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Trends, drivers, and barriers shaping the 3DFP market

A number of potential drivers and challenges for the future evolution of 3DFP were identified in the course of this research. These range from specific R&D activities in research laboratories, the current conditions in the food printer hardware market and related business models, to certain consumer trends and commercial developments that all may influence to what extent the technical potential of 3DFP may lead to viable solutions in the food system in the future.

5.1 3D food printing R&D, academic literature and patenting

To get an overview of trends in the academic literature and patent space we have used customised data analytics tools to capture baseline trends in the evolution of R&D activities related to 3DFP.

Recent reviews of varying quality have looked into the publication evolution of the field (Agunbiade et al., 2022; Baiano, 2022; Derossi et al., 2021; Portanguen et al., 2022). For example, Portanguen and co-workers have used the Science Direct database for their analysis, as shown in figure 11.

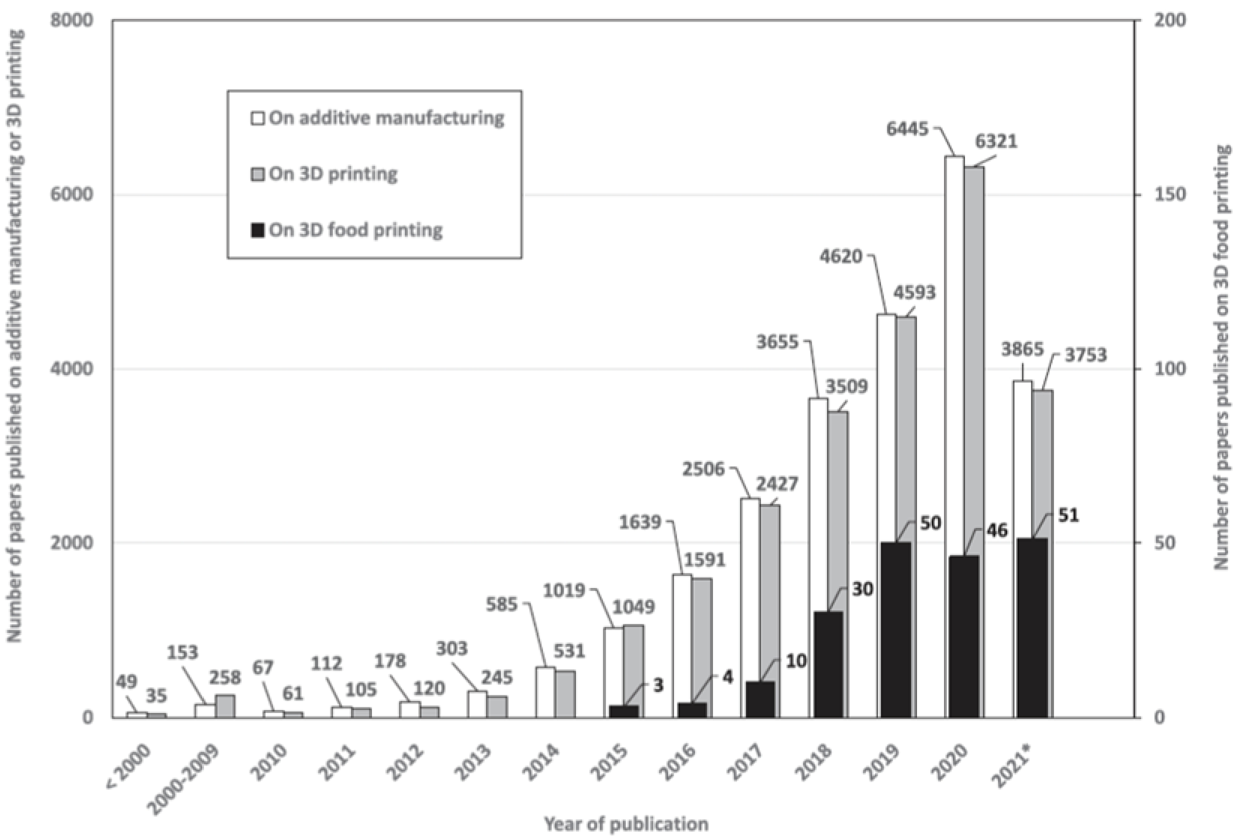

Figure 11: Publication evolution of the academic literature on 3DFP compared with literature on additive manufacturing and 3D printing. Note incomplete data for 2021. Source: Portanguen et al., 2022.

These recent reviews report consistently low numbers of publications, and although absolute numbers vary depending on search strategy and databases used, authors concur that the field of 3DFP has mostly emerged within the past 15 years with a rapid increase in research output over the past five years.

In order to update information and to use an approach that allows for a wider search horizon we have performed literature analysis in the LENS database, for details see methodology section.

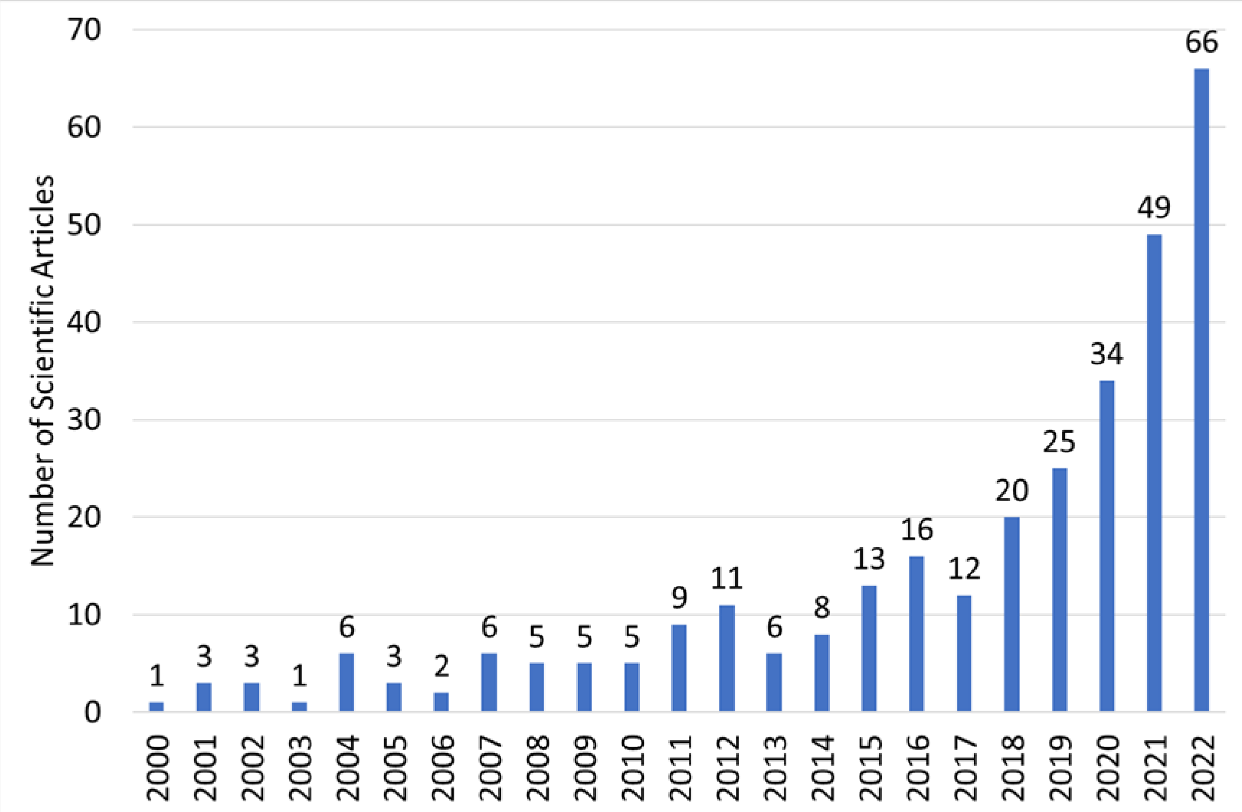

Figure 12: Evolution of the academic literature on 3DFP over the past two decades. Analysed in the LENS database using less stringent search criteria. Note: data from 2022 incomplete (up to 25. November).

This search was carried out in two steps, first applying an algorithm-based approach to cover breadth of sources, followed by researcher based critical review of the data that narrowed down the search to the most relevant data since 2015, yielding a total of 103 publications in peer reviewed journals (fig 13).

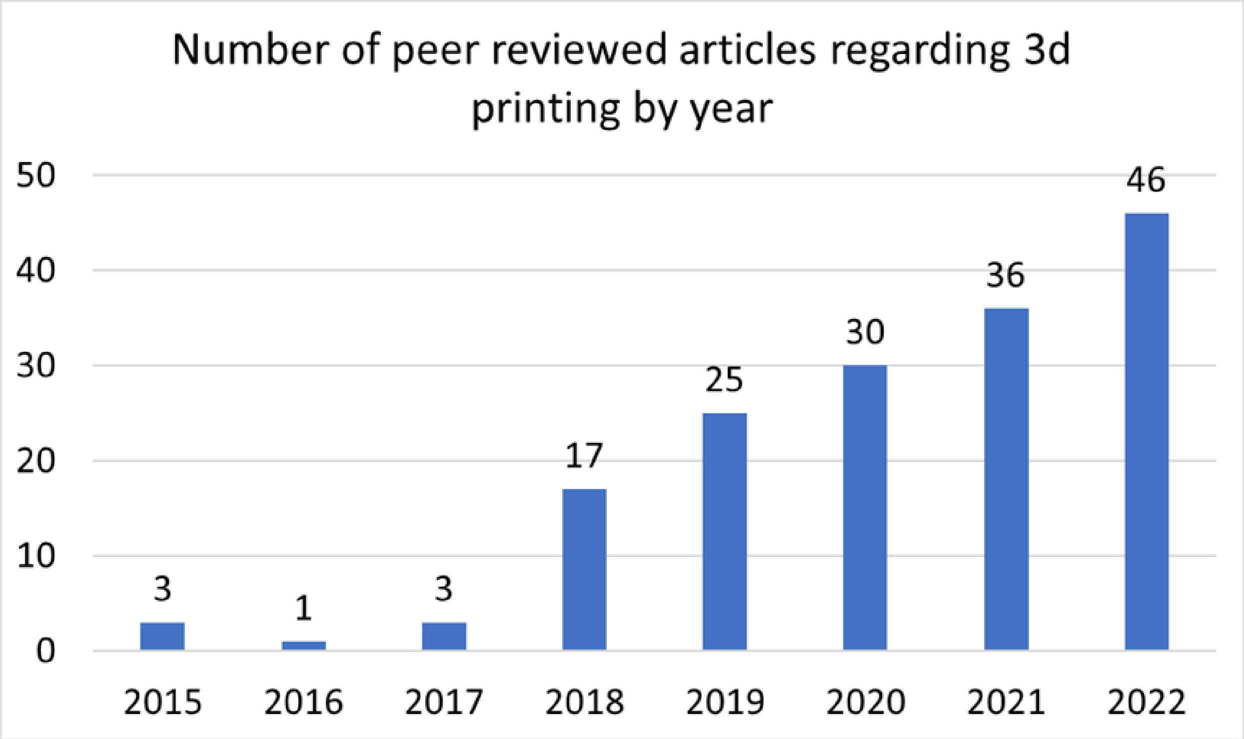

Figure 13: Number of peer-reviewed publications directly relevant to 3DFP. Note: data for 2022 up to November 30.

We can confirm that 3DFP as an academic research field is small, rapidly expanding over the past five years and dominated by a few productive authors that are referenced by a number of the most recent publications, magnifying their impact although this does not necessarily reflect the quality and impact of research work on the progress of the field.

Table 1: Most published authors in the 3DFP literature and their affiliations

Author	Number of publications	Affiliation	Country
Min Zhang	30	Jiangnan University	China
Bhesh Bhandari	24	University of Queensland	Australia
Sangeeta Prakash	11	University of Queensland	Australia
Maarten A.I. Schutyser	7	Wageningen University	NL
Arun S. Mujumdar	6	McGill University	Canada
C. Anandharamakrishnan	5	Food Engineering Department CSIR - CFTRI Mysore	India
Chaohui Yang	5	Jiangnan University	China
Jeyan A. Moses	5	National Institute of Food Technology, Entrepreneurship & Management - Thanjavur | NIFTEM-T India	India
Lu Zhang	5	Wageningen University	NL
Pattarapon Phuhongsung	5	Jiangnan University	China
Zhenbin Liu	5	Jiangnan University	China
Chaofan Guo	4	Jiangnan University	China
Javier Martínez-Monzó	4	Universitat Politècnica de València	Spain
Markus Stieger	4	Wageningen University	NL
Purificación García-Segovia	4	Universitat Politècnica de València	Spain

Author	Number of publications	Affiliation	Country
Sakamon Devahastin	4	King Mongkut's University of Technology Thonburi	Thailand
Sicong Zhu	4	Wageningen University	NL
Sylvester Mantihal	4	Universiti Malaysia Sabah	Malaysia

Research institutions outside of China with a strong focus in 3DFP are for example University of Queensland in Australia, McGill University in Canada, and Wageningen University in the Netherlands. Also Spain has not only two active universities carrying out research on 3DFP, but also a well-networked ecosystem of 3D printing technology developers in the Barcelona region leading to important synergies. When looking into the most researched food items investigated by these most published authors it becomes clear that many are exploring novel ingredients that have traditionally not been printed before, such as vegetable and fruit based ingredients, or microalgae and various proteins and fortifying ingredients, such as vitamins and probiotics (table 2).

Table 2: Food ingredients studied by the most published authors in the 3DFP field

Author	Number of publications	Affiliation	Country	Foods
Min Zhang	30	Jiangnan University	China	Mashed potato, lemon juice gel, steak-like using soy protein, rose-sodium alginate, Nostoc sphaeroides biomass
Bhesh Bhandari	24	University of Queensland	Australia	Mashed potato, dark chocolate, Vitamin-D Enriched Orange Concentrate, steak - like (soy protein)
Sangeeta Prakash	11	University of Queensland	Australia	Chocolate, surimi, food for dysphagia patients, egg white protein, layered beef
Maarten A.I. Schutyser	7	Wageningen University	NL	Chocolate, sodium caseinate - sodium alginate blends, microalgae-enriched 3D-Printed Snacks
Arun S. Mujumdar	6	McGill University	Canada	Potato gel, fermented dough
C. Anandharamakrishnan	5	Food Engineering Department CSIR -CFTRI Mysore	India	Indigenous composite flour, chicken nuggets, encapsulated probiotics
Chaohui Yang	5	Jiangnan University	China	Vitamin-D enriched orange concentrate, mashed potato/strawberry gel
Jeyan A. Moses	5	Nat. Inst. of Food Tech - Thanjavur	India	Composite flour, chicken nuggets
Lu Zhang	5	Wageningen University	NL	Microalgae-enriched 3D-printed snacks, personalised bakery products
Pattarapon Phuhongsung	5	Jiangnan University	China	Composite mixture of soy protein isolate, pumpkin, and beetroot, fermented dough
Zhenbin Liu	5	Jiangnan University	China	Mashed potato, shiitake mushroom for dysphagia diet
Chaofan Guo	4	Jiangnan University	China	Nostoc sphaeroids biomass, lemon juice gel
Javier Martínez-Monzó	4	Universitat Politècnica de València	Spain	cookies, gluten free dough, mashed potato
Markus Stieger	4	Wageningen University	NL	Protein bars, chocolate coated rice waffles (for sensory study), sodium caseinate - sodium alginate blends

Author	Number of publications	Affiliation	Country	Foods
Purificación García-Segovia	4	Universitat Politècnica de València	Spain	cookies, gluten fee dough, potato cookies
Sakamon Devahastin	4	King Mongkut's University of Technology Thonburi	Thailand	Ergosterol-incorporated purple sweet potato pastes, surimi, mixture of soy protein isolate, pumpkin, and beetroot
Sicong Zhu	4	Wageningen University	NL	3D printed protein bars, sodium caseinate - sodium alginate blends, chocolate coated rice waffles (for sensory study)
Sylvester Mantihal	4	Universiti Malaysia Sabah	Malaysia	Chocolate

Using text analysis tools, the frequency of various research topics can also be visualised to give an overview of the whole of the publication space.

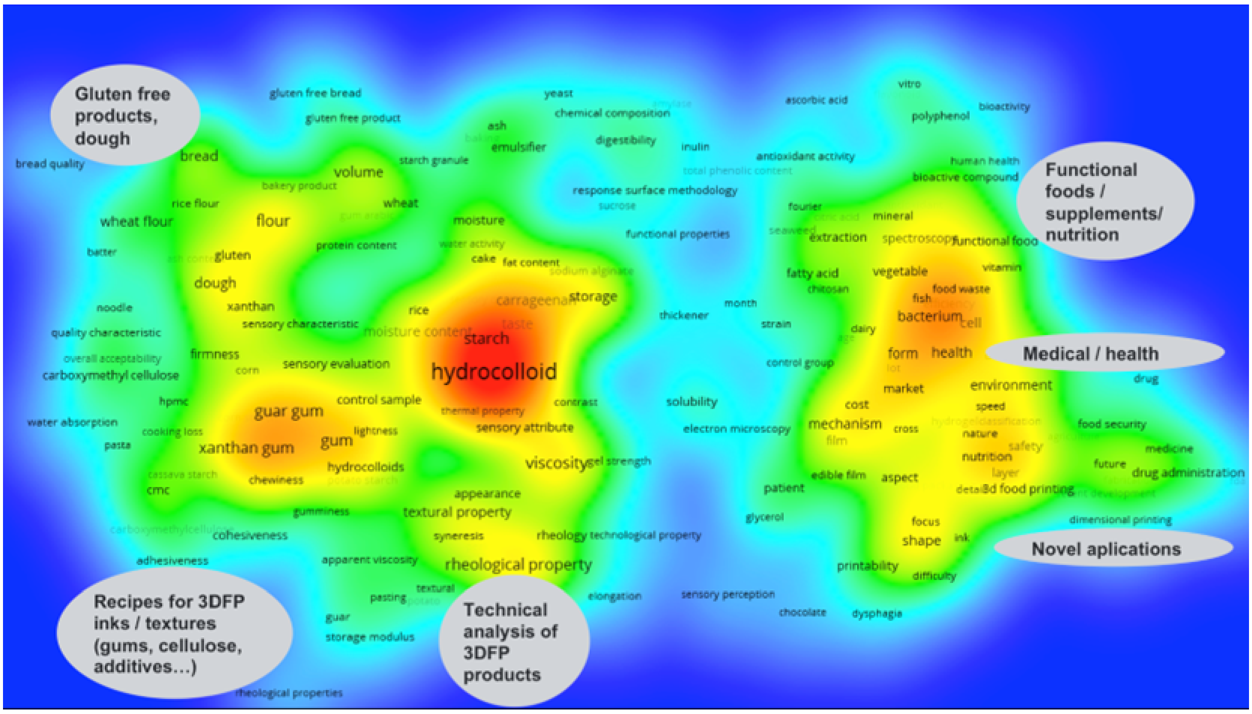

Figure 14: Word frequency landscape visualising topic areas in the 3DFP literature.

Visualisations like this show for example that most of the literature is concerned with the technical aspects of formulating printable food inks and optimising printing conditions using hydrocolloids (such as different types of starch and gums (centre left, and left) to improve printability), indicating that additives are essential for 3DPF to enable the technical printing process, and physical and chemical characterisation of viscosity/rheology of food inks is a major technical research concern (lower centre). This also highlights that extrusion-based printing is the dominant technology, and that binder jetting or selective laser sintering are very much niche technologies within the field. It also shows that some food types are intensively researched for 3D printability, such as dough/flour-based products (top left), reflecting also the fact that commercially available printers for these products exist for some years. Other areas of research that have emerged more recently, are seen in the cluster on the right, with a focus on health and specific nutritional requirements and emerging, proposed application areas.

When looking into the evolution of specific food types that have been researched for 3D printing it also becomes clear that these are still very limited, as for example a timeline graph of the number of publications mentioning specific printed food types shows (figure 15). It also shows that the most recent research on printability of vegetables, fruits or proteins has not yet had sufficient impact on the field as a whole.

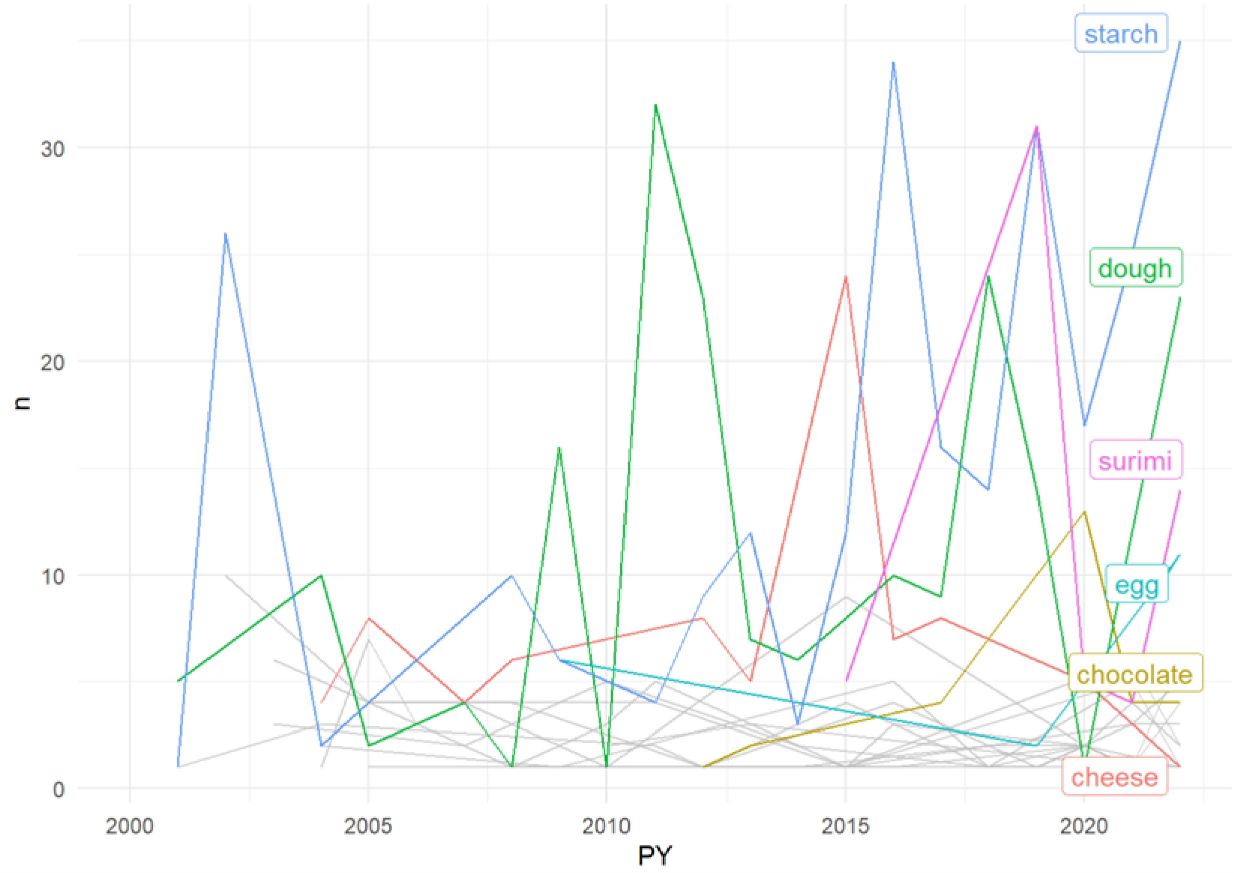

Figure 15: Evolution of publications on specific food types in 3DFP over the past two decades, using less stringent search criteria

The limited number of currently well printable food types corresponds with the capabilities of available food printers on the market (see section 5.2 on food printers).

5.1.2 Trends in the patent space

In order to gain insights into technology trends and innovations in 3DFP that may have been considered of commercial value, patent queries were conducted for the past 10 years in global patent databases from main IP Offices worldwide, namely: WIPO (patentscope), the World Intellectual Property Database; EPO (Espacenet), the European Patent Office, and USPTO, the US full text patent database. 2057 patent documents were obtained. From this original dataset China was found to dominate (1481 patents documents), however experts on Chinese patents estimate that possibly only 10% of filed patents are of value, due to low grant rates, and low commercialisation rates as well as industrialisation and commercialisation rates and a high proportion of abandoned patents (A. He & Centre for International Governance Innovation, 2021). Hence, in most of our analyses China is not included. For a deeper analysis of patents it was decided to focus on patent documents covering US, WO, EU, KR, JP and to focus on patent applications (rather than granted patents) in order to ensure the most recent “up and coming” technologies and applicants would be included as well as to avoid duplication of documents. 303 patent documents were finally analysed after narrowing down searches by direct relevance for 3DFP through critical researcher evaluation. Of those, 173 were directly related to 3D printing of food, which was the dataset finally analysed.

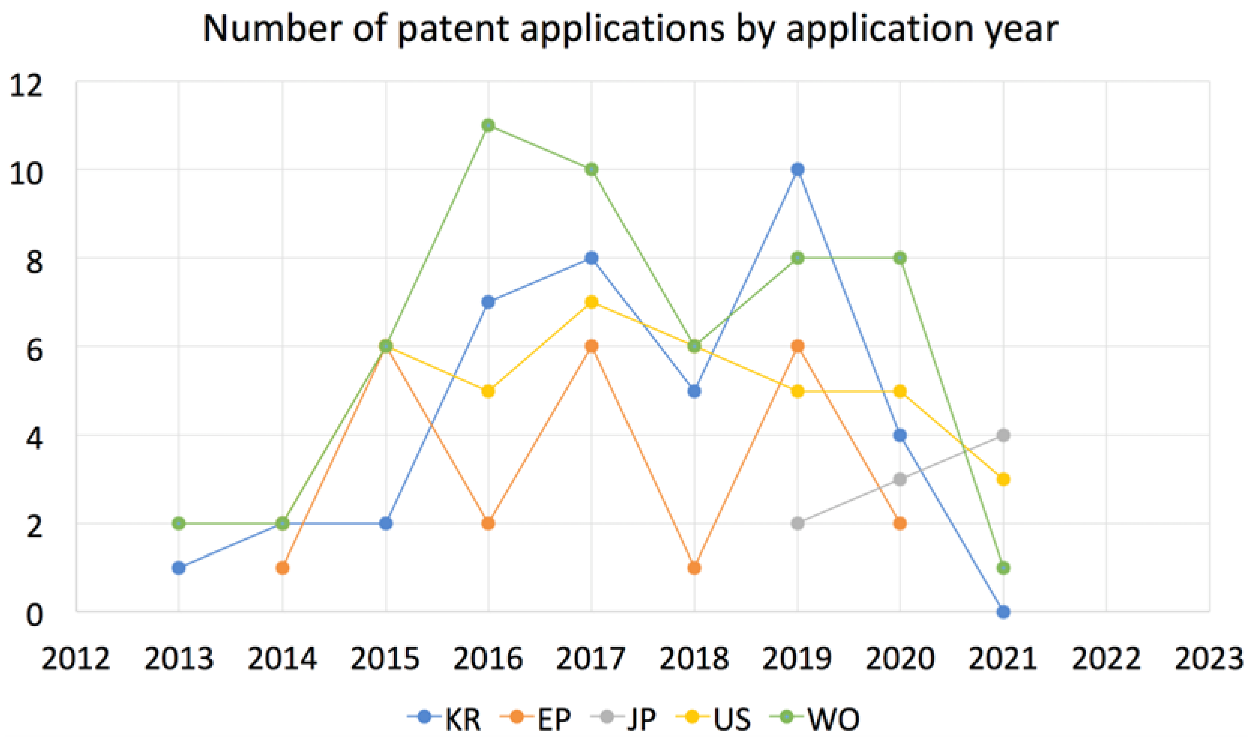

Figure 16: Number of patent applications in 3DFP over the past 10 years by geographical regions. Decline in applications in 2021 likely due to Covid-19 pandemic-related effects. (KR: Korea, EP: Europe, JP: Japan, US: USA, WO: Global).

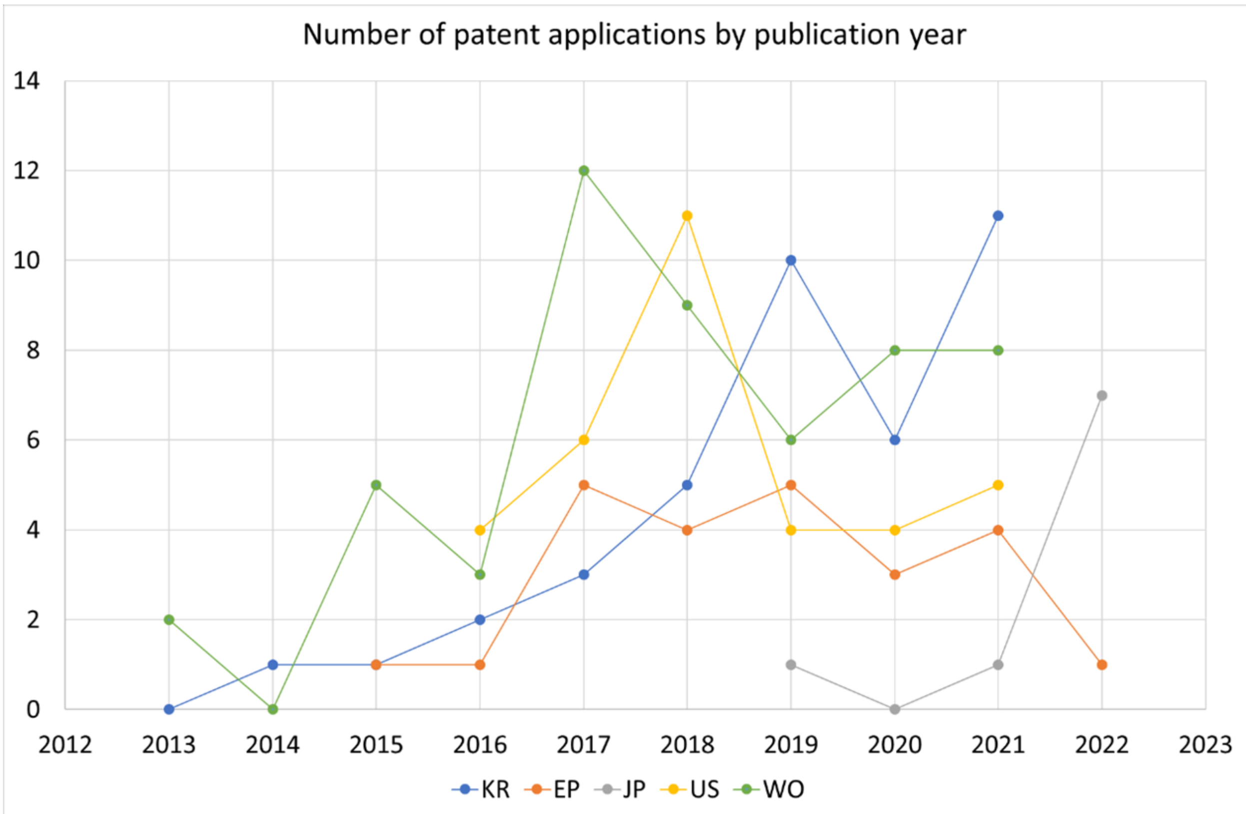

Figure 17: Number of patent applications for 3DFP by publication year and region (latest data included 30.11.2022)

Apart from confirming increasing peak activity in the past five years, generally low numbers of patents were filed, with possibly a drop in patent applications in 2020/21 due to the Covid-19 pandemic. However, one needs to consider that low patent numbers may not necessarily reflect only low interest in technology commercialisation, but might also indicate difficulties in finding prior art novelty in a crowded space of food production technologies based on similar technical principles. An analysis of most active assignees shows that a number of large companies in the food sector, as well as smaller startups, are patenting on 3DFP. However, few assignees hold more than one patent, including large Chinese and European research institutions such as TNO, in the Netherlands, large global corporations in the home appliances manufacturing sector such as, BSH (Bosch Siemens Hausgeräte GmbH), and in the food processing sector, such as General Mills (US), as well as small food 3D printer manufacturers, such as print2taste GmbH (Germany).

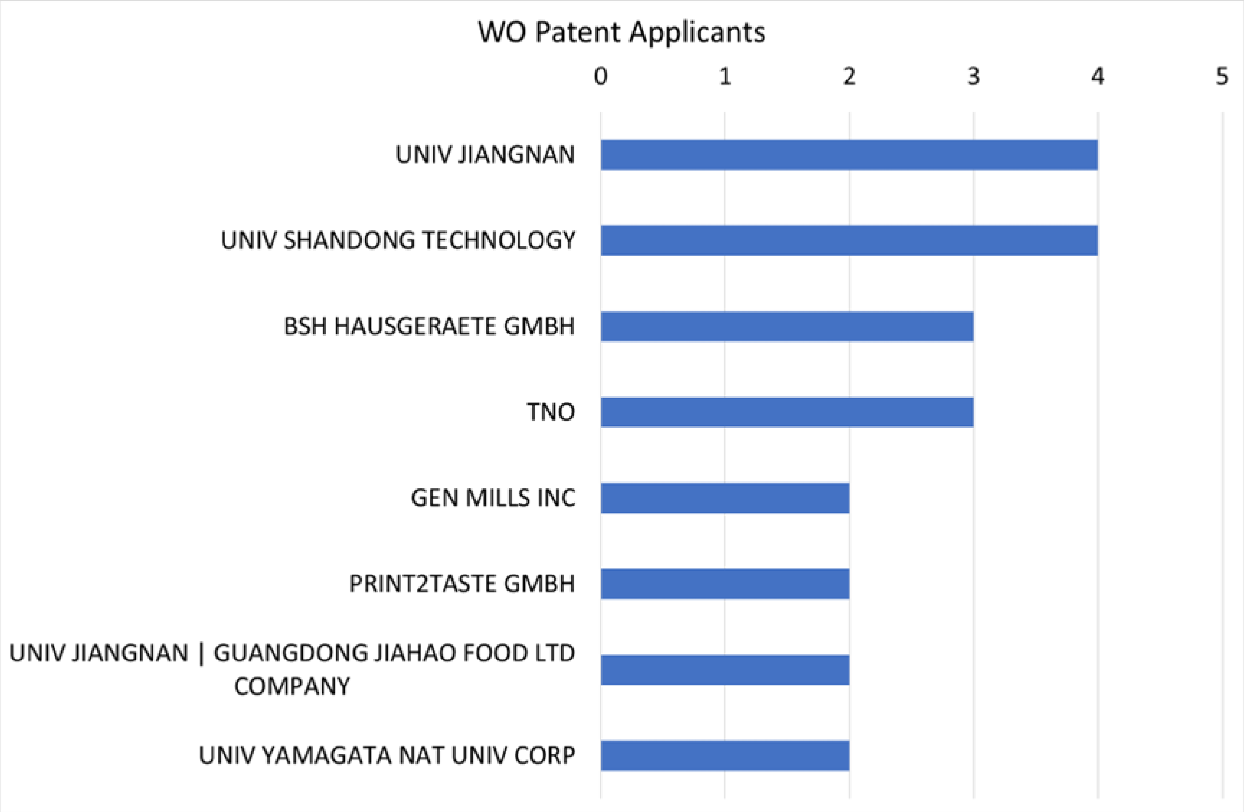

Figure 18: Most significant global patent applicants (WO) for 3DFP applications over the past 10 years.

Technology areas patented by the most significant applicants in 3DFP are shown in table 3 below.

Table 3: Technology areas covered by most significant global applicants

Applicant	Number of patents	Country	Titles

UNIV JIANGNAN	4	China	Microwave-coordinated three-dimensional printing apparatus, and accurate and efficient printing method for plant gel system Single nozzle 3d printing method for non-homogeneous recombinant food containing crushed rose flowers Three-dimensional printing method for food using microwaves and printer 3d accurate printing method for easy-to-swallow dual-colour mashed potato / mashed purple sweet potato cold dish
UNIV SHANDONG TECHNOLOGY	4	China	Method for use in preparing potato starch-based 3D printing material Composite starch 3D printing material preparation and process 3D printing method for ready-to-eat food 3D printing method for ready-to-eat food
BSH HAUSGERAETE GMBH	3	Germany	Control unit, food printer, and method for controlling a food printer Device, domestic appliance comprising such a device, method for producing a printing mass for a food printer, and system for producing a food Food-product printer with nozzle and printing plate
TNO	3	NL	3D printer system and method for filling a cartridge of such a system Method for the production of an edible object using SLS Method for the production of edible objects using SLS and food products
GEN MILLS INC	2	USA	3D printed foods shapeable food seasoning
PRINT2TASTE GMBH*	2	Germany	Microstructured food item Food composition
UNIV JIANGNAN | GUANGDONG JIAHAO FOOD LTD COMPANY	2	China	Method for 3D printing dual-colour stuffed pastry by means of concentrated fruit pulps Method for improving 3D-printing effect by means of prognostic processing of concentrated fruit pulp
UNIV YAMAGATA NAT UNIV CORP	2	Japan	Method and apparatus for three-dimensionally shaping food by irradiating mixture of starch powder and water with laser light Foodstuff three-dimensionally fabricated by combining block-form foods, and method for producing said foodstuff

In summary, patent search confirmed that only a very limited number of food types are currently printable and the intention to print vegetables and fruits as well as more complex mixtures of ingredients are very recent trends, possibly at least five years away from successful commercialisation.

5.2 3D Food printers on the market

From an engineering and hardware manufacturing perspective, 3D food printers are in essence just an extension of earlier existing 3D printing principles using a digital CAD file to build structures in an additive manner. The key premise of 3D and 4D food printing is customisation of shape, colour, flavour, texture, and nutritional content to meet specific individual needs. Similar to 3D printing in other industries, food printers are often advertised as customisation tools for food businesses, such as caterers, facilitating new food product development with the implication that they may have the potential to impact food supply chains by enabling wider access to food customisation. It is important however to differentiate between 3D printing for individual food preparation and other robotic automation of food production processes. The latter is mainly concerned with reduction of labour requirements in large scale production while most players in 3D printing of food emphasise uniqueness of design options, creativity, and ingredient control at the centre of the process (Sun et al., 2015). This distinction has become important also more recently, as several plant based and cultured meat producers are claiming to use ‘3D printing’ for making their products (see also section 3.5.2), however, when analysed more closely these applications are often not 3D printers in the conventional sense, but multi-nozzle micro-extrusion systems that apply some of the 3D printing engineering principles as only one step of a multi-step production process that these companies treat as proprietary and confidential.

Currently 3DFP is carried out both on universal and/or self-developed platforms. Universal platforms are modified open-source commercial printing platforms that are adapted for food printing purposes. These printers are not specific to food applications but universal desktop fabricators that are either compatible with the use of food materials, or can be made food compatible with hardware extensions, examples being the Fab@Home system and MakerBot. Such systems are limited in their food printing capabilities and mainly serve limited R&D purposes.

In contrast, self-developed platforms are built with considerations for desired outcomes and optimised for specific ingredient types. To develop such platforms there is a need for continuous expert research and improvement both for hardware development (for example to increase throughput or print consistency) and the formulation of ingredient mixtures and printing materials to reach optimisation (Sun et al., 2015).

Reviewing the food 3D printers currently available on the market it becomes clear that the choice is limited and defined by optimised input ingredient materials. Historically, food 3D printing started with sugar and chocolate as creative enhancements for the confectionery and cake customisation market. To date these materials remain the most printed food materials as they lend themselves to requirements of the technology easily due to their physical and chemical characteristics. However, over the past five years there have been considerable efforts to advance the technology to enable printability at scale of other food materials, such as different dough and starch-based foods, alternative proteins from plant-based sources, vegetables, fruits and semi liquids such as tomato sauce.

Apart from some limited successes with commercialising sugar and chocolate-based concepts, and to some extent alternative proteins from plant-based sources, the majority of these engineering efforts are mostly still at the R&D stage and are not available as commercial products yet. Given the various uncertainties with regards to technology robustness as well as with market definition, availability of such products to wider consumer segments is possibly at least five years away.

5.2.1 Printers specifically manufactured for food printing (self-developed platforms)

For a complete list of 3D printers purposefully designed exclusively for food printing see appendix A, table 6. A number of different printers were identified that can be classed as self- developed platforms specifically designed for food. A large proportion of them (4 out of 13 existing printers) focus on sugar and chocolate as printing materials with the most advanced also able to print various pastes from dough, vegetable purees and meat pastes. Examples of food printers currently on the market are:

- Foodini, Spain, is possibly the most advanced printer on the market with the ability to use five different foodstuff cartridges for the printing process, enabling the creation of complex foods such as jellies, pizza and spaghetti and potentially even a complete hamburger. The printer is produced by Natural Machines, Spain. The printers are currently only for rent and are not sold.
- MyCusini, Germany, produced by Print4Taste (previously print2taste) is a home printer for printing chocolate using pre-prepared chocolate refill packs that are sold with the printer.
- ProCusini, Germany, also produced by Print4Taste, and sold only B2B as a printer for professionals.
- Choc-Mate, Germany: produced by chocolate3. Apart from the printer the company offers pre-tempered chocolate sticks to be used with the printer so users can avoid the necessary pre-tempering step prior to printing.
- FELIX food printers, The Netherlands: A choice between three different printers is offered, with machines containing two different print heads either working simultaneously to increase volume being printed, or models can be loaded with different pastes to combine foods with the capability of printing pastes, chocolate, purées and meat. They are designed and manufactured by Felix Printers, a Dutch manufacturer of industrial 3D printers for a range of materials.
- byFlow food printers, The Netherlands: manufactured by byFlow and developed in partnership with Eindhoven based VDL Groep, a large industrial manufacturing firm. The printers are aimed at professionals in the bakery industry and they work with refillable cartridges for any sort of paste-type food to create customized meals. They claim that their printers can use either fresh ingredients or ingredients that otherwise would have been thrown away.
- Wiiboox Sweetin, China: is a food specific printer produced by a universal 3D printer manufacturer in China and prints chocolate and other sugar and starch based pastes, such as potato and fruit jam, white bean, and cream candy.
- Choc Creator V2.0 Plus: 3D prints chocolate; is/was manufactured by Choc Edge, UK, , a manufacturer of a chocolate printer and provider of printing services that started as a spinout of University of Exeter in 2012. We could not access the website for the company listed on crunch base while there are a number of pages for the business on social media and videos on YouTube. On some e-commerce sites there are pictures of a 3D printer by Choc Edge for sale, however the company was dissolved in November 2021 according to Companies House register.

5.2.2 Printers based on a universal 3D printer platform

Another group of printers is based on the universal platform concept, namely using general 3D printers that can also print food materials with or without specific hardware extensions. Printers are listed in Appendix A, table 8, and examples are:

- Zmorph FAB, Poland: Zmorph is a manufacturer of standard desktop 3D printers and according to the Zmorph FAB printer manual published on their website the printer can print Nutella®, chocolate, cookie dough, and some pre-prepared food 3D printer filaments. However, everywhere else the company has stopped advertising their printers as suitable for food printing.
- Wasp2040, Italy: Wasp is focused on 3D printers for industrial use and on their website food is not mentioned, however, they have been participating in exhibitions with 3D printers that were demonstrating food printing capabilities with a focus on gluten free food preparations.

In addition to 3D printer manufacturers there are also companies that sell printer parts as adapters/hardware extensions for food printing to be used with universal printers. Examples are ChocoL3D Kit and LuckyBot – 3DFP extruder, an add-on developed by Wiibox for general Wiibox 3D printers and other compatible home 3D printers.

When summarising currently available printers on the market it becomes clear that there is only a very small number of food 3D printer manufacturers offering actual printers as shown in figure 19.

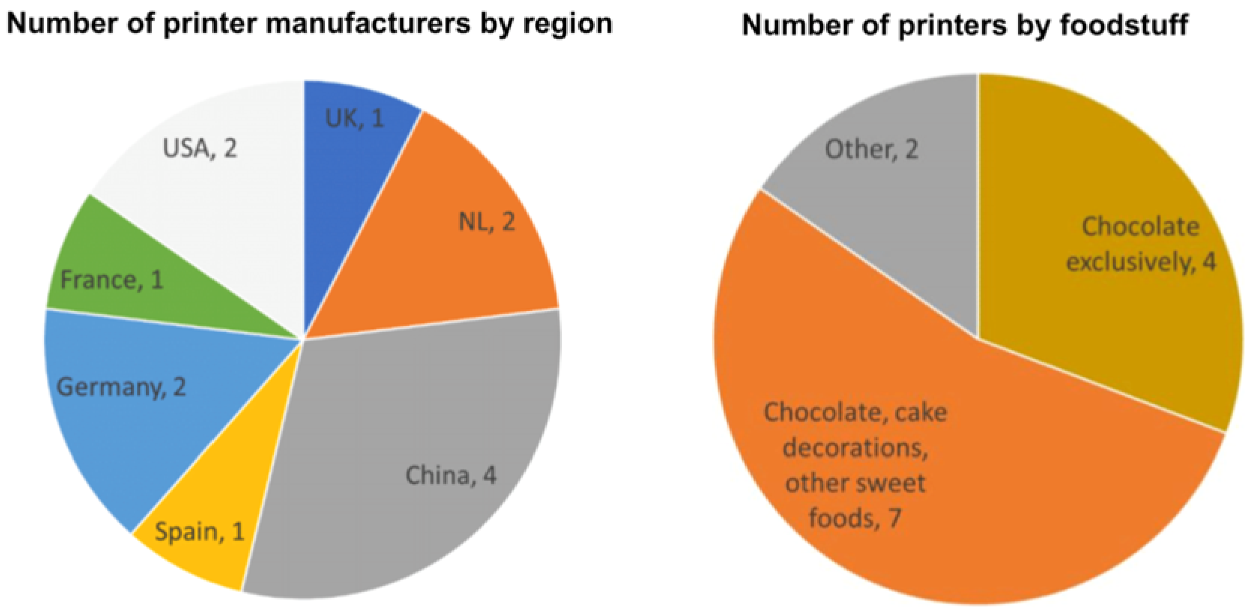

Figure 19: Number of printer manufacturers actually producing and selling food printers, by country (left), and number of printers by foodstuffs printed (right).

Looking into actual availability of printers, we also found a number of products that have been on the market earlier for some time but have recently stopped being traded, either because the company took the product from the market, or because the company ceased to operate, as indicated in figure 20 by *.

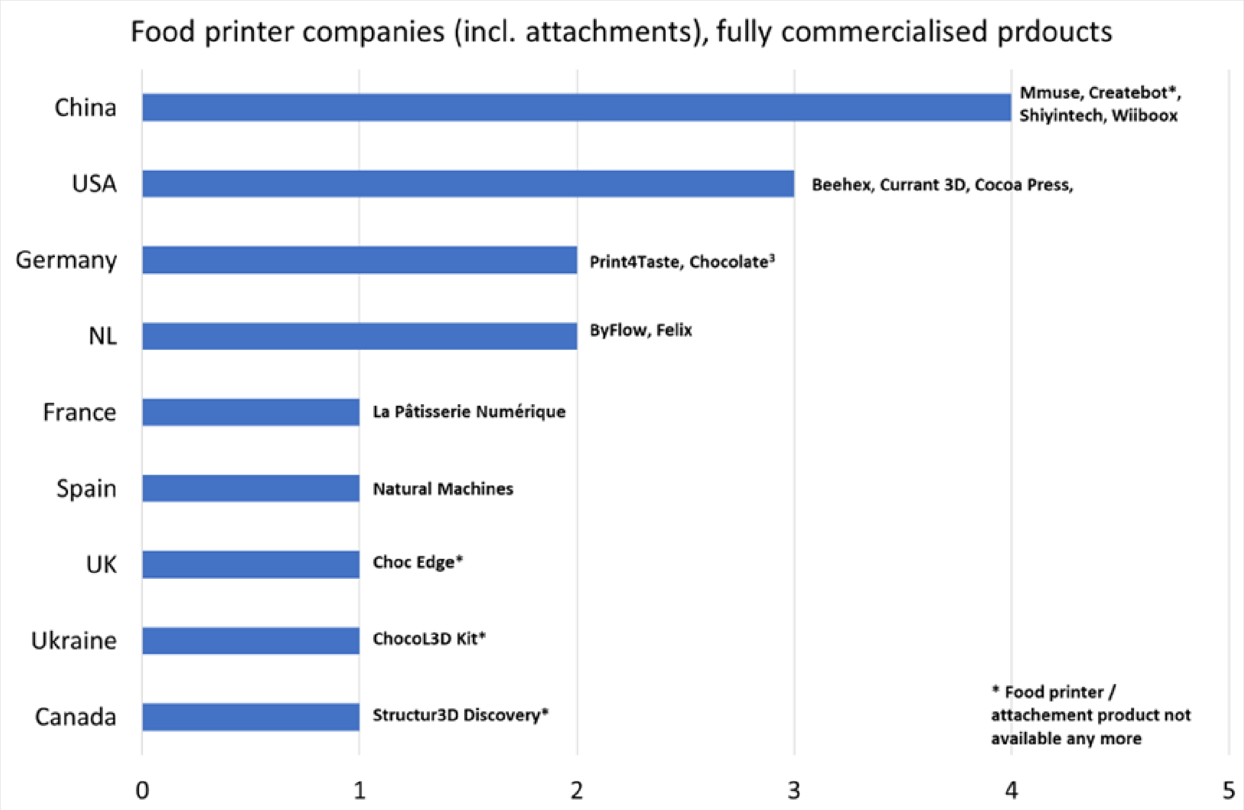

Figure 20: Currently available food printers and past products that are not any more traded, indicated by *

For a complete list of current and past printer manufacturers see also: Appendix A, tables 6, 7, 8. Some examples of printers offered in the past, or continuously postponed product launch are:

- Mmuse - New Desktop Chocolate 3D Printer, with no online evidence for active sales, but Youtube videos demonstrating the printing process. Possibly available on the Chinese market.
- Createbot - 3D food printer not available any more, produce other printers.
- Chefjet (may after almost 10 years in the making and internal business issues become available soon, but who knows?)
- CURRANT 3D Printer for sugar-based products, advertised, but not clear when finally on the market (earlier developed by Sugarlabs, US, almost 10 years ago).

A number of larger 3D printing companies have tried the food 3D printing market in the past, as evidenced by old web postings, and it seems they have meanwhile exited the market as no current food specific 3D printer could be found on their websites. This can be explained by the small market size, lack of viable business models and technical challenges that food 3D printing faces in adapting to higher throughput. Moreover, food printers need to be designed and optimised for specific food ingredients and truly ‘universal’ printers are unlikely to emerge in the near to medium future.

5.3 The 3D food printer/printing market

To put the small number of food 3D printers available on the market in perspective, it may help to look at the potential addressable market size for industrial 3D printing/additive manufacturing. As is common with such estimates, the figures can vary greatly, however two recent market studies estimate the general 3D printing market to be between $8.6bn and $12.9bn with a projected CAGR of 18.2-22.5% until 2026. In contrast the global market size for food 3D manufacturing was valued at $201m in 2022 and is estimated to reach $1.9bn by 2027 with a CAGR of 57.3%.

Clearly the market is small by dimensions, however there is an optimistic view of its growth rate. Nevertheless, it has to be taken into account that 3DFP faces the same challenges that industrial 3D printing has faced in the past, and to some extent does still face today, with the main challenge being the slow speed of production. In the manufacturing industry too there is a trade-off to be had between speed of manufacture and specialised features of the part that is printed, which means there has to be an economic advantage to higher customisation and/or complexity of the part compared to its cheaper mass-produced variants. In high value industries such as automotive, aerospace and medical devices this trade-off point has already proven to be economical for some applications. The main challenge in adapting the economics of 3D printing to the food industry is the commodity nature of food, being a low value, low profit, high volume business.

Reviewing concept startups, which alongside manufacture of self-developed 3D food printers aim to create concepts that have the potential to appeal to consumers, will shed more light on the specific challenges and opportunities the technology faces in establishing itself as a food manufacturing process.

5.4 The 3D food printing concept startup scene

Apart from self-developed 3D food printer manufacturers that are at the startup stage, there are also so called concept startups that innovate on enabling access, create printable foodstuffs and test business models for workability. Concept startups are listed in Appendix A, table 10. So far, commercial success has proven to be scarce, and the majority of these startups do not have an active product on the market but often advertise specific niche application areas, such as food for the elderly, children, or personalised nutrition applications. Examples of concept food printing companies using different foods are:

nufood started out in 2015 and currently offers “food flavour bursts”, small printed shapes of intensely tasting fruit juice-based objects that are used as sensory enhancers with food. It is described as the first food 3D printer that can print liquids that solidify after printing. The chemistry is based on combining fruit juice with powdered sodium alginate and dripping it into cold calcium chloride in a bowl. However, nufood is currently a brand held by Dovetailed, a design studio and innovation lab developing physical and digital experiences. The Nufood 3D printer is one item on its portfolio. The printer can be rented or rather the experience can be hired i.e. a demo of the printer can be bought for a number of guests and with up to three flavours. The products are small fruit flavoured cubes that can be enjoyed with other food or on their own. Dovetailed as a company has other lines of business that generate revenue.

Another 3DFP concept company that offers products on the market is the successor of Sugarlab in California, US. It was founded in 2011 with a focus on printing sugary decorative edible products for special occasions and was the original company developing the Chef Jet food printer. The founders are architects who started out by trying to print a birthday cake for fun. In 2013 3D Systems acquired Sugarlab. In a news piece from October 2022 the original founders bought back the technology from 3D Systems and were raising funds to develop a 3D printer (Chef Jet Pro) claiming that the printer can be developed to print a variety of foodstuffs.

A third example is the Dutch company Gastronology 3D Food Works, founded in 2019 and collaborating with the Dutch research organisation TNO, University of Eindhoven and Wageningen University. The company develops 3D food recipes and natural 3D food shapes for people with chewing and swallowing disorders, such as dysphagia, and it seems that it has reached a certain point of scale as it claims to be building a production line in the near future to print on an industrial scale for care homes and hospitals. The products are moist purées printed as solid, recognisable food shapes to enhance sensory experience for mostly elderly patients and with problems chewing and swallowing. Other advantages of food printing are described on their website as dosing of food portions, longer shelf life and use of residual products and food side streams.

Finally, food 3D printing technologies have been integrated by cultured meat or plant-based meat producers as one step in their production processes to improve textures. Some examples are:

- Revo Foods, Austria. The company focuses on producing plant based seafood alternatives and has been the winner of the EIT manufacturing BoostUp prize and has raised around €2m. Revo has also entered recently a collaboration with Swedish fungal protein producer Mycorena. However, industry insiders question whether their proprietary technology can be justifiably called 3D printing.
- RedefineMeat, Israel, produces plant-based meat. They have raised nearly $170m of funding between March 2019 and January 2022 to develop its 3D Alt-Meat Printer. The investment has helped to improve the palatability of their products for consumers and to increase scale of production. In October 2022 it entered a partnership with Giraudi Meats to enter the European market and use their distribution networks for its “New Meat” steaks produced on 3D printers.
- Steakholderfoods, Israel, produce cultured meat, (formerly MeaTech). The company has raised $17.9m in multiple fundraising rounds and went public in 2021. The company has entered a collaboration with Umami Foods, a Singapore based cultured seafood company, in 2022. Steakholderfoods currently does not have products on the market.

Figure 21: Examples of 3D printed food items as presented by their producers.

The above examples and other concept startups as shown in Appendix A, table 10, that have managed to commercialise products and/or services highlight the fact that the current state of 3DFP technologies, despite its advances in the past decade, limits products and services to niche markets. However, 3D printing technology may act as an enabling technology for other sectors, for example in the meat analogue market at the scale-up phase. Although RedefineMeat, Revo Foods, and Steakholder foods all plan to scale production or have done so, scaling 3D printing operations happens currently mainly through adding more printers to an assembly line of printers (printer farms). Given the added value 3D printing technologies may bring to the alternative meat sector, its products might become the first that bring 3D printing to consumers as a form of food processing technology that is not any more the main selling point for the final product. However, technology experts in 3DFP question whether these highly modified printing appliances can still be considered 3D printers.

5.5 Business models for 3D food printing

Food 3D printing is often advertised as a disruptive technology in the making, despite its current challenges with respect to technical performance and lack of commercial viability. Belief in its potential to 'disrupt the food system' is an established part of the academic discourse on 3DFP.

However, with regards to viable business models it appears that the field is too immature to have any successful case studies to show, and conceptual discussions in the academic literature are mostly not based on empirical evidence. In addition, although specialist startups are working on optimisation of food 3D printers for niche applications, the “dominant design/s” for each of these has not yet emerged, which makes estimations of profitability difficult. In addition, most of the well understood challenges that currently exist for the technology still need addressing before economic modelling can become more evidence based and realistic. The root cause of the technical challenges is due to the fact that 3D printing is a technology invented and adapted initially to other industries and still to date many 3D food printers are adaptations of universal/general 3D printers to food materials. Although progress has been made in the past decade 3DFP faces still a number of key challenges to adoption and scale.

These challenges are around the following issues (Rogers & Streich, 2019):

- Consumer perception
- Manufacturing costs of printers and products
- Supply chain costs
- Change of manufacturing and supply chain models from centralised large scale to decentralised individual or batch production
- Complexity of 3DFP (not easily adaptable to non-specialist or domestic settings)
- Printed food consistency and quality
- Slow speed of printing process (not suitable for mass production)
- Lack of scalability (except if building printer farms)
- Lack of a large enough addressable market

These challenges have so far limited the technology to specific small niche applications. At the same time the advocates of the technology emphasise unique business model opportunities that the technology may have to transform the food industry, namely (Rogers & Streich, 2019):

- Product personalisation, customisation and differentiation
- Personalised nutrition (for people with health issues, athletes or health conscious individuals)
- Upcycling of food waste (food processing industry waste or retail waste)
- New textures and forms
- Creating palatability for new food sources such as algae, insects, and new plant varieties with unusual taste

Besides these considerations on ‘potential’ business models, based on discussions in the academic literature, our survey of 3DFP companies (see Appendix A, tables 6-10), allows grouping them by their service offerings in the following potential business model categories:

- Direct selling of printers (B2B and B2C)
- Selling of printed food products
- Selling of 3DFP services
- Selling of concepts, experiences/events and entertainment

5.5.1 Direct selling of Printers

Companies that manufacture and sell printers only, and do not work on concepts and products themselves are often manufacturers of general 3D printers which have extended their product line into food as well. Nearly all of them sell only to other businesses (B2B). Examples of 3D printer companies with successful demonstrations of 3D food printers are Felix, byFlow and 3D systems , which currently does not have a 3D food printer on the market yet.

We traced other large 3D printer manufacturers that either had produced a food 3D printer in the past, or experimented with development and sales of such, but since have withdrawn from the food 3D printing market. These include e.g. the Italian company WASP, which demonstrated a printer for printing gluten-free food, or the Polish company Zmorph, which has offered a food paste extruder for its standard 3D printers in the past, but do not sell it any longer. Currently Zmorph does not advertise food printing any more on its website.

Withdrawal from this market is not unexpected due to different factors such as small market size and the requirement for adapting 3D printer parts to the type of food it is printing. In addition, with the printer comes the need for the right consumables i.e. the formulation of specific foodstuffs to be printed, which can require considerable R&D efforts to optimise. At present, the only 3D food printer sold as a kitchen appliance for general consumers is the MyCusini home chocolate printer that comes with all accessories and pre-prepared chocolate filaments for use with the machine. This lack of home appliances is not surprising as the technology is still quite complex, needs to be adapted to each food type, and will require cartridges of the optimised food stuff to be delivered for printing, hence a significant B2C market for printers is unlikely to develop at this stage of technology readiness. What may evolve as a more realistic market is the B2B sales of printers to specialist food providers, as is happening to some extent with chocolate printers in the confectionery and catering sectors.

5.5.2 Selling printed food products

In this category successful companies develop their own 3D food printers adapting the printer to the intricacies of the food type they work with and sell the resulting product. This category can also be divided into two groups at this point in time. One group produces specific printed products that may eventually become mass-market products. Examples in this category are the above mentioned meat substitute producers, such as NovaMeat, Redefinemeat, which is one of the rare 3DFP companies with products on the market and expanding due to considerable investments raised, Steakholderfoods, and Revo Foods.

The second group develops and sells specialist niche products for a specific consumer group, for example companies such as BioZoon and Gastronology developing food for people with chewing and swallowing difficulties such as the elderly and dysphagia patients. Another example is Katjes, a confectionery company that has developed a 3D food printer specialising on printing fruit jellies. FabRX a UK printer manufacturer is developing 3D printing of solid pills and tablets, including nutraceuticals. Another UK company, Remedy Health with its brand “nourished”, has developed a business printing personalised nutritional supplements in the form of jelly biscuits.

5.5.3 Selling of 3D food printing services

The most common service provided is still the printing of bespoke 3D food items, mainly as personalized and corporate gifts. Chocolate and sugar candy are still the dominating material for these items also in a B2B setting. Companies that offer professional services include large food manufactures such as Barilla (Italy) who provide a bespoke pasta printing service via its subsidiary BluRhapsody and training courses on how to use their printer. Also French company La Pâtisserie Numérique and Jan Smink, a Dutch restaurant owner offer training courses in food 3D printing, as well as Barry Callebaut, one of the largest cocoa processors globally, who operate “Mona Lisa, the first chocolate 3D printing studio”. A few smaller companies offer services in bespoke printing, such as chocolate3, a company recently set up in Germany, which has also developed their own printer, or Chocolate Prints in Switzerland who also offer to operate “live” at various events and specialise in chocolate-based corporate themed advertising and give-aways.

5.5.4 Selling concepts, experiences/events and entertainment

In this category companies may or may not have their own specialist printer for sale, rather their focus is on generating and selling an experience. Here we have included the emerging limited number of restaurants that have 3D printed desserts and maybe some other printed food items on the menu. In this group the process of 3D printing and production of the end product is part of the experience package that is sold. Examples are nufoods/dovetailed, laMiam factory and smink, which is both a restaurant and a catering service. Other restaurants offering 3D printed food are La Boscana, which collaborates with FoodInk and La Enoteca, which uses Natural Machines' Foodini 3D food printers.

Other emerging integrated "experience" concepts are for example a printer developed by Beehex, called Cake Writer Pro™ for use inside bakery shops for customers to create and print their own designs, or the Japanese company "Open Meals" which is developing a business model of owning the whole value chain: from developing a printer, software and food powders to owning the restaurants for customers to consume 3D printed creations.

Some players in the 3DFP market hope to leverage synergies by partnering with larger established businesses. For example, byFlow, a Dutch manufacturer of food printers has partnered with Verstegen, a Dutch spice and sauce company, to deliver food printers together with the food inks adapted for the printer. They are currently also setting up a print farm for upscaling production of 3D printed products. This partnership aims to join the 3D printing expertise of byFlow with the capacity and long-term experience of Verstegen in food processing and preparation.

In summary, although occasionally the sellers of 3DFP experiences can get a lot of media attention, they operate mostly on small-scale events with low numbers of customers, or as part of a dining experience in a restaurant, hence will not reach wider consumer markets in the near future. In addition, they are mostly operating over limited periods of time to keep the experience interesting.

5.5.5 General considerations regarding business models

Literature research identified a very limited number of articles on business models in 3DFP. The publication of Rogers and Streich 2019 is seminal in the sense that they were the first to interview industry stakeholders explicitly on business models of 3DFP in depth, however, they could not identify any established or preferred business models in the industry and note that businesses turning a profit with printers are rare, and that 3DFP services are mainly sold to other businesses rather than directly to consumers (Rogers & Streich, 2019).

Jayaprakash and co-workers conducted an extensive interview and survey with industry stakeholders followed by a business modelling workshop developing business models for specific use cases such as customised design of chocolates, personalised snacks through vending machines and use of 3DFP in hospital kitchens (Jayaprakash et al., 2020). It is noteworthy that in the described value chain for all three examples there is a need for an ingredient manufacturer providing foodstuffs optimised for the printing process, emphasising the point that pre-preparation of food for 3D printing requires specific parameters that are not easily reproducible in non-specialist settings. Another commonality between the three explored value chains is that in each model there is a need for a printing operations provider; for chocolates in form of a design producer, for snacks an operator of 3DFP vending machines, and in the case of hospitals a specialist caterer. This means, end users are not operating printers in their own environment. In each case there is a specific interface for the end user/consumer to select options and place an order mainly through a web interface. Figure 22 shows a generalised value chain model for the three above mentioned business cases.

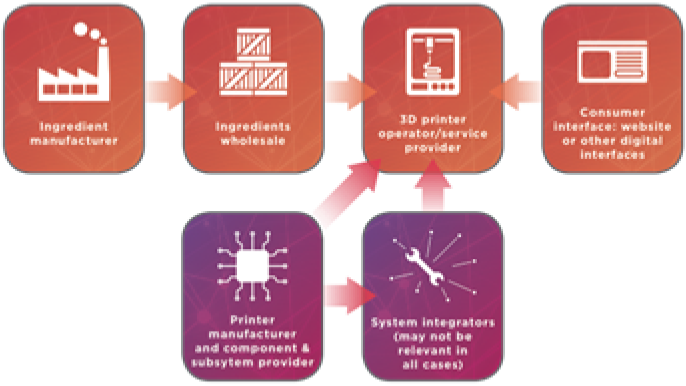

Figure 22: Generalised value chain model for three different 3DFP service offerings, showing the importance of a central service/printer operator. Modified from Jayaprakash et al., 2020.

It is not far-fetched to extrapolate that this generalised value chain model would be valid for a number of 3DFP service offerings, highlighting the fact that expert pre-preparation of ingredients is a bottle neck step in the supply chain. The authors also emphasise that developing business models for 3DFP is challenging as only real-world testing can prove their robustness.

One business case for 3DFP discussed since around 2012 is the potential to produce specialised food for the elderly and patients that have difficulties with chewing and swallowing. Nopparat and Motte describe the outcomes of a two-year project “Future Meals”, investigating the utility of 3DFP in food production for the elderly and patients suffering from dysphagia. In their model too, the value chain is similar to the one shown in figure 22, with separate operators for the preparation of food pastes and for printing the food (Nopparat & Motte, 2022).

An emerging business model for startups with a self-developed 3D food printer is in building collaborations with larger partners that can take on scaling, engineering and producing of the printers and food manufacturers that can bring expertise in preparation of food pastes at scale. We identified one example of such a model with three partners. byFlow a food printer developer, collaborates with VDL Group, a large industrial manufacturing firm and the food manufacturer Verstegen, all based in the Netherlands. This kind of three-way collaboration enables scaling of the operations with engineering skills of VDL group while byFlow and Verstegen focus on food pre-processing and printing.

Similar to any new technology, 3DFP exists in an ecosystem of players and its success depends on the robustness of the ecosystem and support levers for growth. Figure 23 shows the emerging ecosystem for the 3DFP industry.

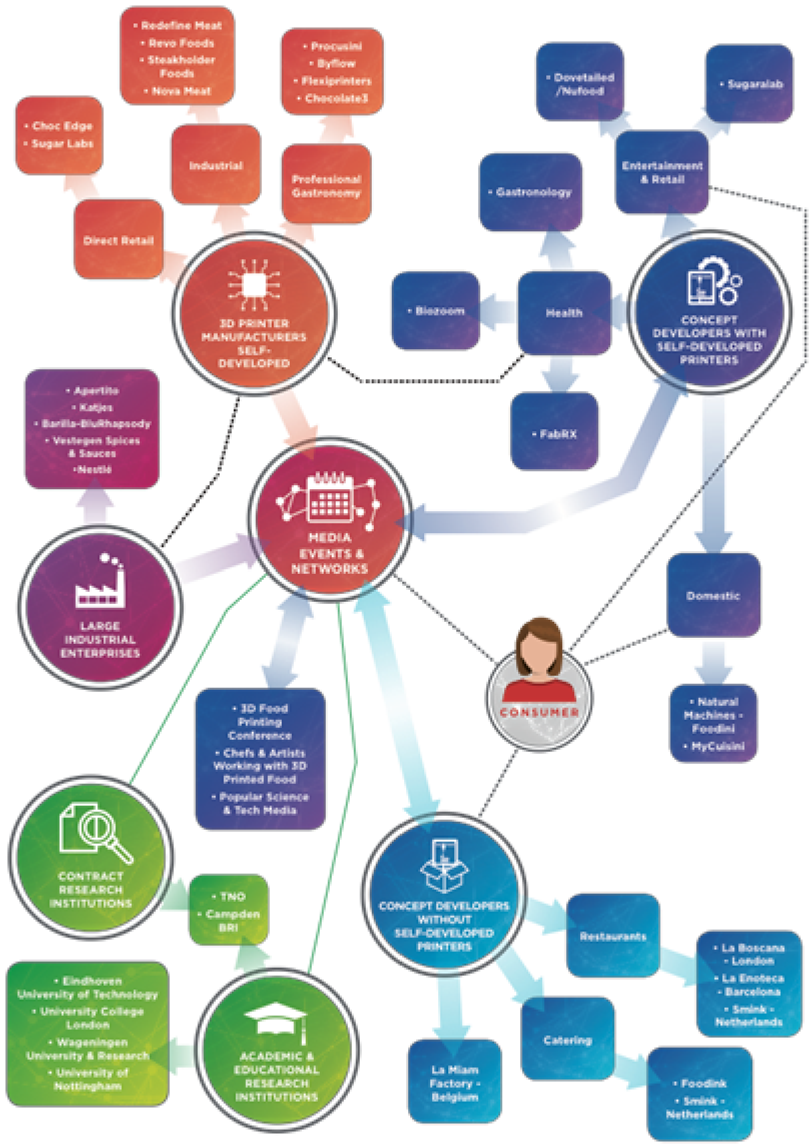

Figure 23: Ecosystem map of 3DFP operators and actors as mentioned in this report.

Media Events and Networks:

Concept Developers without self-developed printers

- Restaurants: la Boscana, London, La Enoteca Barcelona and Smink, Netherlands.
- Catering: FoodInk, Smink, Netherlands.
- La Miam Factory, Belgium.

?????Concept Developers with self-developed printers

- Entertainment and Retail: Sugarlab, Dovetailed/Nufood
- Health: Gastronology, FabRX, Biozoom
- Domestic: Natural Machines Foodini, MyCuisni

Contract research institutions

- TNO, Campden BRI

Academic and Educational Research institutions:

- Eindhoven University of Technology
- University College London
- Wageningen University and Research
- University of Nottingham

Large industrial enterprises

- Katjes
- Barilla-BluRhapsody
- Vestegan Spices and sauces
- Nestle

3D printer manufacturers self-developed

- Direct Retail: Choc Edge, Sugar Labs
- Industrial: Redefine met, Revo foods, Steakholder Foods, Nova Meat
- Professional Gastronomy: Procusini, Byflow, Flexiprinters, Chocolate3

Ecosystem integration faces currently some challenges with the main one being the absence of clear markets for products and services and the low performance of the technology. The latter refers to technical challenges such as:

- Need for adaptation of printers to food types and lack of a universal printer that can print any food
- Slow speed of printing/production
- Requirement for pre-preparation of food into printable pastes
- Complexity of technology for use by non-specialists
- Consumer perception, lack of information
- Being a technology driven market rather than a demand driven market

5.6 Sustainability claims around 3DFP

One of the claims made repeatedly in the academic and grey literature is the potential role of 3DFP in contributing to the sustainability of the food system. As these claims are made without any evidence based analysis or measurement framework to assess sustainability parameters of the technology, it would be wise for developers of business models to consider sustainability criteria for processes, products and supply chains from the outset. This in turn will directly impact the development of business models and help shaping the industry ecosystem. The main claims of the technology on impacting sustainability of the food system are (Rogers & Srivastava, 2021):

- Reducing waste by transforming food waste into edible food
- Recycling of surplus and close to expiry date food
- Shortening supply chains by printing food on demand locally
- Reducing the need for secondary packaging
- Creating palatable food from novel food sources such as algae, insects and unusual plant sources not known to the western consumer

Sustainability through food waste reduction

There are clear regional differences with the most food lost at the retail and consumer level in the USA and Europe, while due to lack of processing capabilities, the loss of food at production stage is highest in the rest of the world.

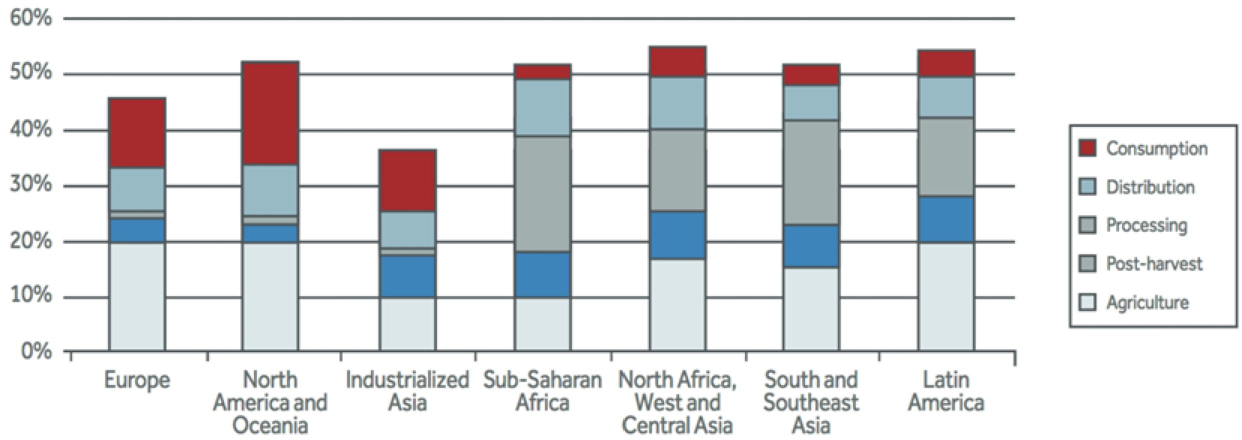

Figure 24: Levels of fruit and vegetable wasted along different stages of the supply chain in different regions of the world. Source Rezaei et al., 2017

Hence there might be a role for 3DFP in repurposing food waste if the technology could achieve a simplified, higher throughput capability, which then could be integrated in different parts of the food supply chain depending on regional requirements and be used to produce food that can be consumed as a main meal and not as the occasional food decoration or niche product. At present, the only startup focusing on this potential use of 3D printing is the Dutch company Upprinting Food, a spinout of Eindhoven University active since 2018, claiming to use retail fruit, vegetable and bread waste to formulate food inks transforming these waste streams into attractive products. It is unclear however, whether regulatory definitions of sell by dates and food expiry for human consumption would need to change in order to make such products commercially viable.

Sustainability through novel supply chain models

Rogers and Srivastava propose co-development of products and supply models with consumers to achieve the best outcomes for waste reduction (Rogers & Srivastava, 2021). They state that creation of an efficient digital services model for the user-centric value chains will improve access as well as customer and consumer attitudes and perception of 3D printed food. Elaborating on this central premise they suggest three potential different supply chain models for the 3DFP products namely the generative, facilitative and selective services at different price points. Figure 25 shows their schematic depiction of the models proposed.

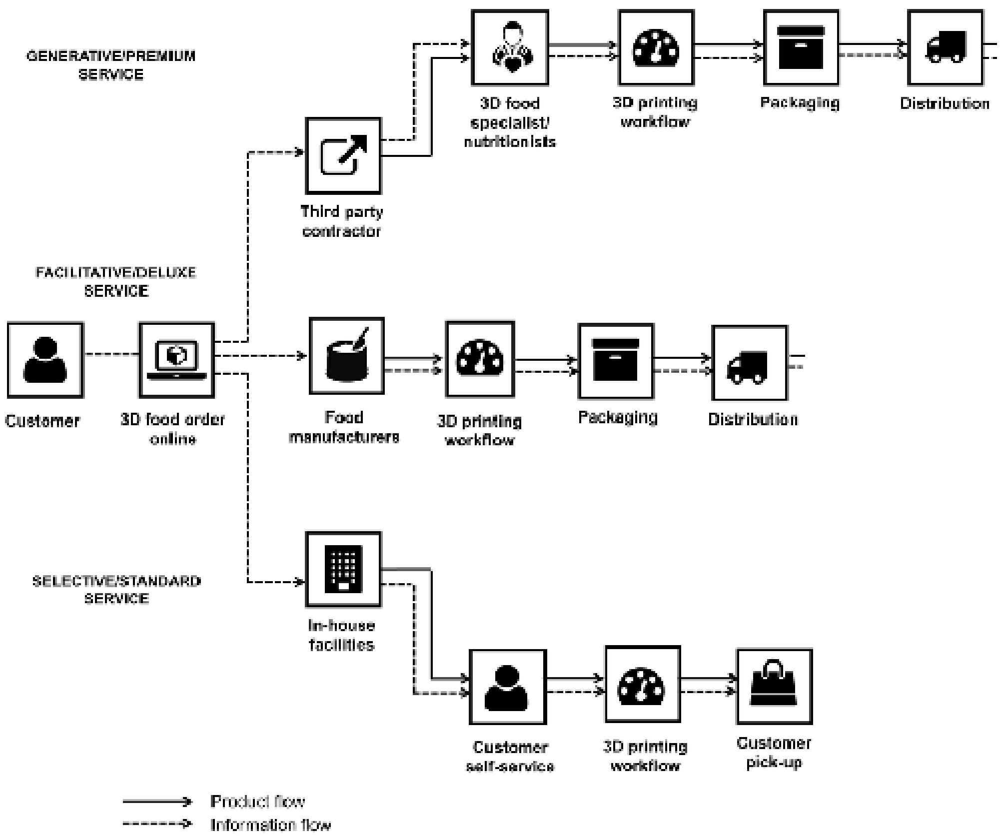

Figure 25: Three different proposed value chain models for 3DFP services at different price points. Source: Rogers & Srivastava, 2021.

All processes start with the customer and the 3D food order online.

Generate/Premium Service:

Third Party Contractor

- 3D food specialist/nutritionists
- 3D printing workflow
- Packaging
- Distribution

Facilitative/Deluxe Service:

Food Manufacturers

- 3D printing workflow
- Packaging
- Distribution

Selective/Standard Service:

- Customer self service
- 3D printing workflow

- Customer pick up

The Generative service model is a premium service operating as a one-stop shop for customers that are prepared to pay the required premium. The service is aimed at personalisation and individual requirement fulfilment. The Facilitative service model is about customisation not personalisation and is fulfilled by manufacturers that customise their products to groups of consumers rather than individuals. Finally, the selective service model is a standard service where the customer receives the instructions from the service provider and has to use potentially local 3DFP services to fulfil the production.

Similar to the value chain design work carried out by Jayaprakash et al. (Jayaprakash et al., 2020), what all three supply chain models have in common is the need for an actor that fulfils the optimisation of food ingredient formulations and printing operations while connecting to the customer via a digital interface. How from a supply chain model perspective a clear opportunity to increase sustainability of overall operations can be achieved, is currently not clear from these academic discussions.

Given the limitations of the technology at this stage to be scaled, except by creating printer farms, there is a clear need for further research into understanding its potential to contribute to the sustainability of the food system. So far, the potential supply models do not depart from the usual processing and logistics requirements of food production as it is today, with the need for equipment manufacturers, food processors, food printers and providers of logistics and delivery. Supply chain models for 3DFP already add one extra step to processing and that is the printing step itself. Therefore, there is a need for further evidence-based research to establish concrete sustainability criteria for the technology and its ensuing supply chain before plausible claims to radically impact the sustainability of the food system can be made.

5.7 Consumer trends and barriers

Since 3DFP has not made much progress with entering wider consumer markets since it first emerged as a tool to create unique designs for niche applications often in the confectionery sector, a number of players active in the field are now trying to position the technology as being able to deliver value around personalisation of food and nutrition. This appears to make sense at first, as 3D printing is known to deliver a high degree of customisation although at low throughput. It should be pointed out however that initially the strength of 3D printing was seen in its capability to create customised shapes, while applications in personalised foods or nutrition would need to focus on the technical capabilities in mixing ingredients in a highly controlled manner as well as creating personalised textures, which are application areas at an early stage of maturity at present. Irrespective of an indeed growing interest in personalisation options for food, 3D printed food is currently still unknown to most consumers (Brunner et al., 2018).

5.7.1 Consumer attitudes and acceptance of 3D food printing

A number of studies have recently tried to assess what the potential psychological barriers to consumer acceptance of 3DFP would be, by analysing attitudes and the willingness to try 3D printed food. Novel Food Technology Neophobia (NFTN) was found to be a significant barrier to acceptance of 3DFP, that could only be lowered to some degree by communicating very specific personal benefits and by an increased trust in science more generally (Ross et al., 2022). The same study also found that the expectation of ‘naturalness’ of food is one of the biggest barriers to the willingness to try 3D printed food. Consumer acceptance has also been studied with respect to whether labelling food as 3D printed would affect consumer perception (Feng et al., 2022). In this study that used conventionally produced chocolate swirls, gummy candy carrots and baked potato Smileys®, labelling these food items as 3D printed, but not more additional information on 3DFP, had a positive influence on the perception of the manufacture quality of the product, but not on taste or sensory ratings.

One of the very few studies testing 3D printed foods in a comparative manner was assessing consumer response and change of attitude to 3D printed snacks over a four-week period (Caulier et al., 2020). In this Dutch study participants overall liked the conventionally produced snack bar the best, confirming earlier results that consumers generally tend to rate foods as less satisfactory when they know that they were produced with novel methods (Novel Food Technology Neophobia). However, when they were repeatedly offered 3D printed bars with a range of customisation options with respect to textures and flavours, they rated the most ‘personalised’ bar the highest and their attitude towards 3D printed food changed after the experience. This finding correlates well with data from the largest interventional study on personalised nutrition, the food4me study, that could show that the perception of a high degree of ‘personalisation’ of dietary advice, irrespective of the scientific methods applied, had a positive impact on the motivation to follow the advice and achieve behavioural change around food intake or nutritional goals (Livingstone et al., 2021).

A comparative study has recently analysed the influence of contextual factors, such as location (at home, in a restaurant, festival, etc.) or social context (with friends, alone, with family etc.) on the willingness to try novel food experiences. The authors compared insect-based foods, cultured meat, plant based meat and 3D printed food, and found that overall willingness to try 3D printed food was similar to willingness to try cultured meat, while plant based meat was rated higher and insects lower. Social context did not have much of an influence, but 3D printed food was stated to be more likely to be tried in a restaurant or festival setting (Motoki et al., 2022).

In summary, consumers are initially sceptical of 3DFP in various study settings, and lack of the social aspects of food consumption, and lack of a ‘natural experience’ are main concerns. After being exposed to more information and potential settings in which 3D printed personalised food might become available, for example via vending machines or as snacks in gyms, consumers raised very practical concerns, such as the slow printing speed, or freshness of the product etc. (Jayaprakash et al., 2020).

5.7.2 Present ‘consumer interest’ in 3D food printing

Despite these limited insights into consumer attitudes that may offer a starting point to explore marketing strategies in the future, the main observation across studies is a lack of consumer knowledge about the technology. Given the possibility that 3DFP could find a foothold in a potential market of at home printing consumers selling printed foodstuffs locally or via social media, as has happened at a low scale with materials 3D printing as part of the maker movement, we wanted to assess whether traces of such activities can be found on social media. In order to gauge this kind of consumer interest in 3DFP more generally, we analysed openly accessible activity on social networks. Facebook/Meta, Twitter and Linkedin pages of 3D printer companies, as well as a number of online 3D printing groups on Facebook/Meta were analysed with regards to their numbers of followers and likes, as well as content on printing foodstuffs.

Table 4: Social media activity around 3D printing of food, and comparative other kitchen appliances.

Company	Facebook followers	Linkedin Followers	Twitter Followers
Choc Edge	1,600	81	1,087

Company	Facebook followers	Linkedin Followers	Twitter Followers
chocolate³	N/A	N/A	N/A
Felix printers	N/A	825	N/A
ByFLow (in partnership with manufacturer VDL Groep, Netherlands)	1,600	837	N/A
Shiyintech	N/A	32	13
Natural Machines	6,000	3,674	2,844
Print4Taste?GmbH, Germany	2,900	330	N/A
La Pâtisserie Numérique	248	1,017	N/A
Wiiboox	41,898	64	N/A
Mmuse	N/A	N/A	N/A
Beehex	607	642	850
Createbot (note: foodprinter not available any more)	N/A	51 (China)	37
Culinary Printworks (also known as "Currant 3D & sugar lab")	9	445	N/A
Wasp (3D printer company)	15,506	8,288	4,295
Nutribullet (for comparison)	> 2 million		
Ninja kitchen (for comparison)	> 1 million		
Thermomix UK and Ireland (for comparison)	55,137		

Companies whose focus is 3D food printers generally have very few likes or followers on social media (from 10s to few 1000's). Companies whose general business is 3D printers for any kind of material have more likes (41k for Wiiboox and 15k for Wasp). When one compares the social media presence of these companies to other kitchen equipment, such as Nutribullet or Ninja Kitchen, one can safely say that there appears to be very little interest in 3DFP companies and products. Nutribullet reached 2 million followers on Facebook/Meta and Thermomix UK & Ireland alone has more than 55,000 followers.

When looking into Facebook/Meta discussion groups with a 3D printing focus and for the frequency of food printing related discussions looking for terms such as 'food' or 'chocolate', in general there were very few posts regarding the actual printing of food, and if food was mentioned it was general, for example with regards to the use of food safe materials for the 3D printing of items such as bespoke cookie cutters.

Table 5: Commentary on 3DFP in Facebook/Meta groups with a focus on 3D printing

Analysis of the following online groups	Members	Comments on food
3D Printing	195,000	Main discussion topic around food was the use of food contact materials, e.g. cookie cutters; Very little discussion on food itself – one re-posting of an introduction of chocolate print attachment by ChocoL3D Kit 3D printing for Beginners
3D printing for Beginners	17,000	No mention of food or chocolate found in any discussion
3D Printing UK	470	No mention of food or chocolate found in any discussion
3D Printing & Makers Things	4,900	Some posts from 2015 and 2016 on food. Richard Li (Foodbot logo) showed 3d printed roses; one post of chocolate printed luxury car logos by Wiiboox in 2021
3D Printing for Women and Girls	7,400	Discussion topic around food with regards to 3D printed food contact materials, but no content regarding the actual printing of foodstuffs

In summary, it appears that consumers are not ready and willing to embrace 3DFP at present and that consumer push is a highly unlikely driver of 3DFP in the near to medium future.

5.8 Potentially relevant regulatory implications for 3D food printing

Given that the field of 3DFP is still at an early stage of maturity there is currently no existing regulation directly targeting the technology and processes used. Literature on regulatory issues is also sparse, however academia and industry are aware of the role that regulation could play in the growth of the industry. We provide here a summary of the limited number of existing documents and legal arguments that relate to 3DFP.

One of the earliest publications on potential regulation of 3DFP considers 3DFP from the perspective of the US legal structure and highlights the challenges the legal system has to contend with should the technology become widely accessible, dividing them mainly into short and long term food safety issues (Tran, 2016). For the short term the author considers two potential scenarios, namely 3D printed food leading to food poisoning should it be mass marketed, or causing allergies in some individuals. These concerns are related to the relative unknown food safety aspects of operating 3D food printers with different foodstuffs over longer periods of time, and potential routes of contamination. Concerns about long-term issues are the currently unknown effects on human health after longer-term consumption of 3D printed foods, as these might be considered currently as ‘highly processed’ foods. Exploring this latter question from a health and legal perspective is currently as unresolvable as similar issues with other novel foods, because at present there is no evidence base to build legal arguments upon due to the lack of long-term population studies investigating the effects of 3D printed food on human health. Hence, the legal question of ultimate responsibility for ‘health changes’ as a result of long-term consumption of 3D printed foods is at present not addressable. Concerning labelling issues J.L. Tran finds similarities between 3DFP and GMO foods with the main issue being unknown long-term effects. Finally, the author quotes Candice Ciresi, Former General Counsel at Stratasys, who in 2016 at a keynote address at the University of Minnesota Law School has stated that “scientists are working on the possibility of creating food from chemical compounds, which could enable food printing to generate new food where scarcity exists”.

Clearly using ‘chemical compounds’ to create food poses a novel challenge to human health as well as legal systems, which currently is not considered widely.

European authors who consider regulatory issues in their work on 3DFP focus particularly on the novelty aspect of 3D printed foods and food safety considerations. Regarding novelty they refer to the EU Novel Foods Regulation 2015/2283, update 2018, and pose the question whether new regulation is required specifically for 3D printed food, or whether the application of existing legal frameworks would be sufficient regarding food safety (Baiano, 2022; Portanguen et al., 2022; Rogers & Srivastava, 2021; The European Parliament and the Council of the European Union, 2015).

The European Novel Foods Regulation covers foods and food ingredients that have not been consumed by humans to a significant degree within the EU before 15th May, 1997. The regulation explicitly stipulates that this includes: “…foods resulting from production processes and practices, and state of the art technologies…, which were not used before 1997.” Besides suggesting that 3D printed food might require some form of labelling in line with the Novel Foods Regulation, authors also consider labelling issues around the possibility that 3D printed food would use ingredients from waste streams such as expired foods or non-food grade chemical compounds to aid the printing process, or novel proteins such as insect proteins.

There have been some considerations as early as 2016 on the issue of 3DFP in Canada, stating that novel food applications should be required for foods that are produced using 3DFP technology. In addition, specific concerns were raised with regards to shelf life and printing additives. In Canada a novel food is defined as “a substance that does not have a history of safe use and has been manufactured, prepared, preserved, or packaged by a process that has not been previously applied to that food, and causes the food to undergo a major change; or genetically modified”. The author also points out that under the Canadian Novel Foods Regulation long processing times of applications, between 6 months to two years needed to be considered if 3DFP businesses intended to apply.

It is important to note that despite the novelty and early stage of technology development, regulation could potentially help rather than hinder innovation. Early regulation by setting specific standards expected for safety, sustainability and human health will help researchers and the industry consider these norms early in the development and avoid costly revisions of technology to adapt to late coming regulation. Furthermore, timely regulation can help change consumer perspective of the technology as regulatory standards will help consumers calibrate their expectations and potentially build trust. As mentioned, discussion is required early whether there is a need for new regulation, or whether existing regulation would suffice with some modification.

One area that may prove relevant to take into consideration when looking at policy and regulatory design for 3DFP is the legislation governing 3D printing of medical devices and drugs. The USA Food and Drug Administration (FDA) has invested substantially in research to understand the field in relation to devices, drugs and the printers themselves for legislative purposes. FDA has already indicated that it may not consider 3D printing a traditional manufacturing process such as moulding and CNC milling and there is the possibility that 3D printers need to be considered as stand-alone medical devices. In depth research into 3D printing of medical devices and pharmaceuticals is out of the scope of this research, however it may be a relevant space to consider for further research to inform policy design.