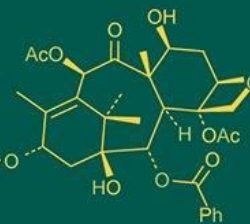
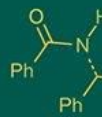
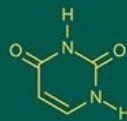
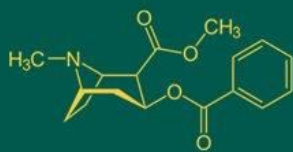


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
 ISSN Online: 2617-4707
 NAAS Rating: 5.29
 IJABR 2025; 9(6): 769-775
www.biochemjournal.com
 Received: 01-04-2025
 Accepted: 05-05-2025

Samar Jan

Ph.D Research Scholar,
 Division of Food Science and
 Technology, Sher-e-Kashmir
 University of Agriculture
 Science and Technology,
 Jammu and Kashmir, India

Sachin GR

M-Tech Research Scholar,
 Division of Food Science and
 Technology, Sher-e-Kashmir
 University of Agriculture
 Science and Technology,
 Jammu and Kashmir, India

Sajad Mohammad Wani

Professor, Division of Food
 Science and Technology, Sher-
 e-Kashmir University of
 Agriculture Science and
 Technology, Jammu and
 Kashmir, India

Mohammad Amaan Seh

Ph.D Research Scholar,
 Division of Food Science and
 Technology, Sher-e-Kashmir
 University of Agriculture
 Science and Technology,
 Jammu and Kashmir, India

The future in layers: A comprehensive review of 3D printing technology

Samar Jan, Sachin GR, Sajad Mohammad Wani and Mohammad Amaan Seh

DOI: <https://www.doi.org/10.33545/26174693.2025.v9.i6i.4611>

Abstract

In recent times, additive manufacturing has positioned itself as a highly promising advancement in production technology. Unlike traditional manufacturing techniques, where materials are either shaped or subtracted, this method constructs intricate designs by layering materials systematically. Additive manufacturing has seen widespread adoption across multiple sectors, such as aerospace, automotive, construction, and healthcare. The food industry has also embraced this technology. Commonly referred to as 3D printing, this method is used to create food products with varied shapes, textures, and nutritional profiles, making 3D food printing (3DFP) a groundbreaking development within the sector. Today's global consumers are highly discerning when it comes to factors such as food appearance, taste, and health benefits. As a result, 3DFP holds the potential to significantly disrupt and enhance the food industry. This paper offers an in-depth review of the processes associated with 3DFP, the edible materials (or inks) involved, and the nutritional aspects of 3D-printed food products.

Keywords: 3D printing, inks, nutrition

Introduction

3D printing is a type of additive manufacturing that constructs a three-dimensional object by layering materials sequentially. A typical food printer consists of three main components: a computer that enables user interaction via specialized software, the software that facilitates communication between the computer and the motor control system, and the motors of the food printer, which are regulated by the control box. The food industry is on the brink of a technological transformation, broadening culinary possibilities. Imagine a 3D printer creating an exquisite culinary creation-3D food printing is making this vision of precisely designed dishes a reality.

Additive manufacturing in the food industry, also known as 3D food printing, integrates elements of culinary arts, engineering, and materials science. With the use of specialized printers, food ingredients are layered to create edible products. This cutting-edge technology enables the precise, layer-by-layer creation of food items. It has the potential to revolutionize the food sector by offering personalized nutrition, allowing meals to be customized with specific dietary components and enabling accurate control of nutritional content. Additionally, 3D food printing could transform how food is produced and consumed by fostering sustainable practices, minimizing food waste, and utilizing resources more efficiently. This rapidly advancing field is set to transform how we create, experience, and interact with food, drawing attention from scientists, producers, and consumers alike. A crucial aspect of 3D food printing is understanding the physical characteristics of food ingredients. What makes this technology unique is the interplay between physics and food, where mastering these physical properties is essential for success. Key factors include viscosity, rheology, surface tension, and thermal effects. Table 1 provides a comprehensive overview of how these physical properties impact the structure and design of 3D-printed food. Viscosity controls the material's flow, influencing how the printer extrudes or deposits it. Rheology plays a role in layer adhesion, requiring properties such as viscosity, shear-thinning behaviour, and viscoelasticity to ensure proper bonding between layers. Surface tension affects the smoothness and shape of the printed food. Moreover, thermal effects regulate temperature, impacting the material's state, texture, and flavour throughout the printing process.

Corresponding Author:

Samar Jan,
 Ph.D Research Scholar,
 Division of Food Science and
 Technology, Sher-e-Kashmir
 University of Agriculture
 Science and Technology,
 Jammu and Kashmir, India

Impact of Physical Characteristics on the Structure and Design of 3D-Printed Food

Table 1: Presents the Impact of Physical Characteristics on the Structure and Design of 3D-Printed Food.

Physics Principle	Impact on the Design and Structural Integrity of 3D-Printed Food	Reference
Rheology	Controls the flow behaviour of food materials throughout the printing process. Adjusts the viscosity and elasticity of the food during extrusion. Influences layer positioning and the overall structural stability of the printed food.	1. Yang, F., Zhang, M., Bhandari, B., & Liu, Y. (2018). Investigation on lemon juice gel as food material for 3D printing and optimization of printing parameters. <i>Lwt</i> , 87, 67-76.
		2. Derossi, A., Caporizzi, R., Azzollini, D., & Severini, C. (2018). Application of 3D printing for customized food. A case on the development of a fruit-based snack for children. <i>Journal of Food Engineering</i> , 220, 65-75.
Heat Transfer	Regulates temperature during printing to oversee phase transitions in food materials. Affects the texture and taste of the final 3D-printed food product.	1. Ma, Y., Schutyser, M. A., Boom, R. M., & Zhang, L. (2022). Thermographic and rheological characterization of viscoelastic materials for hot-extrusion 3D food printing. <i>Innovative Food Science & Emerging Technologies</i> , 81, 103135.
		1. Rando, P., & Ramaoli, M. (2022). Numerical simulations of sintering coupled with heat transfer and application to 3D printing. <i>Additive Manufacturing</i> , 50, 102567.
Mass Transfer	Enhances flavour distribution and nutrient redistribution during printing. Influences the consistency and uniformity of food properties throughout the printed structure.	1. Derossi, A., Caporizzi, R., Paolillo, M., Oral, M. O., & Severini, C. (2021). Drawing the scientific landscape of 3D Food Printing. Maps and interpretation of the global information in the first 13 years of detailed experiments, from 2007 to 2020. <i>Innovative Food Science & Emerging Technologies</i> , 70, 102689.
Solidification	Regulates the cooling rate and crystallization process during printing. Affects the microstructure and overall structural integrity of the printed food.	1. Zhu, S., Wang, W., Stieger, M., van der Goot, A. J., & Schutyser, M. A. (2022). Shear-induced structuring of phase-separated sodium caseinate-sodium alginate blends using extrusion-based 3D printing: Creation of anisotropic aligned micron-size fibrous structures and macroscale filament bundles. <i>Innovative Food Science & Emerging Technologies</i> , 81, 103146.
Phase Separation	Controls the distribution of different components in multi-material printing. Enables the creation of complex food structures with distinct properties.	1. Li, X., Xu, X., Song, L., Bi, A., Wu, C., Ma, Y., & Zhu, B. (2020). High internal phase emulsion for food-grade 3D printing materials. <i>ACS Applied Materials & Interfaces</i> , 12(40), 45493-45503.
Surface Tension	Shapes the form and visual aesthetics of the printed food's surface. Influences the ability to create intricate designs and patterns on the food's exterior.	1. Rahmatabadi, D., Soltanmohammadi, K., Aberoumand, M., Soleyman, E., Ghasemi, I., Baniassadi, M., & Baghani, M. (2023). Development of pure poly vinyl chloride (PVC) with excellent 3D printability and macro-and micro-structural properties. <i>Macromolecular Materials and Engineering</i> , 308(5), 2200568.
Capillary Action	Enables the movement of liquids within porous food materials. Affects the distribution and retention of moisture in the printed food structures.	1. Thangalakshmi, S., Arora, V. K., & Prithviraj, V. (2021, May). Dimensional Accuracy of 3D Printable Food Construct. In 2021 Emerging Trends in Industry 4.0 (ETI 4.0) (pp. 1-4). IEEE.
3D Printing Settings and Variables	Layer height, printing speed, nozzle diameter, and infill density affect the structural integrity and design of the printed food. Proper adjustment of these parameters ensures accurate material deposition and maintains the integrity of the printed structure.	1. Chen, X., Zhang, M., Teng, X., & Mujumdar, A. S. (2022). Recent progress in modeling 3D/4D printing of foods. <i>Food Engineering Reviews</i> , 1-14.
		1. Chen, Y., Zhang, M., Sun, Y., & Phuhongsung, P. (2022). Improving 3D/4D printing characteristics of natural food gels by novel additives: A review. <i>Food Hydrocolloids</i> , 123, 107160.
		2. Jiang, H., Zheng, L., Zou, Y., Tong, Z., Han, S., & Wang, S. (2019). 3D food printing: Main components selection by considering rheological properties. <i>Critical reviews in food science and nutrition</i> , 59(14), 2335-2347.
Digital Simulation and Predictive Modelling	Utilizes simulation tools to optimize food design and predict behaviour during printing. Allows virtual testing of different parameters to achieve better results.	1. Guo, C. F., Zhang, M., & Bhandari, B. (2019). A comparative study between syringe-based and screw-based 3D food printers by computational simulation. <i>Computers and Electronics in Agriculture</i> , 162, 397-404.
		1. Oyinloye, T. M., & Yoon, W. B. (2021). Application of computational fluid dynamics (CFD) simulation for the effective design of food 3D printing (A review). <i>Processes</i> , 9(11), 1867.

The Emergence of First-Generation Food Printers

The conceptual frameworks for initial models of food printers concentrated on the integration of 3D printing technology with culinary practices to improve the customization of food. These printers were designed to meet the unique dietary needs and preferences of individuals, especially those with particular nutritional requirements. The following sections will detail the essential features of those groundbreaking designs

Functional Prototypes

- **Customization Capabilities:** First-generation food printers harness the capabilities of 3D printing technology to fabricate tailored food items that cater to individual preferences. This innovative approach allows for significant alterations in various aspects of the food, including flavor profiles, nutritional composition, and textural characteristics. By utilizing this technology, these printers can produce meals that align closely with

the specific tastes and dietary requirements of consumers, thereby enhancing the overall dining experience. This customization not only satisfies personal preferences but also ensures that nutritional needs are met effectively, making these printers a valuable tool in modern culinary practices (Sun *et al.*, 2015) ^[17].

- **Artistic Integration:** These printers facilitate the creation of visually stunning food designs, effectively blending culinary artistry with engineering innovations. This convergence of creativity and technology serves various applications, catering to both home kitchens and commercial food production environments. By enabling chefs and food designers to explore complex shapes and patterns, these printers push the limits of conventional cooking, fostering the creation of distinctive and visually appealing dishes. Whether in a domestic setting or in large-scale food manufacturing, the integration of these advanced printing technologies empowers users to push the limits of their culinary imaginations while ensuring precision and consistency in food presentation (Sun *et al.*, 2015) ^[17].

Mechanisms and Technologies

- **Printing Mechanisms:** A variety of designs integrate rotating nozzles and specialized printing plates, which enable meticulous regulation of the extrusion and layering processes in food production. This technological advancement allows for enhanced precision in the deposition of ingredients, facilitating the creation of complex and intricate food structures. By controlling the movement and alignment of the nozzles and plates, these designs provide operators with the ability to fine-tune the texture and appearance of the printed food items. Such precision is crucial for achieving the desired culinary results, whether it be for aesthetic purposes or to ensure that each layer contributes effectively to the overall flavor and quality of the dish (Andrew & Lucia, 2018) ^[18].
- **Heating and Extrusion:** Certain models are equipped with heating components designed to warm food materials prior to the extrusion process. This heating system functions to soften the ingredients, enhancing both the aesthetic quality and the structural stability of the final 3D-printed food products. By carefully controlling the temperature, these printers can facilitate a smoother extrusion process, allowing for more uniform and precise layering. As a result, the aesthetic qualities of the printed items are significantly enhanced, making them more visually appealing while also ensuring that the texture and consistency align with culinary expectations. This capability is particularly valuable in producing intricate designs that require a delicate balance between form and function in food presentation (Jingdong, 2015) ^[19].

Market Potential

- **Target Demographics:** The technology offers substantial advantages for the elderly demographic, especially those experiencing challenges with swallowing. This presents a noteworthy market opportunity for the development of personalized food solutions tailored to meet the specific needs of this population. By addressing the unique dietary

requirements of seniors who may struggle with conventional food textures and consistencies, the technology can facilitate the creation of meals that are easier to consume and more enjoyable. This targeted approach not only improves the overall dining experience for individuals with swallowing difficulties but also highlights the potential for innovation within the food industry to cater to a growing segment of the population. The intersection of health and culinary customization in this context underscores the importance of developing specialized food products that enhance nutrition and quality of life for aging individuals (Sun *et al.*, 2015) ^[17].

Although first-generation food printers demonstrate significant potential in terms of customization and operational efficiency, there are still considerable challenges that must be addressed. These include difficulties in scaling up production processes and ensuring compliance with food safety regulations, which could impede broader acceptance and implementation within the food industry. Without effective solutions to these obstacles, the potential of 3D food printing technology may not be fully realized, limiting its integration into mainstream culinary practices and food manufacturing. Addressing these issues will be crucial for fostering confidence among consumers and industry stakeholders alike, thereby facilitating the widespread adoption of this innovative technology.

Applications of 3D Food Printing

3D food printing is a cutting-edge technology that merges digital design with food manufacturing, enabling tailored and personalized food creations. This technology has found applications across various fields such as healthcare, the military, and space missions, thanks to its ability to cater to unique dietary requirements and improve the visual appeal of food. The sections below discuss essential elements of 3D food printing, covering its uses, recent technological progress, and the challenges it faces.

- **Healthcare:** In the realm of healthcare, 3D food printing presents significant potential for producing customized meals tailored to meet the specific needs of patients suffering from conditions such as dysphagia. This condition, characterized by difficulty in swallowing, requires food to have particular textures and consistencies to ensure safe consumption. Through 3D food printing, meals can be precisely formulated to not only align with these medical requirements but also to remain visually appealing and palatable. This approach enhances the patient's mealtime experience, promoting better nutritional intake and overall well-being. The capability to modify textures while preserving an appealing presentation highlights the importance of this technology in enhancing patient-centred care and improving the quality of life for individuals with dietary challenges. (Ma, 2024) ^[21].
- **Military and Space:** In the context of military operations and space exploration, 3D food printing has emerged as a promising technology for creating on-demand food solutions tailored to the unique conditions faced by military personnel and astronauts. These environments often require food that is not only nutrient-dense but also convenient and long-lasting. 3D food printing enables the production of meals that can

be customized to meet the specific dietary and energy needs of individuals in these challenging settings, ensuring optimal nutrition and performance. The ability to print meals on-demand addresses logistical hurdles associated with traditional food supply chains, reducing the need for extensive storage and minimizing waste. For astronauts, who face limited resupply opportunities, and military personnel in remote or combat locations, this technology enhances the variety and quality of their diet, contributing to better health and morale. By integrating advanced food production methods with the operational requirements of these demanding fields, 3D food printing offers a practical solution for sustaining personnel through balanced and personalized nutrition (Almusawi & Tandio, 2024) ^[9].

- **Catering and Personalization:** In the sphere of catering and food personalization, 3D food printing technology has been adopted by chefs to craft intricate

and one-of-a-kind food presentations. This innovative approach allows culinary professionals to push the boundaries of traditional food preparation, resulting in visually striking and meticulously detailed dishes. By leveraging the precision and flexibility of 3D printing, chefs are able to create custom designs that enhance the sensory experience for diners, incorporating artistic elements that elevate the overall dining experience (Millán & Torre, 2024) ^[10]. This technology also supports greater creativity and experimentation, enabling chefs to tailor meals to individual preferences and dietary needs, thus fostering a deeper connection with their guests. The fusion of digital precision and culinary artistry signifies a new frontier in gastronomy, emphasizing both aesthetic appeal and personalization as key components in modern food experiences.

Industries Benefiting from 3D Printing Technology

Following is the Table 2 showing Industries Benefiting from 3D Printing Technology

Manufacturing	Medical	Retail	Others
Aerospace	Prosthetics	Rapid prototyping	Food
Automotive	Custom Implants	Localized manufacturing	Military
Prototype	Medical supplies	Novelty sector	Spare parts
Construction	Organ reconstruction	Consumer goods	Customized items
Architectural	Dental coping	Fashion	

Personalized Nutrition

The customization of food for specific dietary restrictions using 3D food printing represents a groundbreaking method in personalized nutrition. This technology enables the development of food items specifically designed to meet individual dietary requirements, improving both their nutritional value and taste. The subsequent sections will detail the essential elements of this innovative approach.

- **Personalized Nutrient Delivery:** 3D printing technology facilitates the creation of food products that are designed to contain particular nutrients and functional compounds, effectively addressing the unique health needs of individuals. By allowing for precise control over the composition and structure of food items, this innovative method can tailor formulations to enhance nutritional profiles and provide health benefits that align with specific dietary requirements. This capability opens up new possibilities for personalized nutrition, enabling consumers to obtain foods that support their individual wellness goals and health conditions (Severini & Derossi, 2016) ^[13].
- **Targeted Solutions for medical conditions:** For medical conditions such as Inborn Errors of Intermediary Metabolism, 3D printing technology offers the potential to create tailored chewable dosage forms that are specifically designed to meet individual nutritional needs. This capability ensures that patients receive accurate amounts of essential nutrients while adhering to their prescribed dietary regimens. By producing customized formulations that consider the unique metabolic requirements of these conditions, 3D printing can enhance patient compliance and support better health outcomes. This innovative approach not only simplifies the administration of dietary supplements but also contributes to a more effective management of metabolic disorders by providing a convenient and palatable means of delivering necessary

nutrients (Carou-Senra *et al.*, 2023) ^[14].

Textural Adaptation

- **Addressing Dysphagia:** This technology enables the alteration of food textures, rendering them more appropriate for elderly individuals who experience difficulties with swallowing. To achieve the desired soft consistency, hydrocolloids are frequently employed, as they effectively modify the physical properties of food. By utilizing these substances, 3D printing can produce meals that are not only easier to consume but also maintain their nutritional value, thus enhancing the dining experience for seniors. This adaptation is particularly crucial for ensuring that individuals with swallowing challenges receive adequate nourishment while enjoying their meals (Chao *et al.*, 2024) ^[15].
- **Enhanced Sensory Experience:** Through the integration of different food materials, 3D printing technology can enhance the sensory attributes of food, resulting in products that are not only more visually appealing but also easier to eat. This innovative approach allows for the creation of food items that cater to diverse tastes and textures, ultimately improving the overall eating experience. By carefully selecting and combining various ingredients, 3D printing can produce meals that are more enjoyable and satisfying, thereby encouraging greater consumption, particularly among individuals with specific dietary needs or preferences. This enhancement of sensory quality plays a significant role in promoting healthy eating habits and ensuring that meals are both nutritious and pleasurable (Chao *et al.*, 2024) ^[15].

Production Efficiency

Mass Customization Potential: 3D food printing provides an innovative answer to the conventional challenges associated with food customization, including elevated costs

and inefficiencies. By merging the principles of digital gastronomy with the processes of food manufacturing, this technology streamlines the customization of food products. It allows for precise and efficient production methods that can adapt to individual preferences and dietary requirements without the typical economic burden or logistical complications often encountered in traditional food preparation. As a result, 3D food printing not only enhances the accessibility of personalized nutrition but also revolutionizes the way food is created, making it a more feasible option for both consumers and producers (Sun *et al.*, 2015) ^[17].

Although 3D food printing presents considerable potential for personalizing diets, several challenges persist that must be addressed. These include regulatory barriers that may hinder widespread adoption and implementation, as well as the necessity for additional research into the compatibility of various ingredients within this technology. Furthermore, gaining consumer acceptance remains a critical aspect that requires attention, as individuals may have reservations regarding the safety and quality of 3D-printed foods. Overcoming these obstacles is essential for fully realizing the capabilities of 3D food printing in delivering customized dietary solutions that meet the diverse needs of consumers (Dankar *et al.*, 2018) ^[16].

Inks used in 3d Food Printing

The inks utilized in 3D food printing are varied and specifically designed to improve printability, stability, and nutritional benefits. Recent innovations have resulted in a range of edible inks, each possessing distinct properties that are suited to particular printing methods and culinary applications. The following sections will detail the main categories of inks and their unique features:

Multi-Material Inks

- **Y-Junction Nozzle:** This technique enables a smooth transition between two food inks that have varying rheological characteristics, leading to a 74% reduction in printing errors ("Multi-material Direct Ink Writing 3D Food Printing using Multi-channel Nozzle," 2024).
- **Application:** Facilitates the production of intricate food designs featuring anisotropic configurations.

Emulsions and Hydrocolloids

- **HIPPEs:** High internal phase Pickering emulsions formulated with modified pea protein and sodium alginate demonstrate improved printability and stability, preserving their structural integrity for a duration of 24 hours (Ma *et al.*, 2024) ^[21].
- **Hydrocolloid Effects:** Xanthan gum and alginate enhance water retention and rheological characteristics, promoting smooth extrusion and accurate printing (Jeon *et al.*, 2023) ^[22].

Gelatin and Starch-Based Inks

- **Composite Hydrogels:** Mixtures of fish gelatin and gellan gum demonstrate excellent printability and structural integrity (Bian *et al.*, 2023) ^[23].
- **Starch Utilization:** Starch acts as a multifunctional bio-ink, and its modifications improve its physicochemical characteristics for a range of food applications (Chen *et al.*, 2022) ^[24].

While these advancements highlight the potential of 3D food printing, challenges remain in achieving consistent quality and scalable production. Further research is needed to optimize these food inks for broader application in the industry.

Advancements in Technological Innovation

- **Material Development:** In the field of material development for 3D food printing, research is primarily directed towards enhancing the mechanical and rheological properties of food inks to achieve superior printing performance. This involves in-depth studies to refine the composition and behavior of various food substrates, ensuring they exhibit the appropriate viscosity, flow behavior, and structural integrity necessary for accurate and stable printing. Optimizing these properties is crucial for maintaining the precision and consistency of printed food items, which directly influences the final product's texture, appearance, and overall quality. Researchers strive to create formulations that not only meet the technical requirements for effective printing but also preserve the nutritional value and sensory attributes of the food. By advancing the development of tailored food inks, this research supports the broader goal of making 3D food printing a viable and versatile tool in both industrial and consumer applications (Bi *et al.*, 2024) ^[11].
- **Automation:** The integration of 3D printing technology in food production introduces a high level of automation to traditionally labor-intensive processes. This advancement holds significant potential for mitigating the challenges posed by labor shortages within the food industry. By automating tasks that would otherwise require substantial manual effort, 3D food printing streamlines production, enhancing efficiency and reducing the reliance on human labor. This automated approach not only accelerates the food preparation process but also ensures greater consistency and precision, leading to improved product quality. Additionally, it allows for the scaling of operations without a proportional increase in labor costs, making it an economically advantageous solution for food manufacturers and service providers. The application of automation through 3D food printing addresses critical workforce gaps and supports the industry's ability to meet growing consumer demand while maintaining high standards of safety and quality (Niyet *et al.*, 2024).
- **Post-Processing Techniques:** In the realm of 3D food printing, significant attention is being directed toward post-processing techniques to improve the quality and appeal of printed food products. Among these innovations, laser treatment has emerged as a promising method to refine the final characteristics of printed items. This advanced approach involves the application of laser technology to modify surface textures, enhance structural integrity, and achieve desired browning or crisping effects, which contribute to a more appealing appearance and improved sensory qualities. The use of such post-processing methods extends beyond mere aesthetics, as they play a pivotal role in enhancing the overall eating experience by adjusting moisture levels and adding flavor profiles through controlled heat application. By incorporating laser treatment and similar technologies, researchers and industry

professionals aim to elevate the standard of printed foods, ensuring that they meet consumer expectations for taste, texture, and visual presentation. This focus on post-printing refinement reflects the industry's commitment to advancing 3D food printing from a novel concept to a practical and desirable solution for modern food production (Bi *et al.*, 2024) ^[11].

Challenges and Future Directions

- **Standardization and Safety:** In the field of 3D food printing, the absence of standardized food inks and comprehensive safety protocols presents notable challenges that hinder its broader adoption and reliability. Inconsistencies in the composition and formulation of food inks lead to variations in printing performance, structural consistency, and the overall quality of the final products. This inconsistency poses obstacles for scaling up the technology and ensuring that printed food items meet regulatory and consumer expectations for safety and nutritional value. Furthermore, the establishment of rigorous safety guidelines is essential to protect consumers and maintain public trust in this emerging technology. Without clear safety standards, the risk of contamination, improper handling, or unforeseen health effects remains a critical concern. The development of industry-wide protocols would facilitate safer operations, provide a framework for compliance, and promote best practices among food manufacturers and innovators. Addressing these gaps is vital for advancing 3D food printing from an experimental stage to a dependable and mainstream solution in the food industry, ensuring the safety and well-being of consumers while supporting technological progress (Almusawi & Tandio, 2024) ^[9].
- **Consumer Acceptance:** Achieving consumer trust and acceptance represents a significant obstacle to the widespread adoption of 3D food printing technology. Despite its innovative potential and numerous benefits, many consumers remain skeptical about the safety, nutritional quality, and overall appeal of printed food products. This hesitation is often rooted in a lack of familiarity with the technology and concerns regarding the processes involved in 3D food production. To foster greater acceptance, it is imperative for industry stakeholders to engage in comprehensive educational initiatives that inform consumers about the advantages of 3D printed foods, including customization, enhanced nutrition, and sustainability. Transparency in the production processes, ingredient sourcing, and safety measures is essential to alleviate concerns and build confidence among consumers. Furthermore, positive experiences and endorsements from early adopters can play a crucial role in influencing public perception. By addressing misconceptions and demonstrating the reliability and safety of 3D printed foods, the industry can pave the way for broader acceptance and integration of this technology into mainstream culinary practices. Addressing consumer acceptance challenges is essential for fully realizing the potential of 3D food printing and shifting it from a novelty to a mainstream innovation in the food industry.
- **Research Gaps:** There exists a pressing necessity for further research into the functionality and nutritional

value of foods produced through 3D printing. Despite the promising applications of this innovative technology, there remains a significant gap in understanding how the printing process influences the physical properties, texture, and nutritional composition of the final food products. Comprehensive studies are essential to evaluate the bioavailability of nutrients, the impact of different printing parameters on food quality, and the overall health implications of consuming 3D-printed foods. Such research will not only enhance our knowledge of the nutritional profiles of these products but also support the development of formulations that maximize both health benefits and sensory appeal. Additionally, investigating the functionality of 3D-printed foods—such as their textural attributes, stability, and compatibility with various dietary needs—will be crucial in promoting their adoption in diverse culinary and healthcare settings. Ultimately, a robust body of research will provide the necessary evidence to establish the safety, efficacy, and practicality of 3D-printed foods, thus facilitating their acceptance and integration into the broader food industry.

Conclusion

In conclusion, 3D food printing represents a transformative advancement in the culinary landscape, offering innovative solutions for food customization and personalization. By enabling precise control over flavor, texture, and nutritional content, this technology addresses diverse dietary needs and preferences, making it particularly beneficial for individuals with specific health requirements. Despite the promising developments and applications in various sectors, such as healthcare, catering, and food production, challenges related to quality consistency, production scalability, and food safety standards remain significant barriers to widespread adoption. Continued research and innovation are crucial to overcoming these obstacles, optimizing food inks, and enhancing the technology's reliability. As the field evolves, 3D food printing has the potential to revolutionize the way we approach food design and consumption, paving the way for more inclusive and adaptable culinary experiences in the future.

References

1. Waseem M, Tahir AU, Majeed Y. Printing the future of food: The physics perspective on 3D food printing. *Food Phys.* 2024;1:100003.
2. Millen CI. The development of colour 3D food printing system [Master's thesis]. Palmerston North (NZ): Massey University; 2012.
3. Majeed Y, Waseem M. Postharvest handling systems. In: *Encyclopedia of Smart Agriculture Technologies*. Cham: Springer International Publishing; 2022. p. 1-9.
4. Gulzar S, Narciso JO, Elez-Martínez P, Martín-Belloso O, Soliva-Fortuny R. Recent developments in the application of novel technologies for the modification of starch in light of 3D food printing. *Curr Opin Food Sci.* 2023;52:101067.
5. Varvara RA, Szabo K, Vodnar DC. 3D food printing: Principles of obtaining digitally-designed nourishment. *Nutrients.* 2021;13(10):3617.
6. Xie Y, Liu Q, Zhang W, Yang F, Zhao K, Dong X, *et al.* Advances in the potential application of 3D food

- printing to enhance elderly nutritional dietary intake. *Foods*. 2023;12(9):1842.
7. Portanguen S, Tournayre P, Sicard J, Astruc T, Mirade PS. 3D food printing: Genesis, trends and prospects. In: *Future Foods*. Academic Press; 2022. p. 627-44.
 8. Ma Y. 3D food printing: Monitoring, quality assessment and adaptation with machine vision. 2024. doi:10.18174/654521
 9. Almusawi H, Wicaksono J, Tandio. Towards the development of foods 3D printer: Trends and technologies for foods printing. *Heliyon*. 2024; doi:10.1016/j.heliyon.2024.e33882
 10. Dancausa MG, Millán Vázquez de la Torre MG. 3D food printing: Technological advances, personalization and future challenges in the food industry. *Int J Gastron Food Sci*. 2024; doi:10.1016/j.ijgfs.2024.100963
 11. Si W, Bi J, Pi H, Chen H, Zhou Y, Liu R, *et al*. Research landscape and trending topics on 3D food printing - a bibliometric review. *Rapid Prototyp J*. 2024; doi:10.1108/rpj-02-2024-0098
 12. Niyet IZ, Doğan S, Çobanoğlu C. Feeding the future: 3D food printing as a strategic response to labor scarcity. *Worldw Hosp Tour Themes*. 2024; doi:10.1108/whatt-07-2024-2161
 13. Severini C, Derossi A. Could the 3D printing technology be a useful strategy to obtain customized nutrition. *J Clin Gastroenterol*. 2016; doi:10.1097/MCG.0000000000000705
 14. Carou-Senra P, Rodríguez-Pombo L, Monteagudo-Vilavedra E, Awad A, Alvarez-Lorenzo C, Basit AW, *et al*. 3D printing of dietary products for the management of inborn errors of intermediary metabolism in pediatric populations. *Nutrients*. 2023; doi:10.3390/nu16010061
 15. Chao C, Nam HK, Park HJ, Kim HW. Potentials of 3D printing in nutritional and textural customization of personalized food for elderly with dysphagia. *Appl Biol Chem*. 2024; doi:10.1186/s13765-023-00854-7
 16. Dankar I, Haddarah A, El Omar F, Sepulcre F, Pujolà M. 3D printing technology: the new era for food customization and elaboration. *Trends Food Sci Technol*. 2018; doi:10.1016/j.tifs.2018.03.018
 17. Sun J, Peng Z, Yan L, Fuh JYH, Hong GS. 3D food printing: An innovative way of mass customization in food fabrication. *Int J Bioprint*. 2015; doi:10.18063/IJB.2015.01.006
 18. Potter A, Schuster L. Food-product printer with nozzle and printing plate. 2018.
 19. Gou, Jingdong, 3D food printer. 2015.
 20. Multi-material direct ink writing 3D food printing using multi-channel nozzle. *Future Foods*. 2024; doi:10.1016/j.fufo.2024.100376
 21. Ma C, Yan J, Li W, Wang Y, McClements DJ, Liu X, *et al*. Enhanced printability of food-grade edible inks: Emulsions formulated with modified pea protein and sodium alginate. *Food Hydrocoll*. 2024; doi:10.1016/j.foodhyd.2024.109946
 22. Jeon EY, Chun YG, Kim BK. Investigation of carrot/squid blends as edible inks for extrusion 3D printing: Effect of hydrocolloids incorporation. *J Food Eng*. 2023; doi:10.1016/j.jfoodeng.2023.111777
 23. Bian MH, Jiang SY, Liu SL, Zhang LT, Miao S, Zhou FZ, *et al*. Fish gelatin and gellan gum mixture as edible ink for 3D printing. *J Food Eng*. 2023; doi:10.1016/j.jfoodeng.2023.111762
 24. Chen Y, McClements DJ, Peng X, Chen L, Xu Z, Meng M, *et al*. Starch as edible ink in 3D printing for food applications: A review. *Crit Rev Food Sci Nutr*. 2022; doi:10.1080/10408398.2022.2106546
 25. Attarin S, Attaran M. Food printing: Evolving technologies, challenges, opportunities, and best adoption strategies. *J Int Technol Inf Manage*. 2020;29(1):25-55.