BUKTI KORESPONDENSI MANUSKRIP

Jurnal: Journal of Nutrition College

Akreditasi: Sinta 3

Judul:

REVOLUTIONIZING MASS FOOD PRODUCTION: THE POTENTIAL OF 3D FOOD PRINTING

Penulis:

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Dear Dr. Fitriyono Ayustaningwarno,
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I hope this email finds you well.

I am writing to submit the revised version of my manuscript titled "Revolutionizing Mass Food Production: The Potential of 3D Food Printing" to the Journal of Nutrition College. The revisions have been made in accordance with the comments and suggestions provided by the reviewers. I have addressed all feedback comprehensively to enhance the clarity and quality of the paper.

Please find attached:
- The revised manuscript (highlighting the changes made).
- A detailed response document outlining how each reviewer's comment has been addressed.

I am grateful for the reviewers' constructive insights, which have greatly improved the manuscript, and I look forward to hearing from you regarding the next steps in the review process.

Thank you for considering this revised submission. Please do not hesitate to contact me if any additional information or clarification is needed.

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The 5th International Conference on Sustainable Global Agriculture and Food
"*Future Food: Innovation and Sustainability*"
March 7-9, 2024

REVOLUTIONIZING MASS FOOD PRODUCTION: THE POTENTIAL OF 3D FOOD PRINTING

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ABSTRACT

3D food printing has the potential to revolutionize mass food production by enabling the production of highly customized food products, from simple to complex structures and food products tailored to individual nutritional needs. This review explores various critical aspects of this technology, encompassing integration methods, customization possibilities, prospects, and the challenges it faces. Integration demands multidisciplinary collaboration, with a particular emphasis on optimizing parameters like ingredient and printing techniques to ensure flawless operation. The customization potential spans from tailored nutrition to intricate designs, effectively addressing diverse preferences and specific dietary needs. Advancements in the field hold the promise of improved speed, precision, and material diversity, with the potential to address sustainability issues through the utilization of by-products to further expand their capabilities. However, despite the optimistic outlook, significant challenges persist, including issues related to scalability, cost-effectiveness, and regulatory compliance. Overcoming these hurdles demands substantial investment in research and consumer education to facilitate broader adoption and acceptance. Nonetheless, the transformative potential of 3D food printing remains unquestionable, offering avenues for enhanced efficiency, sustainability, and the creation of entirely novel culinary experiences that align with evolving consumer demands and preferences.

***Keywords**: 3D food printing, mass food production, customization, integration methods*

Commented [AA1]: What is the role of 3D food printing in providing precise control over nutritional composition and enabling product customization at scale?

Commented [G2R1]: Thank you for your comment.

Providing **precise control over composition and customization** in this matter means that 3D food printing has the potential to enable the **production highly customized** food products specific to each person's nutritional needs or creating **complex structures** with customized shapes and texture.

I have revised the paper accordingly so that the term **precise control** can be better explained and understood.

Commented [A3]: How effectively does 3D food printing contribute to sustainability, particularly in terms of reducing food waste and utilizing by-products? Are there case studies or data that demonstrate this benefit?

Commented [G4R3]: Thank you for the comment.

Several studies have explored using food waste, such as fruit peels, vegetable scraps, and cereal by-products, as raw materials for 3D food printing (Wong, 2023 and Tan, 2024). This contributes to sustainability by reducing food waste through the utilization of food by-products and repurposing them into printable ingredients.

INTRODUCTION

Traditional methods of food production are currently under severe pressure to satisfy the needs of a growing world population while also catering and attending to sustainability and food security issues. It is increasingly impossible for existing resources and production infrastructure to satisfy the demanding and ever-growing need for food. This situation greatly worsens the problems, as many mass-produced food items do not have the required nutrients to provide proper nourishment, causing widespread hunger and stunting. The challenge, however, is not just about quantity but how adequate the food production is to the nutritional requirements of the population. Despite the improvements in the agricultural sector and the food delivery system, still there are flaws in making nutritious food available for the people that continue the chain of food insecurity and malnutrition. Therefore, solving these complicated problems can be accomplished by seeking revolutionary approaches which go beyond conventional agricultural methods in order to ensure availability of healthy and adequate natural foods.

Prior studies have been mainly aimed to address the nutritional values inside mass-produced foods (Steele *et al.*, 2017; Mediratta *et al.*, 2023). Different strategies including fortification (Dewi & Mahmudiono, 2021; Olson *et al.*, 2021) and supplementation (Amato, 2021) have been applied to make the food product more nutritious. While fortification and supplementation strategies have been employed to enhance the nutritional value of mass-produced foods, these methods often fall short in addressing individual nutritional needs. Over-fortification and over-supplementation can lead to nutrient imbalances, exceeding recommended daily intakes and potentially causing health issues (Tebben *et al*., 2016; Lo¨nnerdal, 2017; Raffaeli *et al.*, 2020). Moreover, the body may not efficiently absorb and utilize excess nutrients, leading to waste.

Previous approaches to personalized nutrition also face significant challenges, especially in both supply and demand aspects. On the supply side, reformulating food products often disrupts their original taste, texture, and functionality. Sustainable sourcing adds further complexity, with companies sometimes resorting to greenwashing instead of meaningful environmental action. On the demand side, consumer acceptance is a major hurdle, as even subtle changes in ingredient

Commented [AA5]: What is the urgency of methods such as fortification and supplementation, and what are their drawbacks in addressing individualised nutritional needs? Is this enough to be able to apply 3D food printing as an alternative solution?

Commented [G6R5]: Thank you for your comment.

While fortification and supplementation strategies have been employed to enhance the nutritional value of mass-produced foods, these methods often fall short in addressing individual nutritional needs. Over-fortification and over-supplementation can lead to nutrient imbalances, exceeding recommended daily intakes and potentially causing health issues. Moreover, the body may not efficiently absorb and utilize excess nutrients, leading to waste.

3D food printing offers a promising alternative by enabling precise control over nutrient composition and the creation of personalized food products tailored to individual needs. By producing foods with specific nutrient profiles, 3D food printing can help minimize the risks associated with overconsumption and nutrient imbalances.

We have revised the following paragraph with some studies that further explains drawbacks of previous studies and highlighting 3D food printing's potential as alternative solution.

composition can lead to sharp sales declines. Reformulation, a strategy of incremental changes without consumer notification, has shown promise, particularly for reducing sodium in products over time. However, high costs, emerging consumer trends for healthier and sustainable foods, and regulatory challenges highlight the intricate balance required to advance personalized nutrition effectively (Callahan, 2021; Fanzo *et al.*, 2023).

Addressing these challenges, the integration of 3D food printing technology has turned out to be an innovative solution which can bring changes to the way we produce food today. Through the capacity of controlling food nutrient, composition, and structure to the detail, 3D printing offers the food industry a new way to manufacture customized products in bulk. In the previous studies, the concept of 3D printed nutrient-dense food considerations tailored to individual needs has been examined (Ren *et al.*, 2023; Guo *et al.*, 2024; Mao & Meng, 2024). These studies indicate the capability of 3D printing to innovate how we produce and consume food as it has the proposed implication of improving nutrition and reducing hunger on a global basis. Nevertheless, 3D food printing has significant prospects, yet the issues of scalability, economics and regulatory factors still need to be addressed before it can be considered for mass production.

In the past few years, the possibility of using 3D technology printing in food manufacture has sparked a great deal of discussion. Nevertheless, the limitations of the findings for mass food production have been recognized. Most prior studies have concentrated on explaining the technical aspects and consumption attitudes of 3D food printing, but they have overwhelmingly failed to discuss the transformational potential of 3D printing in shaping large-scale production. Studies by Mantihal *et al.* (2020), Pitayachaval *et al.* (2023), and Lv *et al.* (2024) discussed the methodology of 3D food printing in depth. Among these studies, Mantihal *et al.* (2020) highlighted that consumer acceptance is influenced by perceived risks, including concerns about safety, hygiene, and food wholesomeness. On the other hand, Wang *et al.* (2022) presented the research landscape of 3D food printing in their research. Consequently, Fernanda Godoi *et al.* (2016) emphasized the criteria of choice of 3D printing methods in food design. The fact that Singhal *et al.* (2020) and Arif *et al.* (2024) have contributed recently has provided emerging trends and

Commented [AA7]: How are the links between food safety and hygiene protocols outlined in this methodology, especially in relation to food safety regulations and standards to the methodology?

Commented [G8R7]: Thank you for your comment.

Unfortunately, these three studies didn't outline food safety regulations and standards of 3D food printing in detail, since they mostly are discussing different methods in creating 3D printed foods.

However, study by Mantihal et al. (2020) briefly discussed the risk regarding consumer or user acceptance that is influenced by the perception of risk such as risks to safety, hygiene or the wholesomeness of food.

We will highlight this finding regarding food safety and hygiene in the following sentence.

advancements in 3D food printing to us. Additionally, one unique review that focused on the social scientific side was found from Ling *et al.* (2022). On the other hand, their input has limited addressing the vital issue of how to integrate this technology into large-scale food production processes, along with its impacts on scalability, efficiency, and cost-effectiveness. In addition, the research gap that arises from the possibility to thoroughly understand the transformative role of 3D food printing in meeting the growing needs of the world population is persistent. This paper aims to bridge this gap by evaluating how 3D food printing could contribute to productivity, customization, and sustainability in industrial mass food production, thereby allowing the adoption of this technology in large scale food production.

Therefore, the aim of this review article is to explore how 3D food printing can overcome the challenges of mass food production. This review aims to contribute to the integration of existing research findings, and discussion of the current developments in the field. Furthermore, the discussion on such integration's impact on the existing food production systems, the transformation of food supply chains, the potential of mass customization, increased precision and accuracy, and their challenges, will also be included in the study. Finally, this review also critically assessed the current state of the art and pinpointing the fields for future research and innovation to become part of the ongoing discussion on sustainable food systems and nutrition security.

INTEGRATION OF 3D FOOD PRINTING INTO MASS FOOD PRODUCTION

Mass production, otherwise known as bulk manufacturing, is the manufacturing of large numbers of identical products for a prolonged duration. This means of production encapsulates the importance of large volume production and high return to capital ratio which determines the efficiency and cost-effectiveness. Through familiarizing production processes and using the high-precision machines, manufacturers are capable to produce a large number of units with lower per-unit costs. This component of mass production is the core in terming customer

Commented [A9]: Given the current high costs associated with 3D food printing, what economic models or funding strategies might make this technology more accessible for widespread commercial use?

Commented [G10R9]: Thank you for the comment.

There is a previous article regarding 3D Food Printing economics model by Rogers (2021) with the title **Emerging Sustainable Supply Chain Models for 3D Food Printing** that highlights 3D food printing (3DFP) offers sustainable benefits, such as material reuse, cost-effective production of complex products, waste reduction, and the use of environmentally friendly materials. By collaborating with food manufacturers, 3D printing services can expand the variety of materials used and reach more geographic areas, increasing economies of scale, and minimizing supply chain costs through direct packing and distribution by manufacturers.

Although 3D Food Printing has the potential to enhance sustainability in existing food supply chains by reducing logistics and energy costs, the technology remains new and requires key enablers. One funding strategy is an open innovation and partnerships with research organizations (universities, 3D printer companies) which may accelerate the development of low-cost 3D food printers. Government authorities can play a crucial role by regulating the technology, ensuring safety, and supporting patents, licenses, and technology transfer.

We have also incorporated this information in the 'Prospects and Challenges' section for further insights on this matter.

expectations fast in an economic way which in a way guarantees market competitiveness and that is good for profitability.

Additionally, mass production focuses on the reproduction of one product or a set of standard products. Manufacturing companies achieve standardization through streamlining processes, reducing variability, and improving quality controls. Such an approach ensures an efficient level of utilization of resources, infrastructure and labor force, thereby creating economies of scope in production. Through uniform production of the same product, companies can use the shared components, production lines, and distribution channels to maximize efficiency and meet diverse customer needs. Consistency of product quality and performance is also an outcome of standardization, thus building the confidence and loyalty of consumers and brand.

Additionally, mass production aims for uninterrupted or long production runs to make sure that there is a continuous supply of goods in the retail market. Stability in supply chains, minimization of inventory fluctuations, and rapid market response are achieved through mass production of this aspect. Manufacturers deliberately arrange production schedules to guarantee consistent output by using forecasting models and production optimization methods. Continuous production for a much longer time helps companies to create their reputation as reliable suppliers, which further reinforces their market position and profits. These three aspects of mass production can be seen in Figure 1.

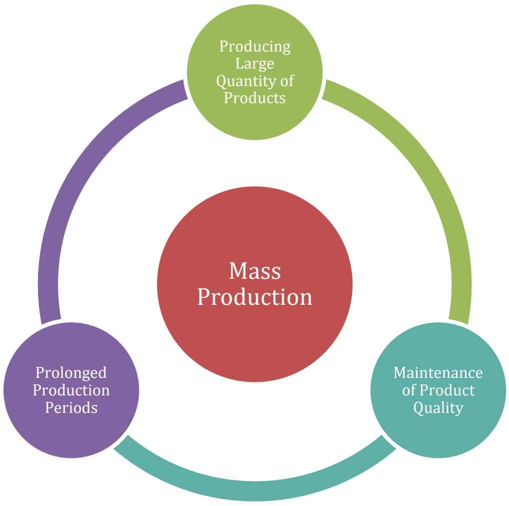

Figure 1. Three aspects of mass production.

In contemplating the potential of 3D food printing by integrating the concept into mass food production, three critical aspects of mass production that should be noted are large quantities production/maintenance or product consistency and quality and sustained or prolonged production period. As in any manufacturing process, controlling the production parameters, the ingredients and the printing processes are the main priorities to promote the uniformity in taste, texture and nutritive value from one batch to another. Vigorous quality control mechanisms which involve using real-time monitoring of printing parameters and strict following of food safety rules is critical for the enhancement of consumer trust and satisfaction.Table 1 provides a summary of the study on the purposes and concepts in integrating 3D food printing into mass food production.

Table 1. Compilation of studies on the purposes and concepts in integrating 3D food printing into mass food production.

Commented [A11]: What are the main regulatory hurdles 3D food printing faces, especially concerning hygiene and food safety, and how could these challenges be addressed industrial production settings?. Give any references to ellaborates

Commented [G12R11]: Thank you for the comment.

You're absolutely right in pointing out about the main regulatory hurdles 3D food printing faces, especially concerning hygiene and food safety.

Severini's (2018) study highlights the importance of maintaining both food safety and hygiene throughout the 3D printing process. It states the need to thoroughly sterilize every part of the 3D printer that interacts with food, ensuring that risks are minimized and consumers are protected at all times.

However, current literature also highlights a significant gap between the rapid pace of innovation in 3D food printing and the existing regulatory frameworks. As these technologies evolve, regulatory bodies have indeed struggled to keep up, particularly when it comes to the approval and safety of new ingredients used in 3D printing. For instance, Wu (2024) in his research on potential novel protein sources emphasizes that current food safety assessments, such as allergen testing and nutritional evaluations, are lacking harmonized international standards.

Given this gap, it's clear that a more coordinated approach to regulation is urgently needed. This could involve global collaboration to develop unified standards for food safety, allergen testing, and ingredient approval. Additionally, ongoing partnerships with research institutions would be crucial for establishing these standards.

We have revised the paper accordingly regarding this food safety and regulation in the '*Prospects and Limitation*' section.

No	Purpose	Concept	Reference
1	Producing Large Quantity of Products	Improving Printing Speed	(Derossi *et al.*, 2020) (Fernandes *et al.*, 2023) (Salvo *et al.*, 2023)
		Improving Printer Parameters	(Yang *et al.*, 2018) (Jonkers *et al.*, 2022) (Lee *et al.*, 2023) (Barrios-Rodríguez *et al.*, 2024) (Pan *et al.*, 2024)
2	Maintenance of Product Quality	Improving Rheology through Additives	(Lille *et al.*, 2018) (Anukiruthika *et al.*, 2020) (Dong *et al.*, 2020) (Feng *et al.*, 2020) (Cen *et al.*, 2022) (Sicong *et al.*, 2022) (Venkatachalam *et al.*, 2023) (Wang *et al.*, 2023) (Shi *et al.*, 2024) (Markovinović *et al.*, 2024) (Wang *et al.*, 2024) (Zhang *et al.*, 2024)
		Improving Rheology using Alternative Material	(Bugarin-Castillo *et al.*, 2023) (Muller *et al.*, 2023) (Wang *et al.*, 2023) (Sun *et al.*, 2024)
3	Prolonged Production Periods	Improving Precision and Accuracy	(Liu *et al.*, 2020) (Bareen *et al.*, 2023) (Genard-Lamproons *et al.*, 2023) (Ma *et al.*, 2023) (Miao *et al.*, 2024) (Ning *et al.*, 2024) (Shi *et al.*, 2024)

PRODUCING LARGE QUANTITY OF PRODUCTS

Although the current 3D food printing implementation is limited, it is capable of reimagining large-scale food production through its unique feature of producing foods on an individual and customized basis. Unlike conventional mass production which is based on standardized procedures and high-volume output, the technology 3D food printing offers unsurpassed ability to manufacture diverse intricate and personalized food items. The utilization of the 3D food printers with the capabilities of precise layer-by-layer material deposition is able to create food products with sophisticated designs, different textures, and customized nutritional compositions according to individual needs.

Improving Printing Speed

Nevertheless, there are some studies that seek to improve 3D food printing processes by exploring the influence of different parameters on the print quality and productivity. Fernandes *et al.* (2023) implemented experiments towards evaluating the effect of nozzle size and printing speed on printing time and printing quality. Using a greater nozzle size and higher printing speed seems to be able to drastically reduce printing time; however, this is followed by visually and dimensionally defective prints. First, nozzle sizes 0.4, 0.6 and 0.8 mm were able to produce good quality prints at speeds up to 100 mm/s with the smallest nozzle showing the lowest quality and frequencies below 100 mm/s showing better quality. Also, Derossi *et al.* (2020) tried to break the common print speed limit of 70 mm/s in 3D food printing by conducting a series experiments. While printing the cereal-based dough at speeds more than 100 mm/s, there was an enormous drop in the quality of print that was observed, as evident by a number of defects. The study has come up with a solution that includes increasing the flow parameter and changing the filament diameter settings. The process of non-printing variables calibration has enabled us to achieve higher print quality at speeds of 200 mm/s, although oozing and stringing defects still remain. However, these data give us useful information for finding ways to improve efficiency and quality of the 3D printing processes.

Moreover, Salvo *et al.* (2023) researched the impact of material flow on the print quality and structural strength of 3D food printing. Analysis showed that material flow has a great effect on print weight and dimensional accuracy of forms, and as the flow increases the difference between a CAD design and the actual dimensions disappears. On the other hand, when the nozzle speed was increased, the printability of the oleogel structures was adversely affected. As the extrusion head sped up, insufficient cooling didn't allow the material to reach a semi-solid state, which caused the structure to fall instead. The results of this study thus shed much light on the complex interplay between printing parameters and material properties in the

Commented [AA13]: What are the critical 3D food printing technical parameters, such as nozzle size setting, extrusion speed, material viscosity, and material stability in the large-scale printing process? Has relevant previous research been properly reviewed to support the methodology and results of this study?

Commented [G14R13]: Thank you for your comment.

However, to the best of the author's knowledge, no research to date has comprehensively addressed the optimization of all critical parameters in 3D food printing, such as nozzle size, extrusion speed, material viscosity, and stability. Current studies primarily focus on individual parameters as foundational investigations.

This is also why in this review article, the authors tried to discuss each of these specific parameters individually and hoping that by synthesizing findings from these studies, presents significant potential for guiding future research toward integrated optimization strategies.

development of 3D printing processes that significantly increase productivity and quality.

Improving Printer Parameters

Other previous studies centered on improving the printer parameters for the sake of maximizing productivity and proficiency of 3D food printing systems. Pan *et al.* (2024) had established that dual-extruder technology provided the answer to low productivity in 3D food printing. This technological innovation paves the road for the designing of the mechanical equipment of manufacturing individualized food products at massive scales. Yet in the programming of the printing path, the design encountered problems not allowing to generate complex 3D models printed using software out in 3 dimensions.

Research conducted by Lee *et al.* (2023) focused on a uniaxial 3D printing method which can be utilized for redesigning product textures and improving printability, especially for materials having a problem with self-support. The following approach indicates how to introduce multi-head printing effects to the already equipped printer. Thus, it opens new opportunities for enhancing texture modification and material print capabilities. Furthermore, Yang *et al.* (2018) presented a new equation to show the connection between nozzle diameter, nozzle movement speed, and extrusion rate in 3D food printing processes. Parameter optimizations at the level of 1 mm nozzle diameter, 24 mm^3/s extrusion rate, and 30 mm/s printing speed were achieved for printing of the lemon juice gel, supplying useful knowledge for tuning printer settings for getting desired results.

Consequently, the research done by Barrios-Rodríguez *et al.* (2024) on the impacts that print type and time of printing have on the 3D printed food quality. While in the experimental environment, the certain nozzle parameter combinations, for example, nozzle diameter, layer height, and print velocity, were established to address under extrusion issues and ensure the continuous and uniform flow of the material supply during the process of printing. However, the data from these experiments can assist in selecting suitable print parameters for higher resolution, efficiency, and product quality consistency in 3D printing process. Also, Jonkers *et al.* (2022) investigated the anisotropic stress-strain behaviour which exists in the case of printed materials and pointed it out as an important issue to consider during printing to achieve desired mechanical properties because of the impact of energy density and orientation.

MAINTENANCE OF PRODUCT QUALITY

Quality perception is a multidimensional construct showing high variance from one individual to another and is also dependent on situational factors. People view quality differently through the various lenses that they have, based on their preferences, cultural backgrounds, and past encounters. For example, the first person may be very much concerned with the taste or freshness of food products, while the second person will focus on the ethical sourcing or environmental sustainability. Such subjective assessments confirm that quality is complex to judge and the fact that more diverse stakeholder's views should be considered in quality management processes. Basically, quality can be perceived as a fluctuating and experiential concept which responds to changing cultures, innovations, and market dynamics.

In addition, quality evaluation can be viewed as either process or outcome oriented based on a specific context. Process-oriented quality is concerned with the effectiveness, efficiency, and uniformity of operational procedures or production methods. It puts forward the compliance to the existing norms, protocols, and methods to guarantee the precision of results and their replication. Conversely, result-oriented quality is concerned with the outcome of the product, evaluating its functionality, performance, and suitability for the designated use. The degree of the processes versus outcomes paying attention in quality assessments could be different across industries and organizational contexts, depending on the differing priorities and objectives. By realizing the interaction between process and outcome quality the stakeholders can use holistic approaches to quality management the merge both perspectives to improve organizational effectiveness and stakeholders' satisfaction.

Improving Rheology through Additives

Therefore, several previous studies have been done on modifying the rheological properties and printability of 3D food printing materials by addition of the different additives so that the finished product may be customized to different sense of quality regardless of the consumers. For example, Venkatachalam *et al.* (2023) studied the effects of multi-nutrients concentration on the quality of food ink printing with the objective of maximizing the quality of the print. Likewise, Wang *et al.* (2024) has also studied the improvement of soy protein isolate (SPI) paste 3D printing characteristics by blending SPI with carrageenan and sodium alginate to form composite materials. The study outlined the rheological and textural effects of polysaccharide type and concentration in the ink, which clarified the mode of interaction between proteins and polysaccharides.

Additionally, research has been done regarding the introduction of new additives for functionalizing 3D printing materials. Markovinović *et al.* (2024) explored the possibility that *Arbutus unedo* fruit could be used to create original functional foods by means of additive manufacturing. Correspondingly, Lille *et al.* (2018) intended to utilize 3D printing in the designing of food structures having high fiber, protein, and low fat and sugar, using various protein, starch, and fiber-rich food ingredients. Such efforts emphasize the continuous search for additive utilization to boost functionality and nutritional value in 3D printed foods.

Zhang *et al.* (2024) focused on the formation of new generation food ink for 3D printed dysphagia diet design by employing a xanthan and gelatin mixed gel with addition of cellulose nanocrystals (CNC). In parallel, Anukiruthika *et al.* (2020) studied the printability of egg yolk and egg white with rice flour blends in order to create a less leaking product with good shape and dimensional stability. Their study has shed light on why mode of action of new combinations should be studied for enhanced rheological properties and enhanced printability in 3D food printing.

Cen *et al.* (2022) aimed to create Pickering emulsions stabilized by β-CD/citrus pectin complexes with curcumin which is suitable for 4D printing applications. In this systematic study, the researchers analyzed how composition and concentration influence microstructures, mechanical properties, and 3D printing performance, showing that additives of a complex nature can modify the printing nature. Likewise, Wang *et al.* (2023) spoke about a deficiency of information concerning the stability of gardenia blue in production and application for 2D and 3D printing. In the investigation, the main target was generating stabilized gelatin-blue systems by crosslinking with genipin to exhibit the possibility of including the stabilizing additives with a view to improving the ink life and print quality.

In this regard, studies have been carried out in order to identify the best additives that will be required to give the resulting prints. To evaluate which type of starch is most suitable for 3D printing, Shi *et al.* (2024) carried out an experiment by assessing the precision and quality of the samples to identify the changes that each attribute brought and their effects on quality. On another note, Feng *et al.* (2020) used yam and high-fiber potato by-product to study the impact structure on texture of air-fried yam snacks and the 3D printing properties of yam powder. Likewise, Dong *et al.* (2020) has investigated the characteristics of printing such as the texture, rheological properties, and water distribution, including the microstructure of 3D printed surimi gel to determine the impacts when different amounts of microbial transglutaminase (MTGase) are used. All of them shows how important additive manufacturing is.

Many recent research papers have seen the advancement of the texture, rheology, and sensory characteristics among products 3D printed food. The work of Sicong *et al.* (2022) examined the effect of starch addition on the fabrication of calcium caseinate (CaCas) formulations, showing that it helped without distortion of printed objects. Moreover, the experiment demonstrated that raising the level of binder has led to an improvement of the bulk of the products, while the changes in protein content of dry powder mixtures greatly influenced the elasticity of the food. These results reinforce the importance of the formulation of ingredients that will achieve the desirable rheological properties and the texture characteristics in the 3D-printed foods.

Improving Rheology using Alternative Material

Furthermore, attempts have been undertaken in the development of custom 3D printing materials with specific properties. Wang *et al.* (2023) was trying to develop a new 3D printing material from *Spirulina platensis* remains which exhibited thixotropic properties, high viscosity, and rapid recovery. Sun *et al.* (2024) mixed different ingredients such as soy protein isolate, pea protein, xanthan gum, guar gum, corn starch, and potato starch into a *Undaria pinnatifida* (UP) slurry liquid to fabricate a UP gel ink. These additives were purposely selected to boost the rheological features and printing facets of the ink, thus revealing the flexibility of additives incorporation in designing printing materials.

Muller *et al.* (2023) research focused on the possibility of using higher viscous materials like wheat dough and melt cheese for layer formation. The research showed that materials could be layered, and at the same time, it became possible to create structured products. Chocolate-based products brought about anisotropic mechanical properties because of the presence of layers. Moreover, the test showed that the cutting force demanded was less when the food product was cut in parallel to the layers instead of perpendicular to them, which reveals that the layer direction influences the mechanical properties of foods printed. By means of these discoveries, a key to improving the entire process in creation of 3D printed food product may be found. Bugarin-Castillo's (2023) research involved studying the extrudability and stability of starch paste, which could provide possibilities for applying 3D printing. The study has shown that the starch paste made of a particular composition showed a good extrudability at a certain temperature combined with stability after the deposition at room temperature, due to the high yield stress and shear-thinning behavior of the paste.

PROLONGED PRODUCTION PERIODS

To explain the need for food production applications that work for a longer period one should take into consideration the combination of population growth and consumer choice. The accelerating population, its range of diverse eating habits, and their ever-growing demand pressurize the food manufacturing facilities to remain in a steady state of operation in order to satisfy the market needs and requirements. Automation and control systems, driven by precision, take care of the real-time monitoring and micro-adjustments of the environmental parameters as well as of the ingredient proportions. The result is consistent product quality for even large production volumes. These are the technological developments that food manufacturers can use to reduce food wastage, and they can also optimize the allocation of resources as well as maintain high levels of health and sensory standards, something that will cater for the diverse preferences of consumers across the world.

While the development of 3D food printing technology had included ongoing progress in terms of accuracy and detail, the technology had demonstrated its potential to bring a major change to the culinary world. The field of 3D food printing constantly evolves with the progress in hardware and software, thus creating better accuracy in the placement of the deposited edible materials. High-precision pot printing heads and intelligent algorithms allow high-fidelity layer-by-layer layering of food components where the smallest faults are almost unnoticeable. Not only do these advances make printed food look beautiful but also add to its architectural robustness and flavor characteristics, providing a completely satisfying meal experience.

Many research yielding unbelievable results on the precision and accuracy of 3D printing of food have now been published. On the other hand, the research conducted by Miao *et al.* (2024) found out that the best printing results were achieved by the fine adjustment of starch and water content. So, when quercetin was considered also it worked out. The studies done by Ma *et al.* (2023) involved the utilization of feedforward control in characterizing fluctuations, successfully preventing under-extrusion, and improving printing accuracy by enhancing both 2D layer formation and 3D filament stacking.

In addition to this, simulation experiments, for instance, those carried out by Ning *et al.* (2024), have emphasized that shear rate and piston pressure were among the significant factors determining the viability of printing. These simulations clarify how the alteration of the viscosity of materials, nozzle diameter, and printing speed can affect extrusion dynamic and at the same time reduce the printing process. Moreover, Genard-Lamproons’ (2023) research utilized reverse-engineering method to re-optimize printing parameters like water content and mechanical-thermal treatment duration to improve printing quality and stability.

Besides that, Bareen *et al.* (2023) invented frameworks that could exactly predict qualitative residual stress and distortion of printed structures. Furthermore, Shi's (2024) article specifically probes the insertion of additives like κ-carrageenan that are supposed to improve the properties of material while at the same time enhancing the extrusion pressure to increase printing accuracy. The direct implication of Liu's (2020) research, is that PCA and Fisher discriminant analysis based on rheological properties are highly efficient in predicting actual 3D printability of mashed potatoes. Such collaborative work highlights the interdisciplinary character of research aimed at improving the precision of 3D food printing, and therefore making the food production process safer and cheaper.

REVOLUTION IN FOOD SUPPLY CHAIN

The demand for large-scale food production is the primary source of food supply chains, which is a network of connected members from farmers to consumers. To kick start the supply chain, farmers cultivate crops, harvest them, or rear livestock for the raw food materials needed by the food industry. These primary agricultural products form the basis upon which other food processing and industrial sectors are built. Food manufacturers can process agricultural inputs by means of specially designed equipment and facilities into an array of processed foods, drinks and packaged goods based on consumers' tastes and market needs.

Distribution and logistics take over after that with responsibility for the safe, timely and efficient transportation of food products from production facilities to retail outlets and distribution centers. Transport networks particularly roads, rails, air and sea freight facilitate the transportation of food over long distances and reach a variety of markets and consumers. On the retail side supermarkets, grocery stores and food services give consumers an opportunity to purchase a variety of food items from food producers. The last step in the food supply chain process is the consumers, who in the end determine demand patterns through their buying choices and consumption behavior. Thus, the huge food production is linked to the complex relationships between the stakeholders and the food chain to ensure safe, nutritious, and diverse food options to citizens of the world. Figure 2 displays a representation of the traditional food supply chain.

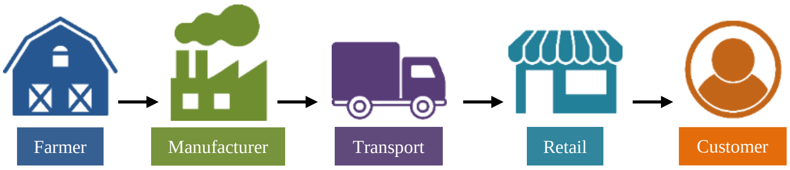

Figure 2. Traditional food supply chain.

Due to the intensity of the transformation required for their 3D printing, these foods are categorized as "processed", since they have undergone such considerable alterations that center around the need to facilitate additive manufacturing. Manufacturers usually whip up a paste-like mixture of the foods in order to allow them to pass through the nozzle and lay down a pattern layer by layer. Therefore, the development of tailor-made materials should be given priority, as it would be a critical requirement for advanced 3D food printing technology to operate optimally and produce complex structures. The integration of 3D food printing into traditional food supply chain could catalyze the emergence of a distinct industry, i.e. 3D Food Material Manufacturer. This industry would make a revolution of the conventional food supplies by specializing none other than in the creation and distribution of food material that is designed and optimized for additive manufacturing processes. This approach ensures easy materials sourcing which can in turn mitigate the problems associated with production, enhance customization and develop new avenues for culinary creativity. Therefore, we suggested a new food supply chain, which is depicted in Figure 3, that is created when 3D food printing is integrated into the food supply chain.

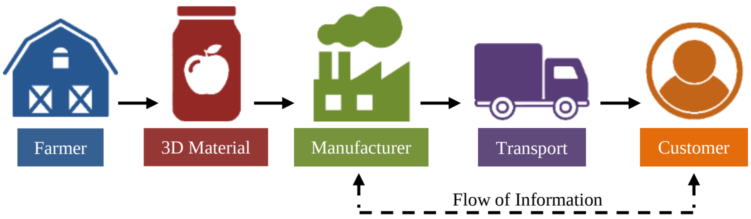

Figure 3. Proposed new food supply chain by integrating 3D food printing.

Development of 3D Food Materials

Previously scientific research regarding 3D food printing have created possibilities for 3D Food Materials suppliers in leading industry by applying their coating technology on pristine materials and edible inks. Wang *et al.* (2022) introduced the use of gelatin as a carrier for a matrix of polychromatic materials such as cchanotenoids (Cc) and chlorophyll (Gy), with the addition of carnosic acid to enhance their capacities. This strategy first allows the choice of the materials which can be printed, and secondly, it creates possibilities for producing not only tasteful but also vitally important foodstuff products through 3D printing.

Dongle *et al.* (2023) intends to take advantage of 3D printing technology to manufacture toddler meals made of corn, fish protein (FP), and fish gelatin (FGG) using fish and soy isolates as raw materials. The research indicated that the aesthetic and swallowing performance characteristics play a significant role in food design, even illustrating the fact that 3D printing can be employed in the production of customized foods that meet different nutritional and sensory needs of diverse consumer populations.

Zhong *et al.* (2024) made egg yolk powder-starch gel bioink the theme, and provided helpful ideas for bio-printed application in food. With that, it not only adds new items to the inventory of printables but also fulfills the growing need for the replacement of protein sources and some nutritional agents in food production.

Moreover, Guedes *et al.* (2023) reported on the usefulness of modified starch gels for 3D printing where starch was utilized as a solid food at the same time. In this research, the study of rheological features and printability is designed, and the main objective is to boost the nutrition and safety of the food products while solving the problems of swallowing for the people in society, which will show that the 3D printing technologies can tackle some dietary issues. In general, these studies can be seen to witness the emergence of 3D food printing as in innovation in the development of new foods, and in creation of food products that take into account varied nutritional needs and preferences of clients.

3D Printed Food as Commercial Food Substitute

While many prior studies have focused on customized 3D food printing to expand the range of foods and to imitate traditional ones. Lv *et al.* (2024) tested using

Pleurotus eryngii protein (PEP) and potato whole powder (PWP) as raw materials for 3D-printed biscuits. In their investigation they worked on the ink formulas to improve the performance of printing, as well as studied various methods of shaping and looked into the impact of baking on the post-processing quality. Furthermore, Pant's (2022) 3D printability of rice flour with chai poh powder to create Asian food such as chwee kueh and orh nee dishes shows the flexibility of 3D printing in the kitchen. These case studies exhibit the trend of tweaking 3D food printing methods to produce different textures, flavors and cultural cuisines, thus providing alternative techniques to food customization and cooking innovations.

Moreover, Zhu *et al.* (2023) also concentrated on the printability of surimi and studied the exploitation of glycerol content, nozzle design, and filling structures for extrusion. The study presented a deep understanding of the function of chemical crosslinking agents, like sodium chloride (NaCl), calcium chloride ($CaCl_2$), and transglutaminase (TG), in the maintenance of the shape and texture of 3D-printed surimi through methods such as low-frequency nuclear magnetic (LFNMR) resonance and microstructural analysis. On the other hand, Yaxin *et al.* (2022) demonstrated the challenge of creating 3D-printable meat analogs that replicate the texture of cooked beef. Chemical methods such as TG catalysis and heating were employed to increase the hardness of protein pastes, representing cutting-edge technology in the field of additive manufacturing. Such efforts emphasize the interdisciplinary characteristics of the 3D food printing studies, a combination of culinary artistry and engineering concepts making the process highly personalizable and bespoke.

Minimizing Waste by 3D Food Printing

Previous research has also explored unconventional ways to reduce food waste by employing non-natural materials on 3D printing food. With the purpose to analyze the feasibility of jackfruit seeds as additive 3D printing substance, Wong *et al.* (2022) designed preliminary experiments. The study showed the opportunity of 3D printing by using unaltered fruit seeds as raw material after undergoing environmental adjustments (pretreatments). Like Tan *et al.* (2022), a researcher investigated the ink formulation for printing of durian husk with varying particle sizes, husk concentration, and hydrocolloid as the rheological modifier. This kind of research shows that the food industry can use food waste streams as valuable materials that could be applied in the 3D printing industry in order to contribute sustainable solutions to the problem of food waste.

Mass Customization and Consequences

The incorporation of 3D food printing has introduced information exchange tools between producers and their consumers. Such platforms have the great chance of revolutionizing food production by enabling mass customization (Warkentin *et al.*, 2000). This technology allows manufacturers to create specialized products that match consumer's dietary requirements and their personal preferences through communication with consumers. Due to this factor, it is possible to make the product more relevant for the customer, and thus to enhance engagement with consumers. As a result, it is possible to facilitate promotion which is targeted. Furthermore, tailored food items would lower the chance of leftover; hence, up to the wanted profiting margins via rational production and less waste is being produced as byproduct. Fortunately, the 3D food printing development has a potential of disrupting the conventional retail shops business operations by enabling direct customer distribution channels. Unlike traditional markets, which involve food products going through several intermediaries before reaching their final consumer, in this case 3D food printing permits immediate and simplified production. This technology allows for the mass production of food items exactly to the preferences chosen by the individual and hence excludes the cost of inventor storage and distribution which is involved in the retail chains.

PROSPECTS AND CHALLENGES

Even though it has a lot of advantages, 3D food printing has obstacles that need to be dealt with for it to be widely accepted in bulk food manufacturing. The technical issues include consumer acceptance, scalability, cost-effectiveness, and regulatory compliance, especially safety and hygiene (Singh *et al.*, 2022). Manufacturers need to spend time on research and development to improve printing technologies in order to meet food safety standards. Further, consumer acceptance and market

Commented [A15]: The article discusses 3D printing's capability for personalized nutrition. What are the limitations and potential benefits of this approach in addressing malnutrition and dietary restrictions on a large scale?

Commented [G16R15]: Thank you for your comment.

3D food printing holds significant potential for personalized nutrition, particularly in addressing malnutrition and dietary restrictions.
The primary benefits of this approach include the ability to create tailored meals that cater to individual nutritional needs, preferences, and health conditions.

For example, 3D food printing can incorporate specific nutrients or modify the texture and consistency of foods to suit individuals with dysphagia or those requiring specialized diets due to medical conditions such as diabetes, celiac disease, or allergies.
By printing food with precise nutrient content, it's possible to address deficiencies and optimize diets at an individual level.

Limitations regarding this potential is explained in the *'Prospects and Challenges'* which 3D food printing is rather new and prone to technical issues include consumer acceptance, scalability, cost-effectiveness, and regulatory compliance, especially safety and hygiene.

Commented [AA17]: Is there an urgency regarding the need for collaboration between different fields of science (food technology, industrial engineering, health) to develop this technology to be ready for large-scale implementation?

Commented [G18R17]: Thank you for your comment.

There is! Thanks for the suggestion, it's undeniable that collaboration between diverse scientific fields is critical to advancing 3D food printing technology.

We have revised the article (last paragraph) accordingly to emphasize the need for this collaboration.

demand will play a significant part in the growth of 3D printed food products uptake.

Consumer Acceptance

Previous investigations have concentrated on shoppers' opinions and preparedness to consume 3D printed foods, which have uncovered varying tastes by different locations. For example, Ng *et al.* (2022) came up with a study conducted in Malaysia that shows neutral attitude towards 3D food printing as the awareness is too low and exposure to the technology is limited in the early stages. Nevertheless, their indication of readiness to consume 3D printed food and acknowledgment of positive benefits signified a favorable bias, albeit the negative attitude was caused by food technology neophobia and lack of familiarity. On the contrary, according to a statistic done by Tesikova *et al.* (2022), the population of Czech Republic proved to be enthusiastic about printed meals and expressed a high interest to try it. Also, people saw in a good light the usage of 3D printing across medical, confectionary, military applications and remote locations, which highlighted that generally respondents strongly supported the technology.

Although positive survey data indicates that consumers have a level of acceptance of 3D Printed Food, food safety and consumer preferences remain the main obstacles. A study by Blutinger *et al.* (2023) proved a shift in consumer perceptions of processed foods, which quashed the issue of whether 3D printed foods could be categorized as such, because of the change required in food preparation process. This changing dietary lifestyle of consumers toward whole foods could pose a threat to the acceptance of 3D food printing technologies, as the technologies are lifestyle-incompatible with current food trends promoting minimally processed ingredients.

Safety and Hygiene Reasons

Moreover, Severini's (2018) study has highlighted the significance of achieving food security and hygiene during the production process of 3D printing. Sterilization of each part of a 3D printer that comes into contact with food must be performed with utmost importance to minimize all risks and achieve consumer safety by all means. Along with the shelf life being put at risk and the possibility of microbial contamination, it clearly emphasizes the need to integrate hygiene and safety measures while the 3D printing process goes on. Aspects like contact with numerous items like steel, plastic, and extruder denotate the complexity of maintaining 3D food printing safety regulations. Fixing these issues becomes vital for nurturing consumers' faith in the reliability and quality of 3D printed food. Current literatures highlight a significant gap between the rapid pace of innovation in 3D food printing and the existing regulatory frameworks. As new technologies and applications continue to evolve, regulatory bodies are struggling to keep up, especially when it comes to the safety and approval of novel ingredients used in 3D printing. The lack of established guidelines for assessing the safety of these ingredients creates challenges for ensuring consumer health and safety. Wu *et al.* (2024), in his research, underscores the absence of internationally harmonized standards for food safety assessments. This gap leaves critical areas such as allergen testing, nutritional evaluation, and ingredient approval vulnerable, making it harder to establish safe practices for integrating new materials into food production.

To address these challenges, a more coordinated approach to regulation is urgently needed. This should include the development of global standards for food safety and ingredient approval that encompass allergen testing, nutritional analysis, and appropriate labeling requirements. As Wu (2024) points out, collaboration between industry stakeholders, regulatory authorities, and research institutions is essential to create these standards and ensure a unified approach to food safety in 3D food printing. By working closely with academic and research organizations, regulatory bodies can more effectively address the evolving safety concerns associated with novel ingredients. Improved safety protocols focusing on comprehensive evaluations of protein sources and the inclusion of rigorous allergen and nutritional assessments will help mitigate risks. Ultimately, for 3D food printing to reach its full potential in commercial applications, the regulatory framework must adapt to support innovation while protecting consumers.

Research Collaboration and Funding

Although a number of issues exist in terms of research and cooperation, especially in specific areas and among scientists, Fasogbon's (2022) paper showed African researchers make a meagre contribution to the 3D food printing field - just 1.93%. This emphasizes the need for strengthening collaboration between African scientists and researchers from developed countries and international institutions to effectively develop the emerging field. Besides that, Fasogbon also pointed out that it is the funding that can ease the research by African governments, they need to allocate more funds to universities and researchers to conduct transformatory studies which can benefit the continent.

According to Derossi et al. (2021), collaboration in 3D food printing remains limited, with only 51 out of 582 researchers actively contributing to collaborative projects. This lack of cooperation is further hampered by weak connections between authors from different institutions or research groups, slowing progress in the field. Derossi underscores the importance of fostering new international partnerships to accelerate advancements in 3D food printing technology.

To truly develop this transformative technology, there is an urgent need for interdisciplinary collaboration involving fields such as food technology, industrial engineering, and health sciences. Such collaboration can integrate expertise in material science, process optimization, and nutritional health to address existing challenges and drive innovation. Overcoming these barriers through combined efforts would not only enhance technological development but also facilitate global scalability and practical applications of 3D food printing in addressing pressing food system challenges.

Another challenge to the widespread adoption of 3D food printing is its currently high costs. Previous study by Rogers and Srivastava (2021) explores the economic models associated with 3D food printing. The study highlights several sustainable advantages offered by 3D food printing, including the reuse of materials, cost-effective production of complex products, waste reduction, and the adoption of environmentally friendly materials. Collaborating with food manufacturers allows 3D printing services to diversify the range of materials used, extend geographical reach, and enhance economies of scale, ultimately reducing supply chain costs through direct packing and distribution by manufacturers.

Despite these benefits, 3D food printing technology remains in its early stages and requires key enablers to reach its full potential. One important funding strategy includes open innovation and partnerships with research organizations, such as universities and 3D printer companies, to accelerate the development of affordable 3D food printers. Government authorities can play a crucial role in regulating 3D food printing technology by ensuring food safety standards are met, while also facilitating the adoption of patents, licenses, and technology transfer. By supporting these initiatives, they can help promote the technology's widespread use and enhance its sustainability within food supply chains. This involvement ensures that innovations in 3D food printing are not only safe for consumers but also align with regulatory frameworks that encourage growth and efficiency in the industry.

CONCLUSION

In conclusion, the development of 3D printing technology is powering the transformation of mass food production by virtue of increased levels of customization, quality, and precision. The ability to produce personalized food products is a unique contribution to the industry that will affect the food industry overall. Nevertheless, as this technology keeps on advancing, it brings about problems that need to be closely inspected and tackled proactively. With the changing dynamics in food supply chain as a result of the shift to highly customized products, there is the need for strategic planning and adaptation which highlights the need for the same. In addition, problems of shortage of research funds, lack of cooperation and issues of safety and hygiene are some of the critical activities that need immediate attention in ensuring that the system of 3D food printing is properly integrated into mass food production.

However, besides these challenges, the growing interest and acceptance from consumers imply a positive development in the uptake of 3D food printing. The consumers' eagerness for the thought of personalized, top-quality food items shows that the possibility for this technology to penetrate the market is high. Through concerted efforts to tackle the challenges, building research consortiums, and ensuring that high safety standards are upheld, 3D food printing offers a pathway to a food industry of the future which is more efficient, customized and consumer-demand based.

FUNDING

This study is funded by a research fund of Soegijapranata Catholic University.

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