteins, fats, carbohydrates) and micronutrients (vitamins, minerals) can be precisely adjusted for each individual's dietary needs.
- **Healthcare Integration:** This is especially useful in healthcare, where patients may need customized meals for conditions like diabetes or dysphagia.
- **Athlete Nutrition:** Can design meals with specific energy requirements and recovery nutrients for athletes.

- **Elderly Care:** Meals can be tailored to ensure soft textures and easy-to-chew formats for elderly patients, addressing both nutritional and physical needs.
- **Real-Time Adjustments:** Using apps or digital interfaces, users can instantly adjust their meal design to match their daily nutritional needs.
- **Sustainability:** By creating precise portion sizes, food waste is minimized, promoting a more sustainable approach to meal preparation.

2. **Sustainability and Alternative Proteins:**

- **Insect Proteins:** 3D printing is being used to integrate sustainable protein sources like edible insects, which are rich in protein and have a low environmental impact.
- **Plant-Based Printing:** Plant-based meats and proteins are used to create eco-friendly alternatives to animal-based products, catering to vegan or environmentally-conscious consumers.
- **Lab-Grown Meat:** The use of lab-cultured meat cells for 3D printing reduces the need for livestock, offering a solution to the environmental impacts of traditional meat production.
- **Reducing Waste:** By using food by-products and underutilized ingredients like vegetable trimmings, 3D printing helps reduce food waste.
- **Minimizing Resource Use:** 3D printing can optimize ingredient use, reducing the need for excess water, land, and energy typically required in conventional food production.
- **Circular Economy:** Food waste from other industries, such as breweries or farms, can be converted into printable food materials.
- **Environmental Impact:** These trends align with global efforts to address the environmental challenges posed by industrial agriculture and food waste.

3. **Customized Food for Special Needs:**

- **Texture Modification:** For people with swallowing difficulties (dysphagia), 3D printers can produce foods with the correct texture and consistency, making them easier to swallow.
- **Medical Diets:** Patients with specific medical conditions, such as gluten intolerance, lactose intolerance, or diabetes, can receive food printed with their exact dietary requirements.
- **Elderly Nutrition:** Custom-made food with softer textures for the elderly can ensure proper nutrition and make meals more enjoyable.
- **IDDSI Standards:** 3D printers can help meet the International Dysphagia Diet Standardization Initiative (IDDSI) by creating foods with the exact consistency required.
- **Precision for Allergies:** Ingredients can be controlled to eliminate allergens, making meals safer for those with food allergies.
- **Children's Nutrition:** 3D printed food can be designed to be visually appealing for children, encouraging healthier eating habits.
- **Sports Nutrition:** Meals for athletes can be customized with specific nutrient content, protein levels, and energy balance to meet their performance goals.

4. **Culinary Art and Fine Dining:**

- **Gourmet Presentations:** Chefs use 3D printing to create visually stunning, complex designs that are difficult or impossible to achieve through traditional cooking methods.
- **Innovative Textures:** 3D printing allows chefs to experiment with unique textures, layering soft, crunchy, and gelatinous components in a single dish.
- **Customization in Real-Time:** Diners can customize their meals based on preferences, with 3D printers adjusting ingredients or presentation on the fly.
- **Showpieces:** High-end restaurants create showpiece desserts and intricate sculptures using 3D printed sugar, chocolate, or pastry components.
- **Unique Flavors:** The technology allows chefs to integrate flavours in novel ways, like embedding different taste elements at specific locations in a dish.
- **Interactive Dining:** Diners may be able to participate in the customization of their meals using apps or at-table 3D food printers.
- **Michelin-Star Kitchens:** 3D printing is increasingly being adopted by gourmet kitchens, offering new ways to surprise and delight customers with artistic and flavourful dishes.

5. **Reduction of Food Waste:**

- **Utilizing By-Products:** Food by-products like vegetable skins or meat scraps can be transformed into edible paste or powder for 3D printing, reducing waste.

- Precision Portioning: 3D printing allows precise portion control, reducing the likelihood of food waste from oversized portions.
- Repurposing Waste: Ingredients that might otherwise be discarded can be reformulated.

Conclusion:

3D food printing represents a significant advancement in the culinary and food production landscape, merging technology and creativity to redefine how we approach food preparation, personalization, and sustainability. As the food industry grapples with evolving consumer demands and environmental challenges, the versatility of 3D food printing offers innovative solutions that can cater to a variety of needs while enhancing the overall dining experience.

At the heart of 3D food printing is its ability to create personalized meals tailored to individual preferences and dietary requirements. This technology allows for precise control over nutritional content, enabling users to design meals that align with their specific health goals, lifestyle choices, and dietary restrictions. From athletes seeking optimal performance nutrition to individuals managing chronic health conditions, the potential to customize meals offers a pathway to healthier eating habits and improved well-being. Additionally, for populations such as the elderly or those with dysphagia, the ability to adjust food texture and consistency can make a profound difference in quality of life, ensuring that nutritious food is accessible and enjoyable.

The implications of 3D food printing extend beyond individual nutrition to address broader societal challenges, particularly in the realm of food sustainability. With growing concerns about food waste, resource consumption, and the environmental impact of traditional agriculture, 3D printing technology presents an opportunity to innovate. By utilizing alternative protein sources, repurposing food by-products, and creating precise portion sizes, this technology can significantly reduce the ecological footprint of food production. Incorporating edible insects and plant-based ingredients not only contributes to sustainable diets but also caters to the increasing consumer demand for environmentally responsible food options.

Moreover, 3D food printing serves as a tool for culinary creativity, allowing chefs to experiment with textures, shapes, and flavors in ways that were previously unattainable. The artistic possibilities opened up by this technology can elevate dining experiences, turning meals into visual masterpieces that engage diners on multiple sensory levels. High-end restaurants are increasingly adopting 3D printing techniques, creating unique and intricate dishes that showcase both skill and innovation. This integration of technology in the culinary arts is not just about aesthetics; it also enhances flavor profiles and overall satisfaction, allowing chefs to craft dishes that surprise and delight their patrons.

However, the journey of 3D food printing is not without its challenges. While the technology has made significant strides, there are still barriers to overcome regarding material limitations, production speed, and consumer acceptance. The diversity of edible materials that can be used in 3D printing is still narrower compared to traditional cooking methods, and ensuring the stability and safety of printed foods remains a critical concern. Moreover, the perception of 3D-printed food as a novelty or gimmick poses an obstacle to its widespread adoption. Addressing these concerns will require ongoing research, development, and education to build consumer trust and understanding of the technology's potential benefits.

As the technology advances, collaboration between researchers, chefs, and food manufacturers will be essential to explore new materials and techniques that enhance the functionality and appeal of 3D-printed foods. Innovations in the field will likely lead to the development of new applications, expanding the possibilities for diverse food products. Furthermore, as the integration of 3D food printing into culinary practices becomes more commonplace, there is potential for the emergence of a new culinary culture that embraces technology alongside traditional techniques, fostering a deeper appreciation for the art of food preparation.

In terms of regulatory and safety standards, as the technology becomes more mainstream, it will be imperative to establish clear guidelines to ensure that 3D-printed foods meet health and safety requirements. These regulations should address sourcing, handling, and hygiene practices to mitigate any potential risks associated with food production and consumption. Transparency in the 3D food printing process will help consumers feel more comfortable with the technology, promoting acceptance and encouraging innovation in the sector.

Ultimately, the future of 3D food printing holds immense promise for reshaping our food systems, enhancing nutrition, and creating engaging culinary experiences. By harnessing this technology, we have the opportunity to not only meet the diverse needs of consumers but also to address the pressing challenges facing our food

systems. As the world continues to evolve, embracing innovative technologies like 3D food printing may be a critical step toward a more sustainable, equitable, and delicious future.

In conclusion, the transformative potential of 3D food printing lies in its ability to bridge the gap between nutrition, sustainability, and culinary artistry. As we move forward, it is crucial to embrace this technology not only as a tool for innovation but also as a means to foster a healthier and more sustainable food culture. The interplay between science and art within the realm of food offers a canvas for creativity, encouraging a reimagination of how we perceive and consume food. Through continuous research, education, and collaboration, we can unlock the full potential of 3D food printing, paving the way for a future where personalized, nutritious, and environmentally friendly food is accessible to all.

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