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Emerging Sustainable Supply Chain Models for 3D Food Printing

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Abstract: 3D printing technology is rapidly transforming supply chains across diverse manufacturing sectors, enabling personalisation of consumer goods ranging from car parts, medical devices, toys, houses, and even clothing. Food production is also included in the breadth of applications of this expanding technology. Increasing consumer awareness about sustainability, including the problem of food waste, as well as growing interest in customised nutrition have led to the emergence of food industry research focused on aspects, such as packaging, portion size, and healthy sustainable ingredients, to satisfy consumer demands. The growing market for personalised food options in particular, requires increased flexibility and agility to tailor ingredients to an individual's specific requirements. Such specificity is not easily fulfilled using traditional mass production methods; however, the emerging technology of 3D food printing (3DFP) may be one solution. This paper evaluates the opportunities, risks, and challenges associated with 3DFP, with a focus on developing sustainable supply chains for future growth. Drawing on 12 semi-structured interviews with 3DFP industry managers and current literature in the domain, we propose three supply chain models for 3DFP services, as well as an overview of the key business drivers.

Keywords: 3D food printing; sustainable food supply chains; food waste; sustainable supply chain models; business models; personalisation

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1. Introduction

Food supply chains (FSCs) are complex, requiring coordination not only across countries but also between continents, to ensure full and timely arrival of products to the end customer [1–4]. Tackling food-related challenges and trends, such as reducing loss and waste, improving the carbon footprint and enabling customised nutrition, is high on the agenda of many governments and organisations across the world [5–9]. The approach to meeting these challenges varies considerably according to the availability of financial and technological resources, as well as the fit with the overall strategy of an organisation [10].

As with many other industries, the pressure to improve sustainability across food value chains is increasing. León-Bravo et al. [11] suggest that sustainability can be driven through food product or supply chain innovation and the fact that one cannot exist without the other. In this context, we pose the broad question 'could 3D food printing (3DFP) enable food supply chains to be both more personalised and more sustainable'? 3DFP is a direct manufacturing technique in which materials are added layer by layer to create individual structures, many of which may not be feasible via traditional production methods [12]. When applied to the food industry, studies have shown that 3D printing could potentially reduce waste, as well as support surplus food recycling [13,14]. This can be achieved by printing on-demand close to the point of final consumption, obviating the need for secondary packaging and enabling close to out-of-date ingredients to be converted into meals.

Previous research has focused on the development of 3DFP but mainly from a technical [12,15–17] or customer acceptance [18,19] perspective. Research on its impact on food supply chains, however, remains scarce [20,21]. More specifically, there is a lack of information at an operational level both in terms of what is needed to increase the adoption of printed foods, as well as how 3DFP can be used to develop sustainable supply chains. This led to the following research questions:

RQ1. How does 3DFP need to develop to meet customer expectations (and hence pave the way for increased acceptance and adoption)?

RQ2. How can 3DFP be used in food supply chains to improve sustainability?

RQ3. As the industry matures, how will 3DFP supply chains be configured?

The paper is organised as follows: first, we briefly discuss current food supply chains and the existing environmental impacts, followed by an overview of the key interview results showing current applications of 3DFP. Finally, three 3DFP supply chain models are proposed, with a particular focus on increasing sustainability.

2. Literature Review

2.1. Current Food Supply Chains and Sustainability Aspects

The Food and Agricultural Organisation, FAO [22] estimates that the world population will increase by 34% by 2050, further increasing the demand for food. To compound this situation, food supply chains use significant amounts of energy, water, land, and other resources, often inefficiently. To indicate the scale of the problem, it has been estimated that food supply chains contribute 20–30% of greenhouse gas emissions [23–25]. Despite improvements in technology and increased efficiencies in the food industry, loss and waste remain high along food supply chains [26,27]. This is because food loss and waste can occur at all stages of the supply chain, with many and varied causes. This ranges from environmental conditions (e.g., crop damage from weather, soil erosion, or fertiliser issues), to government subsidies (encouraging over-production) and labour shortages (timely harvesting not possible), to consumer waste [28–31]. Moreover, many food products are highly perishable, which inevitably, leads to significant losses and waste. The largest share of food waste is generated by private households (61%) and corresponds to 5.8–7.5 million tons per year. Multiple factors contribute to this wastage but of particular significance is the amount of food purchased versus consumed [32]. Food waste can be further classified into avoidable (i.e., could have been eaten), e.g., past sell by date products, wilted vegetables, meal leftovers, etc., versus unavoidable, e.g., chicken bones, oil, and eggshells [27,33]. Three-dimensional printing may assist in reducing avoidable waste by printing on demand and possibly by repurposing nearly expiring food into more appealing and consumable products.

The UN issued guidelines for a 50% reduction in food loss and waste by 2030 in its sustainable development goals [22]. Meeting these goals requires innovative solutions along all segments of food supply chains [34–39]. Research by the Ellen MacArthur Foundation [40] explored the concept of applying the circular economy to the context of food supply chains, focusing on the role of cities. Other concepts, such as life cycle assessment, lean production, and big data analytics, have also been discussed [41]. However, food supply chains are still far from being considered sustainable and new approaches are urgently needed [1,42–44]. Progress is being made to improve 'circularity' in food supply chains. Examples include the use of barcodes and smart labelling to track (and minimise) food loss, use of machine learning to optimise processes and systems (to repurpose, rethink, and redesign the concept of circularity in business models), as well as the use of blockchain technology to tackle food fraud by using stakeholder data throughout the FSC network. Amongst these, 3DFP could particularly enable the reuse of materials, production of complex product at lower cost and less waste, use of environment friendly materials, and intelligent packaging [45].

In a typical food supply chain, food waste can be generated in any of the five key stages: production and harvesting, primary processing, industrial processing, distribution, and retail and domestic consumption contribute to reducing food waste generated during the domestic consumption stage. Several challenges are associated with European food supply chains, which is further exaggerated by the COVID-19 pandemic, with new shocks and crises arising daily [46,47]. One would imagine that European food supply chains would face fewer problems than their counterparts in other continents, owing to well-developed infrastructure and strict regulations. However, as evidenced by the horsemeat scandal of 2013 (among others), food contamination scandals do still occur. Furthermore, changing customer behaviour, for example, in terms of the trend towards increased consumption of plant-based food and decreased red meat consumption [48], is incentivising food companies to change their business models. However, the significant disruptions come from logistics issues [49] as well as food waste and losses [50]. In Europe, although food is wasted during all stages of production, food processing, retail, and distribution, it is the consumption stage that requires the most action as 53% of total food waste is generated by households. The GWP (global warming potential) of food waste in Europe is approximately 186 metric tonnes CO2 eq annually [51,52].

2.2. 3D Printing in the Food Industry

Although 3DFP is currently used primarily for preparing foods for those with special nutritional needs (e.g., dysphagia and associated eating-related conditions), as well as for snack and novelty products [18,53–55], it also has the potential to decrease food waste by recycling 'inferior' foods, such as leftover cuts of meat, seafood scraps, and 'ugly' fruit and vegetables that would otherwise become landfill [13,27]. Other opportunities lie in the growing trend for alternative protein sources, such as insects, algae, duckweed, grass, spirulina, lupin seeds, and beet leaves, to produce foods that satisfy consumer taste and nutritional requirements [56–58]. New forms and figures that were previously impossible to manufacture can now be produced, ranging from chocolates and other desserts to pasta shapes and protein patties. By adding hydrocolloids (examples are xanthan gum and gelatine) to maintain the form, fruits and vegetables in purée form can also be extrusion printed. The fact that they can be easily extruded from a syringe supports their positive printability qualities [59]. Using techniques such as these, 3D printing provides the opportunity to print one dish that contains all necessary daily nutrients. This aspect is paramount in many emerging countries. For example, in China, food habits are changing rapidly towards a high-calorie but low-nutrient diet. More specifically, although the diet is calorie rich, it is deficient in vitamins and minerals. To compensate, consumers may need to supplement their diet and 3D printing can play a role here to incorporate the required nutrients on a personalised basis [60]. As shown in Table 1, there have been several recent studies on 3DP targeting various pertinent aspects of the food supply chain. Some highlighted the challenges associated with consumer acceptance, whereas others evaluated the development of technology and printing materials. However, although these parameters are extremely important, they are of limited commercial value without developing a corresponding business model to integrate all these parameters. In this context, research on business model development for 3D food printing remains scarce but pertinent.

Although the potential of this technology is considerable, there are currently a number of limitations associated with 3DFP that are preventing its wider adoption. Foremost amongst these is the slow speed of the printing process itself (e.g., four pieces of 3D printed pasta can take approximately five minutes to complete). Other limitations include the need for post processing (sometimes including baking), as well as printing reliability and repeatability issues [12]. Some of these may stem from the fact that many 3DFP machines were initially developed for non-food purposes, meaning compromises are inherent when applied to the food production process. This affects the creativity limits of the designs, as well as the texture (mouthfeel) of the end products [53]. The printing parameters need to be adjusted to accommodate mechanical behaviour variations that exist according to the particular food ingredient. These variations depend on factors, such as environmental conditions (e.g., temperature), which in turn leads to repeatability challenges [61]. Repeatability is particularly important for the commercialisation of 3DFP in consumer markets. Another obstacle is consumer attitudes towards 3DFP, with many potential customers having feelings of 'neophobia' [13,18]. Ethical and trust concerns may also arise from the perception by consumers that 3DFP products are designed in the laboratory [16]. Moreover, a gap between the quality standard and range of current product offerings and what consumers actually want and expect means that commercialisation is still limited [13,19,62–64].

A number of strategies were proposed to manage food supply chain issues. One fundamental step is to improve the efficiency of traditional food supply chains through more collaboration with suppliers, real-time monitoring and tracking, etc. However, there is a limit to expanding the boundaries of conventional food supply chains. Circular economy strategies can improve food supply chains by repurposing food byproducts, waste, and recycling nutrients [51]. Other innovations, such as artificial intelligence and machine learning, can also assist in reducing food supply chain issues and impart sustainability through improved monitoring and tracking to maximise freshness and minimise waste. However, although these new initiatives can improve the pressing issues of food supply chains, they are still emerging and until now are still far from achieving large-scale diffusion in food supply chains. Imparting sustainability in the food supply chain means reducing food losses and harmful gases, efficient transportation, less packaging, and gradually less dependence on fossil fuels [65]. Three-dimensional printing could provide part of the solution to these issues as described in this paper.

Table 1. Notable recent contributions to the 3D food printing literature.

Aspect	Ref	Brief Description
Technical	[66]	Overview of properties and opportunities of 3D food printing
	[67]	Applicability of 3D printing in improving wheat starch properties
	[68]	Composite materials for 3D-printed food
Nutritional	[69]	3DP food utilising fresh vegetable hydrocolloids for dysphagic patients
	[13]	Nutritional opportunities and challenges
Business	[70]	Consumer preferences, modification of internal structure of foods, extension of 3DP in industrial food production and hospitality
	[71]	Consumers' perception of 3D-printed food
Process	[72]	3D printing as a value addition in processed food
	[73]	Demand characteristics of 3D food printing materials
	[74]	Valorisation of food waste using 3DP

3. Research Approach and Key Insights

A case-based data collection method was used for this research [75]. For this, the research team contacted the leading organisations actively working in the field of 3DFP in Europe (in 2019), as shown in Table 2.

Of these, 12 agreed to participate and were subsequently interviewed (the interview guide listing the lead questions is provided in Appendix A). These companies offer a variety of products and services in the food industry, but a common feature is that they all use extrusion-based printing technology [15]. Interviews were conducted online by means of videoconferencing and were then transcribed, coded, and analysed, following a thematic analysis approach [76]. A summary of the key insights that emerged from the interview data is shown in Table 3.

3.1. Interviews Highlights

Interviews with 3DFP specialists revealed several key insights. Many of the interviewees shared the vision of 3D food printers becoming a commonplace, easy-to-use kitchen appliance, making food preparation simple and quick, using personalised ingredients and quantities. However, all conceded that the market is currently very small and lacking a clear business model for the mass market. This means that 3DFP is still mainly being used by niche enthusiasts, on university projects, and by industry professionals with relatively little private investment or serious interest from the mainstream food industry. In essence, 3D printed food is very much still considered futuristic to most people. 3DFP companies believe that restaurants and catering services, as well as health professionals could help in co-creation and cooperation activities to further develop 3D printing applications throughout the food value chain.

Table 2. 3DFP companies in Europe (in 2019).

Name	Focus	Country
3D byFlow	3D food printing technology, Services (demonstration, workshops)	Netherlands
3dChef	3D food printing (chocolate, food molds) Services (workshops)	Netherlands
3dible	3D food printing technology (network, open-source project), Services (workshops)	Germany
Apetit	Food research	Germany
Backhaus	Restaurant	Germany
Biozoon	Food innovations	Germany
Blu Rhapsody	3D food printing	Italy
Choc Edge	3D food printing equipment manufacturer	UK
Chocolate	3D food printing	Germany
FELIX Printers	3D food printing equipment manufacturer	Netherlands
Food Ink	Restaurant	UK
Foodjet	3D food printing technology	Netherlands
Katjes/Magic Candy Factory	3D food printing	Germany/UK
La Boscana	Restaurant	Spain
La Enoteca	Restaurant	Spain
La Miam Factory	3D food printing	Belgium
Natural Machines	3D food printing and equipment manufacturer	Spain
Nova Meat	3D food printing equipment manufacturer	Spain
Pancakebot	3D food printing equipment manufacturer	Norway
Print Cheese	3D food printing	Netherlands
Procusini (Print2Taste)	3D food printing technology	Germany
Robots in Gastronomy	3D food printing research and design	Spain
TNO	3D food printing research	Netherlands
Upprinting food	3D food printing research	Netherlands
Verstegen Spices & Sauces	3D food printing supplier	Netherlands
VTT Nutritech	3D food printing research	Finland
Zmorph	3D food printing equipment manufacturer	Poland

A common theme amongst respondents was that it is critical to expand the product portfolio, from mere 'shaping' towards actual personalisation to create higher added value for consumers. It was also evident from the interviews that growing demand for customised services in other areas (e.g., entertainment streaming services, fitness trackers, etc.) fosters demand for personalised 3DFP products but achieving this will require a redesign of existing supply chains. Another theme that emerged was the potential for 3DFP to assist with reducing food waste. Consumers are increasingly interested in using renewable food sources, such as insects, algae, duckweed, grass, lupin seeds, and beet leaves, to produce foods that meet their taste requirements but are unsure how to do this. Upprinting Food [77] is developing new recipes and designs, using these so-called residual food flows (i.e., leftovers). Food waste and vegetable cuttings are not only sustainable but can be the basis for nutritious recipe ingredients, designed to be more attractive to the palate via 3D printing. The same applies to algae and insects, both of which are increasingly being used to produce high-quality products [58]. Although this appears highly promising for future food production, substantial hurdles need to be overcome prior to widescale commercialisation. One crucial aspect to explore is the 'purchasing state' of these materials. For example, what should be the ideal purchasing state of algae, insects, and food waste for consumers? Should they come complete, as flour, in 'gel' form, or 'print ready' form (print capsules)? In other words, how much would be expected of the consumer in terms of technical know-how and food processing skills? The answer to this question could substantially affect consumer willingness to adopt 3DFP technology. Indicative quotes from the interviews and proposed supply chain models are shown in Table 4.

Table 3. Summary of the interview data.

Co.	Focus Product/Service	Technology	Target Group	Challenges and Future Developments
A1	consulting service	extrusion, binder jetting	companies interested in 3DFP	customer perception, manufacturing costs
A2	frozen food distribution	internal R&D only	Generation Z, customers looking for a unique eating experience	complexity of 3DFP, customer perception, manufacturing costs/timings, lack of business cases to benchmark
A3	ingredient developer and product manufacturer (specialist meals and snacks)	FDM	nursing homes and hospitals, athletes	Technical feasibility, printed food quality, customer perception, print duration, multiple printing heads for production of food series
A4	ingredient developer and product manufacturer (customised pasta pieces)	own developed technology	premium/non-price-sensitive consumers	customer perception of 3DFP, upscaling to mass produced industrial volumes, decentralizing production
A5	multimaterial 3D printer, software, technology	FDM	restaurants, university labs, early adopters	customer education/perception, upscaling production
A6	personalised chocolate shapes and recipes	FDM	chefs, businesses, premium consumers looking for innovative and 'fancy food' solutions	manufacturing costs, print duration, optimise website for consumer use (enable self-service)
A7	ingredient developer and product manufacturer	FDM, developing new technology in-house	confectionery retailers, event organisers	customer perception, new 3D printers for printing personalised medicines and nutrition (vitamins and supplements market)
A8	3DFP printer for restaurant and home use	FDM	Professional kitchens, hospitals, catering services, hotels	consumer acceptance, focus on home use
A9	ingredient developer and product manufacturer	FDM	B2B market	variable quality, manufacturing costs, personalised nutrition (e.g., athletes and those with specific health issues), future opportunities for dairy based products

Table 3. *Cont.*

Co.	Focus Product/Service	Technology	Target Group	Challenges and Future Developments
A10	contract research and engineering consultancy for companies, prototype printers	FDM, binder jetting, selective laser sintering	companies working in the 3DFP domain	new food textures and ingredients, upscaling to industrial food printing, open-source software
A11	printable food paste from bread, fruit, and vegetables	FDM	restaurants, those interested in reducing food waste	cost and duration of printing, upscaling to higher volumes
A12	3D food printer technology (hardware)	internal R&D only	bakery and confectionary, catering services	cost and duration of printing, upscaling of production

Table 4. Key interview quotes and applicable 3DFP supply chain model.

Respondent	Key Quotes	Supply Chain Model
3D Food Printing expert (A5)	We want to create new production methods, capable of producing personalised and customised food on a large scale for those suffering from dysphagia (swallowing and mastication problems) who normally need pureed food . . . Next to producing the hardware, we saw that many people do not have the design skills to make their own shapes for 3D printing, so we made it as simple as possible. We are teaming up with big multinationals and working on developing our products for implementation on an industrial scale. We are also gaining expertise from professional food producers to use in for future industrial developments . . . reducing food waste is a big growth opportunity for us. For example, we cooperate with a company who makes sauces and ketchup from food waste.	Generative/Premium
3DFP expert (A10)	Our mission is to increase wellbeing in society. 3D food printing will enable more efficient and sustainable use of the resources we have.	Generative/Premium
Founder (A11)	We want to show consumers how much of the food they normally throw away, is actually still edible. These are actually the raw materials for 3D food printing . . . We are working on new recipes and designs, with different types of food scraps and leftovers as raw materials such as bread, rice, overripe fruit... Residual food flows change with the seasons and therefore our recipes should also change and grow according to these.	Facilitative/Deluxe
Technology Officer (A4)	I can imagine decentralisation of the production process and opening new production facilities. For example, developing new food raw materials and ecosystems that respect people and the planet. We are an established food producer, concentrating on a new business model using 3D food printing and as the sales increase, we will scale up the technology to support this. We do not only sell pasta but design new experiences through pasta...We offer customisation of ingredients, shape and unique gastronomical experience....We are exploring the field of texture for pasta, because we reengineer each shape according to customer needs. We ship frozen pasta to restaurants all over the world but for now our main focus is Europe.	Generative/Premium Facilitative/Deluxe

Table 4. *Cont.*

Respondent	Key Quotes	Supply Chain Model
CEO (A8)	Consumers are looking for smart solutions in their kitchens. Our food printer is a connected device—connected to the Internet—and allows us to have an ongoing relationship with our customers. We provide software updates, so our customers continue to have the latest technology on their printers. Basically, we saw an opportunity in the food industry and 3D food printing was the best way to solve that problem: we can reduce food waste throughout the food value chain: from the customisation of portion sizes, allowing people to print what they want to eat and nothing more, to recovering food that is traditionally classified as food waste—such as "ugly" fruits, vegetables, and cuts of meat—and printing these foods making them an attractive and nutritious food source.	Selective/Standard
Food Printing specialist (A1)	We provide consulting for companies who are interested in 3D food printing or want to get further than just general knowledge, and actually experience 3D food printing. We provide 1–2 days workshops, which includes bringing our printer to test various raw materials.	Generative/Premium
R&D Project Manager (A3)	In the end everyone will be able to buy their own printer and print at home for their own use. Technological difficulties like the printing time (which is in our opinion the biggest challenge) will be further improved. We think that plug and play solutions will be the biggest growth area in the near future.	Generative/Premium Facilitative/Deluxe Selective/Standard
Operations Manager (A7)	We hope in the next 10 years people start to install 3D printers in their kitchens to make food for their everyday meals. We initially focused on confectionery and are now developing new concepts based around personalised nutrition and medicine (a new 3D printer is under patent application). Our 3D printers are available to use in retail outlets, so customers can place an order to print and the retail staff box and bag it.	Generative/Premium Facilitative/Deluxe

3.2. *Proposed Supply Chain Models for the 3D Food Printing Process*

In traditional food supply chains, consumers are typically separated from the production process, both in terms of the product itself and the associated information flows [78,79]. With 3DFP, this is different as the gap between production and consumption is reduced, allowing for a much closer relationship as described by the 3DFP experts during the interviews. One of the most important themes that emerged was co-development activities with customers can substantially improve usability and reduce waste. This agrees with previous research by Jayaprakash et al. [80], who found that if an efficient digital services model is in place, these user-centric value chains can lead to improved customer attitudes and perceptions of 3D printed food. Furthermore, this two-way 'back-and-forth' information flow with customers also assists in refining the service offering, all the way from developing the 3D food printers, through to the printing materials and the range of service delivery modes (e.g., converting potato peelings into input-ready material for the food printer).

The growing demand for customised services, such as direct production of personalised food products, requires the supporting supply chain strategies to be redesigned [21,81]. As customisation takes place at all key stages, i.e., manufacturing, packaging, and distribution, according to customer needs, it can be assumed that the supply network within 3DFP will need to mature and grow to involve specialists with knowledge of personal nutritional requirements, food scientists, and chefs, as well as logistics and distribution management [13,82]. Although most respondents confirmed that 3DFP is still in the emerging phase (and far from mainstream acceptance as a food choice for most consumers), given sufficient support and targeted marketing and awareness campaigns, it has the potential to make an impact. In particular, with a supportive service delivery model, 3D food printing could improve sustainability across the food supply chain. Based on the insights from the interviews and drawing on the model of 3DP services from Rogers et al., [83] and Rogers and Braziotis [84], we propose three possible supply chain models for 3DFP: generative, facilitative, and selective services. These are shown in Figure 1 and will be explained in turn in the next section.

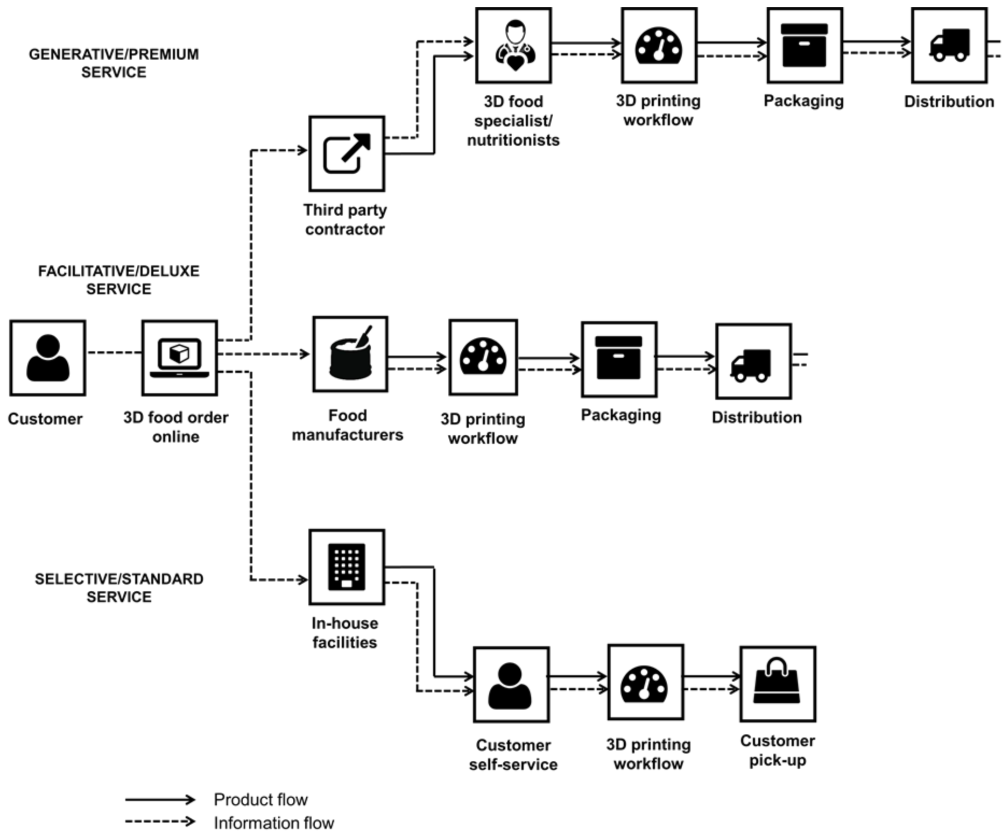

Figure 1. Proposed supply chain models for 3DFP.

(i) Generative/Premium services

A generative service would be aimed at consumers who would be prepared to pay a premium (i.e., extra money) for a one-stop-shop for their 3DFP services. Here, a complete food service delivery system could be created, starting with the customer placing an order using the online portal, then being referred to an appropriate third-party 3DFP service provider who would then coordinate activities (examples are ByFlow, TNO, Katjes Fassin). Once they receive the customers' online order, additional services, such as modifying the nutritional content, texture, design, and information about different recipes, can be provided. These third-party contractors have a network of dietitians/nutritionists, food scientists, designers, and food educators available to help customers modify or further improve their recipes' nutritional content, while staying within technical parameters. Once the customer selects the content, texture, design, and shape with the specialist, the information will be transferred to the production site to print the required food (prepare the mixture for printing, the actual printing process, post-printing work, such as drying, etc.). The 3DFP contractor then coordinates all the other stakeholders along the supply chain to deliver the printed food to the customer (either at their home, a restaurant, or other venue/service delivery point of their choice) depending on their individual needs and location. This individual customisation overcomes any potential lack of technical knowledge by the end customers and also alleviates any potential psychological barriers towards 3D printed food (by allowing the experts to explain any issues along the way). The open end of this supply chain provides the option to link up with existing local distribution service providers, such as Uber Eats, Deliveroo, Zomato, etc. One of the issues highlighted by the respondents was that some 3D printed foods have a fragile texture or structure (e.g., intricate chocolate cake decorations), making transportation problematic.

Additionally, these third-party contractors can also provide 3D food dinner subscriptions by simplifying food preparation and offering different recipes on rotation. As evidenced by the success of existing subscription-based food delivery services (based on conventional food), such as Hello Fresh, this approach creates customer value and is something people are prepared to pay for. This service is beneficial for customers who are willing to pay a premium price to have unique customised food made for them. Typical target customers for this service include health-conscious people, those with diet restrictions (lactose, celiac, soya, keto diet, peanut resistance), those with health conditions, and older adults (seniors), athletes, etc. This service could also be aimed at organisations rather than individuals and may include hospitals, medical centres, rehabilitation centres, elderly care homes, health spas, etc. Personalised digital recipes created by developing, printing, and selling unique recipes 'made for you' provide the basis of the USP in comparison to regular food delivery services.

(ii) Facilitative/Deluxe service

In the facilitative 'deluxe' service, the online customer order is sent directly to the relevant food manufacturer (e.g., BluRhapsody), using 3D printing machines to print individual orders on a small batch production basis using their standard ingredients (e.g., pasta, candies, or chocolate). What differentiates this production is that 3DFP technology requires the input materials to have very specific characteristics in terms of moisture levels, viscosity, size, etc. (to enable smooth running of the 3D printing process). Once these conditions have been understood and met, potential food waste that would otherwise be disposed of can be repurposed and made into viable end products by the food manufacturers at their factories.

Working with food manufacturers provides the 3D printing services with a much broader range of food printing materials and geographic locations, as well as increased economies of scale. In contrast to the generative/premium service, the facilitative/deluxe service will not provide additional personalisation in terms of nutritional content or modification of the recipe. A further difference is that the service is driven by batch customer order fulfilment, rather than one-offs. Once the food is printed and dried or baked as appropriate, it will be packed and distributed by the food manufacturers directly from the production facility, meaning supply chain costs will be kept to a minimum.

(iii) Selective/Standard service

For the selective 'standard' service, the customer's online order is processed and printed in-house by the receiving organisation (e.g., Biozoon and Natural Machines), with the end customer finding a local 3DFP printing centre, selecting the required items, activating the printing process, and taking the finished products home. A more expensive variation of this would be a click and collect service, with customers selecting their items from a predefined list of products but paying more for the actual printing to be done for them. Even home users of 3D food printers could be a part of this model. Home 3DFP, may become more commonplace within the next 10 to 15 years (as indicated during the interviews). The digital transformation of the modern kitchen has already begun, with high-tech 'smart' kitchen equipment featuring in many peoples' homes. Some interviewees believed, however, that it will take time to get this technology into commercial/professional kitchens.

With all of these three models, sustainability is built into food supply chain operations. For example, food production is only triggered once a customer order has been received. Moreover, leftover but still fully viable food from restaurants can be quickly redirected and used to prepare customised food items in an extruded 3D printed form. There is a reduction of packaging in the standard service business model, as food is prepared on demand. Although these three models aim to impart sustainability in the overall food supply chain, it is essential to note that the success of each model depends on several factors, which are described in turn below.

3.3. Enablers for 3DFP Supply Chain Models

These supply chain models can be used to guide and assist 3DFP towards greater commercialisation and acceptance among various consumer segments. Although 3DFP supply chain models can be used to enhance sustainability in existing food supply chains, for example, by reducing logistics and transportation costs and maximizing material and energy efficiency, the technology is relatively new and requires key enablers as shown in Figure 2 [83,85–87]. Moving from the outside to the inside of the model, the first layer depicts enablers or activators required to commercialise 3DFP supply chains. It is important to note that these enablers are interconnected and to maximise the positive impact, they should work in harmony. For example, government support and involvement are paramount to promoting open innovation and developing sustainability measures. This process can be further enriched by using information from food recyclers, educational institutes, nutritional experts, and hospitals. This 'coopetition' mode, whereby all players cooperate to increase the market (i.e., and with it their slice of the overall pie), will aid adoption and hence accelerate commercialisation of 3DFP technology.

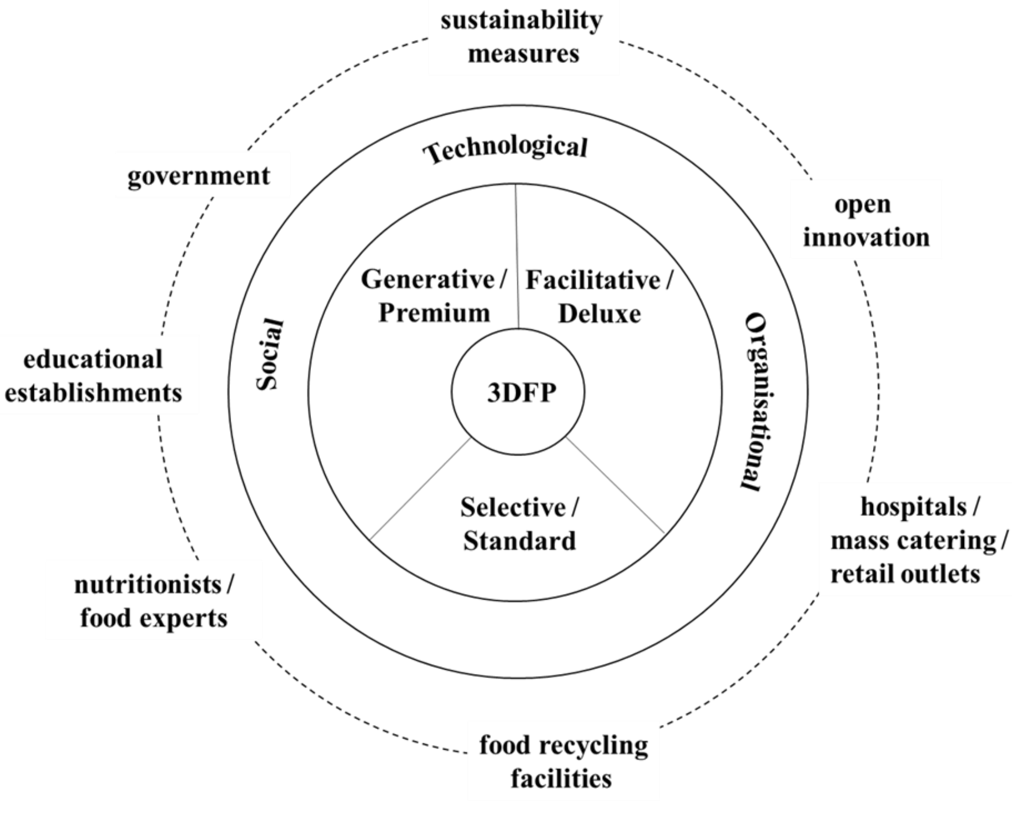

Figure 2. Enablers for 3DFP.

The interview respondents confirmed that 3D food printers are still emerging from the developmental phase, with only a few companies using it on a commercial basis. Consequently, the technological aspects need to be evaluated. One of the main constraints cited during the interviews was regulation and patent law. Firstly, there is no universal law regarding software and 3D printing rights, and digital rights management can vary considerably from country to country (even inside the EU). In the meantime, there is no clear guidance on issues, such as safety rules, parties' responsibilities, and intellectual property of digital recipes. One of the current technical limitations is the slow printing speed. Print times depend on the ingredients, the recipe, and quantity printed (often made in small batches). For example, at BluRhapsody, nine pasta pieces can be printed in 2 min while intricate chocolate sculptures can take 2 h to print. Quantities also have to be taken into consideration, e.g., a small, single serving of ravioli will print faster than the quantity required to feed a family of 5. Additionally, cost was an important factor that emerged during interviews when discussing obstacles to adoption, with professional printers being particularly expensive.

In addition, there are major sociological and organisational aspects requiring attention. For example, the perception towards the safety of 3D printed food and its (unproven) long-term effect on consumers' health and wellbeing. Moreover, clearer guidelines and regulations in terms of future licensing arrangements are required. In this context, concepts, such as open innovation and collaboration with research organisations, can assist. As the technology is new, open innovation can reduce the cost of development and improve its efficiency and performance. A close cooperation with universities, authorities, and research organisations would further boost innovation in developing low-cost/affordable 3D food printers. Government authorities can develop rules for regulating the technology, safety, patent laws, licensing norms, as well as technology transfer [88]. Governments may also need to develop sustainable key performance indicators to measure the environmental impacts of 3DFP as these are currently lacking. For example, companies producing 3D printed food will need to adhere to FDA (Food and Drug Administration) or FSA (Food Standard Agency) directives in terms of appropriate food temperatures, approved shelf life, and labelling requirements. Printed food might face the same issues as genetically modified food with respect to unknown long-term effects. Consumer scepticism will only be overcome once these issues have been addressed, thereby demonstrating 3DFP as a safe, attractive, and appetising alternative to traditionally manufactured food. Only then will it have the potential to shape the future of the food supply chain [13].

One of the major advantages of the 3DFP is the potential to reduce food waste. For this to succeed, clear health and safety regulations are needed (to avoid food poisoning and related issues). However, educating consumers to accept a new technology can be difficult and time-consuming. To achieve this, companies choose and target early adopters who are open to and accepting of new technologies. Thereafter diffusion to the mass market is much easier. For 3DFP, there could be two such 'early adopter segments': first, health-conscious consumers and second those with health issues. Health-conscious people who regularly visit the gym, health centres, and nutritionists could help in building the awareness for 3DFP, accelerating the diffusion of this technology. Similarly, targeting people with health issues could further spread awareness about this technology. Consequently, we need a close and collaborative loop of various stakeholders to achieve this (hospital, nutritionist, mass catering, retail outlets, etc.). These and other enablers are shown in Figure 2.

4. Discussion and Future Research Agenda

The findings of this study identified opportunities, risks, and challenges associated with developing supply chain business models for companies in the 3D printed food industry. 3DFP has several paths of development and market popularisation. This technology can be used as a tool for building complex shapes that are otherwise difficult to achieve (e.g., intricate confectionary), as well as for highly personalised food products tailored to an individual's nutritional or taste needs. 3DFP technology can be viewed more broadly than just the creation of food options, as it aims not to duplicate existing offers in the traditional food market but instead to create new novel value for businesses and individual consumers. Moreover, its potential to reduce food waste through repurposing of food increases its appeal. Despite its potential, 3DFP technology is still immature, meaning services currently run at a very small scale, niche level, and mainly appeal to experimental early adopters. Crucially, consumers are not yet ready or feel insufficiently informed to accept this technology as an alternative to conventionally produced food. Currently, companies in the market require additional investments to further develop the technology and widen its product range (particularly in terms of the variety of ingredients that can be used for printing). The challenges, risks, and opportunities prevalent in this emerging

industry, explored in this study (with reference to the corresponding research question posed at the beginning of the paper), are summarised below.
Customer attitude and sustainability-related aspects (RQ1 and RQ2) How does 3DFP need to develop to meet customer expectations (and hence pave the way for increased acceptance and adoption)? How can 3DFP be used in food supply chains to improve sustainability?)

- Increase awareness of what 3DFP is, away from the perception by some of it being 'artificial' or highly processed food. Be aware that the appeal and acceptance of future food tech (such as 3DFP) are atypical in some cultures [89].
- Focus marketing campaigns on 3DFP's potential to repurpose food waste, as well as to provide unique meals and taste combinations.
- Apply relevant elements of the FAO Sustainable Food Value Chain Framework to the 3DFP context.
- Industry standards and regulations need to be established to determine who owns the data generated for both the printed foods themselves and the associated personal customer data generated as part of the service provision.
- As the industry develops, it will become clearer which supply chain models (generative, facilitative, or selective) will be most efficient and have the potential for future growth.

Supply chain configuration related aspects (RQ3) As the industry matures, how will 3DFP supply chains be configured?

- Currently, one-off orders and small batch production are the main manufacturing mode. Scaling up towards reliable and timely batch or even mass production will be a key supply chain success factor.
- Individual customisation is likely to continue to be a market driver as part of the developing trend for personalised nutrition. As customers will pay a premium for this, they will also expect a high-quality service provision. Further work is needed to determine how individual nutritional requirements of customers can be safely and securely incorporated into 3DFP services.
- The mode and extent of collaboration between supply network partners will evolve over time as the technology becomes more established.
- Developing open-access platforms to provide a forum to exchange technical data with the aim of enhancing quality, reliability, and affordability of 3DFP products and services.
- Taking an open design approach could not only ensure wider appeal and increased product development and applications of the technology but also allay concerns related to intellectual property issues [90]. This leaves the service delivery aspect of the business as a crucial success factor.
- How will 3DFP supply chains manage copyright and patent law, as well as specific country regulations? This aspect is highly important if 3D printed food enters the global food supply chains. If the regulations and intellectual property rights in a given country are not up to the standards, this could further hamper diffusion of the technology.
- If raw materials/food ingredients originate in one country and are printed in another country and then delivered to a third country, how will the global food supply chain be managed? Rules and regulations vary from one country to another. Critically, any provision of future food products requires quality control along all stages of the supply chain, including downstream processing [89].
- To ensure food security, would there be a possibility of incorporating data analytics or blockchain into 3DFP supply chains?

As the technology is still in the growth phase, it will be interesting to see how - and indeed if - firms currently working in the 3DFP sector will choose to collaborate. Typically, when a technology is new with limited 'use cases', firms tend to cooperate and share (some) technical knowledge to encourage more rapid adoption and hence market size [87].

5. Conclusions

Rising public concern for individual health leads to the emergence of new trends for foods that focus on personal care and healthy nutrition concepts. Such personalisation cannot be easily fulfilled using traditional food production methods. In a conventional food supply chain, food customisation at this level can be difficult, owing to packaging requirements (food security, freshness, damage protection, shelf presentation) and logistics reasons (pack sizes, job lots, delivery schedules), all of which can contribute to food waste. Following interviews with 3DFP experts, we propose three supply chain models for the implementation of 3DFP services. These models (i.e., generative/premium, facilitative/deluxe, and selective/standard) are designed to be configured as per individual customer requirements.

It is evident that although 3DFP has potential, both in terms of applications and customer interest, considerable technological, social, and organisational challenges remain. Based on our interview data, we found that 3DFP experts consider consumer neophobia (acceptance), lack of regulatory guidelines, the need to scale up, high manufacturing costs, and long printing times to be the most significant challenges. Further market growth is subject to overcoming these challenges through a combination of increased financial backing, process control, continued innovation in printing materials, and cross industry cooperation. In particular, substantial and continued funding investments and process developments (including post-processing) to ensure a consistently high-quality printed end product are paramount. The mode and extent of collaboration between supply network partners will evolve as this intriguing technology becomes more established. Among the most promising current applications were customised food (including for those with special nutrition needs), delivering unique bespoke eating experiences at novelty restaurants, and perhaps most promising of all, reducing food waste via repurposing of still viable but rejected food. For these reasons, growth in the 3D food printing market is expected to continue and accelerate, bringing greater opportunities for integration between professional 3D printers, novel food materials, design, and 3D printing techniques. As such, there are many pathways for future research in this area. In summary, 3DFP technology has the potential to improve sustainability in food supply chains (e.g., creating value from waste, utilizing novel sources of protein through insects and algae, thereby reducing the environmental impacts of traditional food supply chains, or by reducing the number of food items required to gain nutrients in the form of customised nutrition). In this way, the technology also provides pathways to tackling some of the wider problems facing food supply chains in the future. However, as outlined in this paper, further innovations at both a product and service delivery level are required to enable this technology to make the shift from emerging to emerged. Only then will we begin to see widespread commercialisation.

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Appendix A. Interview Guide

- What is your position and job description?
- How long has your company been involved with the food printing market?
- From your company's perspective, how will the market for 3D printed food change in the next 5–10 years. What will be future needs and wants of the customer?
- Do you think we will all have 3D food printers at home alongside microwaves and kitchen aids? Are they an alternative solution and good implementation of food printing technology in terms of smart homes development?

- What does your company produce? Could you explain your company USP? How would you describe the vision and mission of your company?
- In which countries do you operate?
- Which raw materials/components do you use?
- What is the focus of your company if talking about product range?
- Which technologies do you use for printing your products? What is the price range? How do you promote your product/service? Who is your target customer group?
- Do you work together with any governmental/research institutions and/or have partner companies?
- Describe a typical process of printing a meal? How long does it take to print one meal?
- Which aspects/benefits of 3D printing motivated your company to investigate 3D food printing technology?
- What potential supply chain related challenges do you expect to see over the next 5–10 years?
- What do you consider to be the likely next developments and innovations?
- Specific to your company, what are the upcoming opportunities and challenges of 3DFP?
- Are there any other issues you want to raise?

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